SLAC-481
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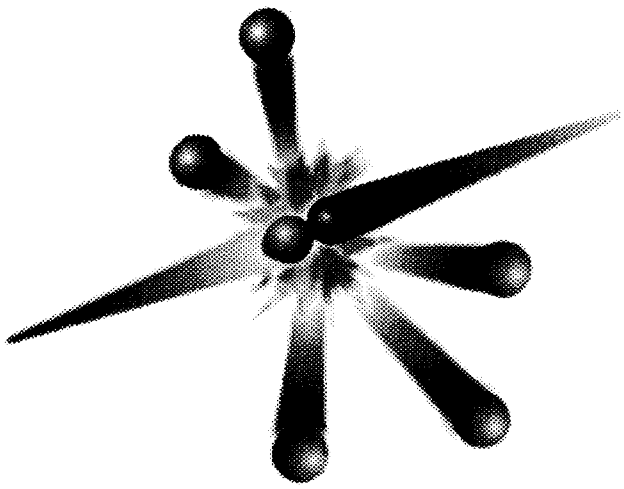
UC-414

1995 Second Modulator-Klystron Workshop

A Modulator-Klystron Workshop for Future Linear Colliders



Organizing Committee:

A.R. Donaldson, Chairman
R.L. Cassel
P.D. Pearce
R. Lai, Workshop Administrator

Stanford Linear Accelerator Center
Stanford University, Stanford, California
Octorber 9–11, 1995

Prepared for the Department of Energy
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Art Credits

The e^- and e^+ collision logo is the work of Terry Anderson, and the workshop photographs are by Dave Ficklin.

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FOREWORD

The first Modulator-Klystron Workshop was held at CERN in October 1991. It focused on improving the operation and reliability of modulator-klystron stations in existing particle accelerators. This second workshop examined the present state of modulator design and attempted an extrapolation for future electron–positron linear colliders. These colliders are currently viewed as multikilometer-long accelerators consisting of a thousand or more RF sources with 500 to 1000, or more, pulsed power systems. The workshop opened with two introductory talks that presented the current approaches to designing these linear colliders, the anticipated RF sources, and the design constraints for pulse power.

The cost of main AC power is a major economic consideration for a future collider, consequently the workshop investigated efficient modulator designs. Techniques that effectively apply the art of power conversion, from the AC mains to the RF output, and specifically, designs that generate output pulses with very fast rise times as compared to the flattop.

There were six sessions that involved one or more presentations based on problems specific to the design and production of thousands of modulator-klystron stations, followed by discussion and debate on the material.

The session leaders were representative of modulator and klystron designers and managers in the accelerator community. This degree of representation extended to 2/3 of the workshop attendees. The other 1/3 represented a commercial-industrial contingent involved in the design and production of modulators, klystrons, thyratrons, pulse transformers and other pulse power components.

A beneficent fraction of the industrial contingent consisting of Triton Services, Inc., Titan-Beta, Stangenes Industries, EEV and EG&G provided financial support for the workshop. Their sponsorship plus financial assistance from SLAC supported the banquet, picnic, and refreshment breaks. Their generosity was the basis for the social success and a significant factor in the general success of the workshop.

The absolute success of this assembly is difficult to gauge. We examined many important issues: efficiency, performance, construction, reliability, diagnostics and the necessity of modulator-klystron integration. But we also left several questions or problems unresolved. The conclusions on the following pages offer an idea of what was answered and what was missed. Our work will eventually have an impact on linear collider design. And even in our design disagreements, we indicated what direction future investigations (workshops and actual research) must take.

The workshop organizers were Dick Cassel, Peter Pearce and the writer. Ruby Lai did a superb job organizing the announcements, invitations, and registration as well as being the editorial assistant. She also arranged and coordinated the entire social scene for the workshop. Justine Mello assisted Ms. Lai with the registration-attendance database and registration. Alfredo Saab merits all credit for proposing SLAC as the site and host.

One other detail requires an explanation. The 1991 workshop was called a Klystron-Modulator Technical Meeting. The workshop organizers have used K-M and M-K indiscriminately. However this writer prefers Modulator-Klystron Workshop. It is an extension of left to right (in to out), from the wall plug, to the power supply, to the modulator and finally to the klystron. This volume is labeled the Second Modulator-Klystron Workshop. I trust that Peter Pearce, the organizer of the first meeting, will excuse me and understand my motive.

A.R. Donaldson

WORKSHOP CONCLUSIONS

A.R. Donaldson

The workshop was divided into six topics or sessions. The topics and session leaders are listed along with abbreviated session conclusions.

1. Klystrons– George Caryotakis, Bob Phillips and Ed Wright [SLAC]
   Klystrons for Linear Colliders
   S , X , or C band
   Modulator-klystron integration

X band klystron performance was presented. Multiple gun structures were also discussed. With X band as the present path, a major klystron issue was lifetime. The klystron designers initially proposed a 20 kHr lifetime, but several attendees realized that with 2000 to 4000 klystrons, a far more practical lifetime would be 50 kHr. Several modulator engineers were annoyed because klystron efficiency was not considered as high a priority as modulator efficiency. Secondary issues concerned perveance control and the possibility of C band devices. Design parameters for optimal modulator and klystron integration were presented.

2. Modulator Efficiency– Dick Cassel [SLAC] and Lou Reginato [LBL]
   Mains to gun pulse efficiency
   Mains power conversion
   Energy storage
   Pulse transformers

The general consensus of the attendees was that 70 to 75% was possible with present technology. Cassel proposed that 80% is possible, but it will require continuing research. He set up an energy/efficiency budget with a 75 Joule loss based on 375 Joules of energy storage. Cassel prefers distributed Blumleins for the PFL. SLAC has been unable to find low inductance (≤ 100 nF), high voltage (≥ 75 kV), capacitors for lumped PFN's. The Blumleins would use oil filled Andrews Heliax© cable. This cable is available in 4 and 5 inch diameters. Various diameters and dielectrics could be selected for various impedances and then connected as cumulative wave lines. Command pulse charging would be utilized.

The modulator would use a thyratron switch and conventional pulse transformer (PT) with a low step up ratio, e.g., 1:6 or 1:7. The PT inductance must be less than 100 μH for a 1 kΩ klystron load. Klystron capacitance can not exceed 100pF. At 100 pF and 500 kV, the required charging energy is 25 Joules. This is 1/3 of Cassel's efficiency budget. The rise time for the switch should be less than 100 ns. The number of PFN sections is dependent on the 100 ns rise time, but this is degraded by any inductance internal to the capacitor. The PT design must limit stray inductance to less than 1 μH for a 10 Ω load.

There was a discussion of PFN/PFL charging with switching power supplies which resulted in a disagreement as to how the manufacturers specify efficiency. The majority of workshop participants felt that switching power supplies should be considered.

The group split into various factions regarding PFN's versus Blumleins. A few participants argued that Blumleins were inefficient and dispersive. Several attendees volunteered that Europeans manufacture low inductance capacitors applicable for high voltage PFN's or lumped Blumleins. Another contingent expressed their reservations of using 150 kV switches to discharge the PFN's and the consequent size of the thyratron and enclosure. The thyratron manufacturers were not concerned about the production or application of 150 kV thyratrons.

3. Modulator Construction– Ron Koontz, Saul Gold [SLAC] and Howie Pfeffer [Fermilab]

Circuit topology for efficiency
Modulator construction for efficiency
Economic constraints to construction
Mass production

This session considered possible modulator designs with an emphasis on a particular design. During the discussion period, participants noted that the stripline inductance would increase because of magnetic coupling between the sections. A shielded line design would eliminate this coupling effect. Modularity was not discussed. Economic issues were mentioned during the discussion. We were unable to focus on the cost issues. This topic will be pursued more aggressively in future workshops. During the conclusions session, Ford and GM were mentioned in passing as examples of "mass production."

4. Modulator Switches

• Thyratrons– John Dinkel [Fermilab] and Gary Wait [TRIUMF]

Representatives of Triton, EEV, EG&G and Litton actively participated in this session. The thyratron manufacturers claimed they could meet the performance objectives and, by employing dispenser cathodes, lifetimes of 50 kHr or greater are achievable. The majority of workshop participants agreed with this conclusion.

• Switch Alternatives– Eugene Vossenberg [CERN]

Pseudo-spark devices and BLT's (Back Lit Thyratrons). These devices cannot be considered as serious alternatives for thyratrons until they meet the lifetime, repetition rate and temporal stability performance of thyratrons.

• Switch Alternatives– Mike Barnes [TRIUMF]

Solid state possibilities. Several solid state devices were discussed. Symmetrical GTO's (Gate Turn-Off Thyristors) offered the best chance of fulfilling the performance criteria. But only one manufacturer presently produces a high voltage, high current, symmetrical GTO.

5. Reliability Session– John Sheppard [SLAC]

Availability and Maintainability. The various Linac system managers from CERN, KEK, POSTECH, and SLAC presented their modulator-klystron system reliability data. They also offered lifetime data for klystrons and thyratrons. CERN accumulated data on six modulator-klystron systems. KEK collected data for 52 systems. POSTECH compiled data for 11 systems and SLAC for 244.

6. Diagnostic Session– Peter Pearce [CERN]

The "smart" modulator. This session focused on modulator/klystron diagnostics. Smart modulator/klystron design is essential for system efficiency and accelerator availability. The design issues can be summarized into three parts:

Maximize system reliability and efficiency
Minimize system diagnosis and reset time
Minimize system repair time

Each issue was discussed in general terms based upon the various laboratories' modulator-klystron experience. CERN's approach to "smart" modulators was specifically discussed, since their diagnostic scheme is actively interfaced to the accelerator control system.

INDUSTRIAL SPONSORS

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The Next Linear Collider RF System

RON RUTH
Modulator workshop
10/7/95

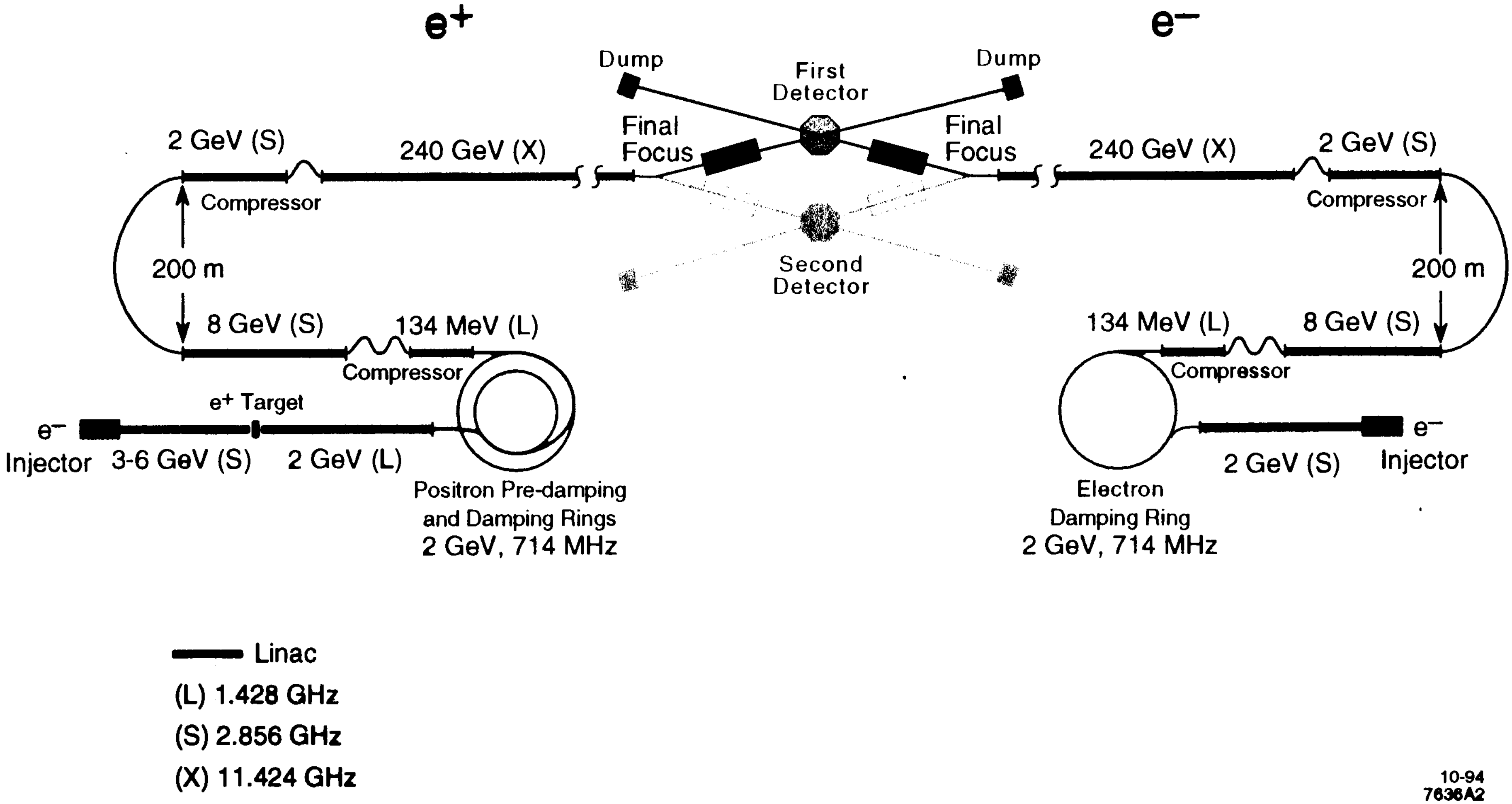
1.) The NLC Overview

2.) Test Facilities

3.) RF System Status

NLC Diagram

not to Scale
(500 GeV c. of m.)



NLC Design Criteria

Collider optimized for 0.5 to 1.0 TeV.
(compatable with few hundred GeV to 1.5 TeV)

First Stage 500 GeV 5×10^{33} cm^{-2} s^{-1}

Proven technology that exists at the outset.

Second Stage 1 TeV $\geq 10^{34}$ cm^{-2} s^{-1}

Expected improvement in rf technology of first stage.

$\Longrightarrow$ Adiabatic upgrade

Expansion 1.5 TeV $\geq 10^{34}$ cm^{-2} s^{-1}

First stage must be compatible with highest energy.
May require (longer) rf development. not necessarily adiabatic

e.g. gridded klystrons
cluster klystrons
TB relativistic klystrons

SPACE IN POST-LINAC REGION
FOR 1.5 TeV c.m. beamline.

Parameters of NLC designs.

CM Energy [TeV]	0.5	1.0	1.5
Luminosity [10^{33}]	7.1	14.5	16.1
Rep. Rate [Hz]	180	120	120
Bunch Charge [10^{10}]	0.7	1.1	1.1
Bunches/RF Pulse	90	75	75
Bunch Sep. [ns]	1.4	1.4	1.4
$\gamma\epsilon_x/\gamma\epsilon_y$ IP [10^{-8} m-rad]	500/5	500/5	500/5
β_x/β_y IP [mm]	10/0.1	25/0.1	37/0.15
σ_x/σ_y IP [nm]	320/3.2	360/2.3	360/2.3
σ_z IP [μm]	100	100	100
Upsilon	0.09	0.27	0.41
Pinch Enhancement	1.3	1.4	1.5
Beamstrahlung δ_B [%]	2.3	7	9
# Photons per e^-/e^+	0.8	1.1	1.1
Loaded Gradient [MV/m]	37	63	63
Active Linac Length [km]	14.2	17.0	25.5
Total Site Length [km]	20.0	25.5	36.2
# of Klystrons	3940	9456	7092
Klyst. Peak Pwr. [MW]	50	72	76
Pulse Comp. Gain	3.6	3.6	6.8
Power/Beam [MW]	4.2	7.9	11.9
AC Power [MW]	103	202	240

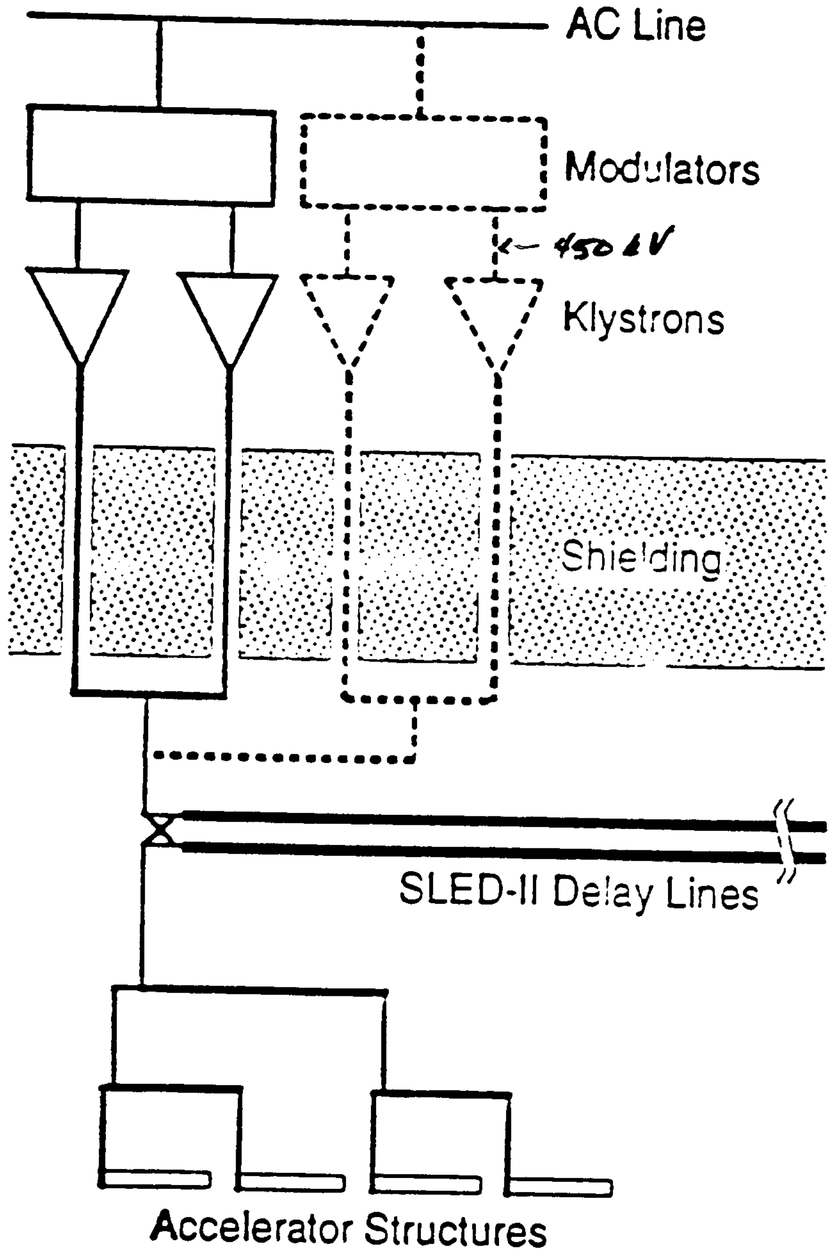
Table 8.1 NLC RF Parameters

	500 GeV TRC Design	1 TeV Upgrade
General Parameters		
RF Frequency (GHz)	11.4	11.4
Accel. Gradient (MV/m) Unloaded /Loaded	50/37	85/63
Active Linac Length (km) (20 GeV inj. + 10% O.H)	14.2	17.0
Total Linac Length (km) (1·1 × Active)	15.6	18.7
No. of 7.2 m RF Units (= No. P.C. Systems)	1970	2364
No. of Modulators (PFN's + thyratrons)	1970	4728
No. of Klystrons	3840	9456
Peak Power/meter (MW/m)	50	145
RF Pulse Length at Accel. Structure Input (ns)	240	220
Repetition Rate (Hz)	180	120
Particles per Bunch (10^{10})	0.65	1.1
No. Bunches/Pulse	90	75
Peak Beam Current (A)	0.74	1.26
RF En./Pulse at Str. Input (J/m)	12.0	31.8
Total Ave. RF Pwr. at Str. (MW)	30.6	64.9
Klystron		
Output Power (MW)	50	72
Pulse Length (μs)	1.2	1.1
Microperveance	0.6	0.75
Electronic Efficiency (%)	60 (sim ≈ 66%)	60 (sim ≈ 64%)
Beam Voltage (kV)	455	480
Beam Energy/Pulse (J)	100	132
Focusing	PPM	PPM
Cathode Loading (A/cm^2)	7.2	7.2
Overall Length (m)	1.3	1.3
Cathode Heater Pwr. (kW)*	(0.4)	(0.5)

NLC RF System
(X – Band)

500 GeV

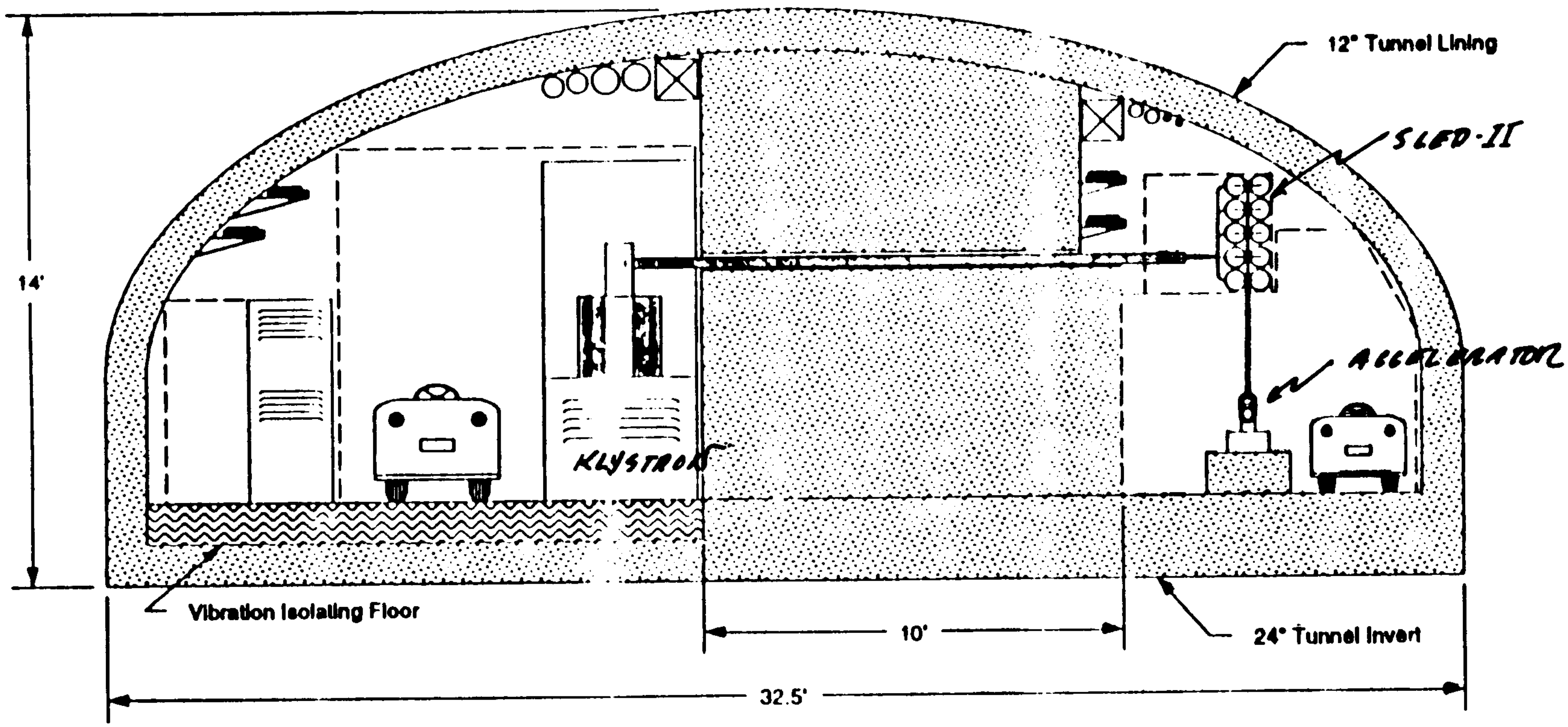
1 TeV



500 GeV	1 TeV
50 MW ✓ 1.2 µs ✓ (55 MW 1.5 µs)	75 MW 1.2 µs
× 3.6 ✓ (× 4.4)	× 3.6
50 MV/m ✓ (70 MV/m (power limited))	85 MV/m

Achieved Parameters

Semi-elliptical Highway Style Tunnel (KEK type)

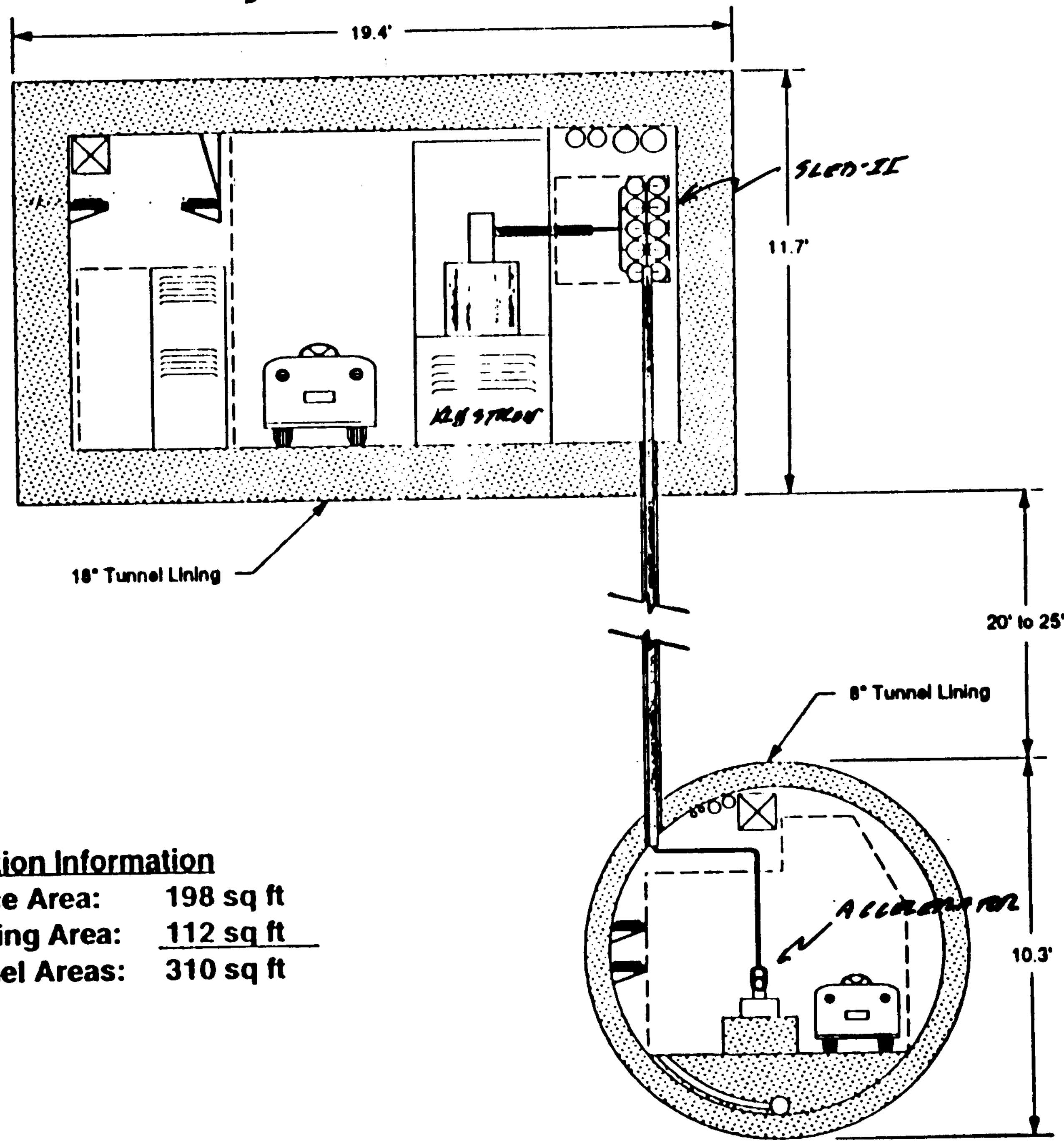


Cross Section Information

Open Space Area:	180 sq ft
Concrete Barrier Area:	103 sq ft
Tunnel Lining Area:	109 sq ft
Total Tunnel Area:	392 sq ft

SPV 3/22/95

Klystron Gallery w/Beamline Tunnel (SLAC type)



Cross Section Information

Open Space Area:	198 sq ft
Tunnel Lining Area:	112 sq ft
Total Tunnel Areas:	310 sq ft

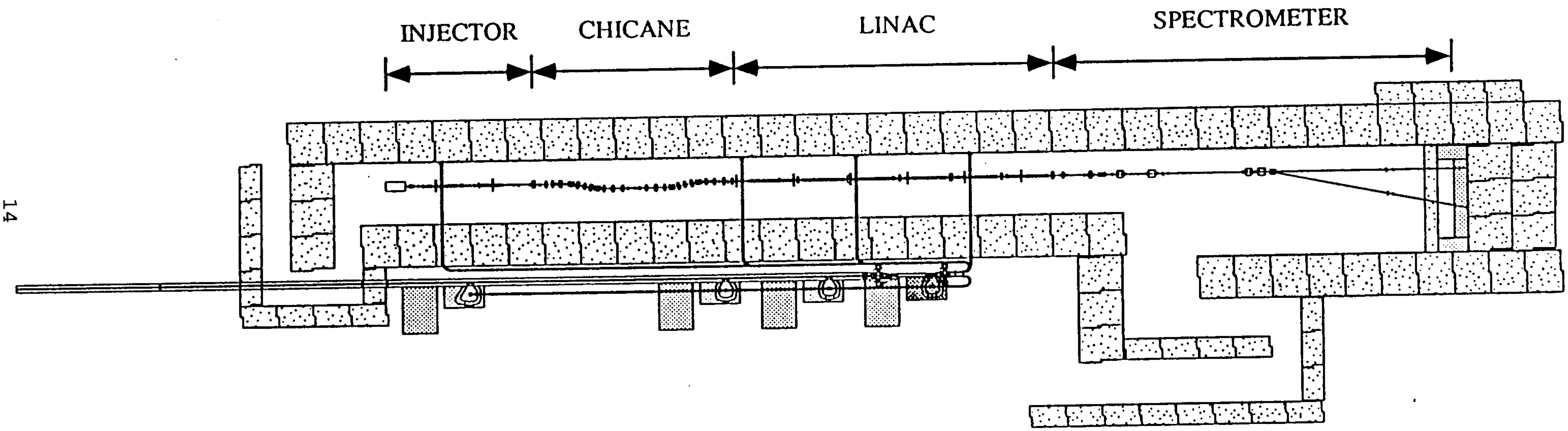
SPV 3/22/95

3

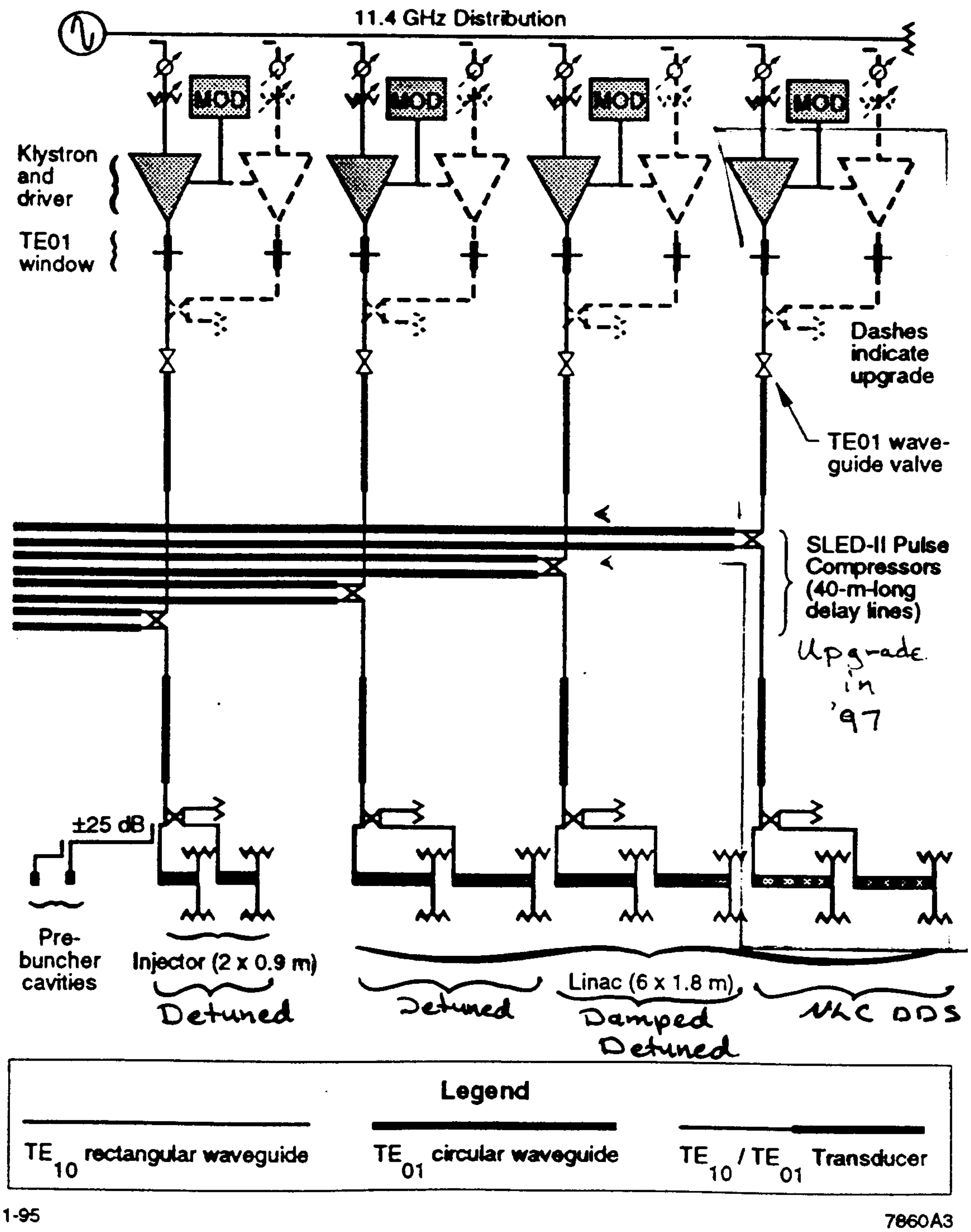
Linear Collider Test Facilities

Facility	Location	Goal	Operations
*SLC	SLAC	Prototype Collider	1988 → 1998
*ATF	KEK	Injector Damping Ring	1995 1996
SBTF	DESY	S-Band Linac	1996
*NLCTA	SLAC	X-Band Linac	1996
TTF	DESY	SuperC. Linac	1995 (Injector) 1997 (Full OPS)
CTF	CERN	2-Beam Linac	1996 (Phase I) 1998 (Phase II)
*FFTB	SLAC INT'L. COLLAB.	Final Focus IP	1994 →
†RTA	LBL	REL. KLYSTRON TWO BEAM ACC.	START 95 END 2000.
VLEPP	BNP	"X"-BAND SINGLE BUNCH	?

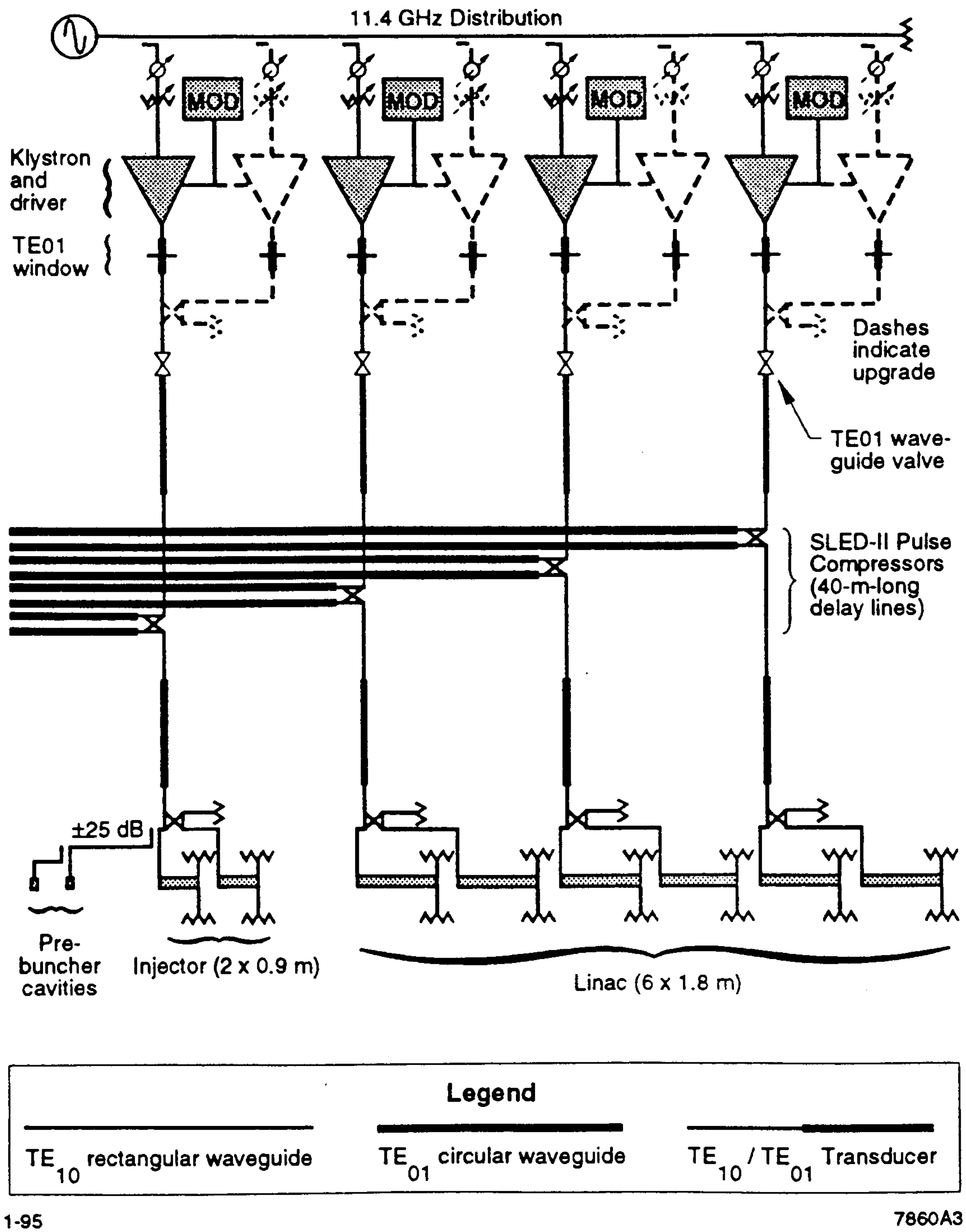
NEXT LINEAR COLLIDER TEST ACCELERATOR
(NLCTA)



NLCTA RF System



NLCTA RF System



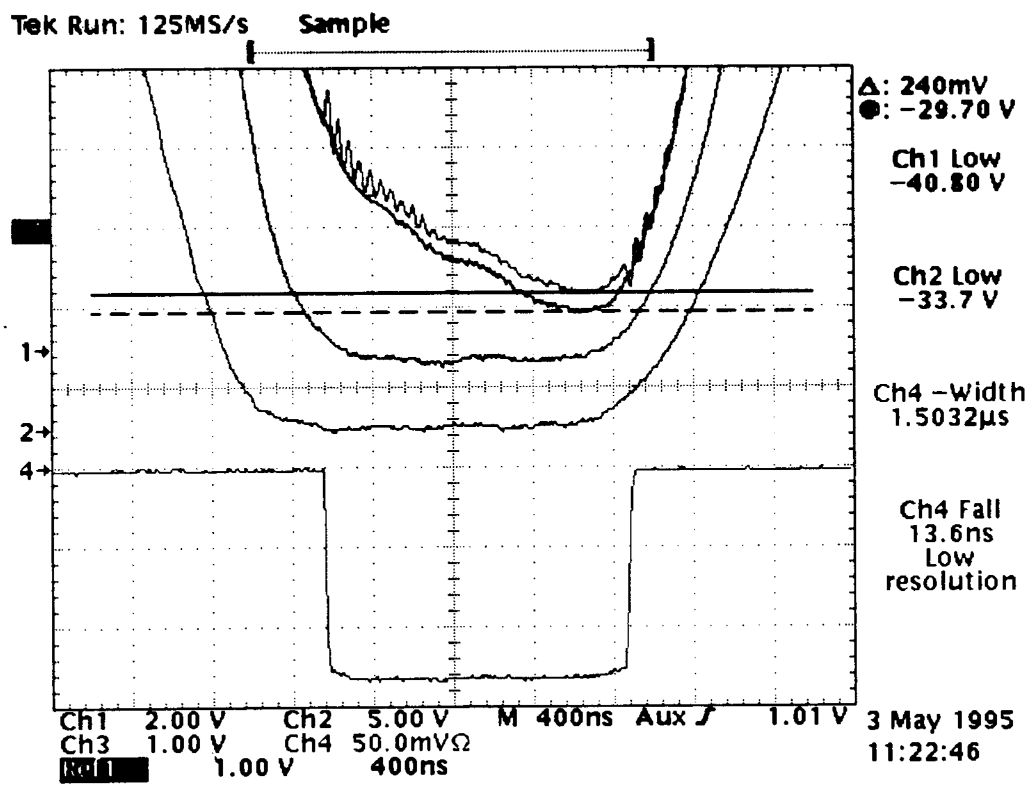
Klystron Status

9/12/95

NLCTA Spec: 50 MW, 1.5 μsec.

- 3 Klystrons operate at NLCTA Spec.
- XL2, XL3 - increased Band Width.
- XL4 to be completed this Fall.
- XL2, XL3, XL4 go to NLCTA.
- PPM Klystron detailed design in progress.

XL3 Klystron Test Data



Legend

Cathode Voltage: 432 kV
Cathode Current: 337 A
Collector Current with rf on (0.8% intercepted current)
Collector Current with rf off
Klystron Output Power: 50 MW (Pin=631 W)

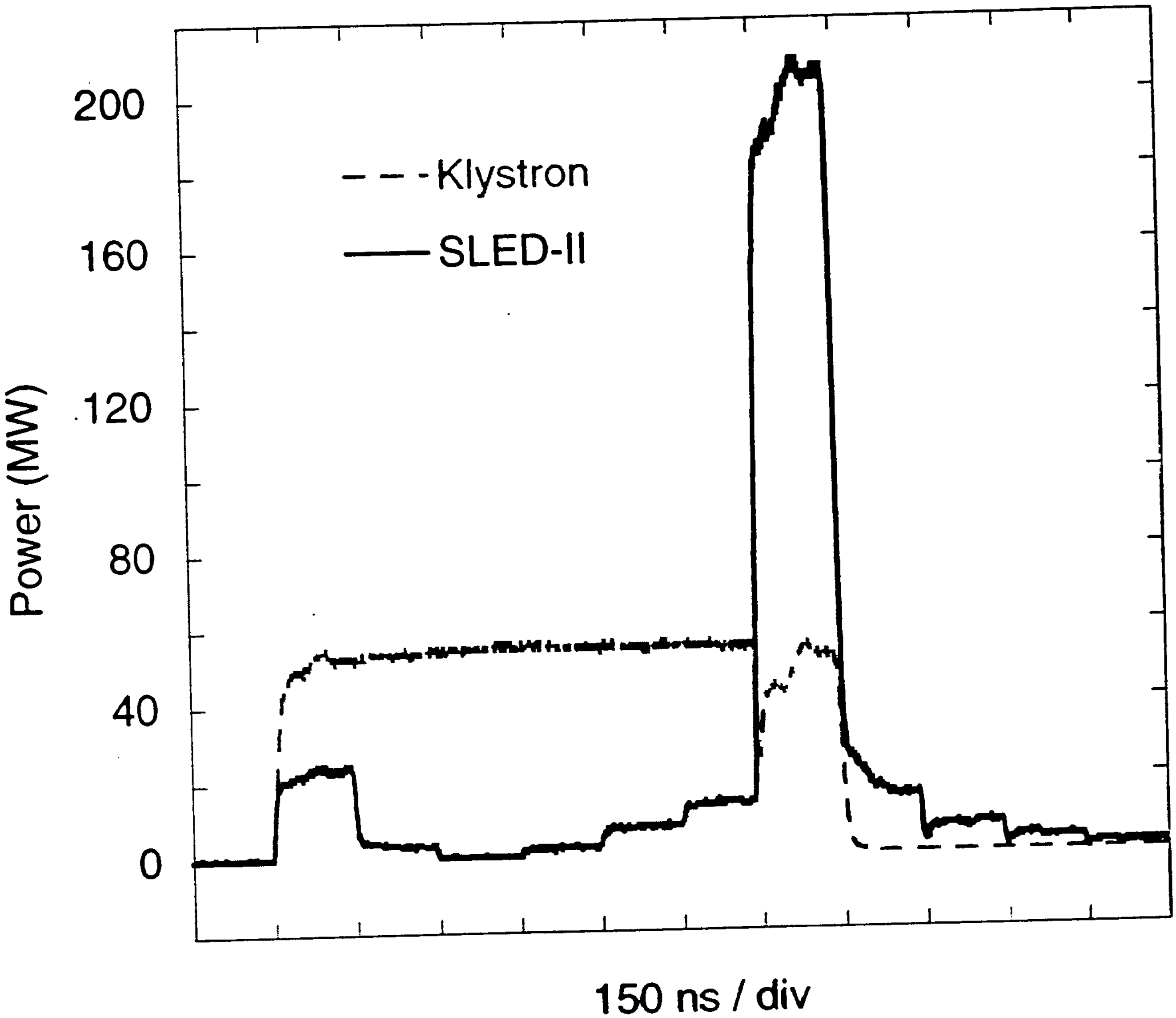
RF Pulse Compression Status

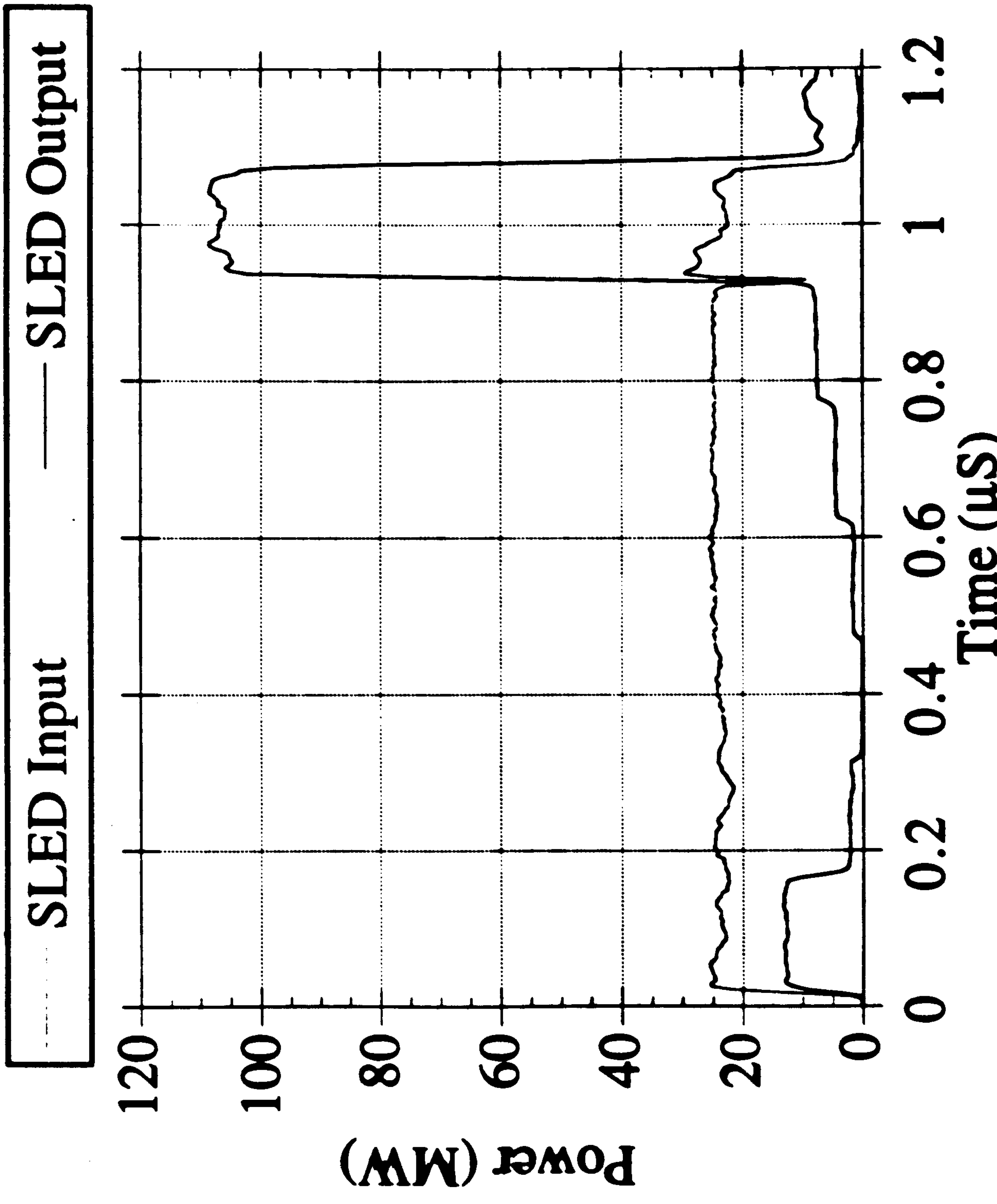
9/12/95

NLCTA Spec: x6 compression
200 MW x 250 ns out

- Prototype SLED II System Tested
  - x6 190 MW x 150 nsec output
  - x7 205 MW x 150 nsec output
- NLCTA production components:
  - detailed design complete.
  - SLED II delay lines machined, ready for flanges
  - RF Transport waveguide machined, ready for flanges
  - Misc parts, mode converters, couplers, bends, tapers in production.

VLCTA SLED-II Prototype





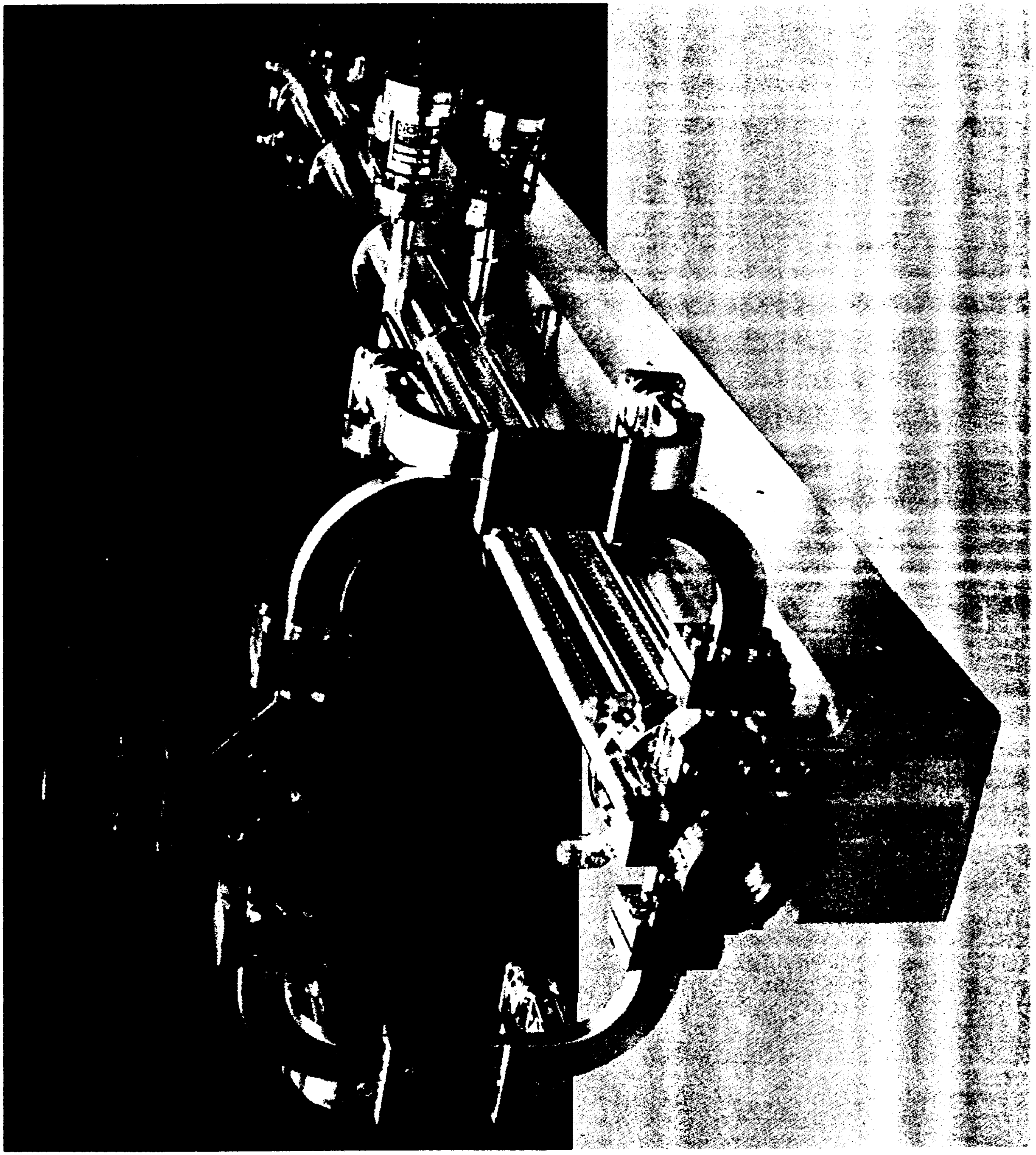
SLED Input
SLED Output
Power (MW)
0
20
40
60
80
100
120
Time (μS)
0
0.2
0.4
0.6
0.8
1
1.2

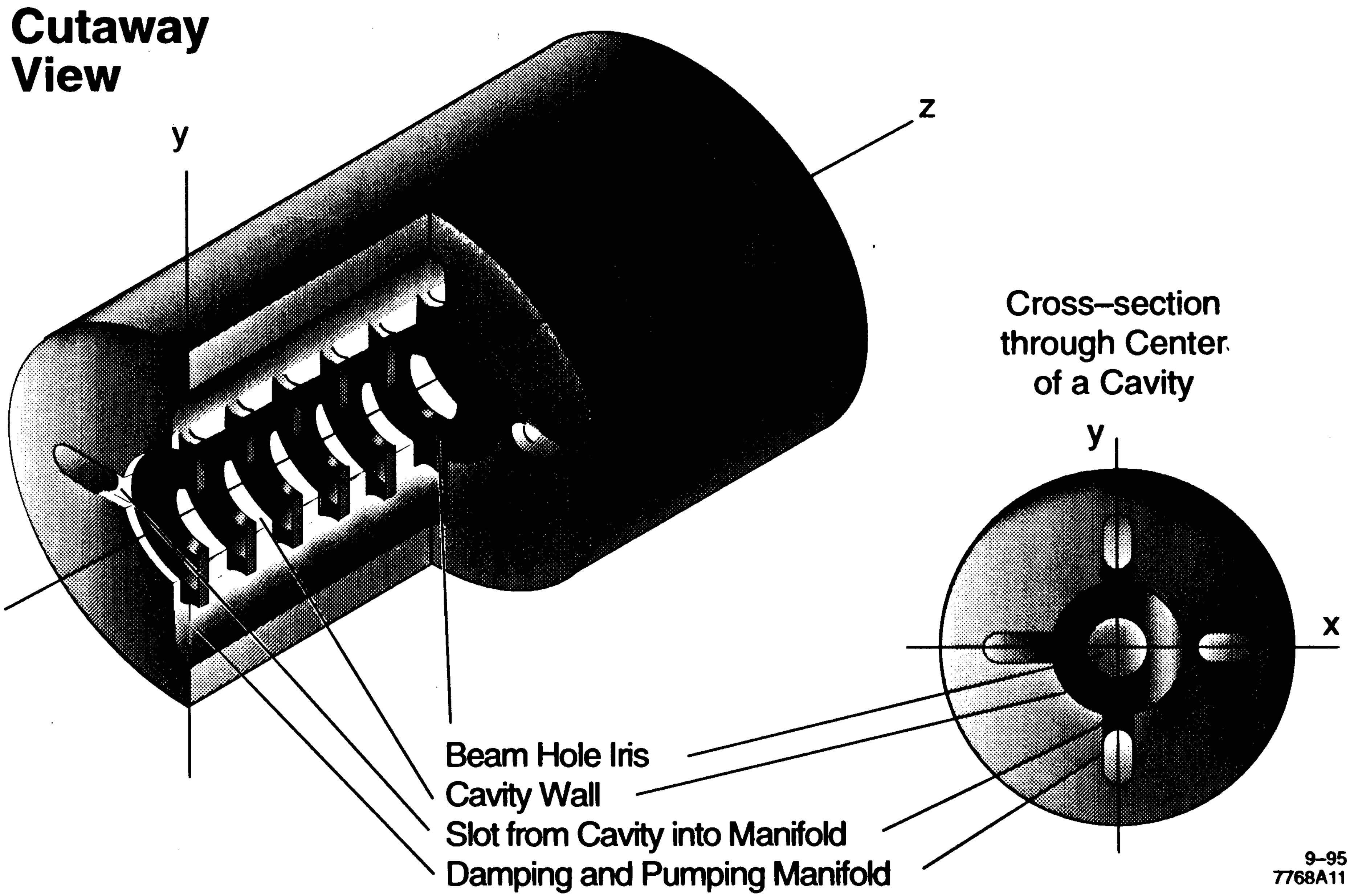
RF Structure Status

9/12/95

NLCTA Spec: 50 MV/m --> 85 MV/m
1.8m Detuned or Damped Detuned Structure

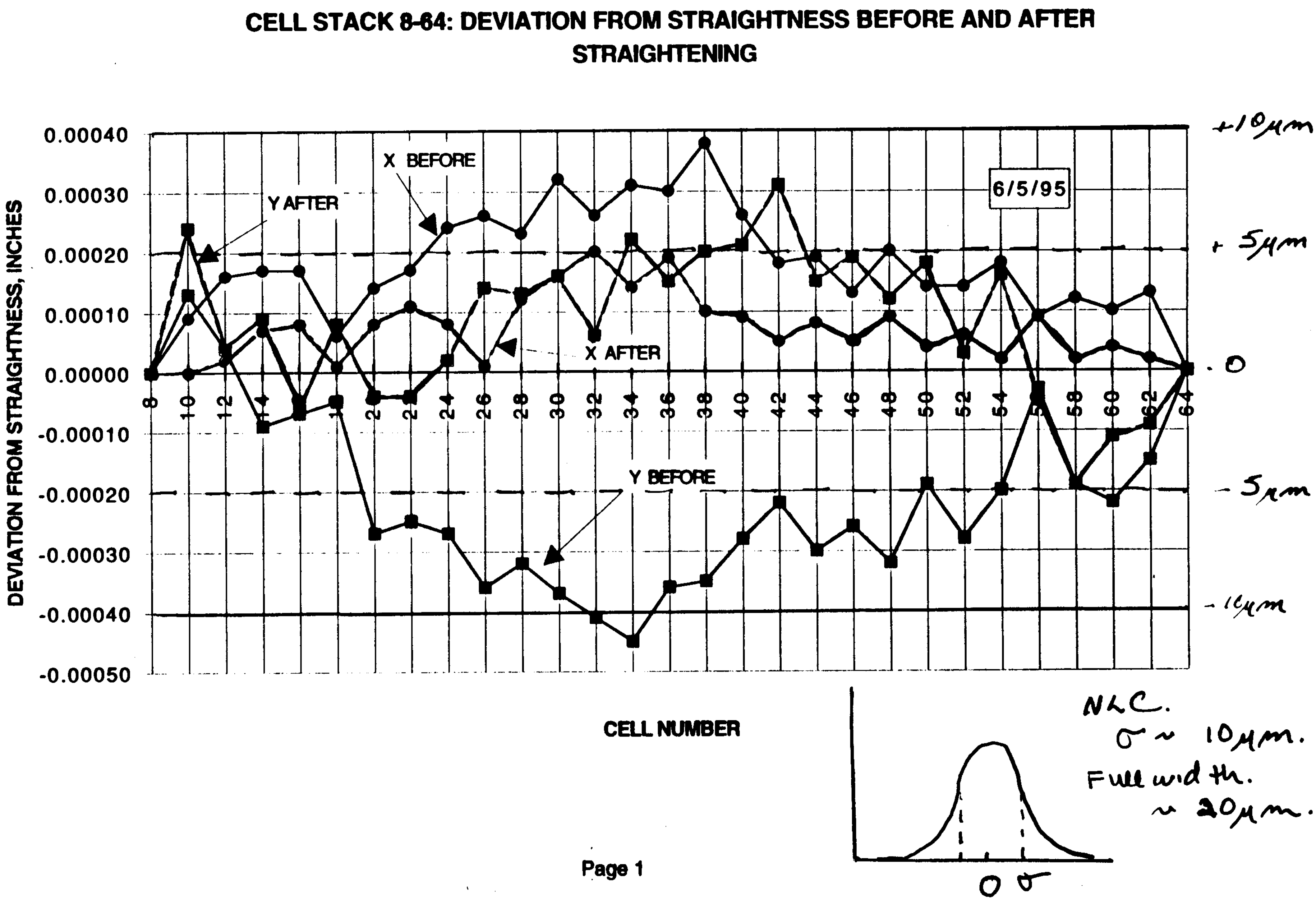
- First Structure:
  - Asset Test Wakefield O.K.
  - High power Test --> 65 MV/m (power limit)
- 400 additional Cells received
  - 200 --> 2 injector structures.
  - short stacks, couplers brazed .
  - 200 --> KEK --> diamond point finish machining.
  - Delivery expected mid September.
- Damped Detuned Structure (DDS)
  - SLAC/KEK collaboration to construct 2 DDS structures.
  - Detailed design in progress
  - First cold test stack tested
  - Remaining 4 cold test stacks due mid September
  - Asset Test scheduled for 6/96




Cutaway View
y
z
Cross–section through Center of a Cavity
y
x
Beam Hole Iris
Cavity Wall
Slot from Cavity into Manifold
Damping and Pumping Manifold
9–95
7768A11

STACK 8-64 STRAIGHTENING

Injector Section — Conventional Machining



Page 1

NLC.
σ ~ 10μm.
Full width.
~ 20μm.

Modulator Status

9/12/95

- 1 of 2 Power Supplies installed.
- First Modulator delivered to NLCTA.
- Check out next two months.
- Remaining Modulators to be installed sequentially.
- Can drive two 75 MW Klystrons

	500 GeV TRC Design	1 TeV Upgrade
Modulator (Blumlein PFN, trans. ratio = 7:1)		
PFN Voltage (kV)	65	68
Rise/Fall Energy Efficiency (%)	80	83
I^2R + Thyratron Loss Efficiency (%)	97	97
Net Energy Transfer Efficiency (%)	77.5	80
$\frac{1}{2}CV^2$, 2 klystrons (J)	258	330
Power Supply Efficiency (%)	93	95
Net Modulator Efficiency (%)	72	76
Thyratron Heater + Res. Pwr. (kW)*	(1.5)	(1.5)
Ave. AC Input Power (kW) (Excluding Aux. Pwr.)	50.0	41.7
Pulse Compression		
Type of P.C. System	SLED-II	SLED-II
Compression Ratio	5	5
Intrinsic Efficiency (%)	80.4	80.4
Loss Efficiency (Delay Lines, Hybrid and 2 F.P.'s) (%)	96	96
SLED-II Efficiency (%)	77	77
SLED-II Power Gain	3.85	3.85
Power Trans. Efficiency (%)	94	94
Net P. C. Efficiency, Incl. Pwr. Trans. Loss (%)	72	72
Net Power Gain	3.6	3.6
Net RF System Parameters		
Total AC Power. (MW) (Excluding Aux. Pwr.)	98	197
RF System Efficiency (%) (Excluding Aux. Pwr.)	31	33
Total Aux. Power (MW)	4.5	12
Total AC Power., incl. Aux. (MW)	103	209
RF System Efficiency, incl. Aux. (%)	30	31
Ave. Beam Power (MW)	8.4	15.9
RF to Beam Efficiency (%)	8.2	7.6

Summary of TRC* Report on Klystron / Modulator Requirements for Future Linear Colliders ☆

P. B. Wilson
Modulator / Klystron Workshop
SLAC Oct. 9, 1995

* TRC = Technical Review Committee
☆ Mainly 500 GeV c.m. designs

The TRC Report

Development and Advances in Conventional

High Power RF Systems*

Perry B. Wilson

SLAC

Presented at the 1995 Particle Accelerator Conference, Dallas, Texas

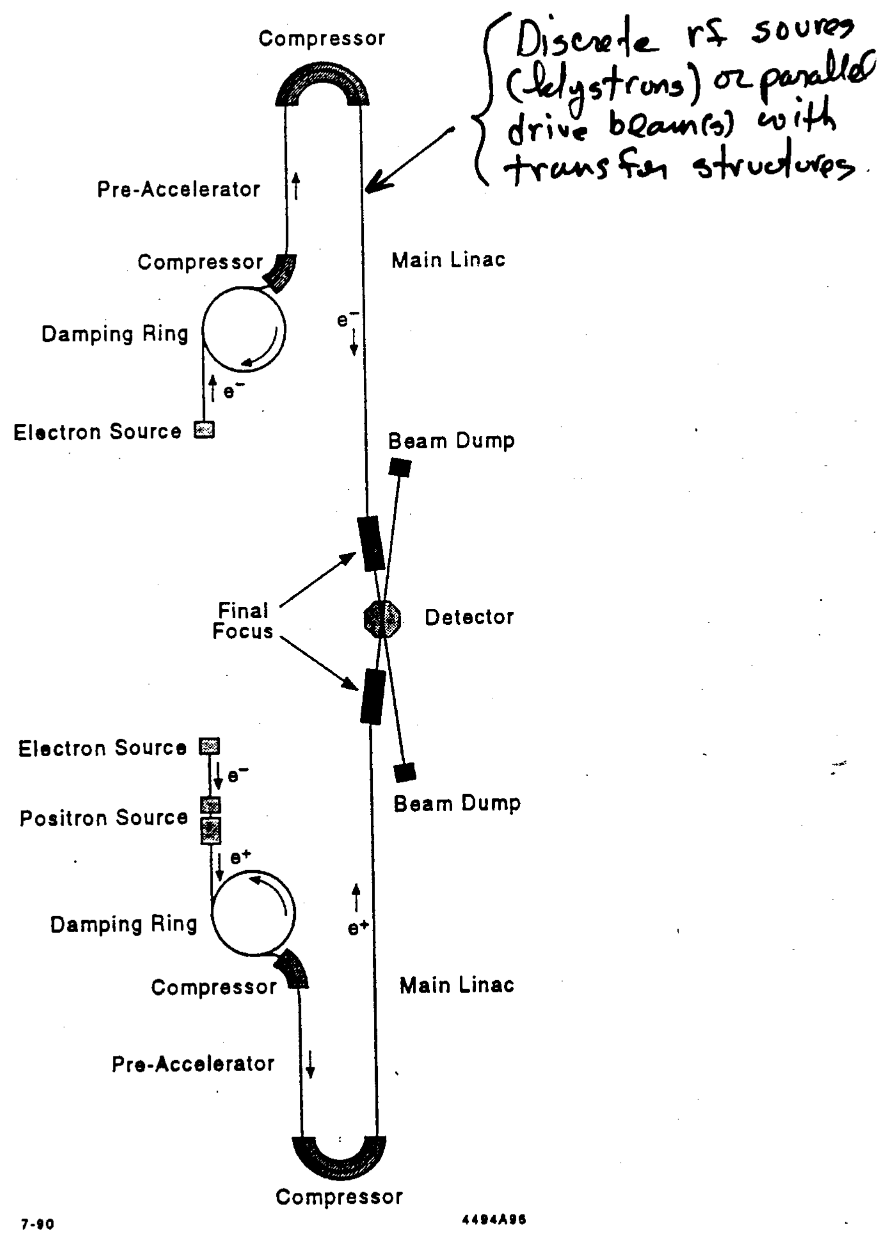
May 5, 1995

There now exists an *International Collaboration for R&D Toward TeV-Scale Electron-Positron Linear Colliders*. At EPAC'94, the Council of the Collaboration appointed a Technical Review Committee (TRC), charged with preparing a report on the status of linear collider technology and the progress to be expected by further R&D over the next few years. The report is to be submitted to the Collaboration Council shortly after ☆ the LC'95 meeting (Tsukuba, Japan, March 27-31, 1995). This talk is based in large part on material collected for Chapter ~~3~~ 8 & 3 (Linac Technology) of the TRC report.

* Mainly for linear colliders
But also: compact injectors for storage rings, FELs, ----

☆ Maybe October 1995

Typical Linear Collider Layout



MEET THE PLAYERS

500 GeV Center-of-Mass Linear Collider Proposals
Potential upgrades to 1-1.5 TeV

TESLA (TEV Superconducting Linear Accelerator) 1.3 GHz

International collaboration coordinated by DESY, Hamburg, Germany

[SLC (SLAC Linear Collider) 2.856 GHz
100 GeV c.m. test bed for future Linear Colliders]

SBLC (S-Band Linear Collider) 3.0 GHz

DESY, Hamburg
Exploits existing S-Band technology (SLC)

JLC (Japan Linear Collider) 11.4 GHz

KEK, Tsukuba, Japan
Close collaboration with NLC
Also considering S-Band, C-Band

NLC (Next Linear Collider) 11.424 GHz (4 x SLC)

SLAC -----

TBNLC (Two-Beam NLC) "

Proposed by LBL, LLNL
Alternate rf source for NLC
Drive beam powered by induction linac modules

VLEPP (Colliding Linear Electron Positron Beams)

BINP (Branch, Inst. Nucl. Phys. (Novosibirsk))
but at Protvino (Serpukhov), Russia 14 GHz

CLIC (CERN Linear Collider) Geneva, Switzerland

Two-beam accelerator, drive beam accelerated by superconducting cavities 30 GHz

Some Basic Scaling Relations for Linear Colliders

Dark current capture threshold

* $G_{th}\,\lambda_{rf} = 1.60$ MV
  $G_{th} \sim \omega$

	Collider Proposal	RF Frequency (GHz)	G_{th} (MV/m)	Design G* (MV/m)
SC	TESLA	1.3	7	25-40
Cu	SLC	2.856	15	20
Cu	SBLC	3.0	16	17-34
Cu	JLC/NLC	11.4	61	53/(37-63)
Cu	VLEPP	14	75	91
Two Beam	(TBNLC)	(11.4)	61	75
Two Beam	CLIC	30	160	78

* Beam loaded; 0.5-1.0 TeV

$(\text{Energy})^{1/2}$ decrement time

$$T_D = \frac{2Q_0}{\omega} \sim \omega^{-3/2}$$

(Cu) Machine	Frequency (GHz)	T_D (ns)
SBLC	3.0	1400
JLC/NLC	11.4	200
VLEPP	14	135
CLIC	30	45

Stored energy per unit length

$$U_m \sim G^2 \lambda^2 \cdot [f(a/\lambda)] \qquad f(a/\lambda) \sim \omega^{1/6}$$

* For $G\lambda = \text{const}$ $\qquad U_m = \text{const}$
  $[U_m \sim \omega^{1/6}]$

Peak power per meter

$$\hat{P}_m \sim \frac{U_m}{T_0} \sim G^2 \omega^{-1/2} \cdot [f(a/\lambda)]$$

* For $G\lambda = \text{const}$:

$$\hat{P}_m \sim \omega^{3/2}$$

$$\left[\hat{P}_m \sim \omega^{1.67}\right]$$

Machine*	Design*: $\hat{P}_m$ (MW/m)	Scaled: $\hat{P}_m \sim \omega^{1.6}$ (MV/m)
TESLA	0.2	—
SBLC	12	12
JLC/NLC	100/50	112
VLEPP	120	157
CLIC (TBNLC)	144 200	560 112

* 0.5 TeV c.m.

Active linac length

$$L_{linac} \approx 1.1 \frac{E_{c.m.}}{G}$$

* For $G\lambda = \text{const}$:

$$L_{linac} \sim E_{c.m.} \lambda$$

$$\left[L_{linac} \sim E_{c.m.} \lambda^{5/6}\right]$$

Average AC power

$$\bar{P}_{AC} \sim \frac{f_{rep} U_m L_{linac}}{\eta_{rf}}$$

* For $G\lambda = \text{const}$:

$$\bar{P}_{AC} \sim \frac{f_{rep}}{\eta_{rf}} \cdot E_{c.m.} \lambda$$

$$\left[\bar{P}_{AC} \sim \frac{f_{rep}}{\eta_{rf}} \cdot E_{c.m.} \lambda^{5/6}\right.$$

TRC report

Table 2.3.1

General RF Design Parameters for Main Linac

	TESLA	SBLC	JLC	NLC	TBNLC	VLEPP	CLIC
RF frequency (GHz)	1.3	3.0	11.4	11.4	11.4	14	30
Accelerating Gradient Unloaded/Loaded (MV/m)	25/25	21/17	73/53	50/37	100/74	100/91	80/78
Active Linac Length[1] (km)	20	30.2	9.5	14.2	7.1	5.8	6.3
Total Linac Length[2] (km)	29	33	10.3	15.6	7.8	7.0	9.4
Peak Power per Meter (MW/m)	0.206	12.2	100	50	200	120	144
Structures per Power Unit	32	2	4	4	1	4	2
Structure length per PU (m)	33.2	12	5.2	7.2	1.8	4.0	0.56
Total Number of Power Units[3]	604	2517	1804	1970	3938	1400	11233
Total Number of Klystrons	604	2517	3608	3940	—	1400	—
Total Number of Modulators[4]	604	2517	3608	1970	26	140	2
Repetition Rate (Hz)	10	50	150	180	120	300	2530/ 1210
RF Pulse Length at Str. (μs)	1315	2.8	0.23	0.240	0.242[5]	0.11	.0116
Peak Beam Current[6] (A)	.0083	0.30	0.80	0.74	1.49	SB	SB/1.94
Total Ave. RF Pwr. at Str. (MW)	54	51.6	32.4	30.5	41	22	26.5

1) Active length = [(500 GeV - 2 × injection energy)/(loaded gradient)] × [factor for BNS damping and energy management].

2) Total linac length = Active length plus allowance for beam line components, including cryostat.

3) Number of power units = number of klystrons for TESLA, SBLC and VLEPP, = number of pulse compression units for JLC and NLC, = number of transfer structures for TBA and CLIC. For VLEPP there are two pulse compressors per power unit.

4) Number of drive beams for TBA and CLIC and number of high voltage sources (supermodules) for VLEPP.

5) Equivalent length for a rectangular pulse.

6) SB = single bunch acceleration.

Summary

RF System Efficiencys and AC Power Requirements: 500 GeV Machine Design Goals

		η_{Kly}	η_{Mod}	$\eta_{p.c.} + \eta_{trans}$	$\eta(net)_{rf}$ *	Total AC Power	η AC→Beam Pwr
SC	TESLA	70%	86%	96%	35%	155 MW	21
Cu	SBLC	50	80	97	37	139	10
Cu	JLC	45	82	95	30	114	6
Cu	NLC	60	72	72	30	102	7
Cu	VLEPP	60	95 (3)	70	39	57	8
TBA	TBNLC	92 1)	44 2)	98	39	106	17
TBA	CLIC	75 1)	55 2)	90	26	100	2/8
	SLC	45	60	61/88	14.5	24	0.3

* Includes cryogenic and auxiliary power

1) Conversion of drive beam power to RF

2) Drive beam production efficiency

3) Gridded Klystron

Comments

① These are paper numbers with varying degrees of conservatism. ∴ $\eta_{rf} \approx 1/3$ for all machines. With further R&D, can improve to $\eta_{rf} \approx 40-50\%$

② P_{AC} correlated with λ_{rf} ($\sim \lambda^{2/3}$) for Cu machines. But correlation not very stable

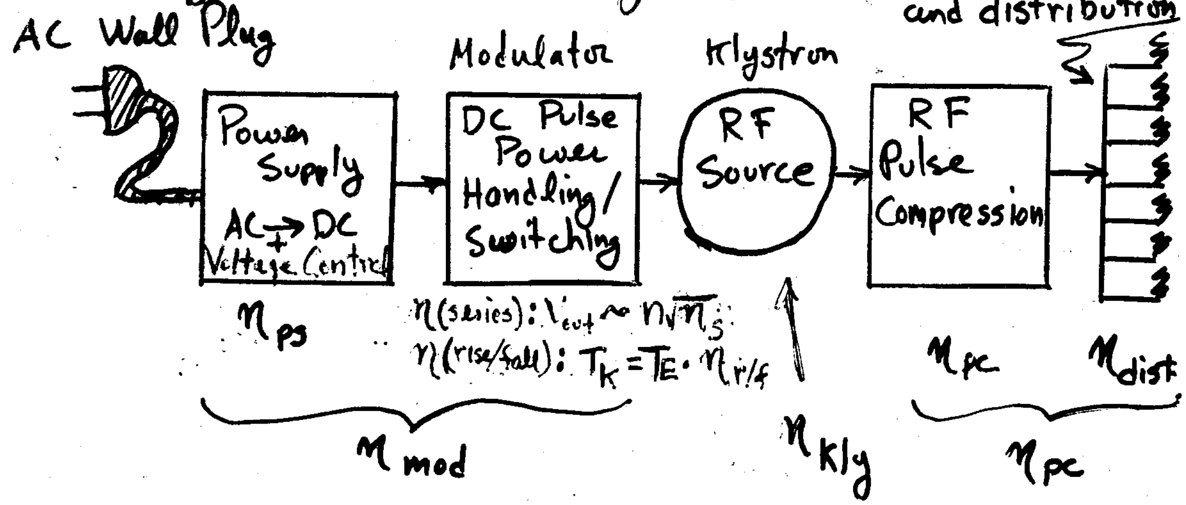
Efficiency is a primary concern for a linear collider

For $P_{AC} = 100$ MW:

50 - 51% ⟶ - 2 MW

70 - 71% ⟶ - 1½ MW

RF System Efficiency



Trade-offs:

No RF PC (crossed out) $\Rightarrow$
- More $\hat{P}$ from RF source
- More DC pulse compression
- Lower η_{mod}

Higher η_{Kly} $\Rightarrow$
- Lower K_μ (Microperveance)
- Higher V_{Beam} *
- Higher n_{turns} and/or higher V_{DC}
- Lower η_{mod} and/or higher costs

* or go to extended beam / multiple beam source

There are losses and inefficiencies at each stage in this power handling and processing chain. If you beat down the losses / inefficiencies in one stage, take care that it is not at the expense of increased loss in another stage of the chain.

TRC Table 2.3.3

Beam switched by grid ↓ (VLEPP)

Klystron Parameters: Design Goals and Achieved to Date

	TESLA		SBLC		JLC		NLC		VLEPP	
	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d
RF Frequency (GHz)	1.3	1.3	3.0	3.0	11.4	11.4	11.4	11.4	14	14
Peak Output Power (MW)	7.1	5.0	150	150	135	96/50	50	58/52 *	150	60
Pulse Length (μs)	1314	2010	2.8	3	0.5	0.1/0.2	1.2	0.2/1.5	0.50	0.7
Repetition Rate (Hz)	10	10	50	60	150		180	60	300	2
Ave. Output Power (kW)	93		21	27	10		11	1/5	24	
Microperveance	0.5[1)]	2.0	1.2	1.8	1.2	1.2	0.6	1.2	0.25	0.15
Electronic Efficiency (%)	70	45	50	42	45	33	60	43/37	60	40
Scaled Max. Efficiency[2)] (%)	73	50	62	53	62	62	71	62	76	78
Beam Voltage (kV)	110	130	575	528	600	620	455	400	1000	1000
Beam Energy per Pulse[3)] (J)	13,300	10,100	840	1070	150	170	100		125	
Cathode Loading (A/cm^2)			6	6	13.5	13.5	7.4	7.6.	5	5
Cathode Heater Pwr. (kW)	0.5		1	2	0.5	0.5	0.4		1.0	1.0
Focusing Type	Sol.	Sol.	PPM	Sol.	SCM	Sol.	PPM	Sol.	PPM	PPM
Solenoid Power (kW)	4	4	—	15 +	1	40 +	—	≈ 20 +	—	—
Output Window Type	Coax	Pillbox	Pillbox	Pillbox	TE_{11} TW	TE_{11} $\lambda/2$	TE_{01} * TW	TE_{01} SW	TE_{11} TW	TE_{11}
No. of Windows/Klystron	1	1	2	4	2	2	1	1	2	2
Overall Length (m)		2.0	2.5	2.5	1.5	1.5	1.3	1.3	1.46	1.46

1) Perveance per beam in multibeam klystron.

2) η (Max) ≈ 0.80-(0.15 × Microperveance).

3) In flat-top portion of pulse.

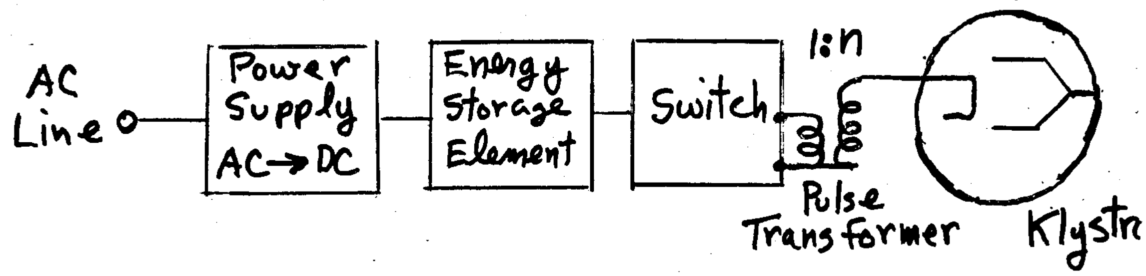
* Tested to > 100 MW @ 1 μs in resonant ring

+ Replace with PPM (periodic permanent magnet) or SCM (superconducting magnet)

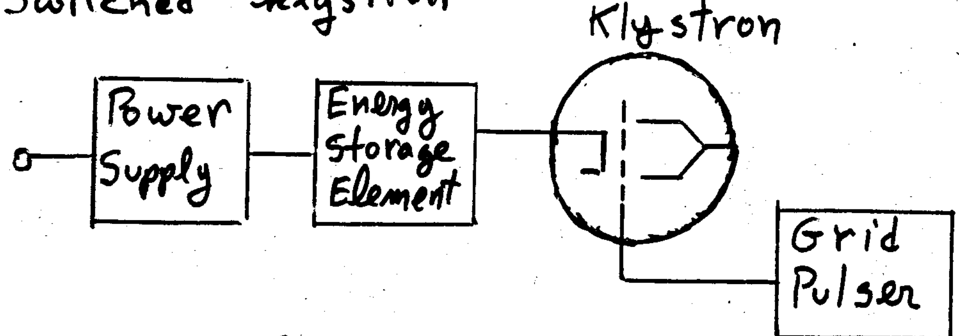
* three tubes > 50 MW to date

Modulator Technology

Standard modulator (e.g. SLAC: 240 mod's x 30 years



Grid-Switched klystron

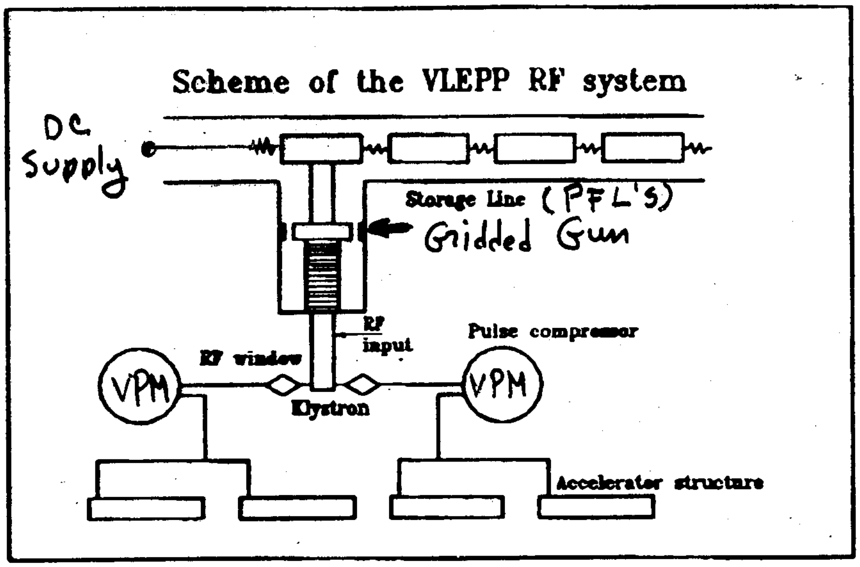


Machine	Pulse Length (μs)	Energy Storage Element	Switch	Pulse X former 1:n	Energy Efficiency* η_E
TESLA	1300	Capacitor	Thyristor	1:12	0.99
SBLC	2.8	PFN	Thyratron	1:18	0.70
JLC	0.5	x2 PFN	Thyratron	1:5	0.79
NLC	1.2	x2 PFL	Thyratron	1:7	0.81
VLEPP	0.5	PFL	Kly. Grid	—	>0.95 ?

* For Puls Trans. (scale

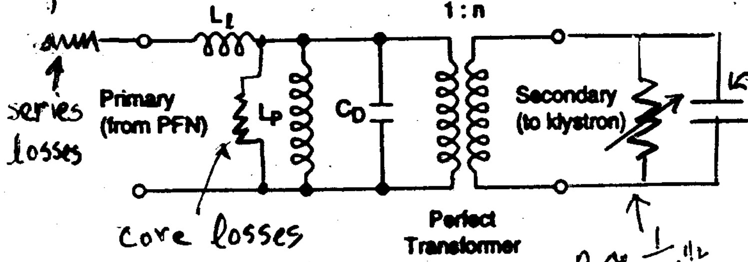
PFN = Pulse Forming Network (lumped elements)
PFL = Pulse Forming Line (smooth transmission line)

PFN: $V_{out} = \frac{n}{2} V_{PFN}$ x2 PFN = Blumlein: $V_{out} = n V_{PFN}$

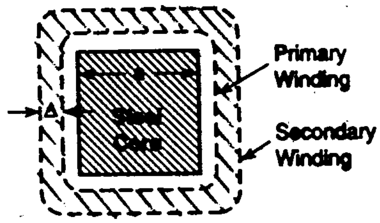


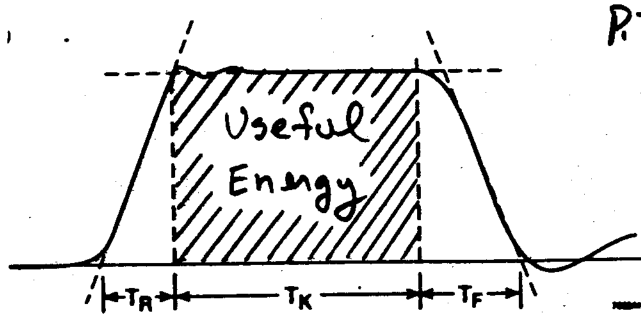
VPM = VLEPP Power Multiplier

Pulse Transformer Efficiency



C_K = Kly. Capacitance
C_D = P.T. Distributed Cap.
L_ℓ = P.T. Leakeage Induct.
L_p = Primary Ind. (Droop)





P.T. Energy Efficiency:

$$\eta_E \equiv \frac{\text{Useful Energy}}{\text{Total pulse Energy}} = \frac{T_K}{T_K + c_1 T_R + c_2 T_F + c\ldots}$$

$$\eta_E \equiv \frac{T_K}{T_E} \approx \frac{T_K}{T_K + \alpha T_R}$$

$\alpha \approx 1.1$ Depends on definition of rise time and flat top

Rise Time

$$T_R \sim \frac{1}{\omega(L_\ell, C_D)} \sim (L_\ell C_D)^{1/2}$$

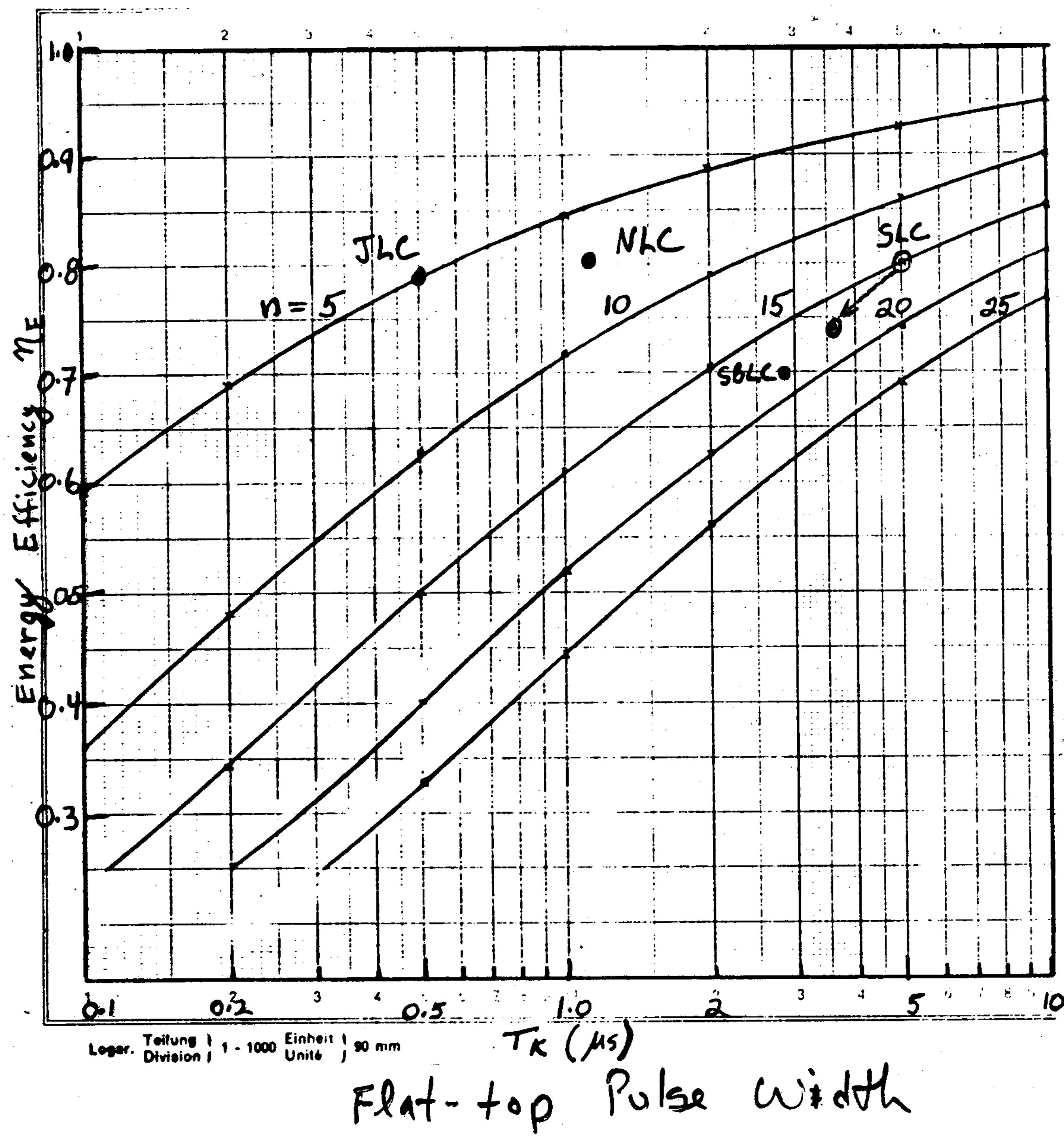
$$L_\ell \sim n^2 \cdot 4a \cdot \Delta \; ; \; C_D \sim 4a \cdot \frac{1}{\Delta}$$

$T_E \sim$ volt seconds $\sim$ core area $= a^2$

$$T_R \sim na \sim n T_E^{1/2}$$

Pulse Transformer Energy Efficiency
(as a function of n, T_K)

Scaled



TRC - Table 2.3.4

Modulator Parameters: Design Goals and Achieved to Date

	TESLA		SBLC		JLC		NLC		VLEPP	
Modulator Type[1]	Storage cap. with bouncer		PFN		Blumlein PFN		Blumlein PFL		Gridded Gun	
	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d[5]	Design	Ach.'d
Flat Top Pulse Length, $T_k(\mu s)$	1314	2010	2.8	3.0	0.5	0.7	1.2	1.5	0.50	0.50
PFN Voltage (kV)	9	10	65	43	120	80	68	45	1000	960
Transformer Ratio n	1:12	1:13	1:18	1:23	1:5	1:7	1:7	1:20	—	—
Rise/Fall Energy Efficiency (%)			86.5	≈ 65	89	70	80	≈ 60		
Scaled Energy Efficiency[2] (%)	99	—	70	65	79	70	81	58	—	—
I^2R/Thy./Core Loss Efficiency (%)			97	95	97		97			
Energy Stored on PFN[3] (J)			1000	1650	174		258			
Power Supply Efficiency (%)			95	90	95		93	≈ 90		
Mod. Eff. without Aux. Power (%)			79.5	≈ 60	82		72	≈ 52	95	
Auxiliary Power[4] (kW)			1.5	3	1.5		1.5	1.5	0.3	
Net Modulator Efficiency (%)	86	86	77.5	59	80		70		92.5	5
Ave. AC Input Power (kW) (Including Auxiliary Power)	155		54.2	88	29		51.5		40.5	

1) PFN = lumped element pulse forming network; PFL = pulse forming line (transmission line).

2) See text.

3) Energy switched per pulse from storage element for TESLA and VLEPP.

4) Includes thyratron cathode heater, reservoir heater and other control power.

5) Standard (not Blumlein) PFN.

Efficiency (100–200 MW AC power

Cost (Large numbers: 600 – 4000)

Reliability (operating cost)
and physics production!

SLAC-PUB-95-6957
June 1995

Development And Advances In Conventional High Power RF Systems*

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The development of rf systems capable of producing high peak power (hundreds of megawatts) at relatively short pulse lengths (0.1-5 microseconds) is currently being driven mainly by the requirements of future high energy linear colliders, although there may be applications to industrial, medical and research linacs as well. The production of high peak power rf typically involves four basic elements: a power supply to convert ac from the "wall plug" to dc; a modulator, or some sort of switching element, to produce pulsed dc power; an rf source to convert the pulsed dc to pulsed rf power; and possibly an rf pulse compression system to further enhance the peak rf power. Each element in this rf chain from wall plug to accelerating structure must perform with high efficiency in a linear collider application, such that the overall system efficiency is 30% or more. Basic design concepts are discussed for klystrons, modulators and rf pulse compression systems, and their present design status is summarized for applications to proposed linear colliders.

I. INTRODUCTION

There now exists an *Interlaboratory Collaboration for R&D Toward TeV-Scale Electron-Positron Linear Colliders*. The collaboration consists of some 23 member institutions in Europe, Asia and the United States with an interest in linear collider development. The Council of the Collaboration (consisting of one representative from each member institution) met at EPAC'94, and decided to appoint a Technical Review Committee (TRC). This committee was charged with preparing a report on the present status of linear collider technology, and the further R&D needed over the next few years to reach these design goals: an initial luminosity in excess of $10^{33}cm^{-2}s^{-1}$ at a center-of-mass energy of 500 GeV, with the capability of being expanded in energy and luminosity to reach 1 TeV center-of-mass energy with a luminosity of $10^{34}cm^{-2}s^{-1}$. A draft of the report will be submitted to the Collaboration Council in June, 1995. This paper is based in large part on material collected for Chapter 3 (Linac Technology) of the TRC report.

The major proposals for future linear colliders have been described in detail elsewhere (see for example the survey talks in [1]). TESLA (TeV Superconducting Linear Accelerator) is a proposal for a linear collider based on the use of superconducting accelerating cavities at 1.3 GHz. The TESLA R&D program is an international collaboration of about a dozen laboratories, coordinated by the DESY laboratory in Hamburg, Germany. Use of a superconducting cavity avoids the need for very high peak rf power. Such a cavity is in essence an rf pulse compressor, storing energy over a relatively long time period (on the order of a millisecond) from an RF pulse with a relatively low peak power. An advantage of the low TESLA rf frequency is a larger beam cross-section and looser tolerances on construction and alignment. The SBLC (S-Band Linear Collider) is a proposal, also based at DESY, for a linear collider with an rf frequency of 3 GHz. Because of the relatively low rf frequency, the SBLC also has comparatively loose tolerances. A strong point of this proposal is that it is supported by a wide base of existing S-band accelerator technology, in particular the SLC prototype linear collider at SLAC. The NLC (Next Linear Collider) is a proposal by SLAC for a linear collider at 11.4 GHz, exactly four times the SLC frequency. The principal advantage of a higher rf frequency is that a higher accelerating gradient can be obtained for the same ac input power, resulting in a shorter length and possibly lower cost for the main linac. A major disadvantage is that tighter tolerances are required for the construction and alignment of the accelerating sections and focusing magnets. Also, higher peak power is required from the rf sources, with a consequence that some form of rf pulse compression is necessary. The KEK laboratory in Tsukuba, Japan, has proposed the JLC (Japan Linear Collider), also at 11.4 GHz; it is quite similar to the NLC in its main design parameters. VLEPP (standing for "Colliding Linear Electron-Positron Beams" in Russian) is a proposal for a linear collider at 14 GHz, which originated at the Institute of Nuclear Physics (INP) in Novosibirsk, Russia. The R&D for the collider is actually taking place at Protvino, Russia, near Serpukhov (about 100 km south of Moscow). It is being carried out by personnel from a Branch of the above institute (BINP). Unfortunately, the economic situation in present-day Russia is such that a full-scale VLEPP will probably not be funded. However, a strong R&D program is still going forward at Protvino; this work will provide useful results which can expedite the other collider programs. CLIC (CERN Linear Collider) is a proposal for a two-beam linear collider based at CERN in Geneva, Switzerland. In the CLIC design (see paper by K. Hübner in [1]), 350 MHz superconducting cavities are used to accelerate a high-current drive beam to 3 GeV. The drive beam consists of trains of bunches in which the spacing between bunches in each train is the rf wavelength at 30 GHz. These trains pass through a series of low impedance "transfer structures", where they induce about 90 MW of peak rf power for a pulse duration of 12 ns. This power is then transferred through waveguides (two for each transfer structure) to the accelerating sections in the main linac. The TBNLC (Two-Beam NLC), proposed by a group at LBL and LLNL, is also a two-beam accelerator scheme, but in this case the drive beam is powered by induction linac modules. The TBNLC is proposed as an alternative power source for the NLC, in particular as a high-gradient upgrade to 1 TeV. Instead, of a single drive beam per main linac, as in the case of CLIC, the TBNLC would consist of 18 separate drive beam units for each of the two main linacs. There would be 150 transfer structures per drive beam, each supplying 360 MW of power to a single 1.8 m NLC accelerating section.

The various proposed colliders and their operating frequencies are listed in Table I, along with other basic

* Work supported by the Department of Energy, contract DE-AC03-76SF00515.

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parameters to be discussed in the following sections. The SLC is listed for comparison.

II. SCALING COLLIDER PARAMETERS WITH FREQUENCY

All of the proposed linear collide designs are based on the production and manipulation of RF power in the frequency range 1.3-30 GHz. The rf system itself must convert power from the ac mains (wall plug) to rf power at the input of the accelerating structure with the greatest possible efficiency. In general, it is easier to attain a high accelerating gradient at a higher rf frequency. Nature has, however, imposed a powerful limitation on the gradient achievable for routine operation of a copper accelerating structure --- the dark current capture threshold. This threshold is given by

$$G_{th}\lambda = 1.605\ \mathrm{MV} \qquad (1)$$

where λ is the RF wavelength. The threshold gradients for the various colliders are listed in Table I, together with the design gradients for a 500 GeV machine. It is indeed possible to exceed this threshold gradient by some reasonable factor; for example the SLC routinely operates 30% above it with barely detectable dark current. However, the dark current beam power dissipation, and hence the difficulty in processing a structure to a given gradient level, tends to become worse exponentially as the capture threshold is exceeded by a still larger factor. In the case of a superconducting structure, field emission will necessarily be reduced to a low level by special cleaning and processing techniques to avoid unacceptable power dissipation at low temperature. Perhaps these heroic cleaning and handling procedures can be adapted to copper structures as well. But in any case, if operation is planned at a gradient significantly above the capture threshold, dark current effects must be carefully studied in an appropriate test facility (such as the TESLA Test Facility under construction at DESY).

For a high frequency high gradient linear collider with a copper accelerating structure, nature has unfortunately imposed another limitation on the rf system. The energy stored per unit length on the accelerating structure will scale roughly as $G^2\lambda^2$. If the gradient is set at some factor times the capture threshold gradient, then the stored energy per unit length remains roughly constant, independent of frequency. However, the time allowed for this energy to be collected in the accelerating structure depends on the energy decrement time,

$$\tau_d = Q/\omega \sim \omega^{-3/2} \qquad (2)$$

Thus the RF pulse length will also tend to scale as $\omega^{-3/2}$, and since the stored energy per meter is roughly constant under the above scaling assumption, the peak power required per meter will tend to scale as $\omega^{3/2}$. Unfortunately, the maximum output power available from a klystron tends to decrease rather than increase as frequency increase. Therefore high frequency RF systems using klystrons to generate the RF power (NLC, JLC, VLEPP) require some sort of pulse compression to enhance the peak power output. However, the additional loss associated with the compression process tends to lower the overall efficiency of the RF system. The two-beam accelerator concept (TBNLC, CLIC) bypasses the limitations imposed by conventional klystrons in producing high frequency, high peak power at short pulse lengths. The drive beam in a two-beam accelerator is, in fact, equivalent to the beam in a klystron, and the TBA scheme is also called a "relativistic klystron." A collider using a superconducting accelerating structure (TESLA) increases the Q/ω limitation on energy collection time by a large factor over that of copper, allowing a long pulse, low peak power, efficient RF system. (As will be discussed later, a long pulse modulator tends to be more efficient than one which must produce short, very high peak power pulses). However, this gain in the efficiency of RF power generation is offset to a large extent by the additional power required by the refrigeration system.

Energy decrement times and peak RF power requirements for the collider designs are listed in Table I. For machines with copper structures, the structure filling times (except for CLIC) are quite close to the values given for τ_d; the RF pulse lengths are typically several times longer to allow for acceleration of a bunch train. The pulse lengths at the accelerating structure (in nanoseconds) are: SBLC (2800); JLC (230); NLC (240); VLEPP (110); CLIC (12). In the case of TESLA, the pulse length (1.3 ms) is reduced below the decrement time approximately by the ratio of the refrigeration power required per Watt of power dissipated at 4.2°K ($\approx$ 300). The peak powers do not scale as $\omega^{3/2}$ as discussed above, because the actual design gradients do not closely follow a G_{th} scaling. However, as seen in Table I, the peak power per meter does increase rapidly with increasing frequency. Likewise, the linac length would be roughly proportional to λ for $G \sim G_{th}$ scaling. The actual design lengths do show a strong correlation with frequency. Since the stored energy per meter remains approximately constant for $G \sim G_{th}$ scaling, the average AC wall-plug power should scale roughly as $\overline{P}_{AC} \sim f_r\lambda/\eta_{rf}$, where f_r is the repetition rate and η_{rf} is the RF system efficiency. As frequency increases, the colliders in Table I trade at least part of their wavelength advantage for a higher repetition rate. These rates are (in Hz): TESLA (10); SBLC (50); JLC (150); NLC (180); VLEPP (300).

III. RF SYSTEM TECHNOLOGY

A. Klystrons

At a constant beam voltage, the RF output of a klystron (or other microwave power source) increases as the beam current increases. However, a higher beam current, I_b, at a given beam voltage, V_b, inevitably lead to a lower efficiency because of the detrimental effects of space charge forces. These forces tend to blow apart the sharply defined bunches needed for high output efficiency. The microperveance (defined by $K_\mu = I_b/V_b^{3/2} \times 10^6$) is commonly taken as a measure of these space charge effects. If klystron efficiencies, obtained from both measured performance and simulations, are plotted as a function of microperveance, it is found that the collection of points (see for example [2], Fig. 3) is quite sharply bounded by the line

$$\eta_{kly} \approx 0.80 - 0.15 K_{\mu} \,. \qquad (2)$$

Low frequency, long pulse or CW klystrons tend to fall closer to this performance limit than high frequency, high peak power tubes. The intercept at zero perveance has some theoretical justification. A 100% efficiency implies that all the electrons in the beam are just brought to rest by the RF voltage of the output circuit. This is not possible in a real klystron because there is an energy spread in the beam due to the bunching process, and because the RF voltage varies with radius across the gap. Also, even a single electron cannot be stopped in a gridless gap; an electron on axis can lose at most about 85% of its energy [3].

There is also the perennial question concerning limitations on peak klystron output power as a function of frequency. This can be roughly estimated as follows. First, the beam radius is limited to something like $\lambda/8$ to allow for reasonable gap coupling. Second, the current density per unit area from the cathode (cathode loading, I_A) is limited to about 10 A/cm^2 for good cathode lifetime. Third, the area compression ratio, C_A, of the beam in the gun region is limited by optics and tolerances to perhaps 150. Putting these factors together gives

$$P_{max} \approx \eta V_b \left[I_A C_A \pi (\lambda/8)^2 \right] = 74 \eta V_b (\lambda/cm)^2 \quad (3)$$

where η is the electronic efficiency. If the tube is to be efficient, and if we apply Eq. (2) conservatively, then the microperveance for an efficiency of 50-60% is limited to $K_{\mu} \leq 1$. Using Eq. (2) together with $P_K = \eta (K_{\mu} \times 10^6) V_b^{5/2}$, we find that for V_b= 500 kV the maximum output power is about 100 MW up to 14 GHz, then falls off as λ^2 above this frequency.

Table II lists klystron parameters for the five collider proposals that use klystrons as an RF source. Both design parameters and values actually achieved to date are shown. The numbers given for "scaled maximum efficiency" are obtained from Eq. (2). Note that the design values for efficiency are all well below these maximum values, except for the low frequency, long pulse TESLA klystron where good efficiency should be relatively easy to achieve. Two of the klystrons have achieved the design peak power. The SBLC S-band klystron, designed in collaboration with SLAC, has reached 150 MW at a 2.8 μs pulse length [4]. The NLC X-band klystron has achieved 50 MW at 1.5 μs [5]. Both klystrons still fall short in efficiency, and both must eventually replace power-consuming solenoids with PPM (periodic permanent magnet) focusing or superconducting solenoids.

B. Modulators

The rise time of a modulator pulse is an important parameter in determining the modulator efficiency. In a conventional modulator, the pulse forming network (PFN) capacitance is charged by a DC power supply to a voltage V_{PFN}. This network can be either a length of smooth transmission line, or a series of discrete capacitors and inductors which model such a line. The line is then discharged by a switching device, usually a thyratron, through the primary of a pulse transformer with a turns ratio n. The output of the pulse transformer produces a voltage $nV_{PFN}/2$ (single stage PFN), or nV_{PFN} (two stage, or Blumlein PFN). In the case of the TESLA modulator, an energy storage capacitor is partially discharged through the primary of the pulse transformer. The switching is done by solid state devices (thyristors). A "bouncer" circuit is used to compensate for voltage droop.

The energy efficiency, η_E, of the pulse transformer is defined as the useful energy in the flat-top portion of the pulse divided by the total energy in the pulse. The energy in the fall-time portion of the pulse tends to scale in proportion to the rise time, T_R, so that the energy efficiency can be written as $\eta_E \equiv T_K/T_E = T_K/(T_K + \alpha T_R)$, where T_K is the useful flat-top pulse width, T_E is the energy width, and α is a coefficient between 1.0 and 1.2 which depends on the pulse shape and the definition of rise time. In turn, a simple physical argument [6] leads to the scaling $T_R \sim nT_E^{1/2}$. Combined with the preceding relation, this gives

$$T_E = \frac{1}{4}\left[\beta n + (\beta^2 n^2 + 4T_K)^{1/2}\right]^2 \qquad (4)$$

where β is a constant that can be obtained by fitting to existing pulse transformer designs. For the pulse transformer driving the 5045 SLAC klystrons, β = 0.033 $(\mu s)^{1/2}$. It is found that the above expression then gives a good fit to a number of other pulse transformers measured at SLAC having a variety of turns ratios and pulse lengths. Using Eq. (4), the energy efficiency is plotted in Fig. 1.

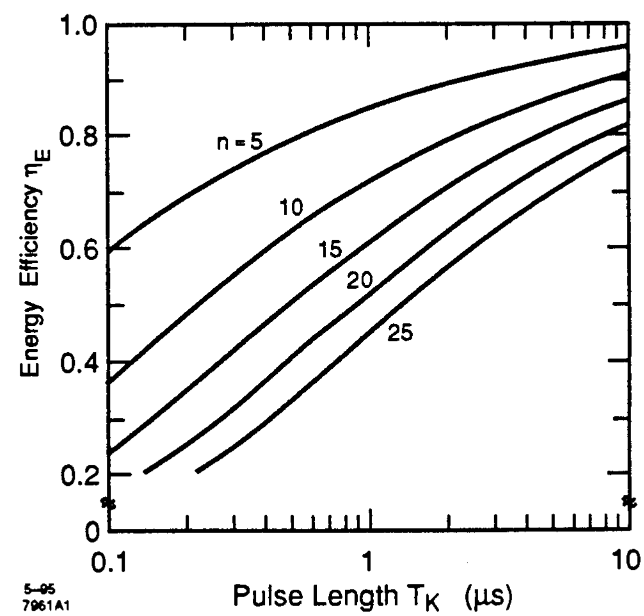

Figure 1 - Energy Efficiency for a typical pulse transformer as a function of pulse length and turns ration n.

Along with T_K and n, values of η_E from Eq. (4) are listed in Table III (as the scaled energy efficiency) for the modulator designs for the various collider proposals. An accurate calculation of energy efficiency must also include the effect of the load (klystron) capacitance, the series inductance of the thyratron, transformer core losses, and the inductances of the cables and leads connecting the components. Of course, the best efficiency is obtained by eliminating the modulator entirely by using a klystron with a gridded gun to switch the beam, as proposed for VLEPP.

C. RF Pulse Compression

RF pulse compression is a method of enhancing klystron output power at the expense of pulse width. Although some energy is lost in the compression process, the efficiency can in principle be quite high. High-Q energy storage elements are required to achieve efficient pulse compression; these can be either resonant cavities or lengths of shorted delay line.

RF pulse compression is used in three of the 500 GeV collider designs. VLEPP and NLC use a SLED-type scheme (SBLC plans to use a SLED system in a 1 TeV upgrade). In a SLED pulse compression system [7], energy builds up in a storage element (resonant cavity or resonant delay line) over the major part of the klystron output pulse. During the final part of the pulse, equal to the desired output pulse length, a phase reversal at the klystron input triggers a discharge of this stored energy, which then adds to the energy coming directly from the klystron. During the filling time of the storage device, there is an unavoidable power reflection; in addition, some energy is left behind in the storage element. Together, these factors lead to a maximum intrinsic efficiency for a SLED system on the order of 80%, even assuming lossless components. Taking losses into account reduces the efficiency to approximately 75%. On the other hand, the JLC uses a compression method, the Delay Line Distribution System (DLDS), which is inherently 100% efficient. Although related to Binary Pulse Compression [8], the DLDS system uses less delay line pipe by feeding power in the up-stream beam direction, thus taking advantage of the beam transit time to achieve a factor of two reduction in the required delay line length. Both the DLDS and the SLED-II compression systems have the advantage or producing a flat output pulse. This is a necessity for accelerating long bunch trains (the beam pulse length is about 120 ns for JLC and NLC). The VLEPP compression system is based on the use of a single traveling-wave "open" cavity resonator of unique design [9], and is therefore very compact. Although the output pulse is not inherently flat, this is of no consequence for the acceleration of a single bunch, as is the case for VLEPP. Parameters for the three pulse compression systems are given in Table IV.

IV. RF SYSTEM EFFICIENCY

The overall RF system efficiency is an important parameter for a linear collider. The AC power requirements (see Table I) for the various collider proposals range from 60-150 MW. Thus a 1% improvement in efficiency can reduce the AC power consumption by a megawatt or more. The net system efficiency, shown in the last column in Table I, is the product of the separate efficiencies of the klystron, modulator, and pulse compression systems. If there is no compression system, the efficiency for transmitting power from the klystron to the accelerating structure must be included instead. The system efficiency can be calculated with and without auxiliary power. This includes power for the klystron cathode heater, klystron focusing solenoid, thyratron cathode and reservoir heaters, and power for the cryogenic systems in TESLA and CLIC (which uses superconducting cavities to accelerate the drive beam). The net RF system efficiency is, on the average, about one-third.

It is obviously highly desirable to increase the net RF system efficiency. For example, one can think of eliminating the pulse compression system and the losses associated with it. However, more dc pulse compression must then be carried out in the modulator (or in the induction linac modules in the case of the TBNLC). As another example, a better klystron efficiency can be obtained by raising the beam voltage and lowering the perveance. Again, this implies a lower modulator efficiency because a pulse transformer with a larger turns ratio will be required (or a higher V_{PFN} could be used, which is more expensive and technically difficult). There are losses and inefficiencies in each stage of the power handling and processing chain between the AC wall plug and RF at the input to the accelerating structure. Care must be taken that an efficiency improvement at one step in this chain is not made at the expense of increases loss at another stage.

A long-range expectation for the efficiency of the RF system for a linear collider might be on the order of 50%. This efficiency could be attained by a low perveance, high efficiency klystron (65%) with grid switching (95% efficient), and a high-gain Binary Pulse Compression system (81% efficient including power transmission). The BPC system would use 10 or so discrete cavities per stage to eliminate long delay lines.

V. ACKNOWLEDGMENT

The principal results on the status and development of high power RF systems, as reported here, are contained in Tables I through IV. These tables are the result of hard work over many months by members of the Linac Technology working group of the Technical Review Committee mentioned in the Introduction. In particular D. Proch (TESLA), N. Holtkamp (SBLC), T. Higo and H. Mizuno (JLC), N. Solyak (VLEPP), G. Westenskow (TBNLC) and I. Wilson (CLIC) were responsible for the major portion of this effort, with substantial input from A. Gamp on the TESLA rf system.

VI. REFERENCES

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Table I Basic Parameters for Proposed Linear Colliders Designs at 500 GeV

Collider Proposal	Type(1)	RF Freq (GHz)	G_{th} from Eq. (1) (MV/m)	Gradient(2) (MV/m)	Decrement Time τ_d (ns)	Peak Power per meter (MW/m)	Active Length(3) (km)	AC Power(4) (MW)	RF System Efficiency(5) (%)
TESLA	SCA	1.3	7	25/25	0.6×10^9	0.21	20	154	35/58
SLC	Cu	2.856	15	20/21	730	12	2.8	24	13.6/14.5
SBLC	Cu	3.0	16	17/21	720	12	30	139	37/38
JLC	Cu	11.4	61	53/73	95	100	10	114	30/34
NLC	Cu	11.4	61	37/50	98	50	14	103	30/31
VLEPP	Cu	14	75	91/100	68	120	6	57	39/40
TBNLC	TBA	11.4	61	74/100	98	200	7	106	39/40
CLIC	TBA	30	160	78/80	22	144	6	100	26/35

(1) SCA = superconducting accelerating structure; Cu = copper accelerating structure; TBA = two-beam accelerator (with copper main linac structure).
(2) Design gradient with/without beam loading (bunch on crest).
(3) Includes overhead for BNS damping and energy management (see text).
(4) AC power required for producing main linac RF; includes cryogenic and auxiliary power (see text).
(5) Efficiencies are given with/without cryogenic and auxiliary power included.

Table II Klystron Parameters: Design Goals and Achieved to Date

	TESLA		SBLC		JLC		NLC		VLEPP	
	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d
RF Frequency (GHz)	1.3	1.3	3.0	3.0	11.4	11.4	11.4	11.4	14	14
Peak Output Pwr. (MW)	7.1	5.0	150	150	135	96/50	50	58/52	150	60
Pulse Length (μs)	1314	2010	2.8	3	0.5	0.1/0.2	1.2	0.2/1.5	0.50	0.7
Repetition Rate (Hz)	10	10	50	60	150		180	60	300	2
Ave. Output Pwr. (kW)	93		21	27	10		11	1/5	24	
Microperveance	0.5 1)	2.0	1.2	1.8	1.2	1.2	0.6	1.2	0.25	0.15
Electronic Effic. (%)	70	45	50	42	45	33	60	43/37	60	40
Scaled Max. Effic. 2) (%)	73	50	62	53	62	62	71	62	76	78
Beam Voltage (kV)	110	130	575	528	600	620	455	400	1000	1000
Beam Energy/Pulse 3) (J)	13,300	10,100	840	1070	150	170	100		125	
Cathode Load(A/cm^2)	3.1		6	6	13.5	13.5	7.4	7.6.	5	5
Cathode Heat Pwr. (kW)	0.5		1	2	0.5	0.5	0.4		1.0	1.0
Focusing Type	Sol.	Sol.	PPM	Sol.	SCM	Sol.	PPM	Sol.	PPM	PPM
Solenoid Power (kW)	4	4	—	15	1	40	—	≈20	—	—
Output Window Type	Coax	Pillbox	Pillbox	Pillbox	TE_{11} TW	TE_{11} λ/2	TE_{01} TW	TE_{01} TW	TE_{11} TW	TE_{11}
Windows/Klystron	1	1	2	4	2	2	1	1	2	2
Overall Length (m)		2.0	2.5	2.5	1.5	1.5	1.3	1.3	1.46	1.46

(1) Perveance per beam in multibeam klystron. (2) $\eta(\text{Max}) \approx 0.80 - 0.15 \times$ Microperveance. (3) In flat-top portion of pulse.

Table III. Modulator Parameters: Design Goals and Achieved to Date

	TESLA		SBLC		JLC		NLC		VLEPP	
Modulator Type[1]	Storage cap. with bouncer		PFN		Blumlein PFN		Blumlein PFL		Gridded Gun see 6)	
	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d	Design	Ach.[5]	Design	Ach.'d
Flat Top Pulse Length, Tk (μs)	1314	2010	2.8	3.0	0.5	0.7	1.2	1.5	0.50	0.50
PFN Voltage (kV)	9	10	65	43	120	80	455	400	1000	960
Transformer Ratio n	1:13	1:13	1:18	1:23	1:5	1:7	1:7	1:20	—	—
Rise/Fall Energy Effic (%)			86.5	≈65	89	70	80	≈60		
Scaled Energy Effic.[2] (%)	99	—	70	65	79	70	81	58	—	—
I^2R/Thy./Core Loss Effic. (%)			97	95	97		97			
Energy Stored on PFN[3] (J)			1000	1650	174		258			
Power Supply Efficiency (%)			95	90	95		93	≈90		
Mod. Eff. without Aux. Power (%)			79.5	≈60	82		72	≈52	95	
Auxiliary Power[4] (kW)			1.5	3	1.5		1.5	1.5	0.3	
Net Modulator Efficiency (%)	86	86	77.5	59	80		70		92.5	
Ave. AC Input Power (kW) (Including Auxiliary Power)	155		54.2	88	29		51.5		40.5	

(1) PFN = lumped element pulse forming network; PFL = pulse forming line (transmission line).
(2) See text.
(3) Energy switched per pulse from storage element for TESLA and VLEPP.
(4) Includes thyratron cathode heater and reservoir heater power.
(5) With standard (not Blumlein) PFN.
(6) Uses a PFL as energy storage element.

Table IV. RF Pulse Compression and Power Transmission: Design and Achieved to Date

	JLC		NLC		VLEPP	
Type of Pulse Comp. System[1]	DLDS		SLED-II		SLED-I (VPM)	
	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d
Compression Ratio	2		5	6	4.55	4.55
Input/Output Pulse Length (ns)	500/250		1200/240	900/150	500/110	500/110
Compression Efficiency (%)	98		76.5	73	74	72
Power Gain	1.96		3.83	3.7	3.37	3.3
Power Transmission Efficiency (%)[2]	95		94	84	95	95
Power Gain Including Transmission Loss	1.86		3.60	3.0	3.20	3.1
Net Efficiency Including Trans. Loss (%)	93		72		70	
Length of Structure per Power Unit (m)[3]	5.24		7.20		4.00	
Power at Structure per Power Unit (MW)	524		360	150	480	
Maximum Power in P.C. System (MW)	282		380	205	250	150
Required Klystron Power (MW)	2 × 141		2 × 50		2 × 75	

(1) DLDS = Delay Line Distribution System; VPM = VLEPP Power Multiplier.
(2) The power transmission efficiency in percent for TESLA, SBLC, TBNLC and CLIC are, respectively, 96, 97,98, and 90.
(3) A power unit is: TESLA, one klystron with modulator feeding thirty-two 1.04 m accelerating sections; SBLC, one klystron with modulator feeding two 6.0 m sections; JLC, two klystrons with two modulators driving one pulse compression unit which feeds four 1.31 m sections; NLC, one modulator driving two klystrons which together drive one pulse compression unit feeding four 1.8 m sections; TBNLC, one transfer structure for each 1.8 m section; VLEPP, one grid-modulated klystron driving two VPM cavities which together feed four 1.0 m sections; CLIC, one transfer structure driving two 0.28 m sections. The total number of power units (2 linacs) are: TESLA, 604; SBLC, 2517; JLC, 1804; NLC, 1968; TBNLC, 3938; VLEPP, 1400; CLIC, 11233.

MODULATOR - POWER SUPPLY PARAMETER SPACE FOR FUTURE LINEAR COLLIDERS

GEORGE CARYOTAKIS

- SLAC - NLC

  X
  S
  L

- DESY

  S - Expanded SLC
  L - Superconducting Cavities - Tesla

- MODULATION

  Diode - Line type
  Grid -
  Switch Tube

- REQUIREMENTS FOR 1 TEV+

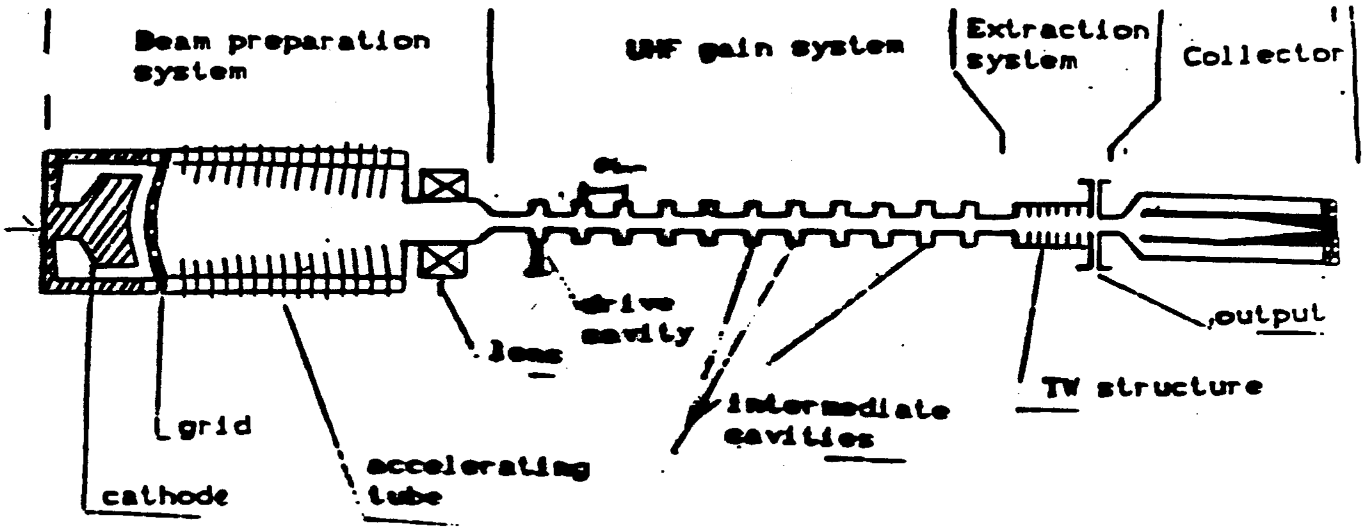


FIG 1. Klystron configuration

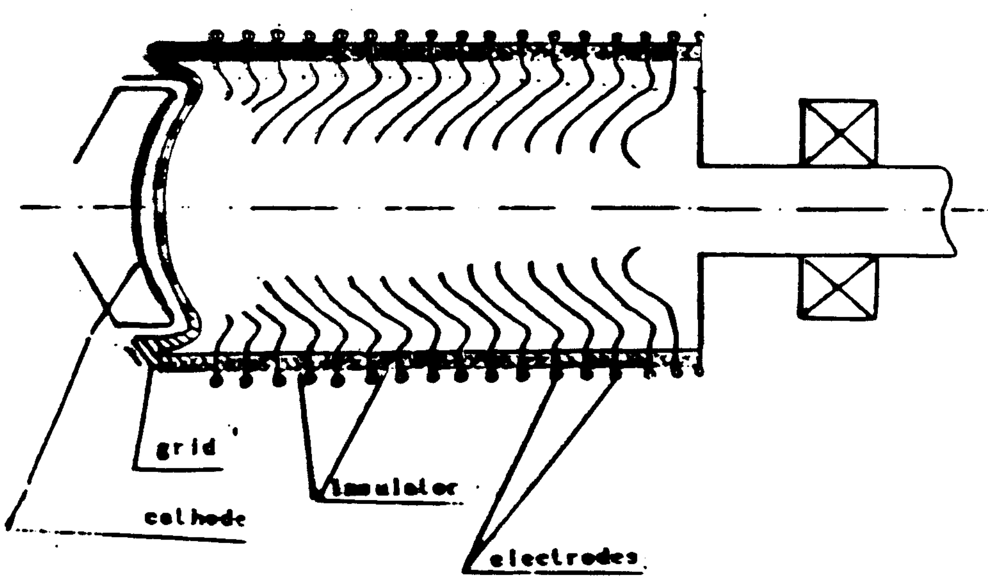
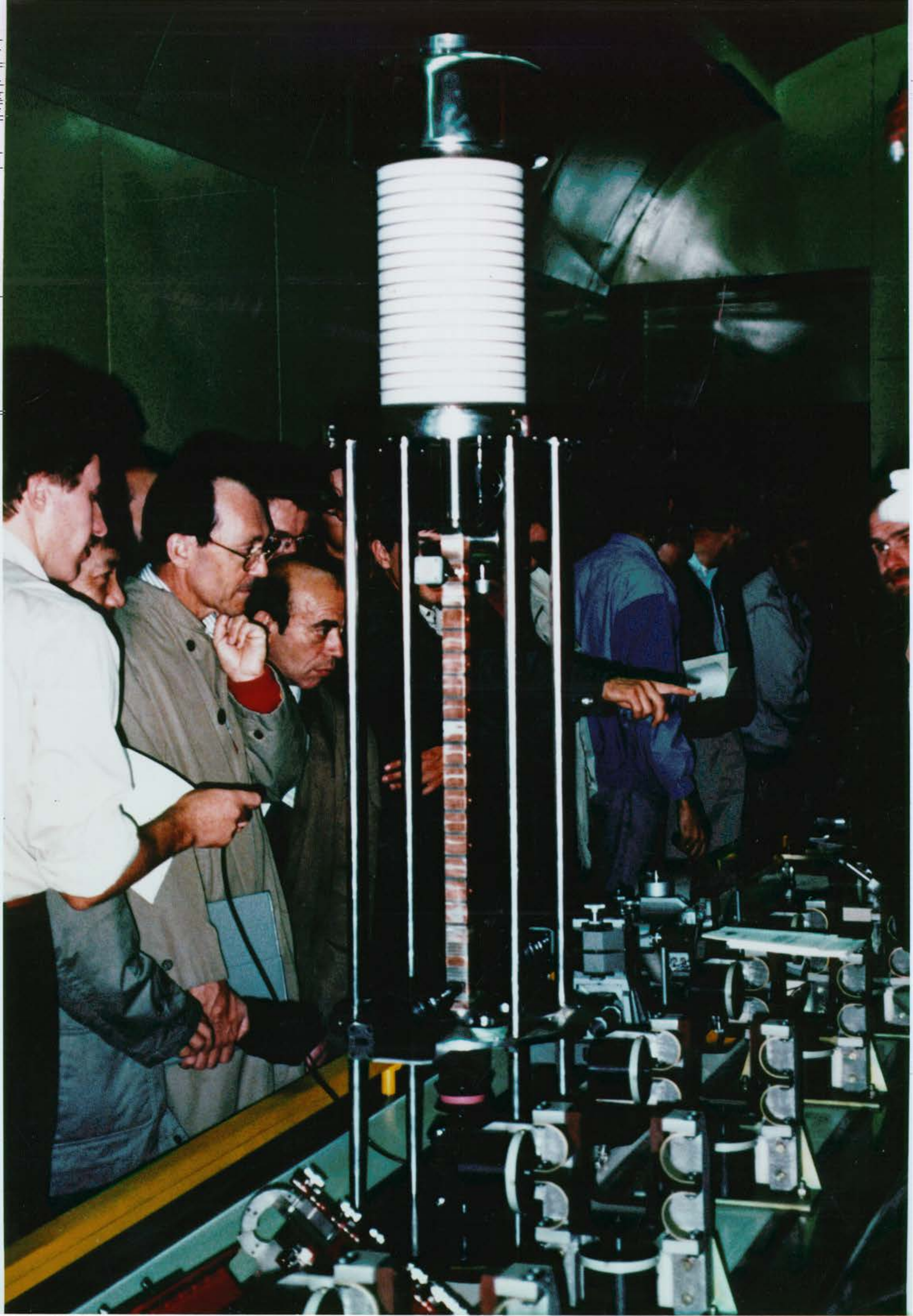
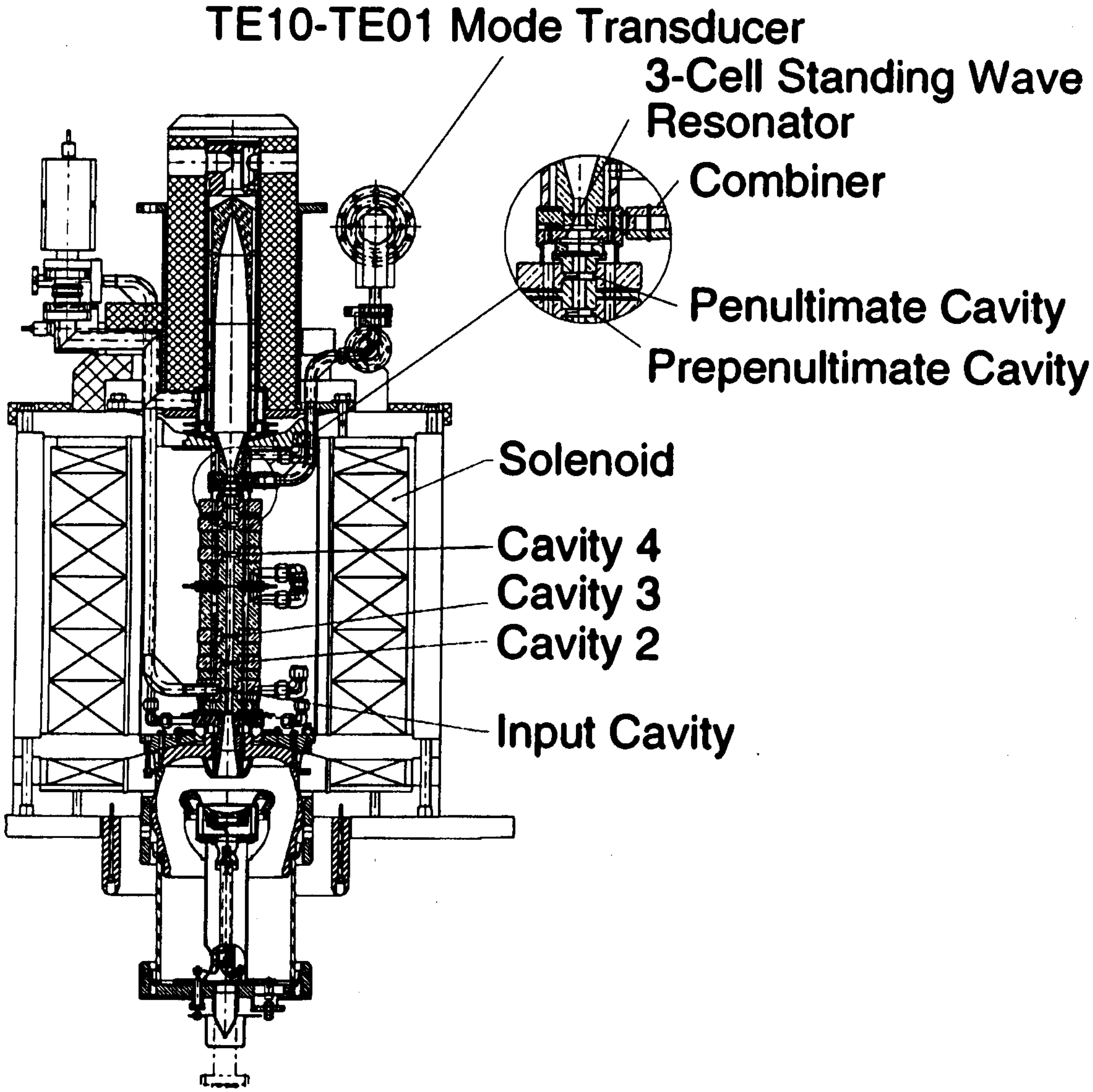


FIG 2. Beam preparation system

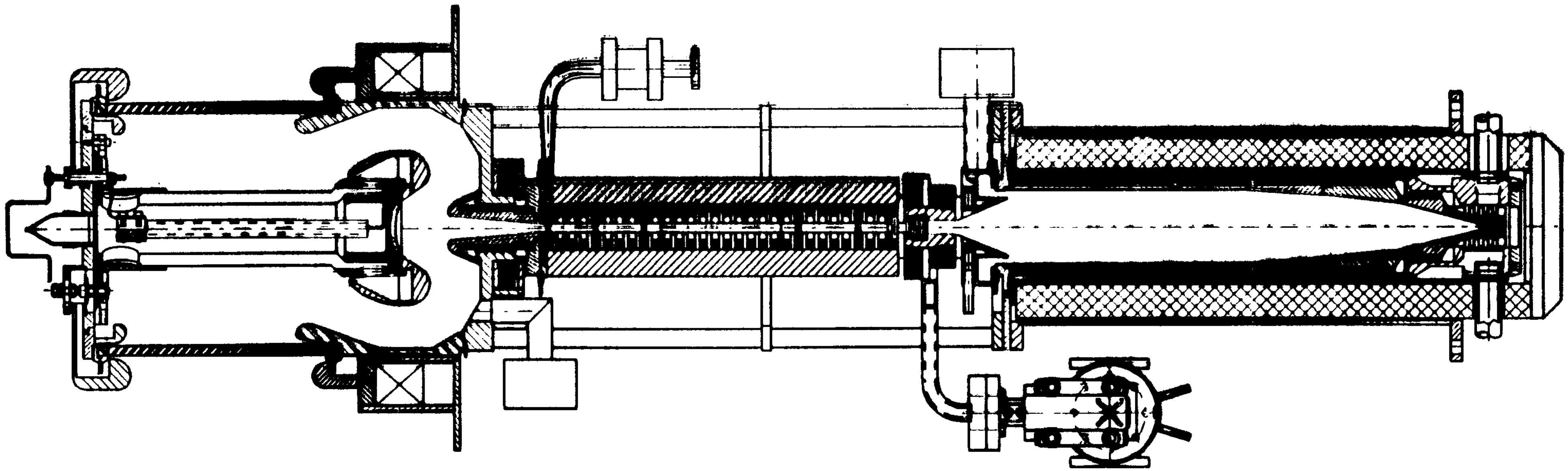


KLYSTRON LAYOUT AND SPECIFICATION



Beam Voltage	440	kV
Beam Current	350	A
Microperveance	1.2	$A/V^{3/2}$
Frequency	11.424	GHz
Peak RF Output Power	50	MW
Average Power	13.5	kW
Gain	>50	dB
RF Pulse Width	1.5	us
PRF	180	pps
Tunnel Diameter	9.525	mm
Beam Diameter	6.35	mm
Cathode Diameter	71.4	mm
Beam Area Convergence	125:1	
Cathode Loading	12.8	A/cm^2 (max)
Magnetic Field	0.47	T

3-12-95



50 MW PPM X-Band Klystron

DESIGN AND PERFORMANCE (SIMULATION) PARAMETERS FOR X5011 AND X7217 PPM KLYSTRONS

Parameter	Units	X5011	X7217
Electrical			
Frequency	GHz	11.424	11.424
Peak Power	MW	50	72
Beam Voltage	KV	465	497
Beam Current	Amps	190	263
Beam Microperveance	$(\mu A/volts)^{3/2}$	0.6	0.75
Gain	dB	57	57
Bandwidth	MHz	100	100
Beam Modulation		Cathode Pulsed	Cathode Pulsed
Pulse Duration	µs	1.20	1.20
Rep Rate	Hertz	180	180
RF Efficiency	%	57	55
Cathode Current Density	$Amps/cm^2$	7.4	7.6
Heater Voltage	Volts	15	15
Heater Current	Amps	21.5	27
Mechanical & Magnetic			
Tunnel Diameter	cm	.953	1.080
Beam Focusing		PPM	PPM
Tube Weight	KG	32 (WO lead)	32
Tube Length	Meters	1.3	1.3
Cathode Diameter	cm	5.72	6.75
Cathode Half Angle	Degrees	25	29
Beam Area Convergence		144	124

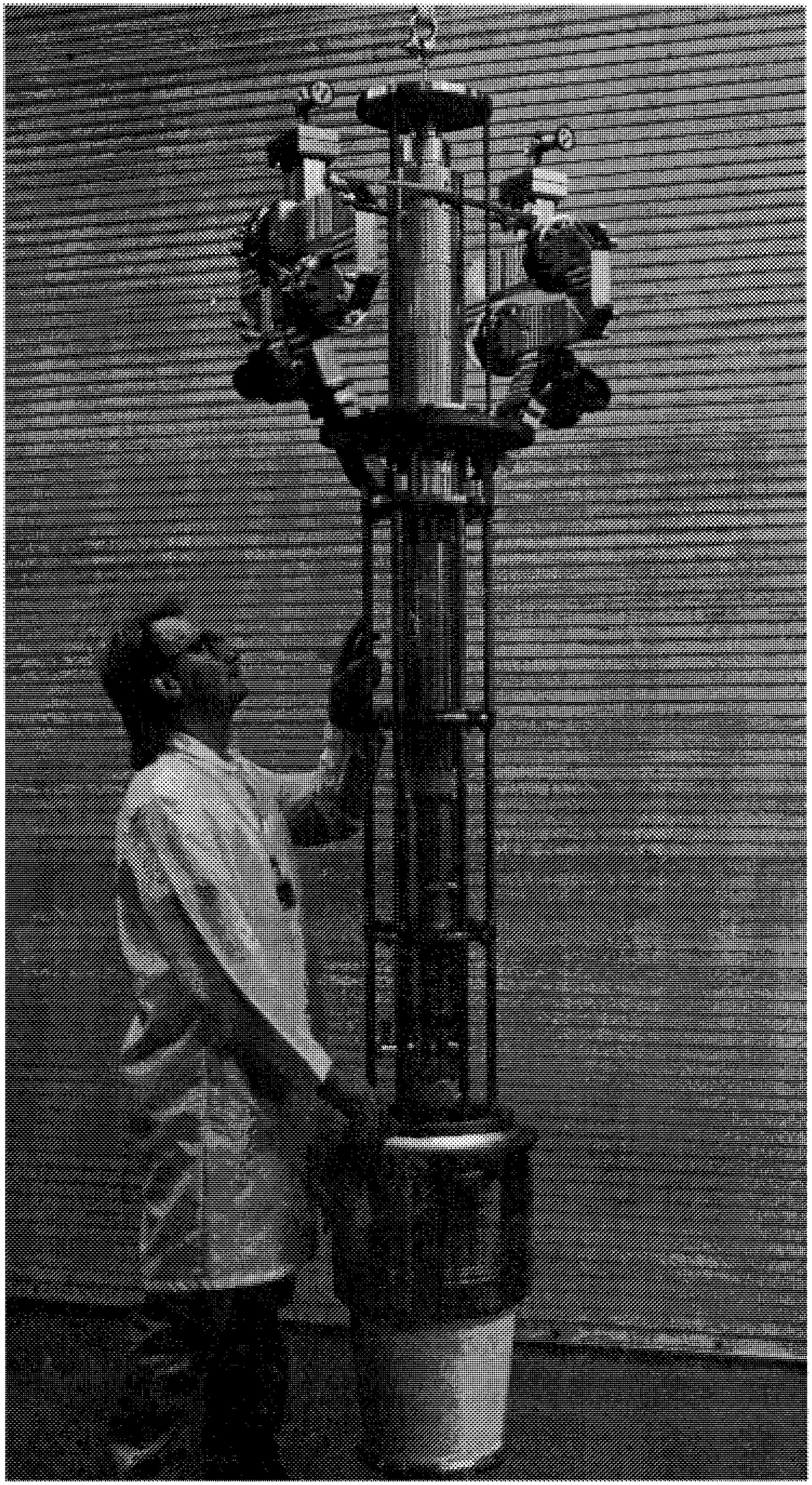
DESY CANDIDATES FOR FUTURE COLLIDER (KLYSTRON)

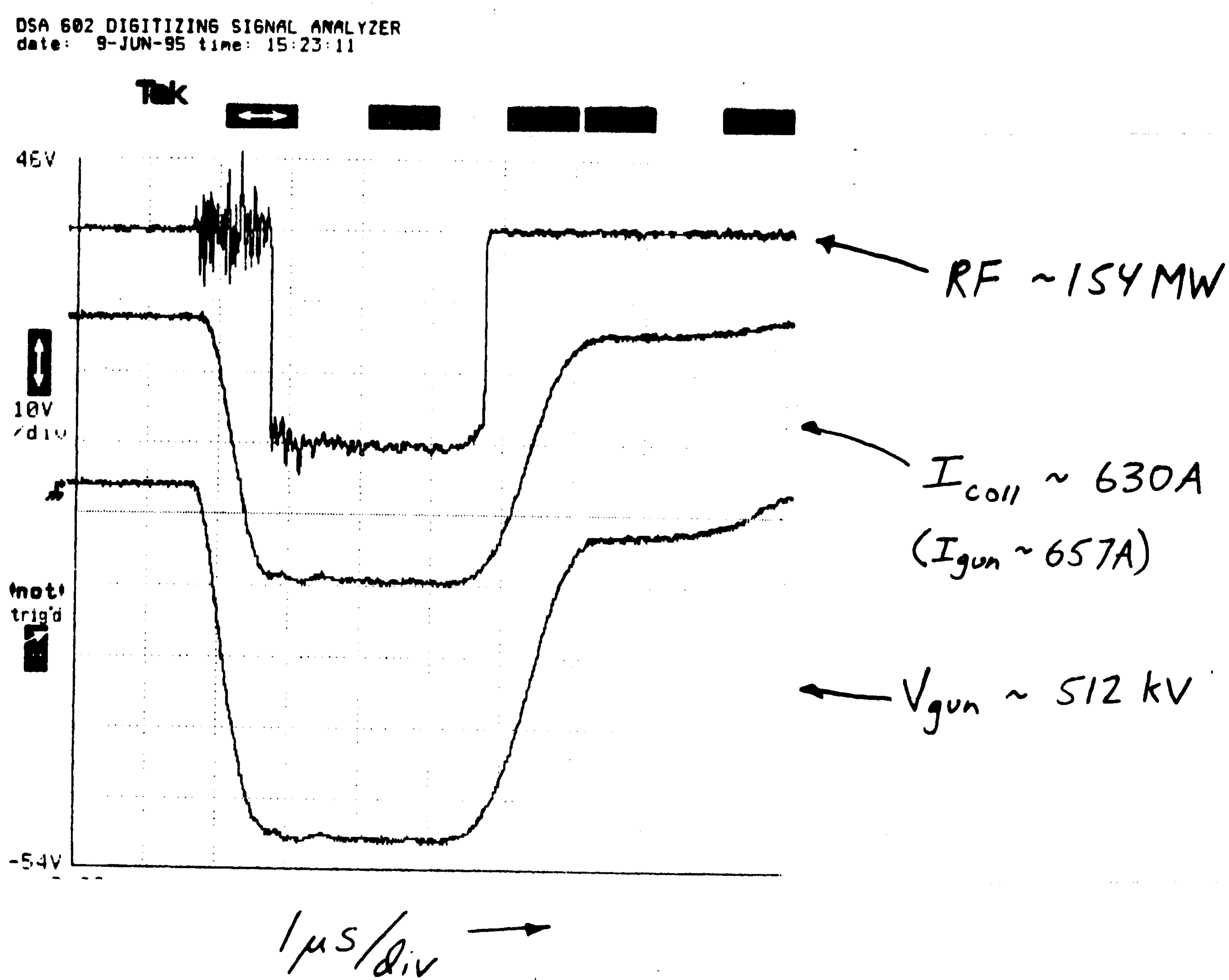
- S-Band

Peak	150 MW
Avg.	22.5 kW
Pulse Length	3μs
Rep Rate	30 Hz
Beam Voltage	530 kV
Beam Current	700 Amps

- L-Band

RF Power	
Peak	7.1 MW
Avg.	93 kW
Pulse Length	1314μs
Rep Rate	10 Hz

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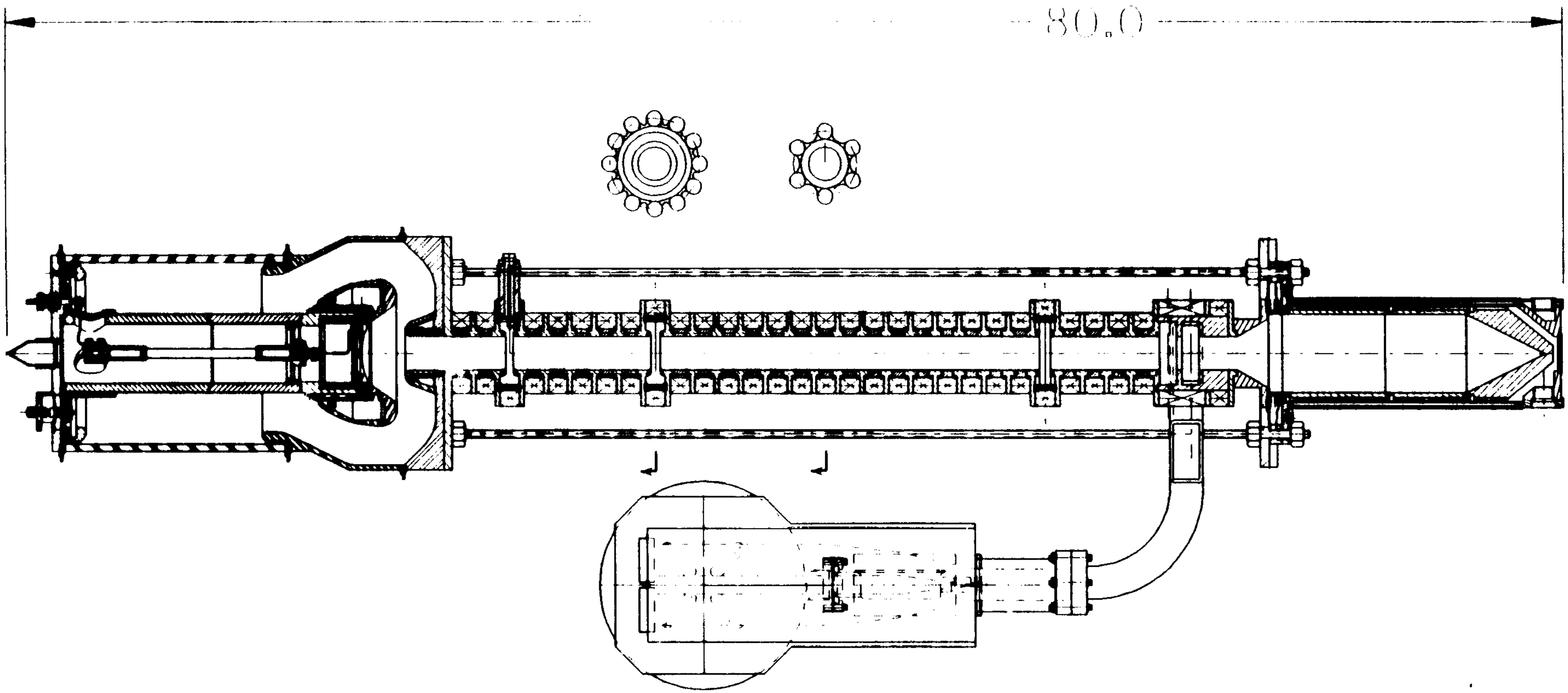
-54V
RF ~154 MW
I coll ~ 630A
(I gun ~ 657A)
V gun ~ 512 kV
1 μs/div

Existing and simulated high power S-band klystron designs

Parameter	DESY Klystron (Measurements)	Proposed Klystron (Simulation)	
Beam voltage	527	600	kV
Beam current	670	669	A
Pin	0.62	156	kW
Pout	155	203	MW
Efficiency	44	50.6	%
Saturated Gain	54	31	dB
Tube Length	104	80	inches
Tube and Magnet Weight:	5000	400	lbs
Cavities	7	4	

Fig. 4



200 MW S-BAND PPM KLYSTRON

200sppm.dgn/J. Stanfield/05-31-95

CONVENTIONAL KLYSTRON BEAM MODULATION MODES

FREQ	DIODE	GRID	SWITCH TUBE
X	√	?	√
S	√	√	√

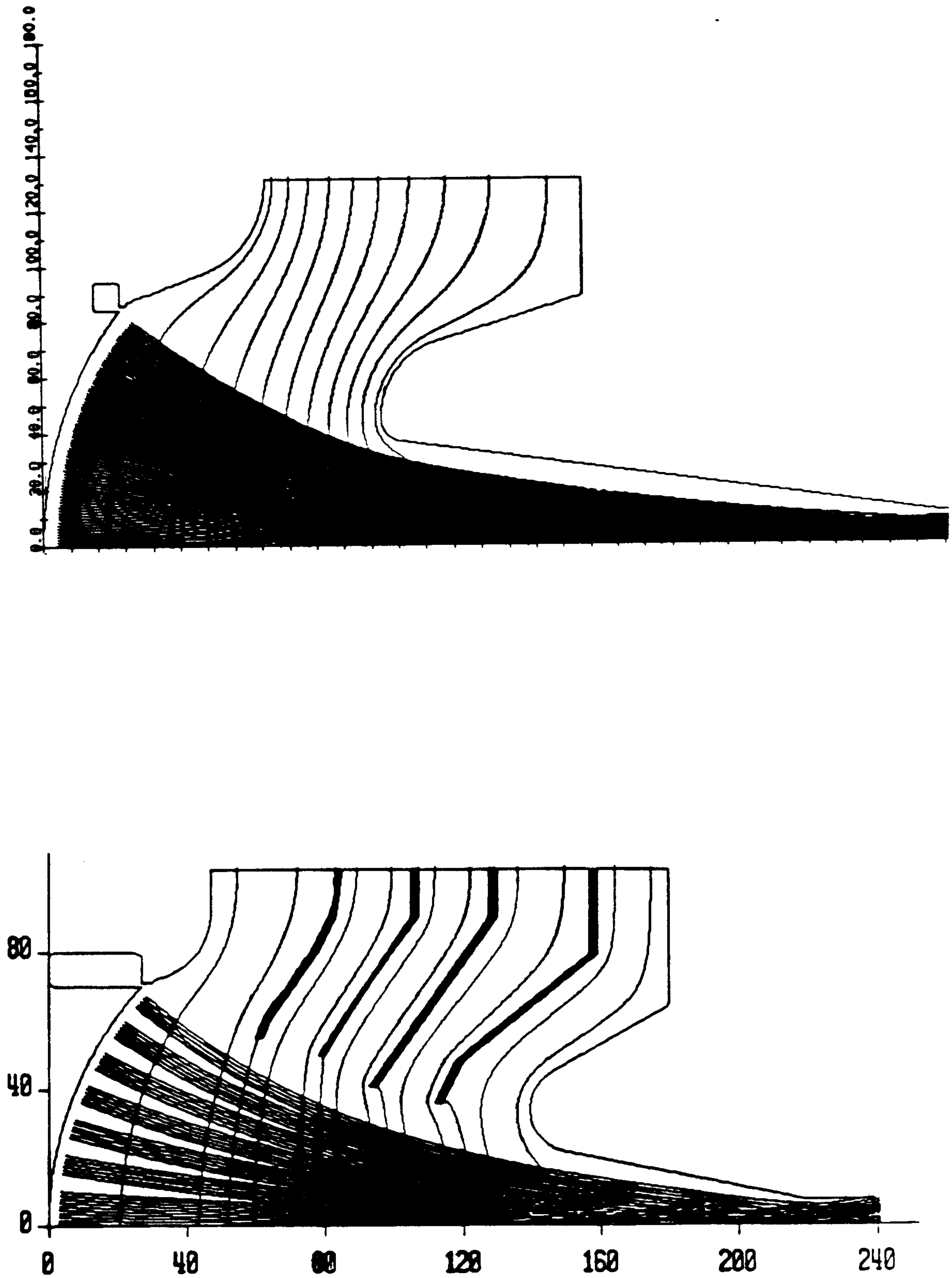


figure 3: Finished triode simulation at 500 kV, 254 A. Four accelerating electrodes are utilized to distribute the gradient.

CONCLUSION

The basic principles and practical feasibility of a 425 MHz multiple beam klystron has been demonstrated.

The main problems related to asymmetries in the radial components of the magnetic focusing field and interaction electric field in the cavities have found general solutions applicable to an extensive power-frequency domain.

The main advantage of the MBK is its comparatively low voltage which reduces the overall length of the tube and simplifies HV power supplies and X radiation protection. Voltage breakdown are reduced and in many cases oil isolation of the gun can be avoided.

Because the perveance of elementary beams can remain low, interaction efficiencies as high as 60 - 65 % are to be expected. Large instantaneous bandwidths are also anticipated as a corollary of cavity high (R/Q) values.

Increasing power and frequency of operation implies further development of the gun and cavities. At higher frequencies an attractive solution would be to use a Pierce type converging gun with discrete circular emitting area on the cathode.

Up to L band, cavities operating on the fundamental or lowest modes are certainly feasible, but at S band oversized cavities will have to be used. In both cases, adjacent mode interference and reduction of (R/Q) values will be the problems to solve.

The type of cavity structure selected will set the ultimate limits of power capability.

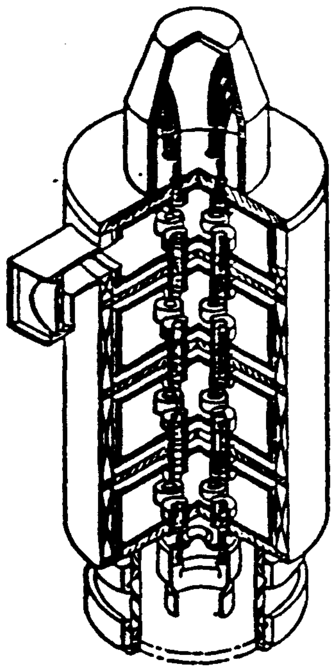


FIG.1 : MBK STRUCTURE

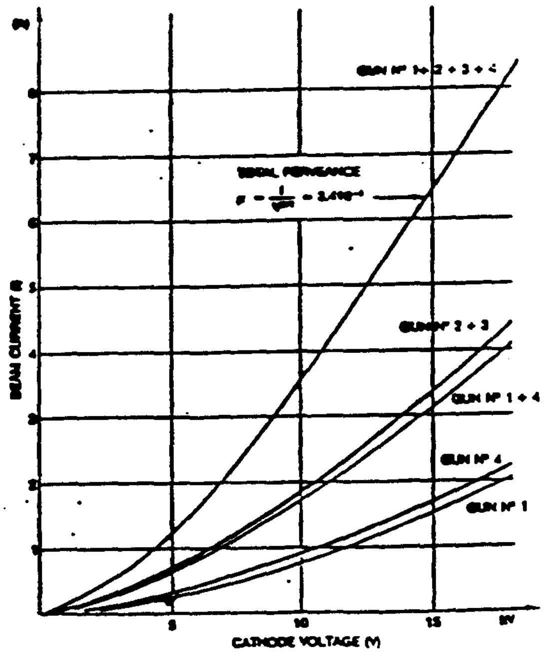


FIG.2 : BEAM CURRENT CHARACTERISTICS

BEAM-VOLTAGE PARAMETER RANGE FOR 200 MW KLYSTRON

Vo	Io	S(μPERV)	No of Beams
200	2000	22.4	20
300	1333	8.1	10
400	1000	3.95	5/10
500	800	2.26	4
600	667	1.43	2

NLC KLYSTRON REQUIREMENTS

- 2 GEV (Positron Booster Linac)

Freq.	L
Peak power/pulse length	150 MW/10μs or 250 MW/5μs
No. Required	12

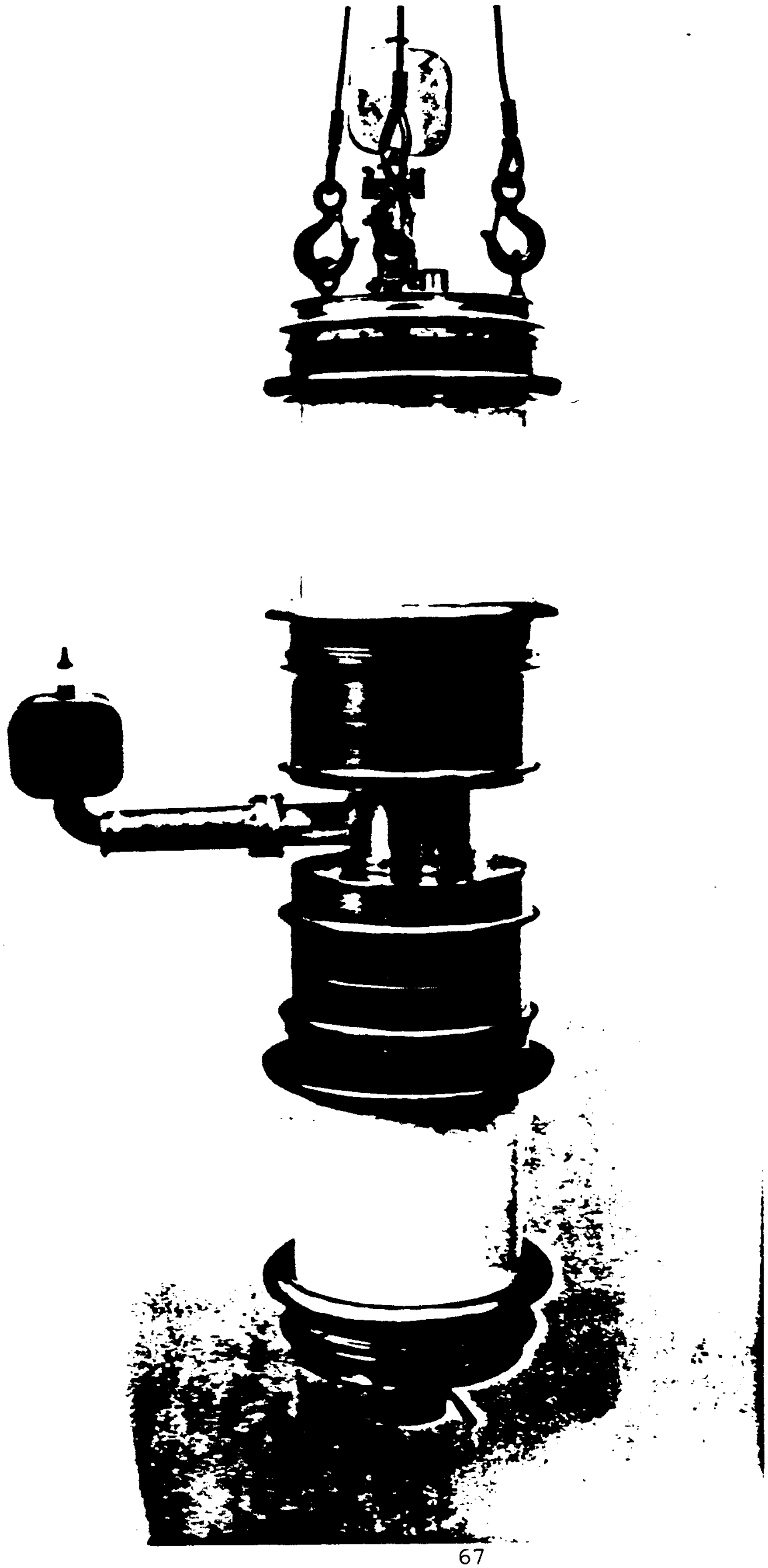
- 28 GEV (Various)

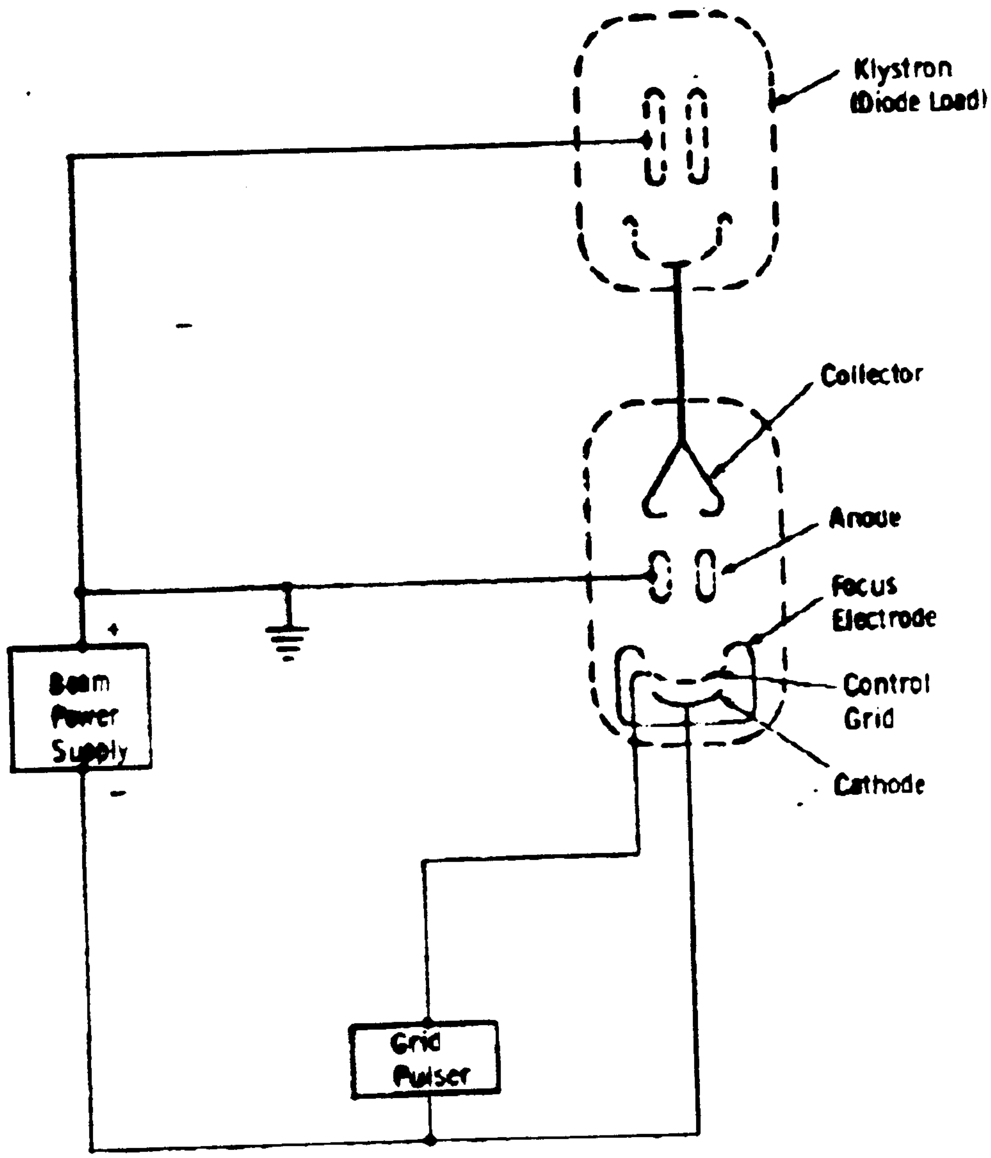
Freq.	S
Peak power/pulse length	150 MW/3.5μs
No. Required	150

- 500/1000 GEV (Main Linac)

Freq.	X (11.424)
Peak power/pulse length	50-75 MW/1.2μs
No. Required	4,000-10,000

X3069-1 LINEAR BEAM TETRODE SWITCH TUBE





SCHEMATIC DIAGRAM TETRODE SWITCH TUBE SERIES MODULATOR

FUTURE PLANS

- Evaluate X-band PPM 50 MW and 75 MW klystrons. Build several prototypes.
- Do paper design of L-band and S-band μs MBK's. Consider MB switch tubes.
- Look at possibility of a gridded S-band MBK, although tubes too few for serious efficiency concerns.
- If there is interest and the numbers look promising, consider a 10-beam, 200 MW X-band MBK, (short pulse, no pulse compression) with a series MB switch tube.
- Design for manufacturing

RESEARCH PROJECTS

(FUNDED BY SLAC AND THE USAF)

IMPEDIMENTS TO HIGHER POWER SOURCES FOR 1.5 TeV COLLIDER:

1. OUTPUT CIRCUIT RF BREAKDOWN
2. CATHODE CURRENT DENSITY (HIGH CURRENT)
3. GUN BREAKDOWN (HIGH VOLTAGE)

ONGOING AND PLANNED PROGRAMS:

(1.) RF BREAKDOWN AND METHODS FOR RAISING THRESHOLD.
STUDY USING X-BAND RESONANT RING

(2) PLAN TO INITIATE OXIDE CATHODE STUDY. BELIEVE THAT CURRENT DENSITIES OF 50 A/cm² ARE POSSIBLE WITH PROPER PROCESSING

(3) MULTIPLE BEAM KLYSTRONS (INDIVIDUALLY FOCUSED BEAMS)

KLYSTRON SESSION SUMMARY

S. GOLD

- **PRESENT NLCTA USES 50MW KLYSTRONS, 440KV @ uk=1.2**
- **NLC PLAN (X-BAND)**
  - **50MW PPM KLYSTRONS, 465KV @ uk=0.6 1.5uS**
  - **UPGRADE , 72MW PPM KLYSTRONS, 497KV @ uk=0.75**
- **S-BAND (DESY & NLC)**
  - **150MW, 535KV @ uk=1.8 , 3uS**
  - **UPGRADE , 200MW PPM, 600KV @ uk=1.4**

MODULATOR-KLYSTRON INTEGRATION ISSUES
TUESDAY OCTOBER 10, 1995 13:30-14:00
SPEAKER: ED WRIGHT (SLAC)

MAJOR ISSUES TO CONSIDER IN INTEGRATING MODULATOR AND KLYSTRON.

1. What type of a load does klystron present to the modulator? Resistance, Capacitance, Maximum voltage, Rise Time.

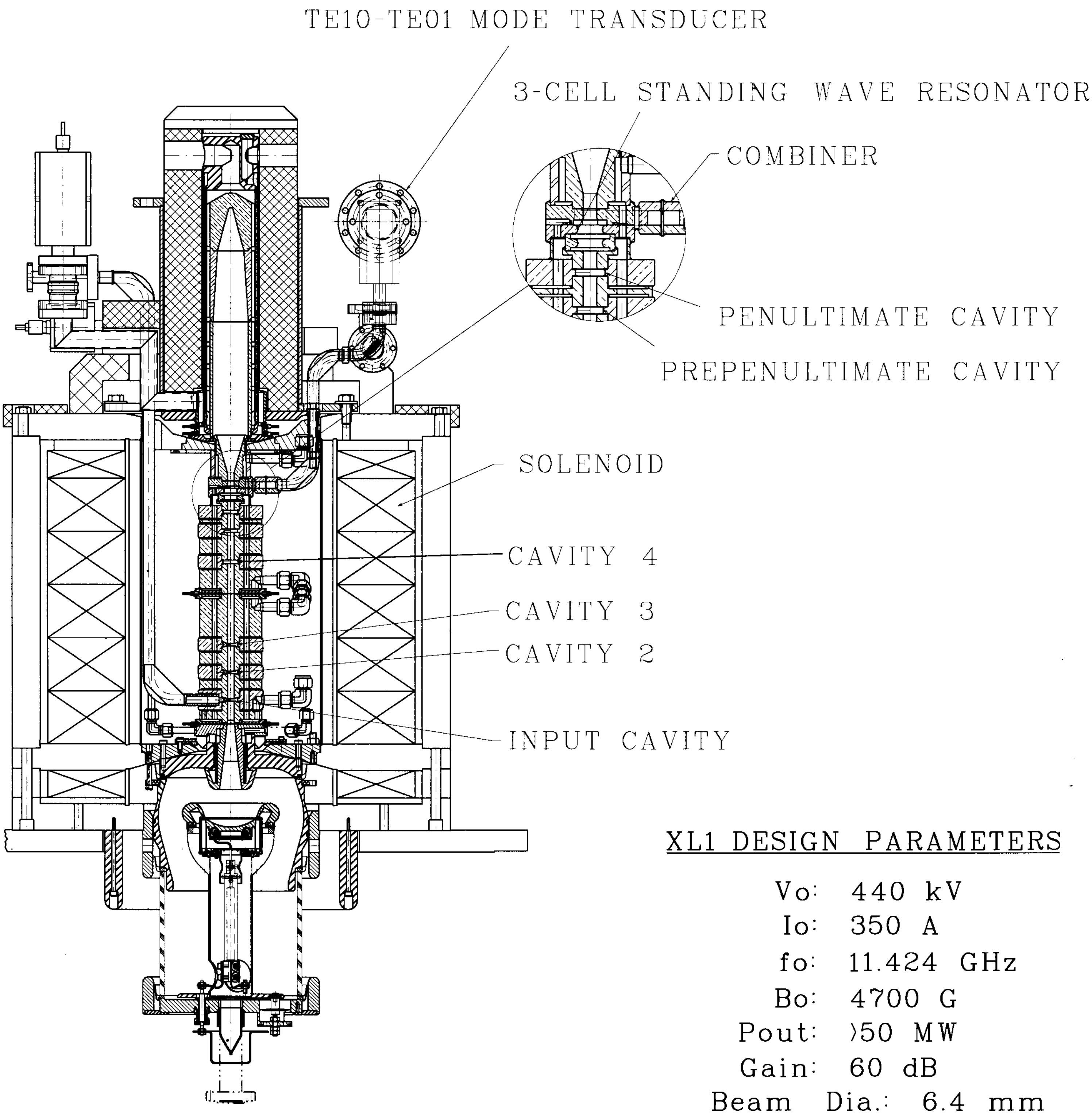
2. What does the klystron expect from the modulator? Would like and ideal pulse shape of voltage.

3. Since it appears one modulator will be used to drive two klystrons, what will the load look like to the modulator should one klystron fail and what action should the modulator take? The impedance will double if one modulator fails. The consenses is that the modulator should fault and go off-line until the klystron is replaced.

4. How should a new klystron be processed? begin with a narrow pulse width at a low duty and slowly increase the width until the design width is obtained. Slow increase the duty until the design duty is reached.

5. As the tube ages the beam current will decrease at a fixed filament current due to the change in perveance of the tube. Therefore the need to adjust the filament voltage to maintain the beam current was discussed. No conclusion was reached.

6. Maximum beam voltage ripple to maintain phase modulation was discussed. A chart to maintain a maximum of 10^0 phase ripple is enclosed.



XL1 DESIGN PARAMETERS

Vo: 440 kV
Io: 350 A
fo: 11.424 GHz
Bo: 4700 G
Pout: >50 MW
Gain: 60 dB
Beam Dia.: 6.4 mm
Cathode Dia.: 71.5 mm

XL1 KLYSTRON

? What does the klystron 'look' like to a modulator?

A: For the high power X-band sources developed at SLAC:

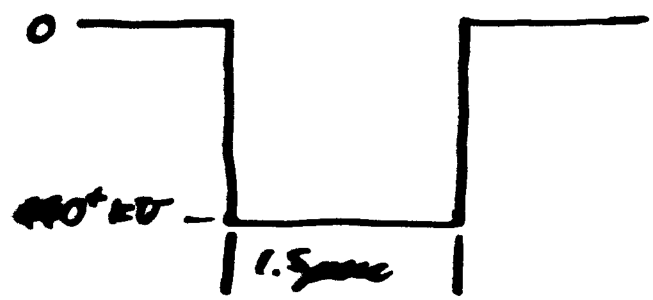
$$2500\,\Omega > R_0 > 1250\,\Omega$$

$$^{*}C \leq 50\,pF \qquad \text{* measured in air.}$$

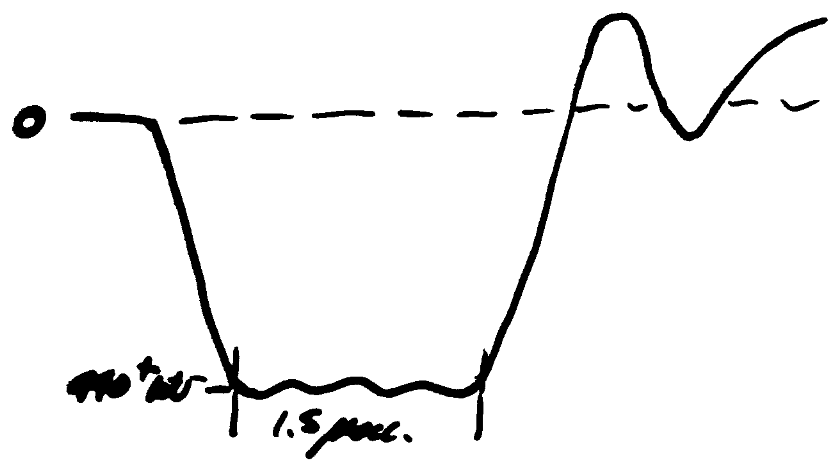
$$L : ?$$

? How should the Modulator 'look' to the tube?

Want ⇒

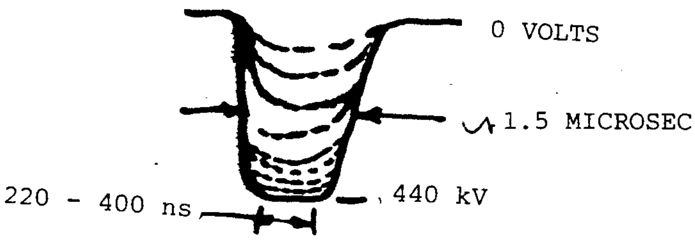


Get ⇒



KLYSTRON PROCESSING

1. Condition the tube to full voltage, narrow cathode pulse.



A. Voltage increments during process of between 25 to 10 kV (25 kV @ low voltage; 10 kV at high voltage)

B. Time to 440 kV is usually between 8 and 12 hours. (@ 60 pps)

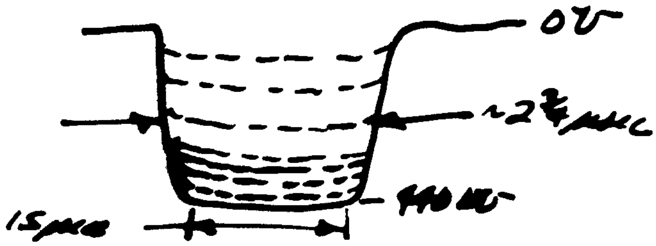
C. Under these conditions we will observe between 20 to 40 end of line clipper faults (Gun arcs). The klystron is manually recycled.

2. Evaluation of the klystron

A. Check peak output power of klystron with narrow (50ns $\leq \tau \leq$ 400 ns rf pulse.

KLYSTRON PROCESSING cont.

③ Add L-C elements to the line for approx. 1.5 μsec flat-top; Wide Cathode Pulse.



A) Voltage increments again 25 kV to 10 kV.

B.) Time to 440 kV again 8 to 12 hours. (@60 PPS)

C) Under these conditions, we observe on average less than 10 End of Line Clipper Faults. The klystron is manually recycled.

④ RF evaluation of the klystron

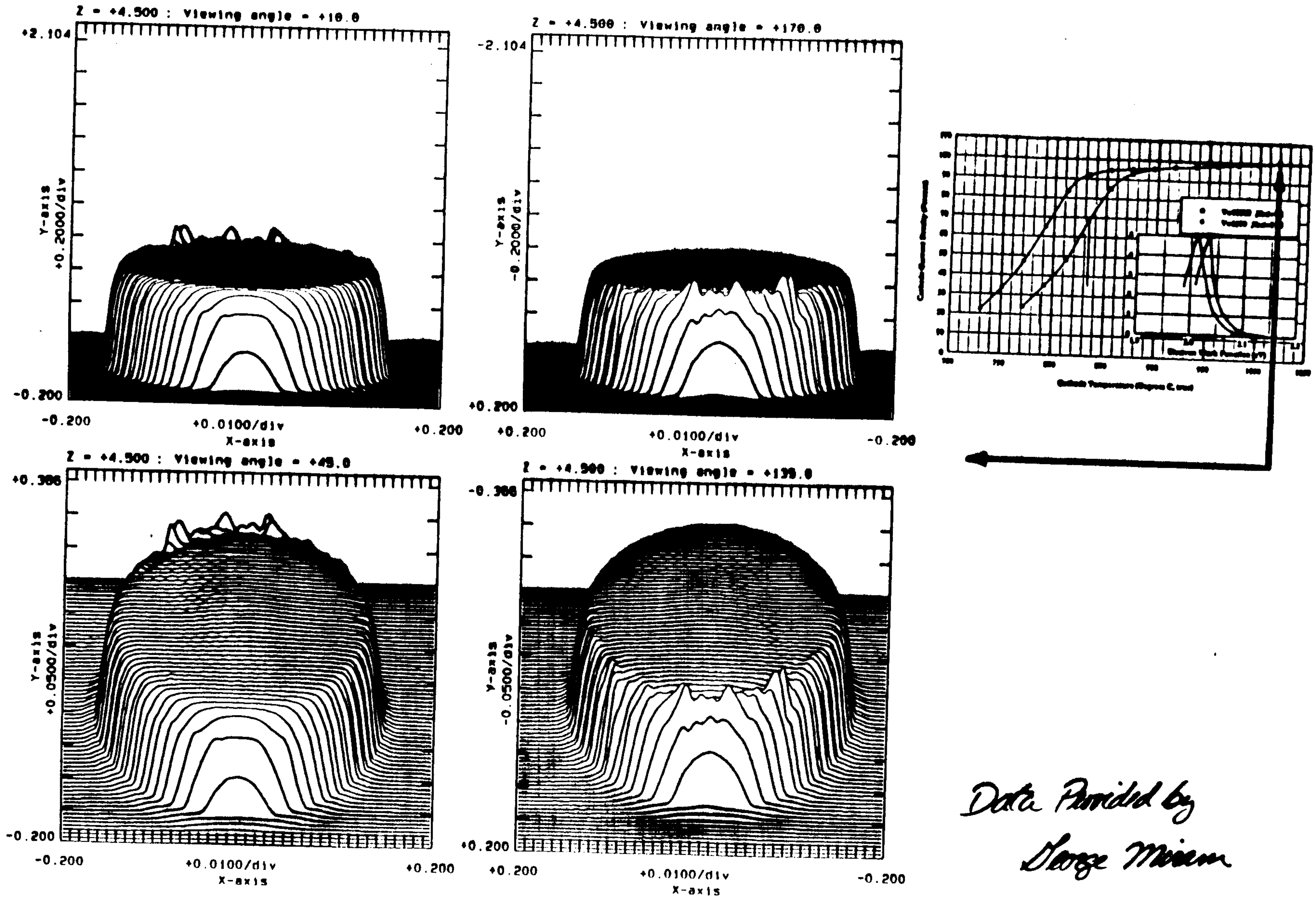
Ⓐ Process to 1.5 μsec and saturate klystron.
$50 \leq \hat{P}_{rf} \leq 55$ MW for XL1, XL2, & XL3.

Ⓑ We generally see 1 EOLC fault per day, thereafter. The klystron is manually recycled.

varian

microwave power tube products

BEAM CURRENT DENSITY PROFILE
100% CURRENT AT 1020 °C

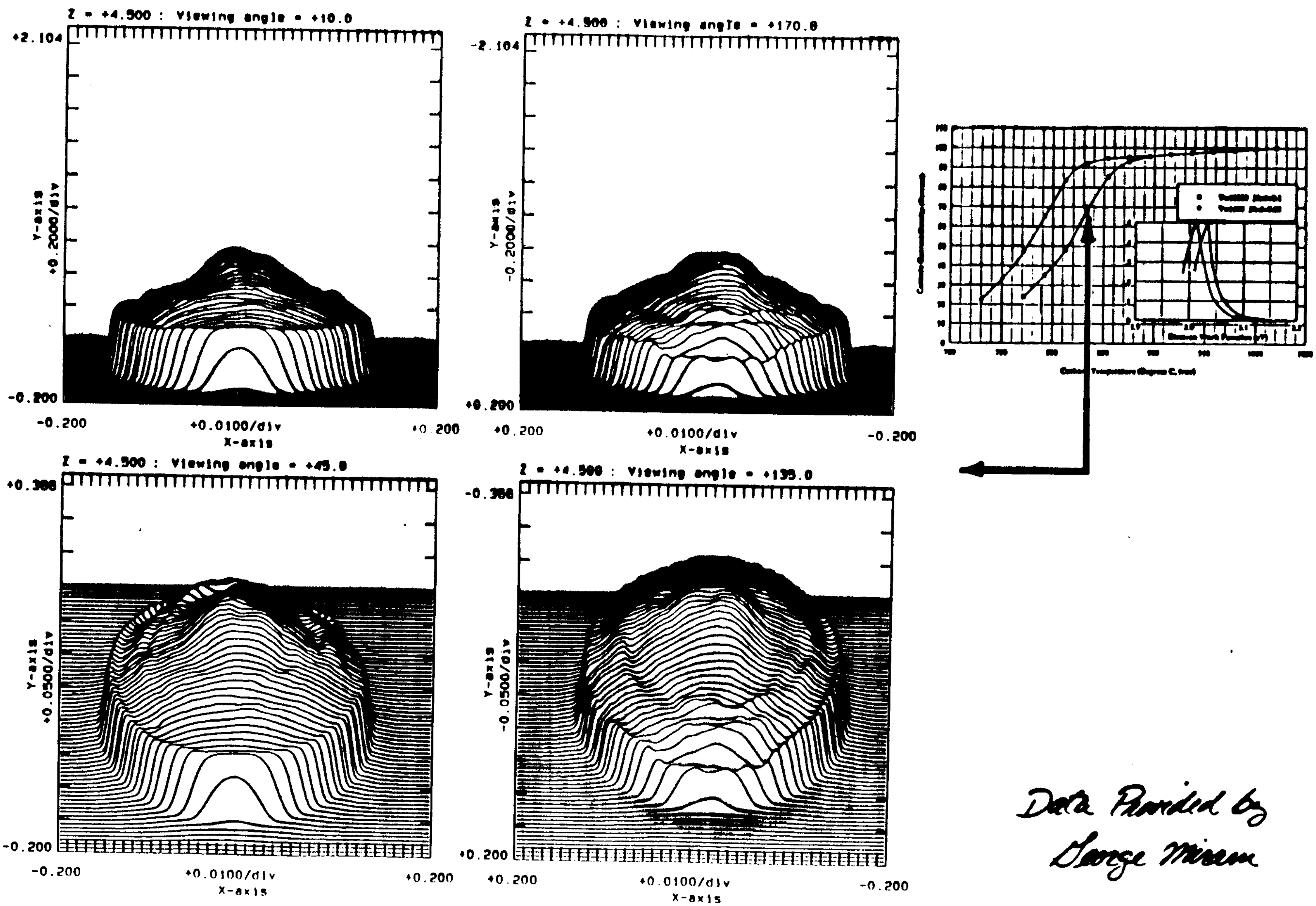


Data Provided by
George Miram

varian

microwave power tube products

BEAM CURRENT DENSITY PROFILE
68.8% CURRENT AT 834 °C



Data Provided by
George Misam

Calculating Maximum Allowable Voltage Ripple for a given Maximum rf Phase Ripple.

$$\frac{\Delta V}{V} = -\frac{mc^2}{e} \cdot \frac{\lambda_0}{L_{i,o}} \cdot \frac{(\gamma^2-1)^{3/2}}{V_0} \cdot \frac{\Delta\phi}{360}$$

λ_0 = free space wavelength.

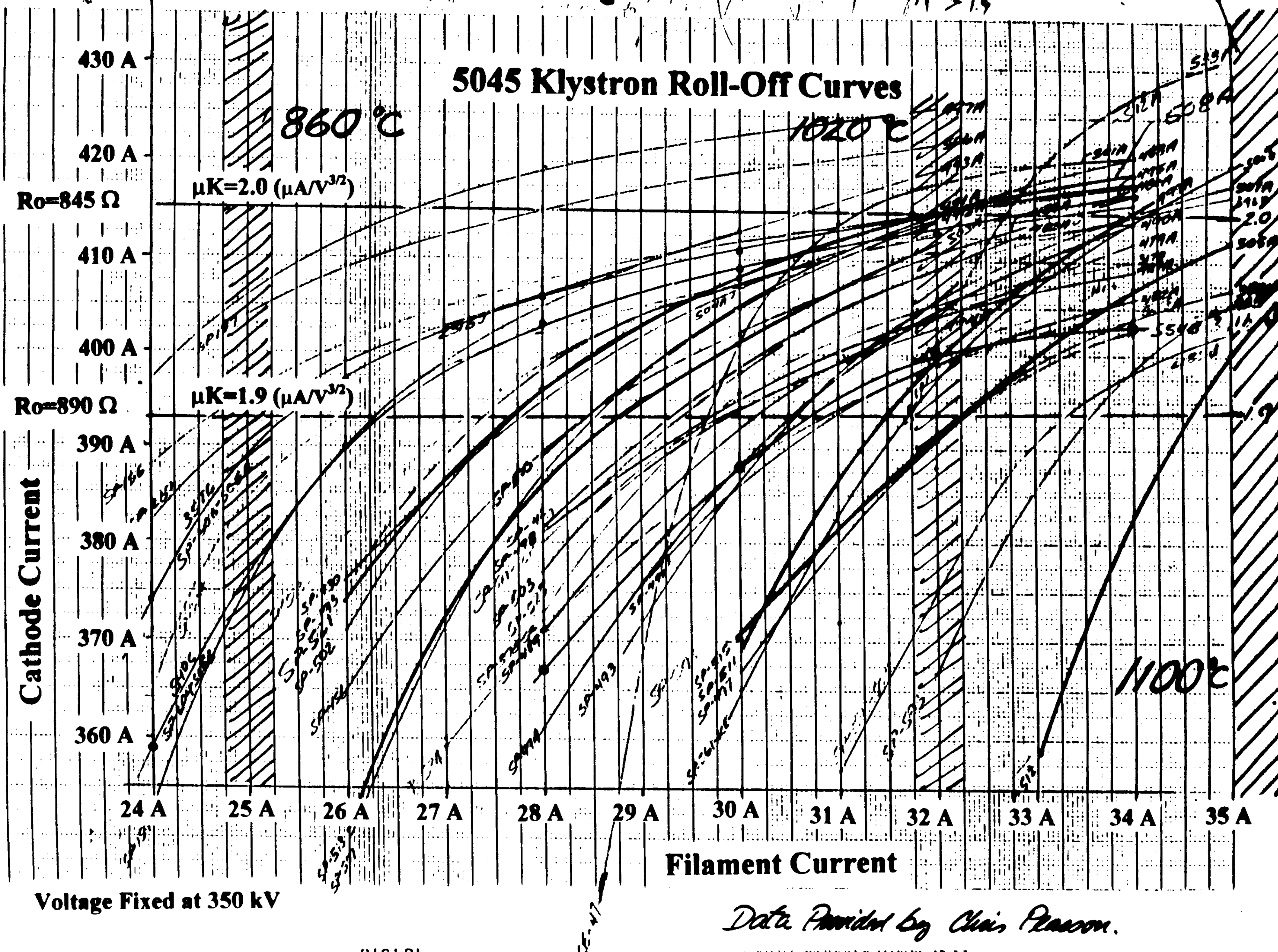
$L_{i,o}$ = Tube length (input cavity to output cavity)

$$\gamma = 1 + \frac{V_0}{511}$$

Voltage Ripple for Several Tube Designs

Beam Power Constant at 154 MW

	Case 1*	Case 2	Case 3	units
Beam Voltage	440	500	560	kV
Beam Current	350	308	275	A
Tunnel Radius	4.76	4.76	4.76	mm
Beam Radius	3.2	3.2	3.2	mm
Reduced Plasma Propagation Constant (Beta-Q)	13.13	9.912	7.953	rad/m
Tube Length (input cavity-output cavity) with Phase Length Constant at 232 Degrees.	309.0	409.3	510.1	mm
% Voltage Regulation Required for a Maximum 10 Degree rf phase ripple.	1.06	0.91	0.81	%


5045 Klystron Roll-Off Curves
860 °C
1020 °C
1100 °C
Ro=845 Ω
μK=2.0 (μA/V^3/2)
Ro=890 Ω
μK=1.9 (μA/V^3/2)
430 A
420 A
410 A
400 A
390 A
380 A
370 A
360 A
Cathode Current
24 A
25 A
26 A
27 A
28 A
29 A
30 A
31 A
32 A
33 A
34 A
35 A
Filament Current
Voltage Fixed at 350 kV
Data Provided by Chris Pearson.

NLC KLYSTRON
MODULATOR

R. CASSEL

KLYSTRON PARAMETER

* MICRO PERVEANCE 0.75
* EFFICIENCY 60%
* POWER IN PULSE 75 MW RF → 125 MW VIDEO
* → VOLTAGE 488 KV CURRENT 256 AMPS
* → CHARACTERISTICS IMPEDANCE 1900 OHMS
* PULSE LENGTH 1200 NANOSECONDS
* → VIDEO JOULES 150 JOULES PER PULSE

NLC KLYSTRON MODULATOR

R. CASSEL

SWITCH REQUIREMENT (ONE KLYSTRON)

* PULSE LENGTH > 1.5 MICRO SECONDS
* SWITCHING POWER 250 MW
* RISE TIME << 100 NANO SECONDS
* → 100 KV 2.5 KA OR 40 OHMS IMPEDANCE
* → 70 KV 3.5 KA OR 20 OHMS IMPEDANCE
* → 50 KV 5 KA OR 10 OHMS IMPEDANCE

NLC KLYSTRON
MODULATOR

R. CASSEL

<u>SO WHAT'S THE PROBLEM WITH STANDARD SLAC MODULATOR</u>

* **EFFICIENCY AND COST!**
* **PRESENT EFFICIENCY LESS THAN 50% COST > 250K$**
* **EFFICIENCY MAINLY DUE TO RISE AND FALL TIME OF PULSE**
* **COST *<u>IS NOT</u>* DETERMINED BY MAJOR PARTS**
* **GOAL FOR EFFICIENCY 80%**
* **COST GOAL < 180K$**

NLC KLYSTRON
MODULATOR

R. CASSEL

SWITCH REQUIREMENT (TWO KLYSTRON)

* PULSE LENGTH > 1.5 MICRO SECONDS
* SWITCHING POWER 500 MW
* RISE TIME << 100 NANO SECONDS
* → 100 KV 5.0 KA OR 20 OHMS IMPEDANCE
* → 70 KV 7.0 KA OR 10 OHMS IMPEDANCE
* → 50 KV 10 KA OR 5 OHMS IMPEDANCE

NLC KLYSTRON
MODULATOR

R. CASSEL

RISE TIME GOAL <200 NSEC

PULSE TRANSFORMER INDUCTANCE MUST BE <100 μHY WITH A KLYSTRON IMPEDANCE OF 1000 OHMS

* KLYSTRON CAPACITANCE TOTAL < 100 pFD
  100 pfd @ 500KV=25 JOULES

* SWITCH RISE TIME <100 NSEC @ 10 OHMS

* PFN RISE TIME <100 NSEC
  (NUMBER OF SECTION, CAPACITOR INDUCTANCE)

* STRAY INDUCTANCE OF LESS THAN 1 μHY @ 10 OHMS

NLC KLYSTRON
MODULATOR

R. CASSEL

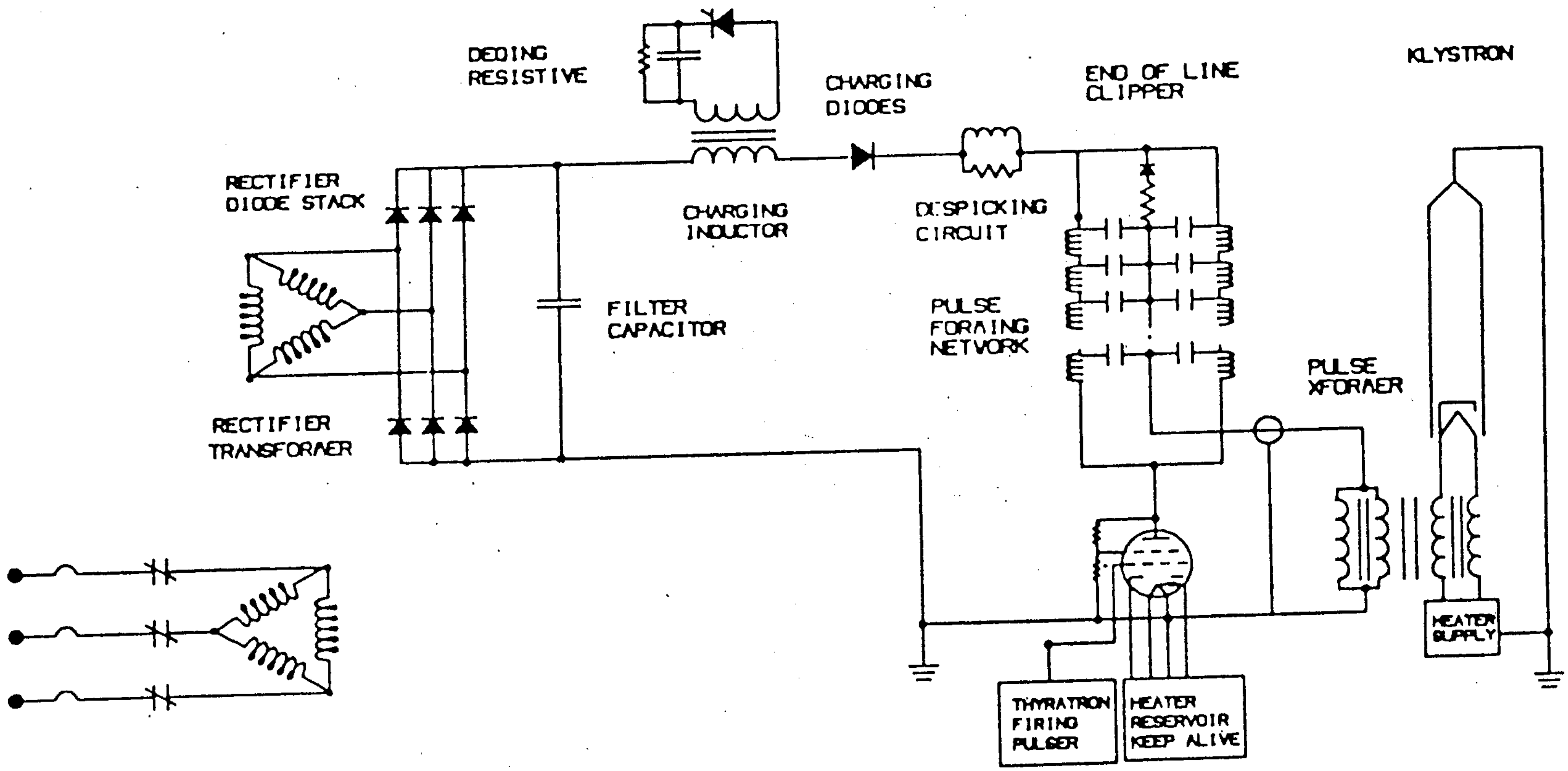
EFFICIENCY
TWO KLYSTRON

- * EFFICIENCY GOAL 80% WITH KLYSTRON OF 300 JOULES /PULSE
- * → 75 JOULES LOSS OR 375 JOULES TOTAL PER PULSE

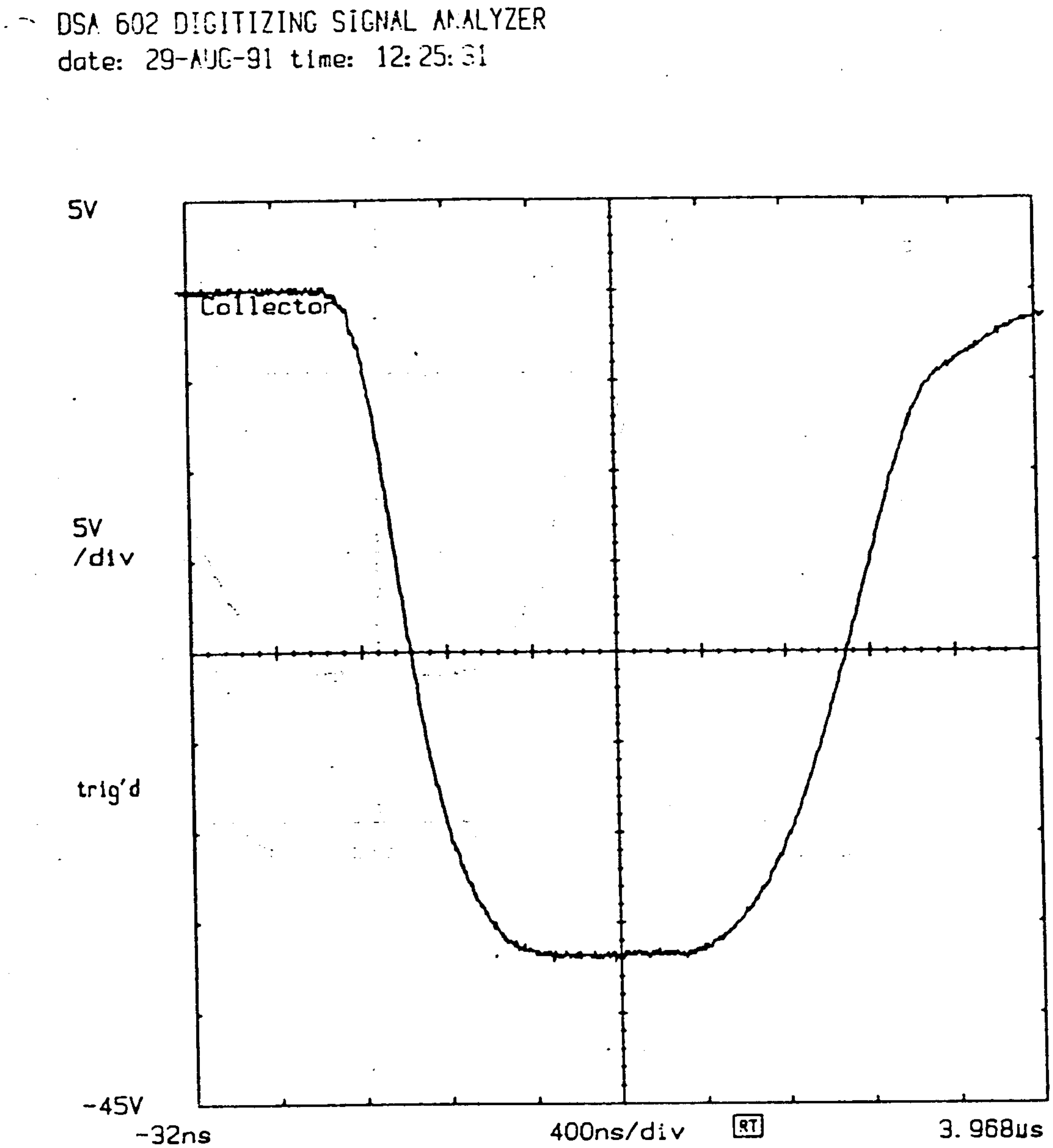
POSSIBLE DIVISION OF LOSSES

- * 35 JOULES FOR RISE TIME
- * 8 JOULES FOR PULSE TRANSFORMER (CORE, COPPER)
- * 20 JOULES FOR POWER SUPPLY (95% EFFICIENCY)
- * 4 JOULES FOR SWITCH (270 V @ 10 KA FOR 1.5 μSEC)
- * 6 JOULES MISMATCH (5% NON RECOVERABLE)
- * 2 JOULES FOR PFN

SLAC KLYSTRON MODULATOR



SLAC TYPE MODULATOR
KLYSTRON TEST STAND
PULSE



NLCTA KLYSTRON MODULATOR

R. CASSEL
12/14/92

WHAT ARE THE OBJECTIVES ?

* KLYSTRON TEST MODULATOR 600 KV 560 AMPS 1.2 μSEC
* MODULATOR 480 KV 400 AMPS 1.5 μSEC FOR NLCTA
* UPGRADE TO 600 KV 560 AMPS 1.5 μSEC
* DEVELOPMENT MODULATOR FOR FUTURE LINEAR COLLIDER

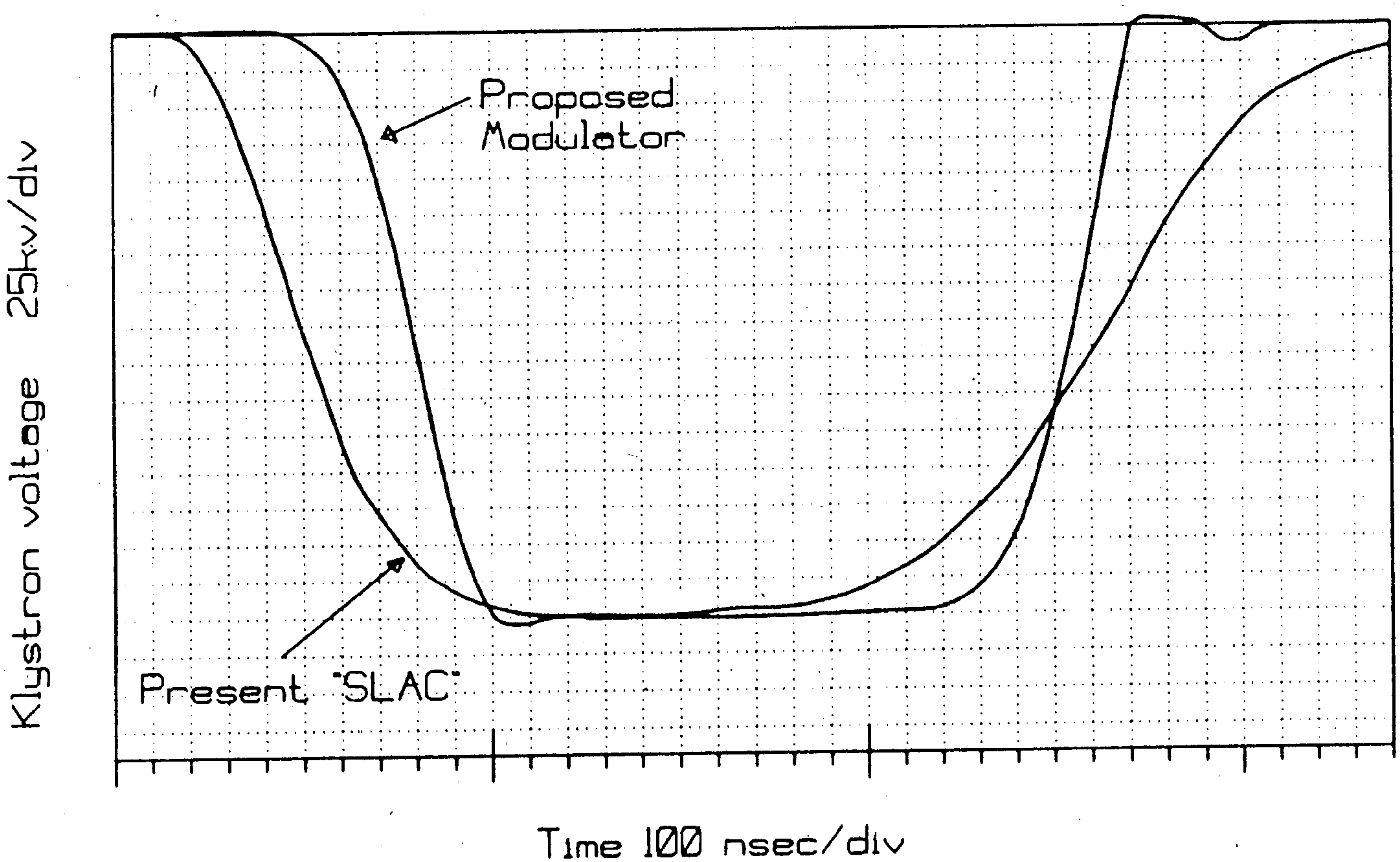
NLCTA KLYSTRON MODULATOR DESIGN

R. CASSEL
12/14/92

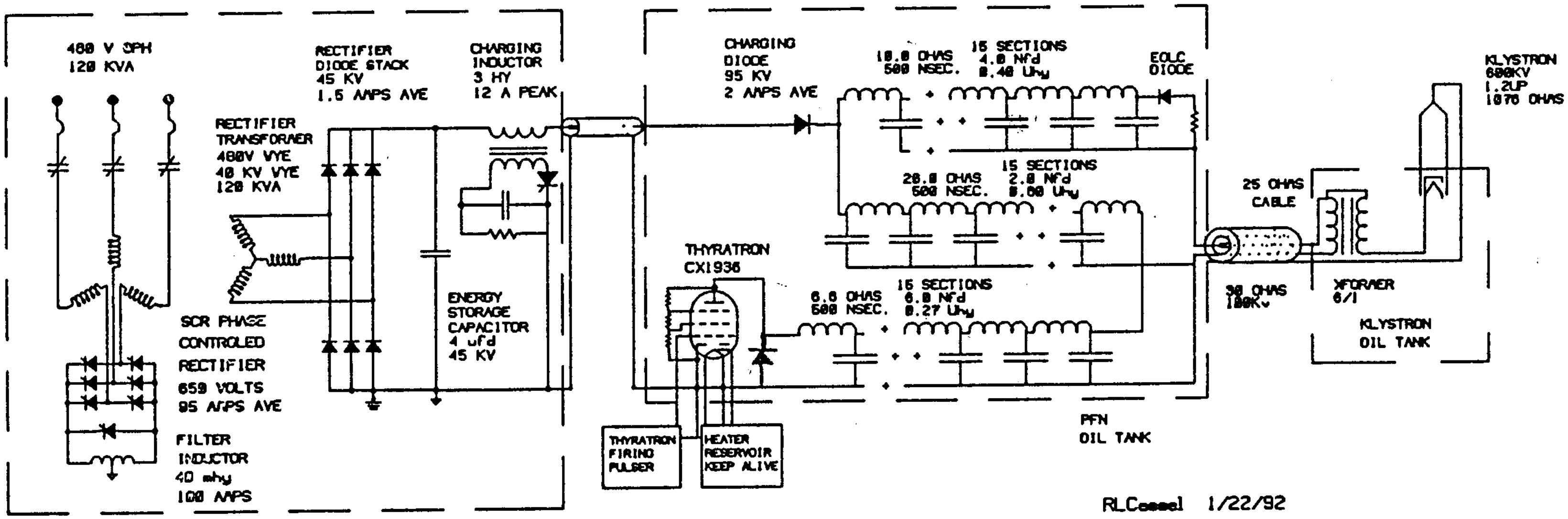
<u>SO WHAT IS THE DESIGN ?</u>

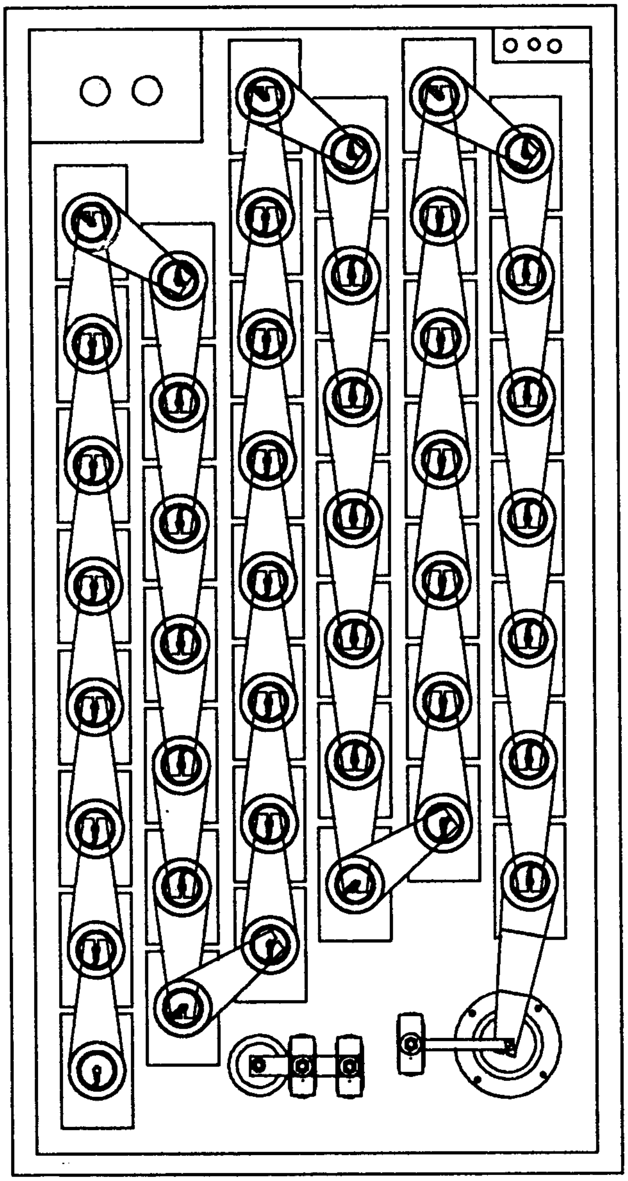
- CUMULATIVE WAVE LINE (MULTIPLYING BLUMLEIN 1.5)
- LOW TURNS RATION 6/1 AUTO TRANSFORMER
- LOW LEAKAGE INDUCTANCE TRANSFORMER <80 μH
- LARGE NUMBER OF PFN SECTIONS >14 PER PFN
  (OR WATER DIELECTRIC TRIAXIAL CABLE)
- PFN DIRECT COUPLED TO PULSE TRANSFORMER AND THYRATRON
- FAST PULSED CHARGING

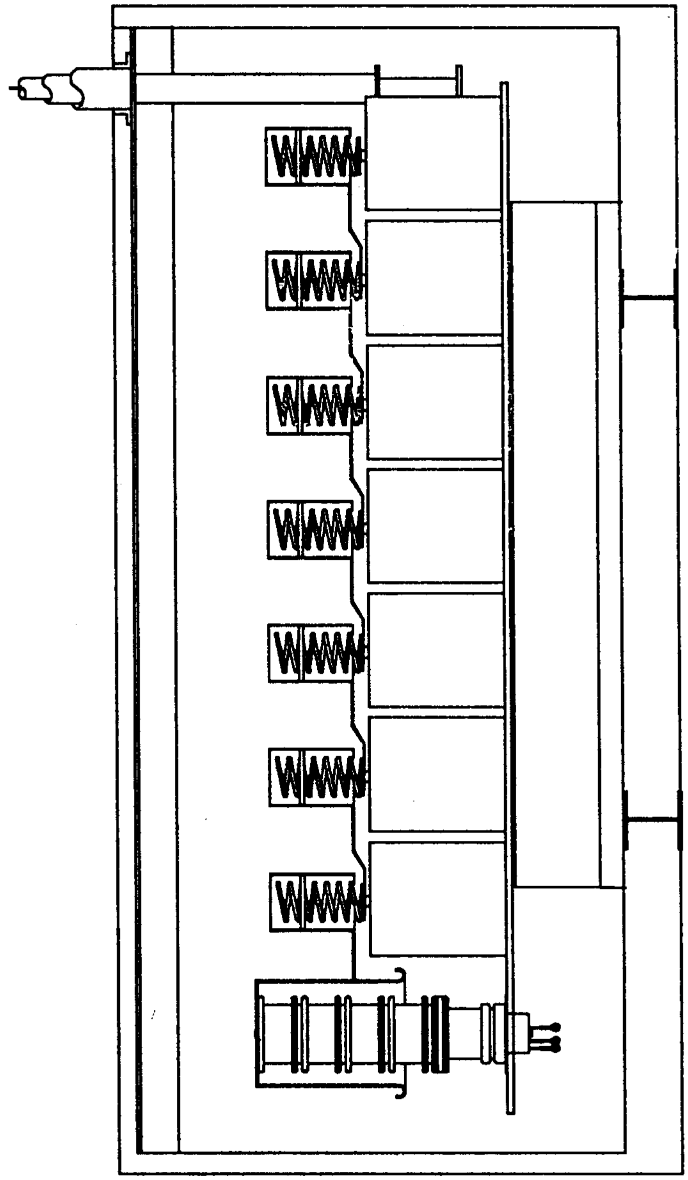
KLYSTRON MODULATOR VOLTAGE WAVEFORM

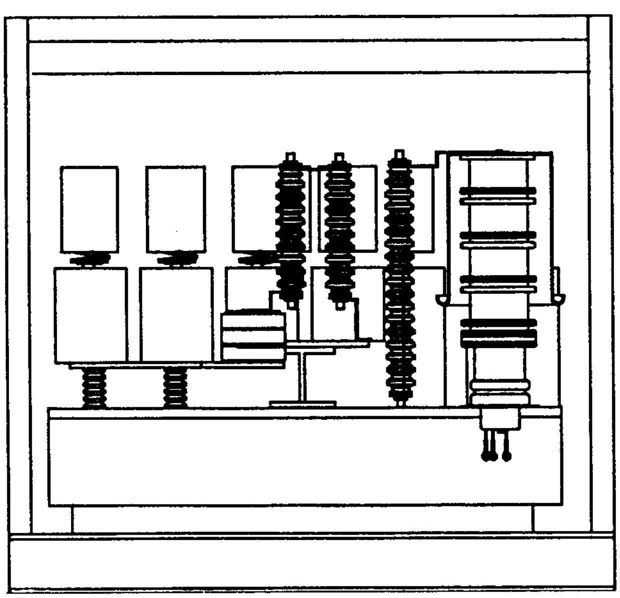


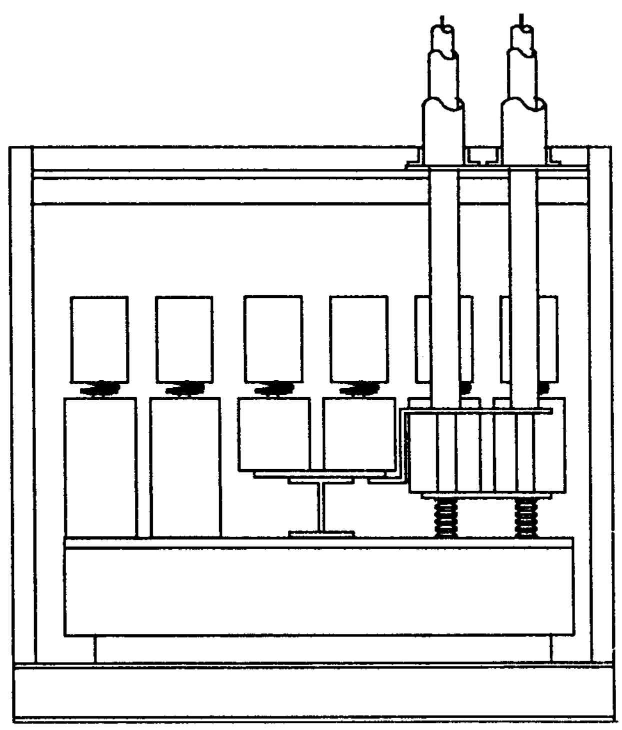
NLC TEST STAND MODULATOR



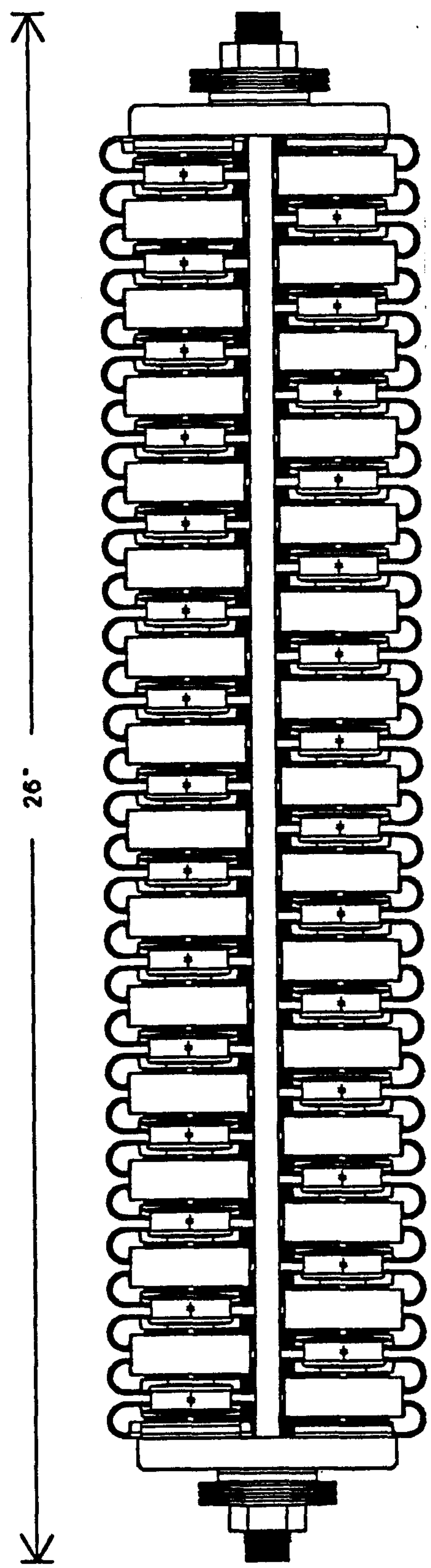


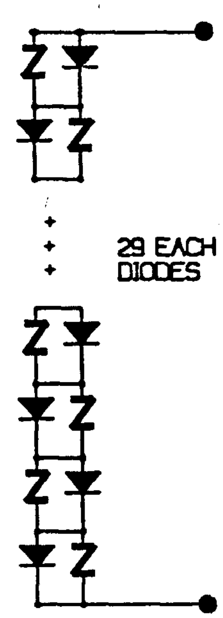


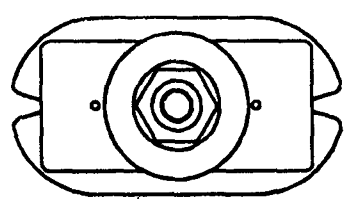




DIODE
80KV
40 A @ 100°C
500A @ 100KV

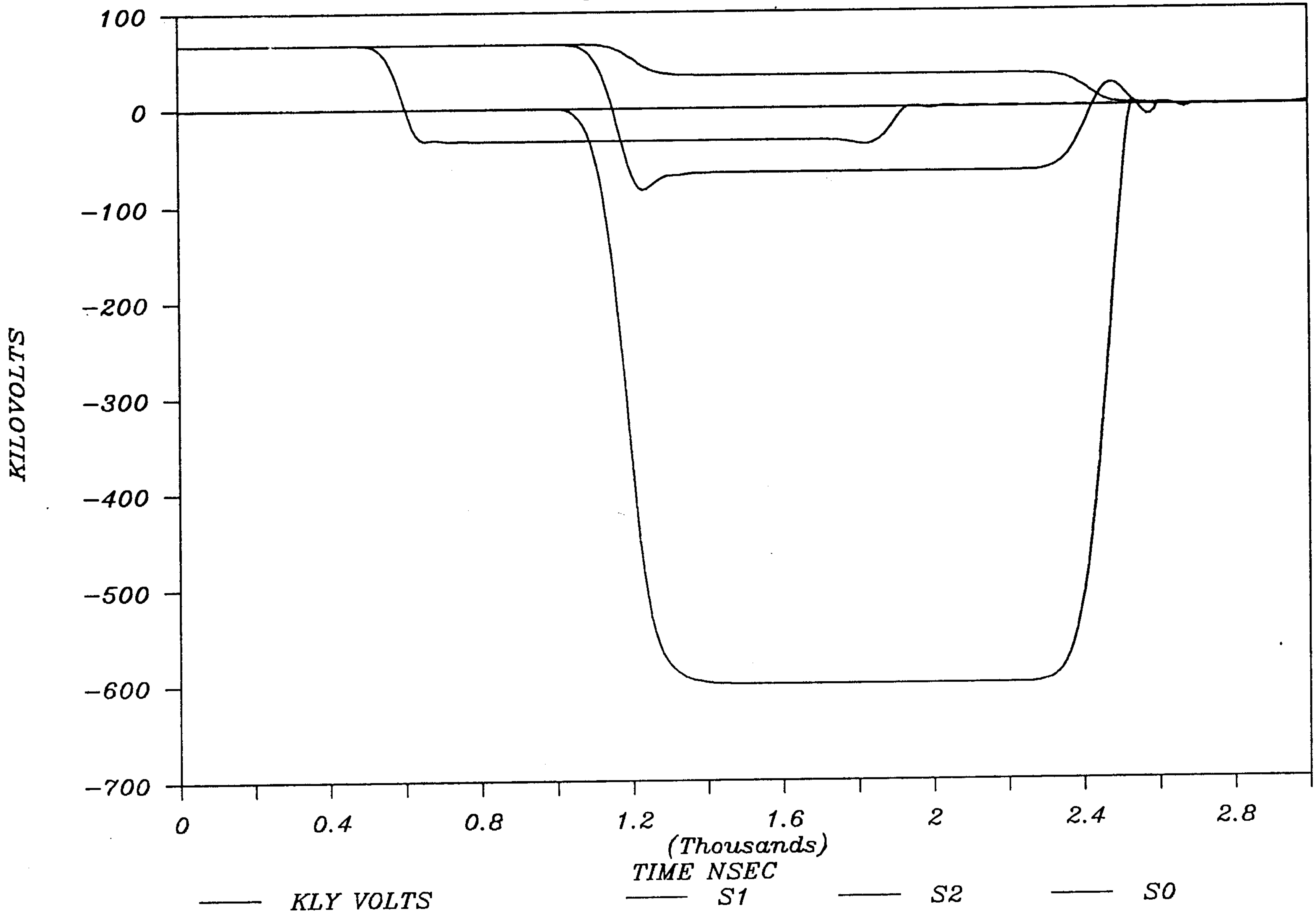






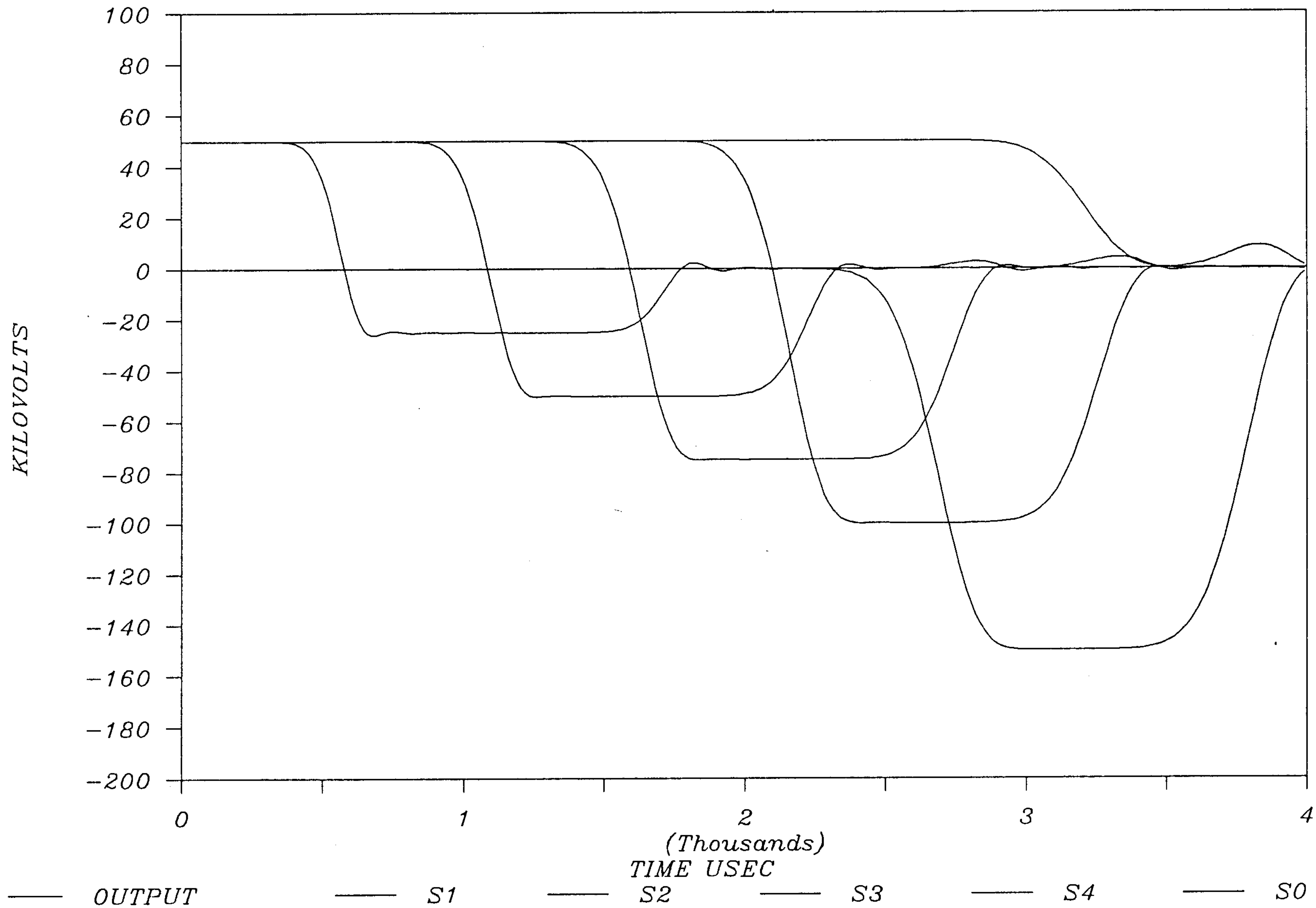
CWL KLYSTRON MODULATOR

80 uhy, 220 ufd, 6/1, CABLE

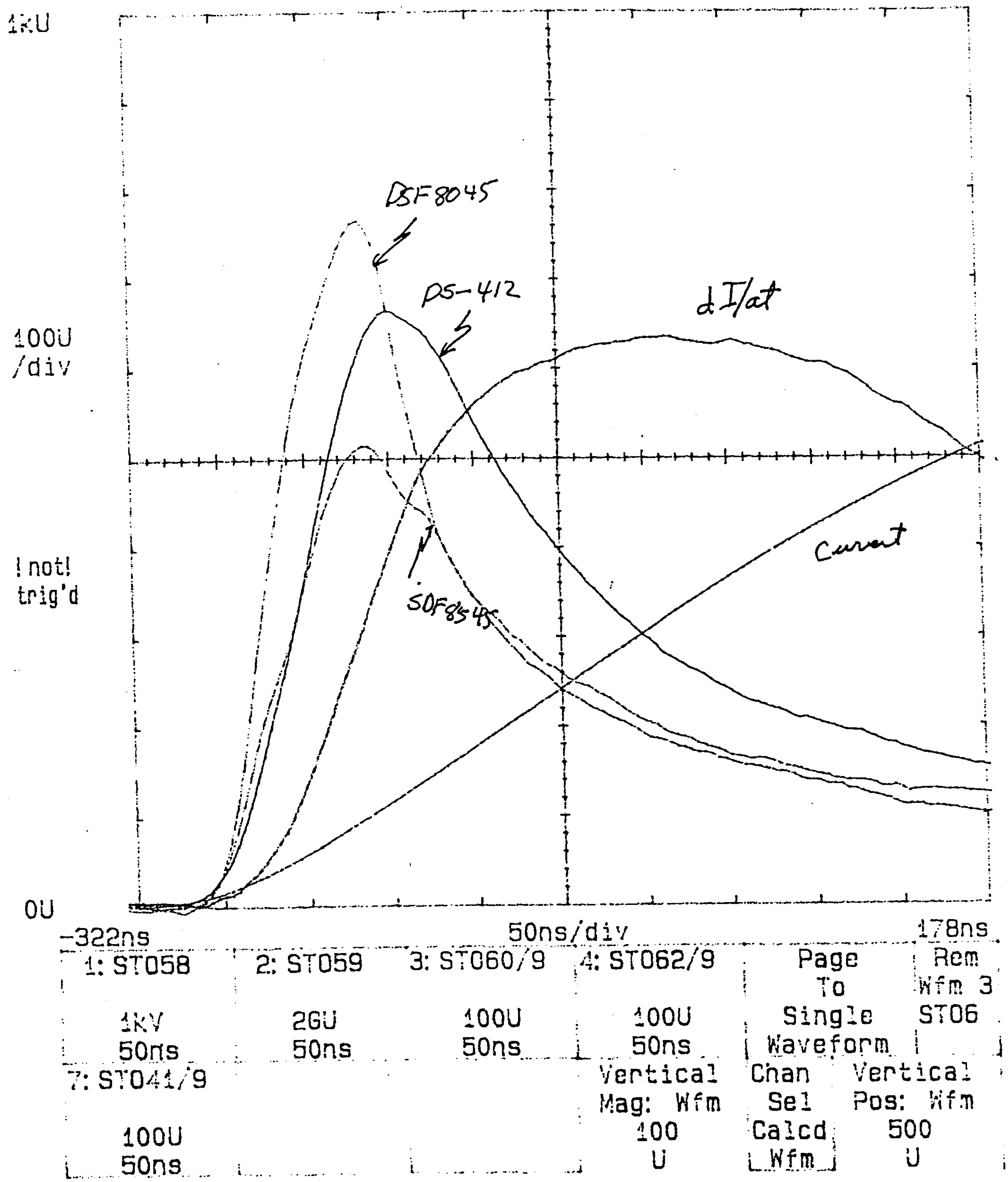


CUMULATIVE WAVE LINE

1000 OHMS 5 STAGE 1 USEC 15 SECTIONS

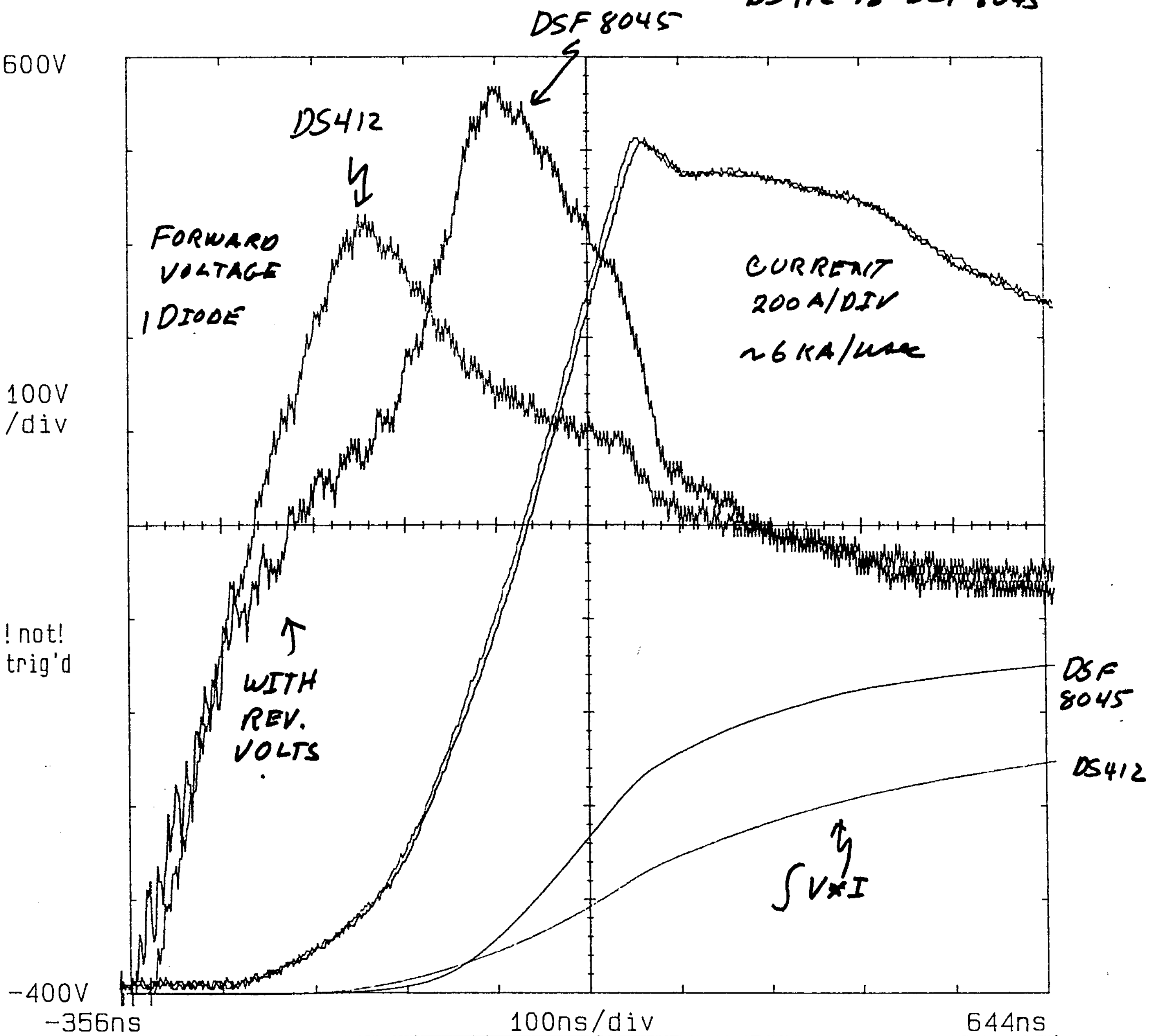


DSA 602 DIGITIZING SIGNAL ANALYZER
date: 1-JUN-93 time: 8:34:53



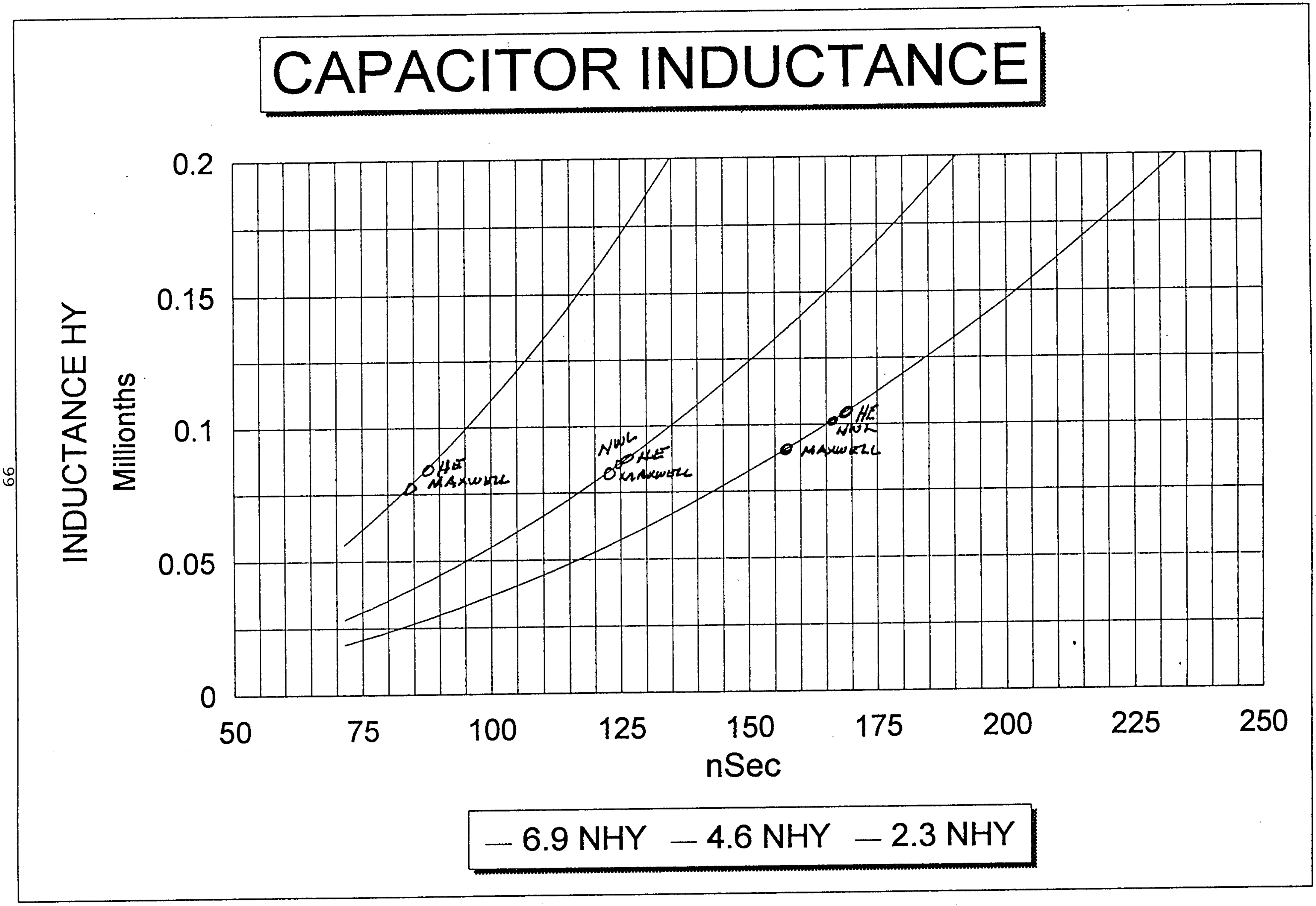
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 9-SEP-92 time: 14:50:49

COMPARE
DS412 To DSF 8045



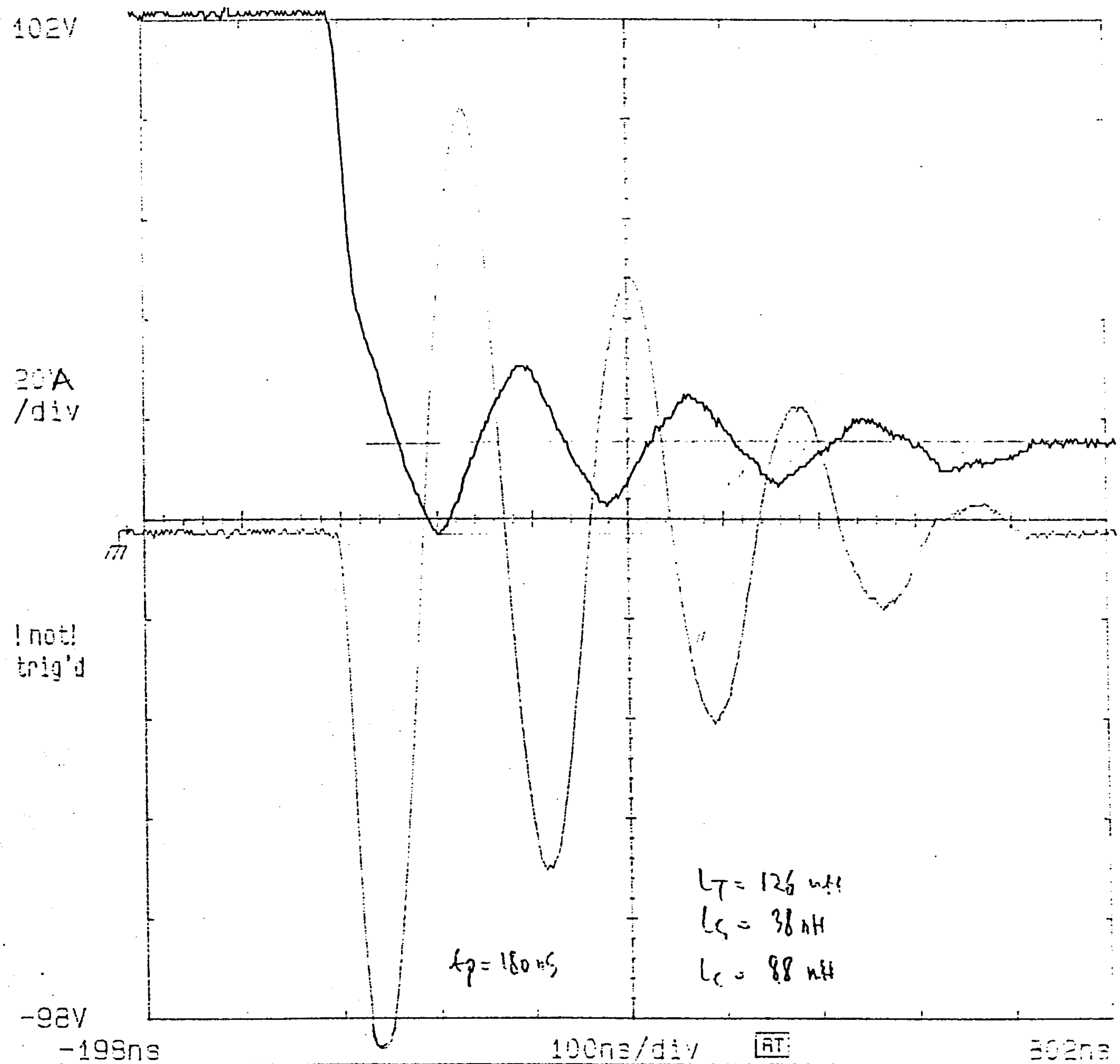
1: ST041 200V 100ns	2: ST042 100V 100ns	3: Intg (ST 50mU 100ns	4: ST033 200V 100ns	Page To Single Waveform		Rem Wfm 2 ST042
5: ST034 100V 100ns	6: Intg (ST 50mU 100ns		Horizontal Magnify 2 x	Pan/ Zoom On	Horizontal Pos Gr 156 pts	

FIG 6


CAPACITOR INDUCTANCE
INDUCTANCE HY
Millionths
0.2
0.15
0.1
0.05
0
50
75
100
125
150
175
200
225
250
nSec
HE
MAXWELL
NWL
HE
MAXWELL
HE
NWL
MAXWELL
— 6.9 NHY — 4.6 NHY — 2.3 NHY

DSA 602 DIGITIZING SIGNAL ANALYZER
date: 12-AUG-93 time: 10:29:29

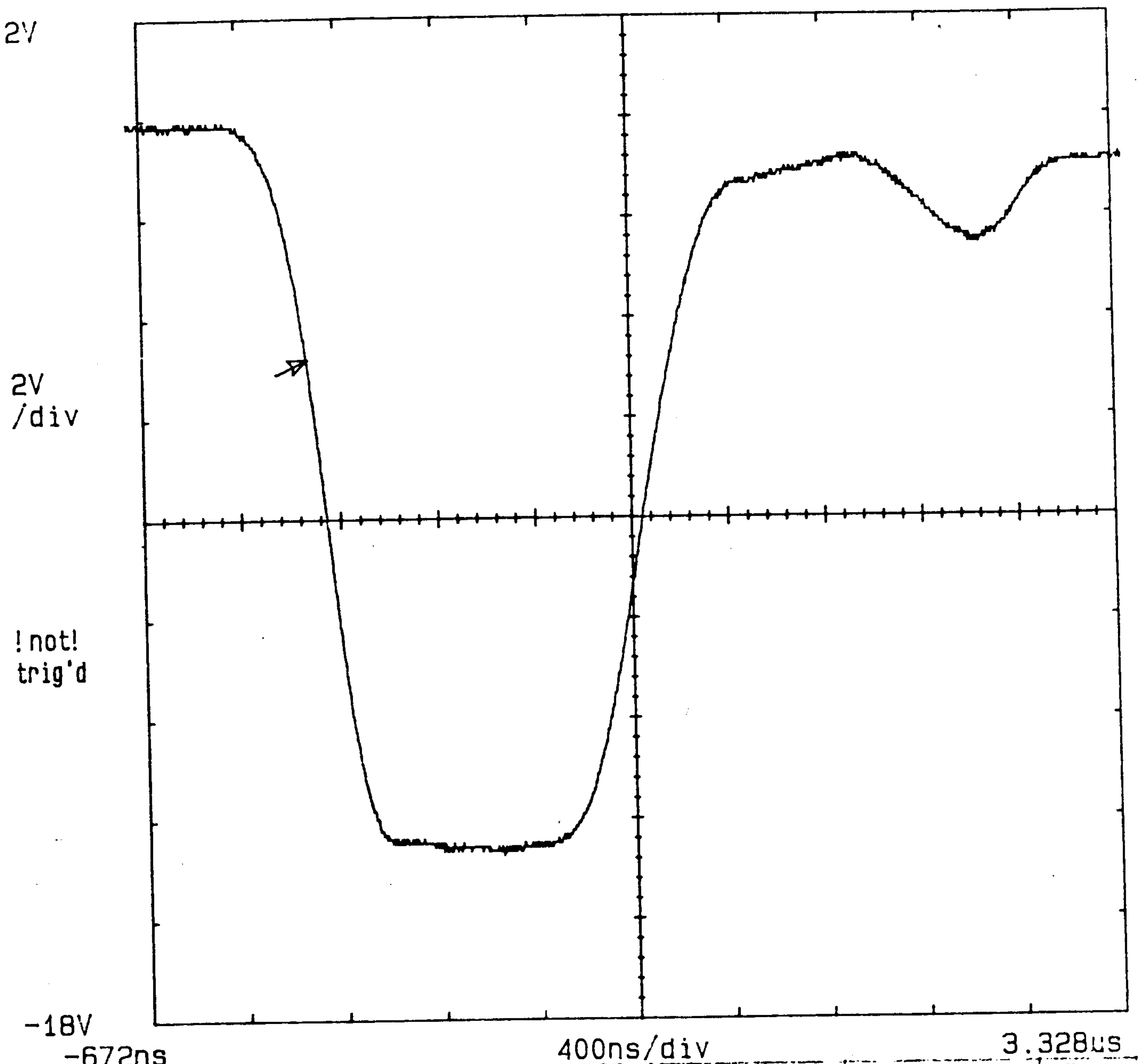
MAXWELL 6.5uF /80KV



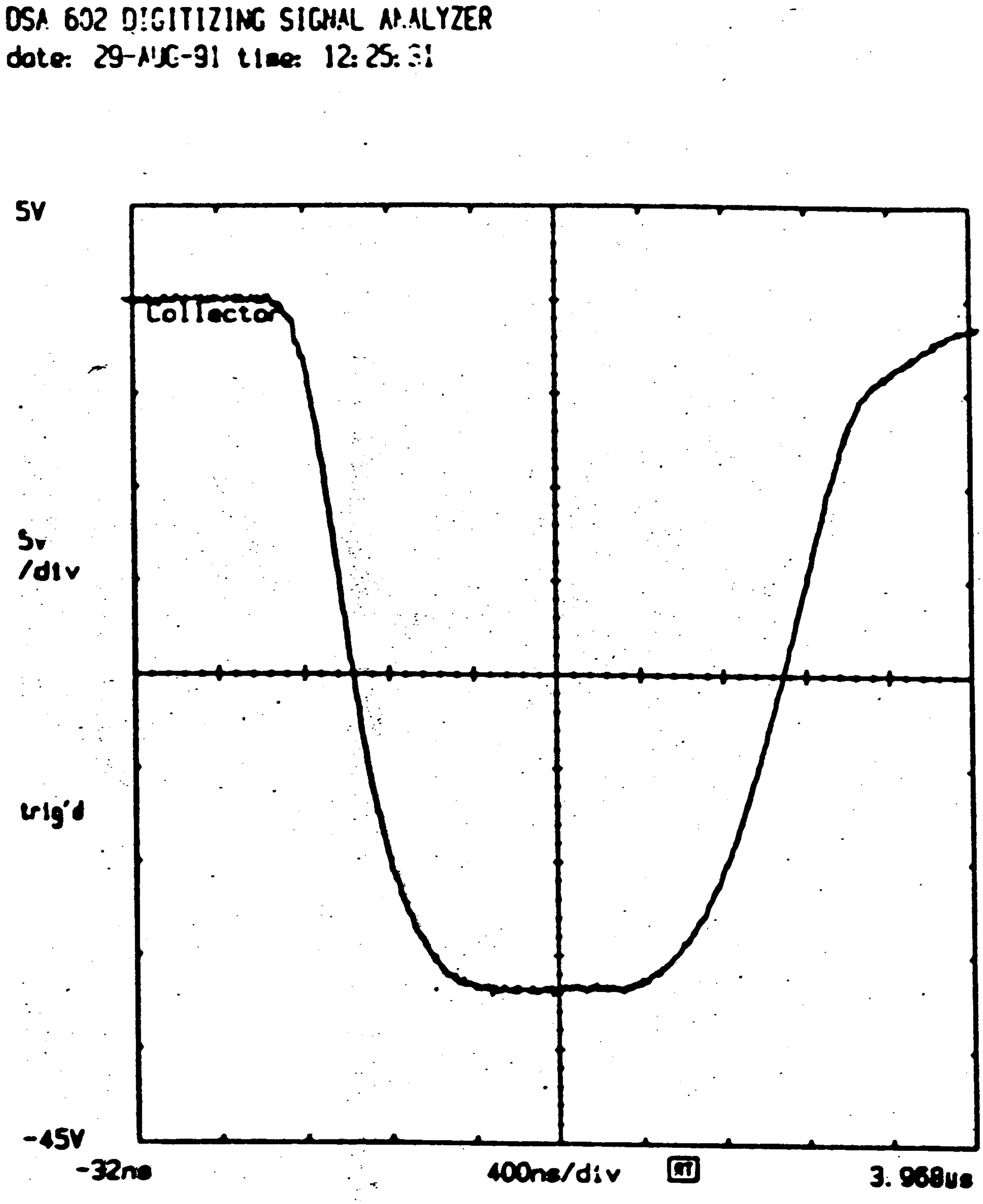
Store Waveform	Recall Waveform	Clear Waveform	Delete Waveform	Page to Stored Wfm Scan	Rem Wfm 4 R1/(Main
Store Setting	Recall Setting	Delete Setting	Main Size 100n s/div	Pan/ Zoom Off	Main Position -210n s

STO 31 & 32

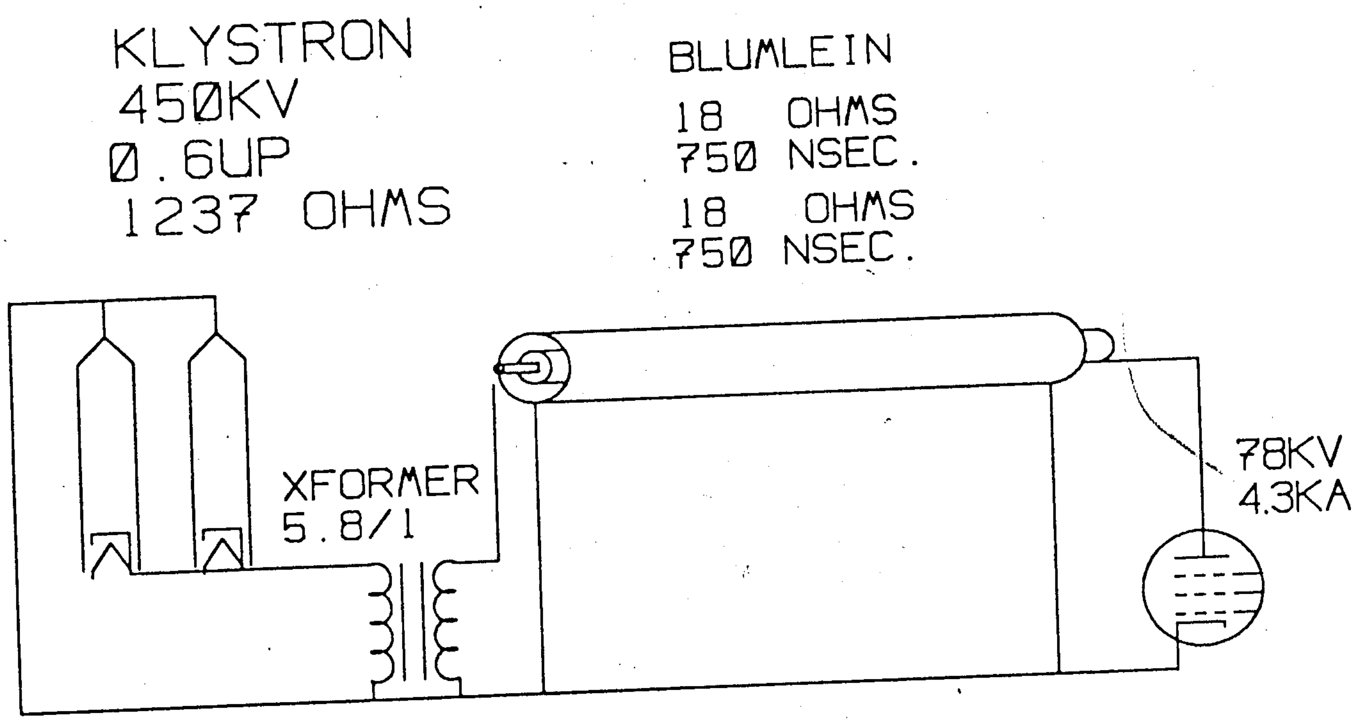
DSA 602 DIGITIZING SIGNAL ANALYZER
date: 15-SEP-93 time: 14:37:29



Max	Rise	Min	Measure-ments	Statistics Comp & Def continuous	Rem Wfm 1 ST092
-80.0002 mV	538.0 ns	-14.7200 V			
Fall			Horizontal Magnify 1 x	Pan/ Zoom On	Horizontal Pos Gr 0 pts
330.0 ns					

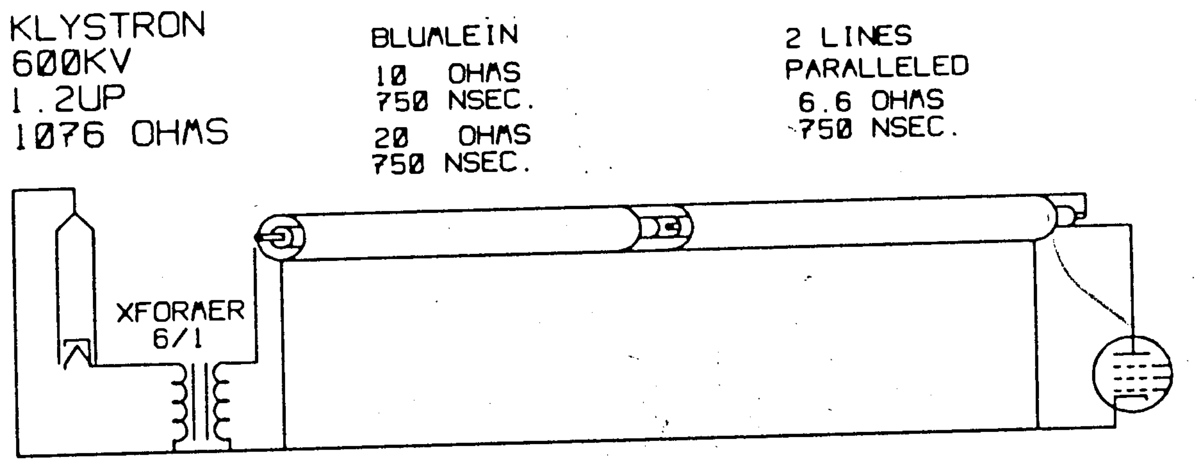

DSA 602 DIGITIZING SIGNAL ANALYZER
date: 29-AUG-91 time: 12:25:31
5V
Collector
5v
/div
trig'd
-45V
-32ns
400ns/div
3.968us

NLCTA KLYSTRON MODULATOR



R. CASSEL
12/1/94

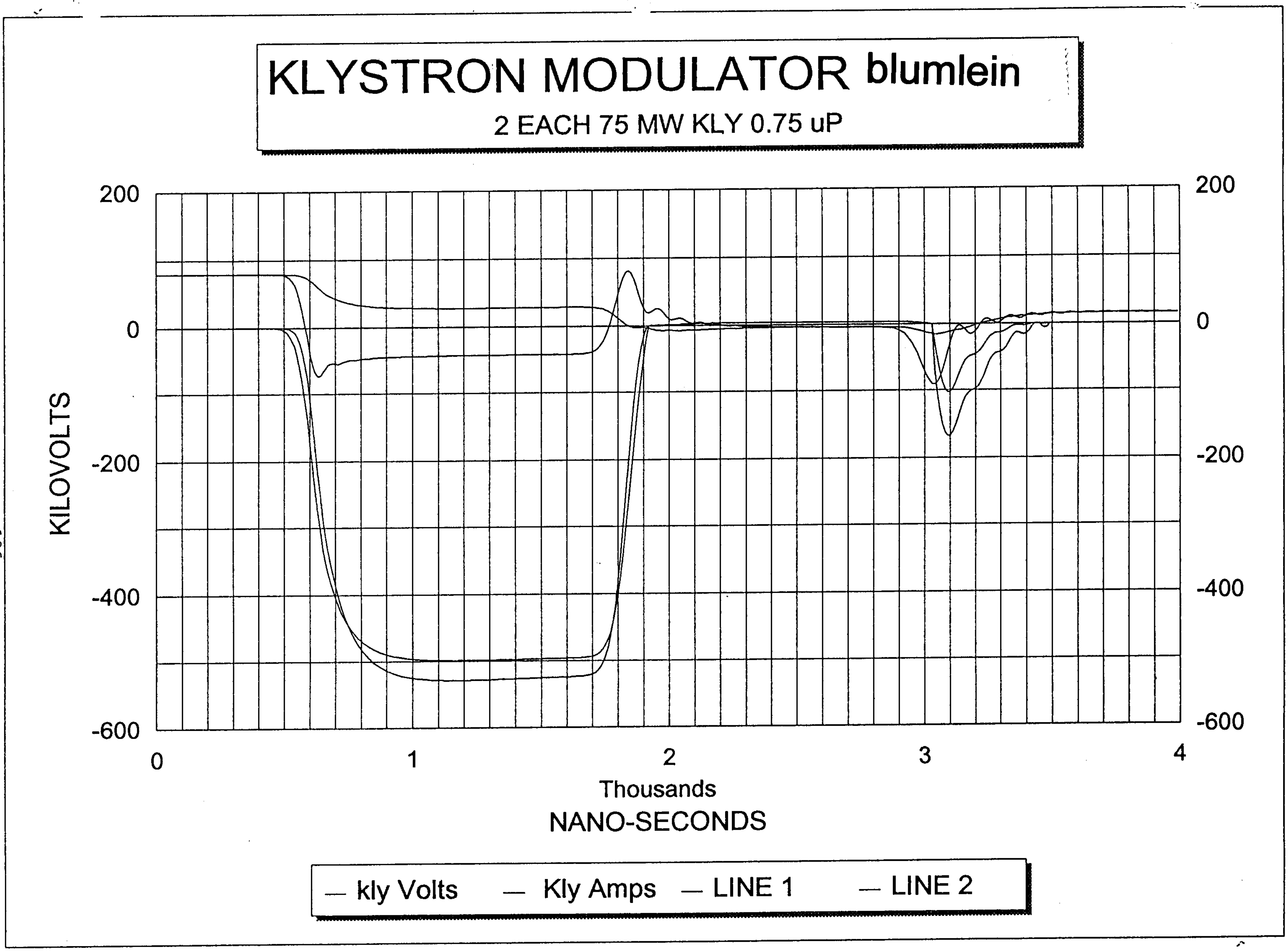
NLCTA KLYSTRON MODULATOR



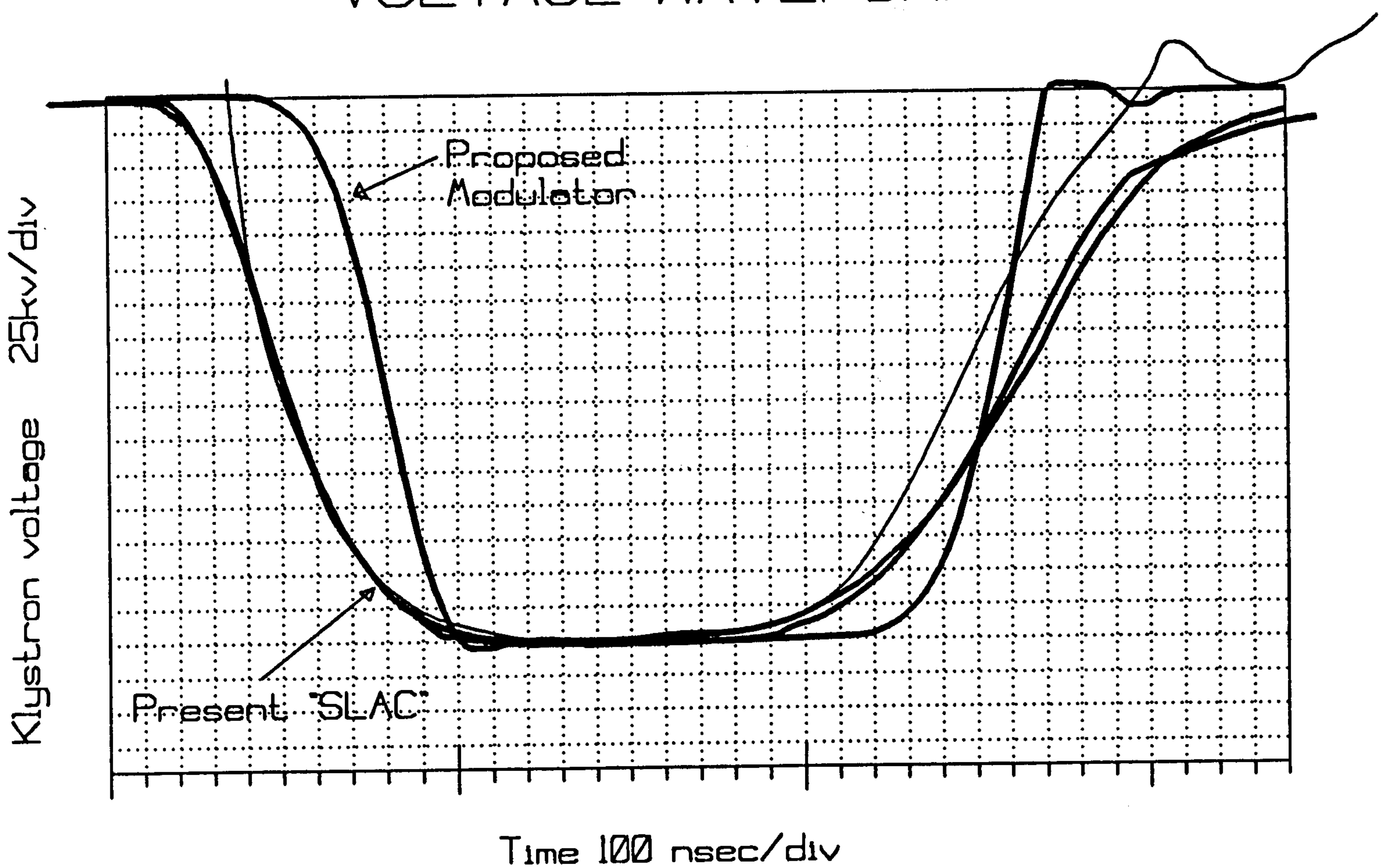
R. CASSEL
7/5/91

0.75	u-perv	75000	volts	67828	volts	70000	volts	55182	volts
60%	efficiency		turns ratio	7.2	turns		turns ratio	5.9	turns
75	mw rf		drive imp	18.40	ohms		drive imp	27.41	ohms
125	mw video		thy amps	7,372	amps		thy amps	9,061	amps
488,359	volts		impedance	18.4	ohms		impedance	18.3	ohms
256	amps		stray thy	1.840	uhy		stray thy	1.218	uhy
1,908	ohms		stray ind	1.840	uhy		stray ind	2.741	uhy
954	ohms 2 each			7.5	dielectic			7.5	dielectic
100	nsec			50.4	ohms			50.0	ohms
76	uhy			237	feet			548	feet
1,300									

line				blumlein				1.5 mult			
45000	volts			45000	volts			45000	volts		
	turns ratio	22.0	turns		turns ratio	10.9	turns		turns ratio	7.2	turns
	drive imp	1.97	ohms		drive imp	8.10	ohms		drive imp	18.23	ohms
	thy amps	11,262	amps		thy amps	11,111	amps		thy amps	11,111	amps
	impedance	4.0	ohms		impedance	4.1	ohms		impedance	4.1	ohms
	stray thy	0.400	uhy		stray thy	0.405	uhy		stray thy	0.405	uhy
	stray ind	0.197	uhy		stray ind	0.810	uhy		stray ind	1.823	uhy
70000	volts			70000	volts			70000	volts		
	turns ratio	14.0	turns		turns ratio	7.0	turns		turns ratio	4.7	turns
	drive imp	4.87	ohms		drive imp	19.60	ohms		drive imp	44.10	ohms
	thy amps	7,167	amps		thy amps	7,143	amps		thy amps	7,143	amps
	impedance	9.8	ohms		impedance	9.8	ohms		impedance	9.8	ohms
	stray thy	0.977	uhy		stray thy	0.980	uhy		stray thy	0.980	uhy
	stray ind	0.487	uhy		stray ind	1.960	uhy		stray ind	4.410	uhy
94000	volts			94000	volts			94000	volts		
	turns ratio	10.0	turns		turns ratio	5.0	turns		turns ratio	4.0	turns
	drive imp	9.54	ohms		drive imp	38.16	ohms		drive imp	59.62	ohms
	thy amps	5,119	amps		thy amps	5,119	amps		thy amps	6,143	amps
	impedance	18.4	ohms		impedance	18.4	ohms		impedance	15.3	ohms
	stray thy	1.836	uhy		stray thy	1.836	uhy		stray thy	1.530	uhy
	stray ind	0.954	uhy		stray ind	3.816	uhy		stray ind	5.962	uhy


KLYSTRON MODULATOR blumlein
2 EACH 75 MW KLY 0.75 uP
200
0
-200
-400
-600
KILOVOLTS
0
1
2
3
4
Thousands
NANO-SECONDS
kly Volts
Kly Amps
LINE 1
LINE 2

KLYSTRON MODULATOR VOLTAGE WAVEFORM

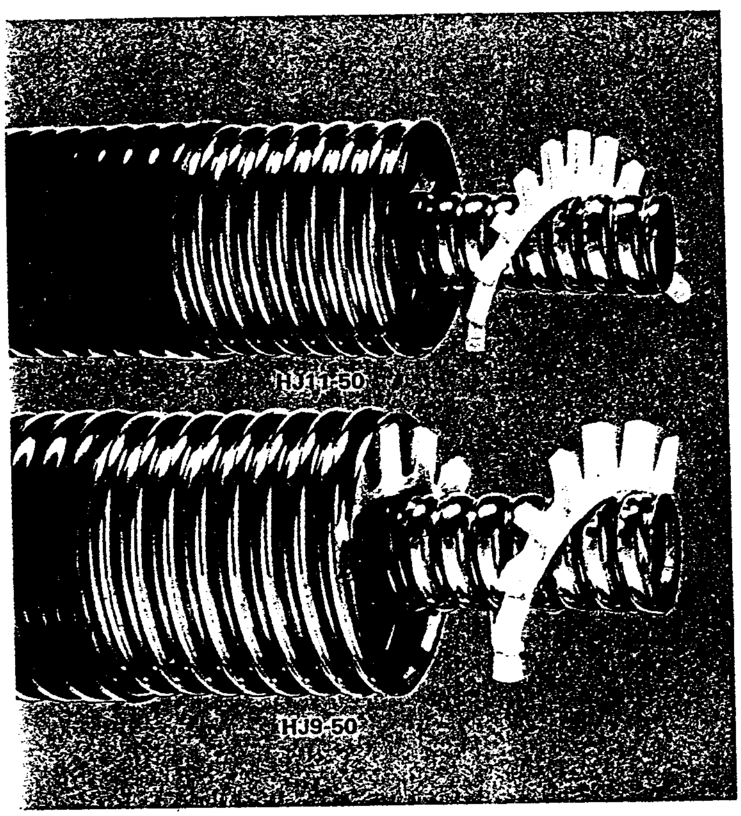


NLCTA KLYSTRON
MODULATOR

R. CASSEL
12/14/92

<u>WATER DIELECTRIC LINE</u>
<u>ANDREW CABLE</u>

4" AND 5" HELIAX® AIR-DIELECTRIC CABLE



ANDREWS CABLE BLUMLEIN

klystron line calculations

klystron	
490.0	kV
954.0	ohms
513.6	amps
251.7	Mw
transformer	
7.1	ratio
blumlein	
69.5	kV
3,621.1	amps
19.2	ohms
thyratron	
69.5	kV
7,242.1	amps
9.6	ohms
2 parallel	18
klystron	
490.0	kV
954.0	ohms
513.6	amps
251.7	Mw
transformer	
6.7	ratio
blumlein	
73.1	kV
3,441.3	amps
21.3	ohms
thyratron	
73.1	kV
6,882.6	amps
10.6	ohms

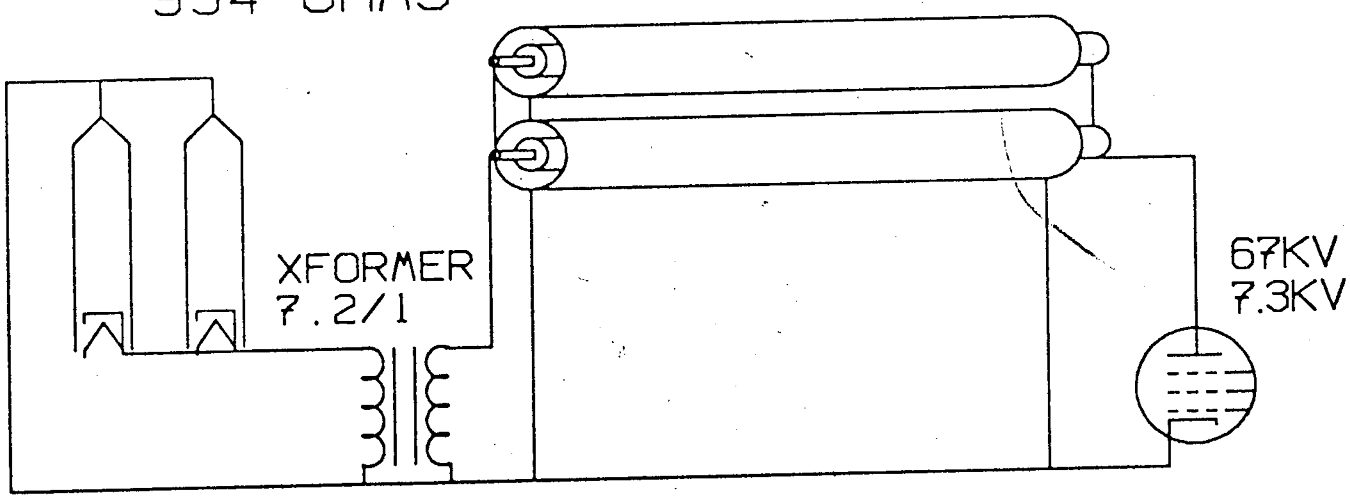
1.2 usec

		oil blumlein			oil blumlein	
	INSIDE	OUTSIDE		INSIDE	OUTSIDE	
voltage	70000	70000	volts	73000	73000	volts
LENGTH	226	226	feet	226	226	feet
	HJ4-50 I	HJ9-50 I		HJ5-50 O	HJ8-50 O	
IN INSIDE	0.603	1.316	inch	1.570	2.500	inch
IN OUTSIDE	0.713	1.550	inch	1.830	2.850	inch
INNER	0.658	1.433	inch	1.700	2.675	inch
	HJ4-50 O	HJ9-50 O		HJ8-50 O	HJ11-50 O	
OUT INSIDE	1.316	3.365	inch	2.500	4.440	inch
OUT OUTSIDE	1.550	3.840	inch	2.850	5.000	inch
OUTER	1.433	3.603	inch	2.675	4.720	inch
insulation	0.603	1.08475	inch	0.4875	1.0225	inch
volts/mil	116	65	v/mil	150	71	v/mil
LOG	0.83	0.83		0.45	0.47	
	1	1		1	1	
INDUCTANCE	0.05	0.05	UHY/FT	0.03	0.03	UHY/FT
TOTAL L	11.44	11.50	UHY	6.27	6.46	UHY
DIELECTRIC	6.80	6.80		6.80	6.80	
CAPACITANCE	138.96	138.20	PF/FT	253.52	245.86	PF/FT
TOTAL C	31.45	31.28	MFD	57.38	55.64	MFD
IMPEDANCE	19.1	19.2	OHMS	10.4	10.8	OHMS
SQRT(L/C)	19.07	19.18		10.45	10.78	
delay	2.651	2.651	nsec/ft	2.651	2.651	nsec/ft

NLCTA KLYSTRON MODULATOR

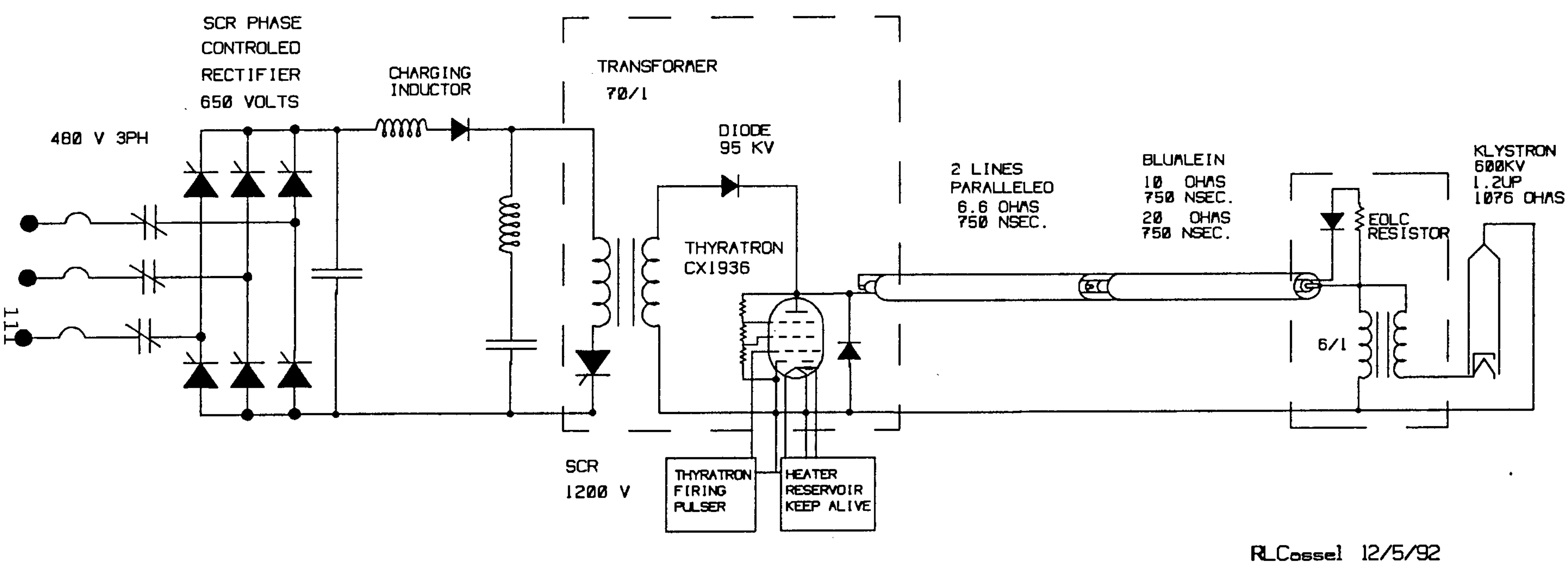
2 EACH 75MW
KLYSTRON
490KV
Ø.75 UP
954 OHMS

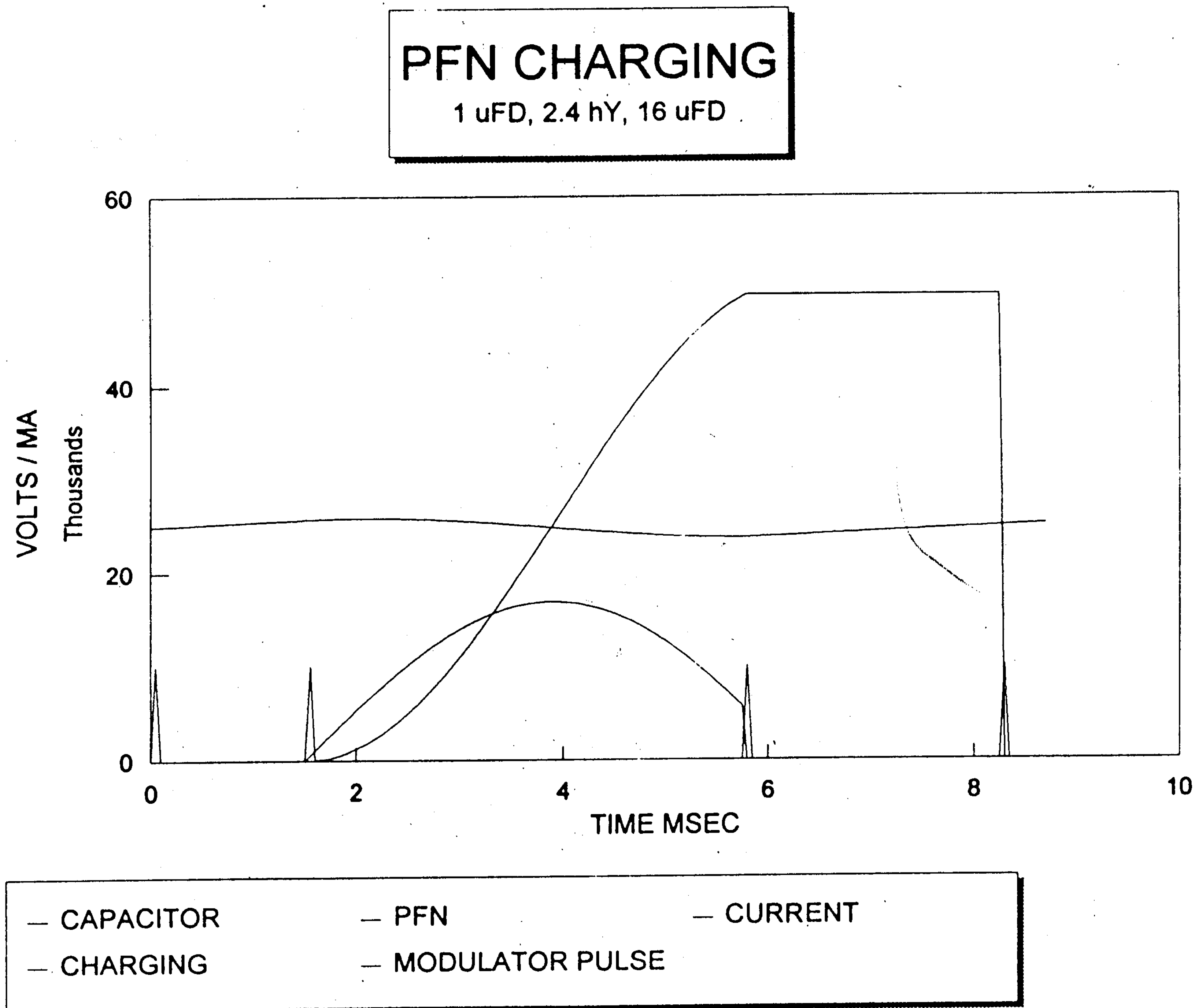
BLUMLEIN
18 OHMS
750 NSEC.
18 OHMS
750 NSEC.

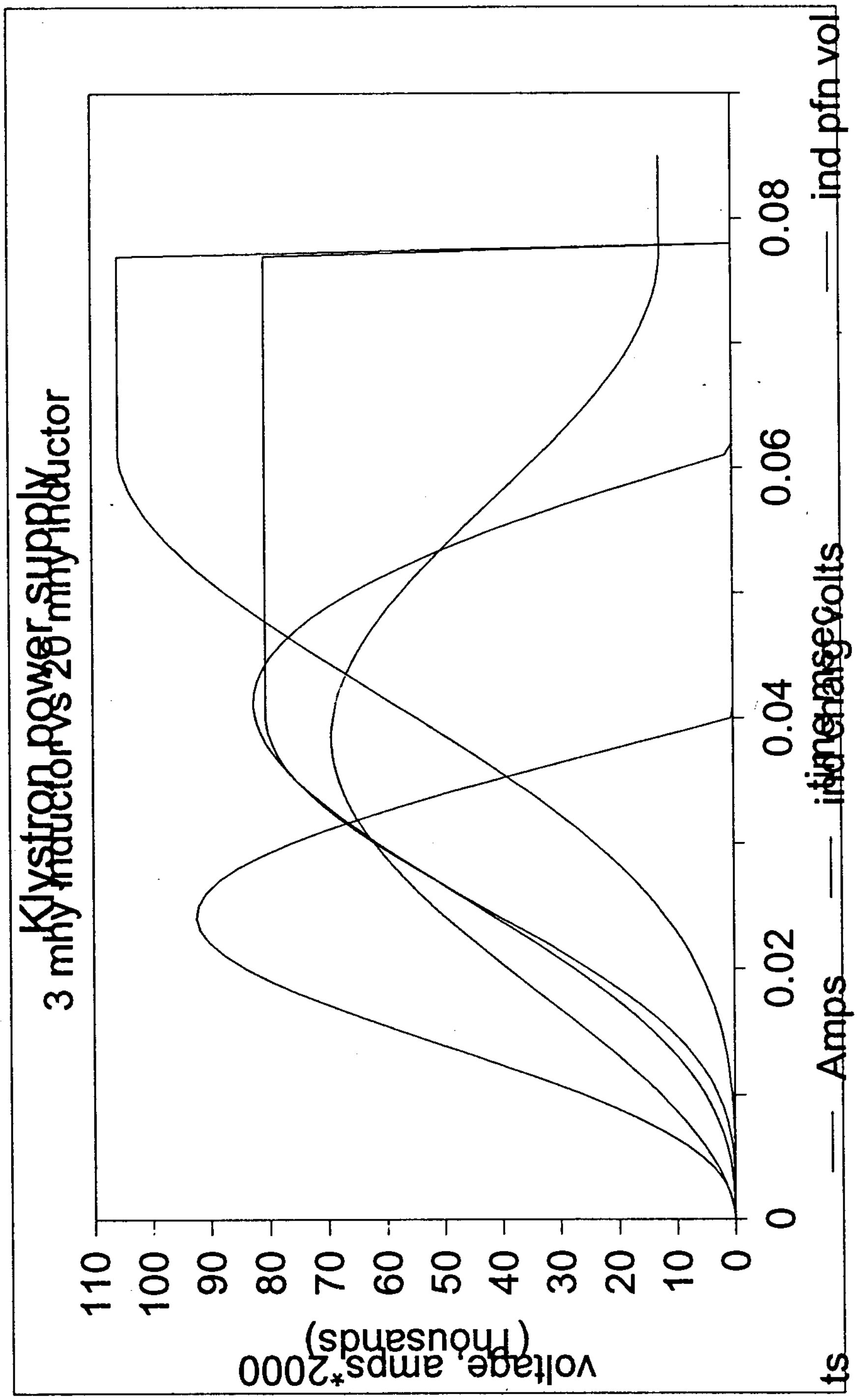


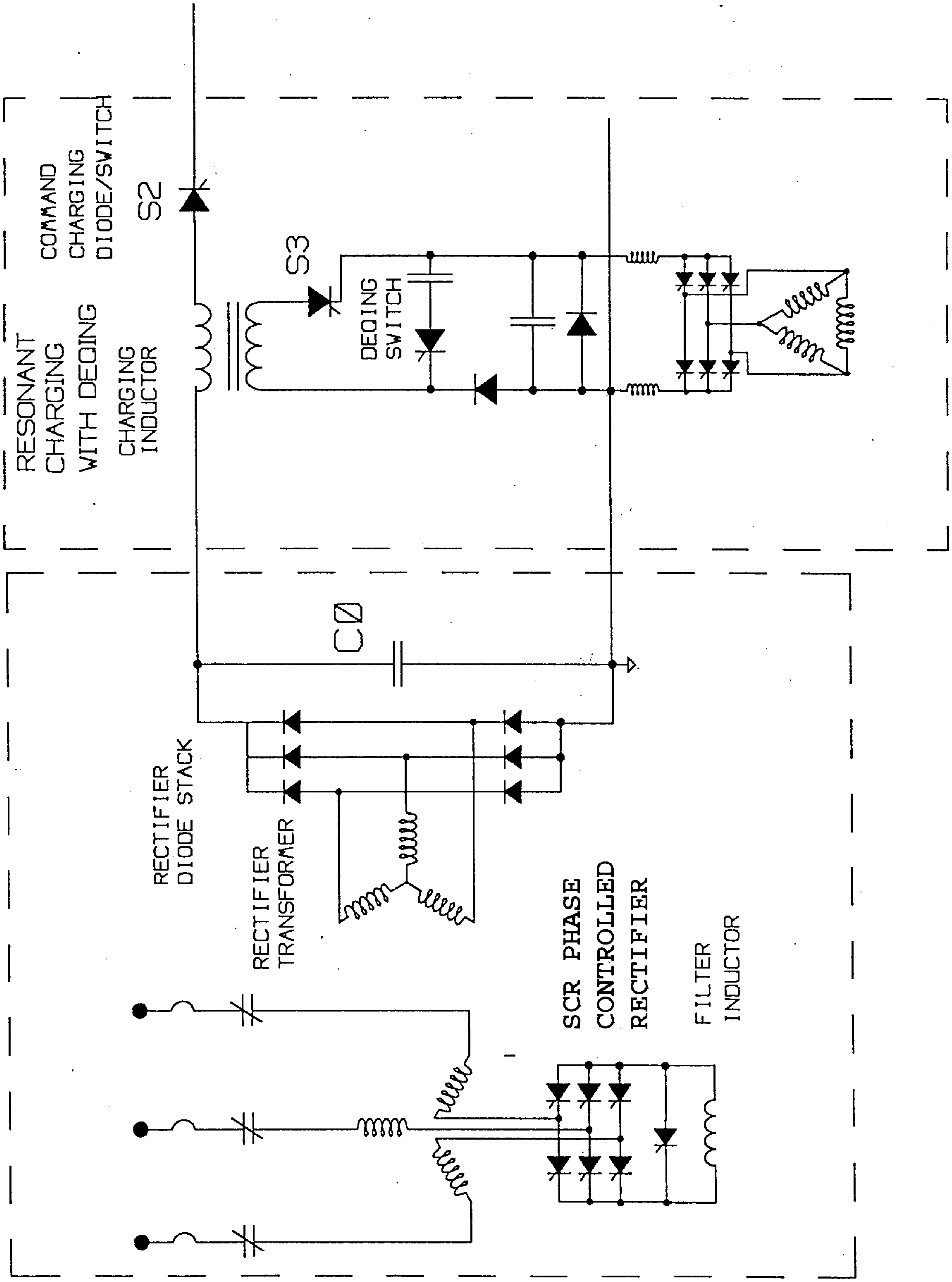
R. CASSEL
12/1/94

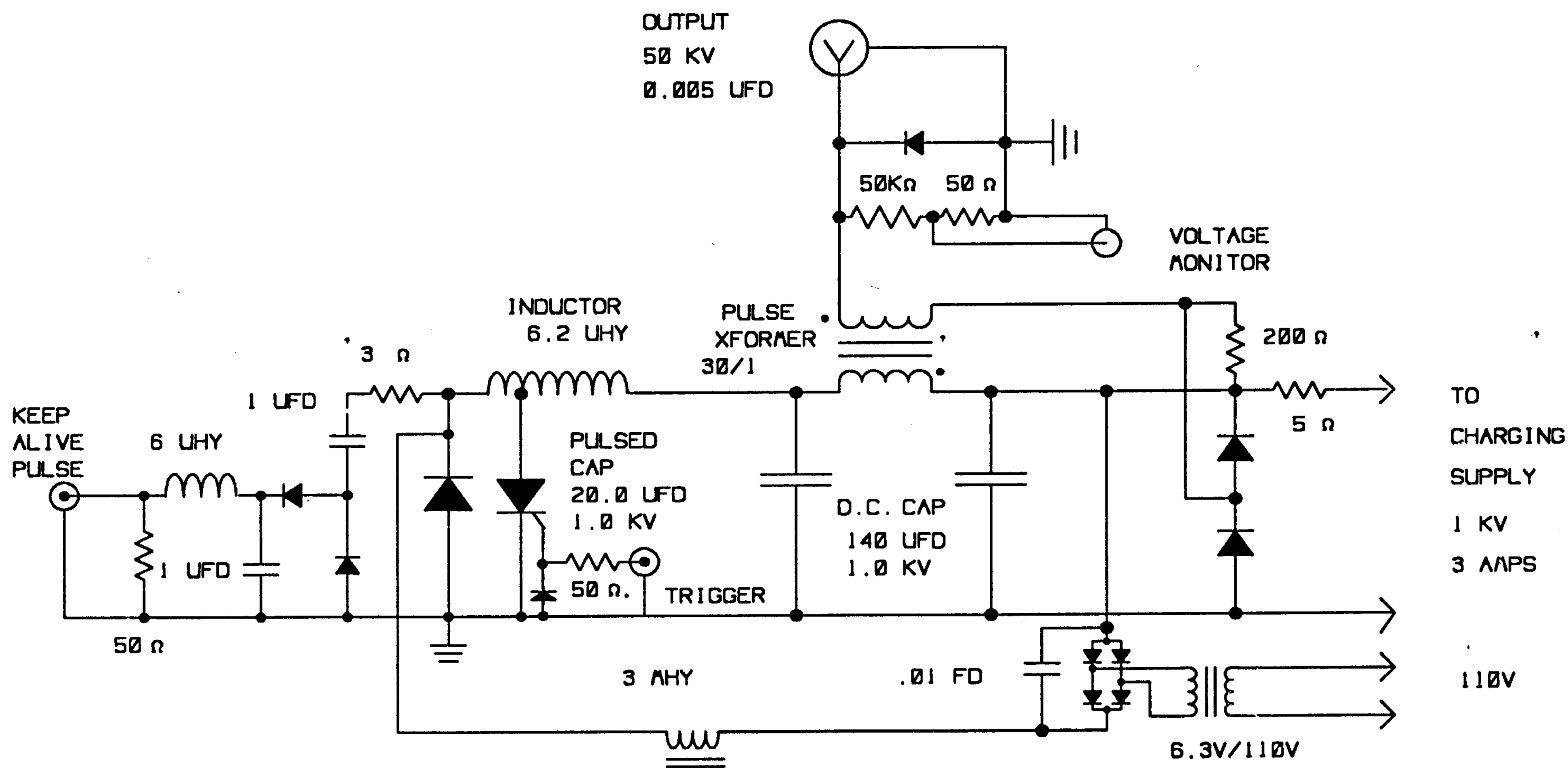
NLCTA MODULATOR




PFN CHARGING
1 uFD, 2.4 hY, 16 uFD
VOLTS / MA
Thousands
60
40
20
0
0
2
4
6
8
10
TIME MSEC
CAPACITOR
PFN
CURRENT
CHARGING
MODULATOR PULSE

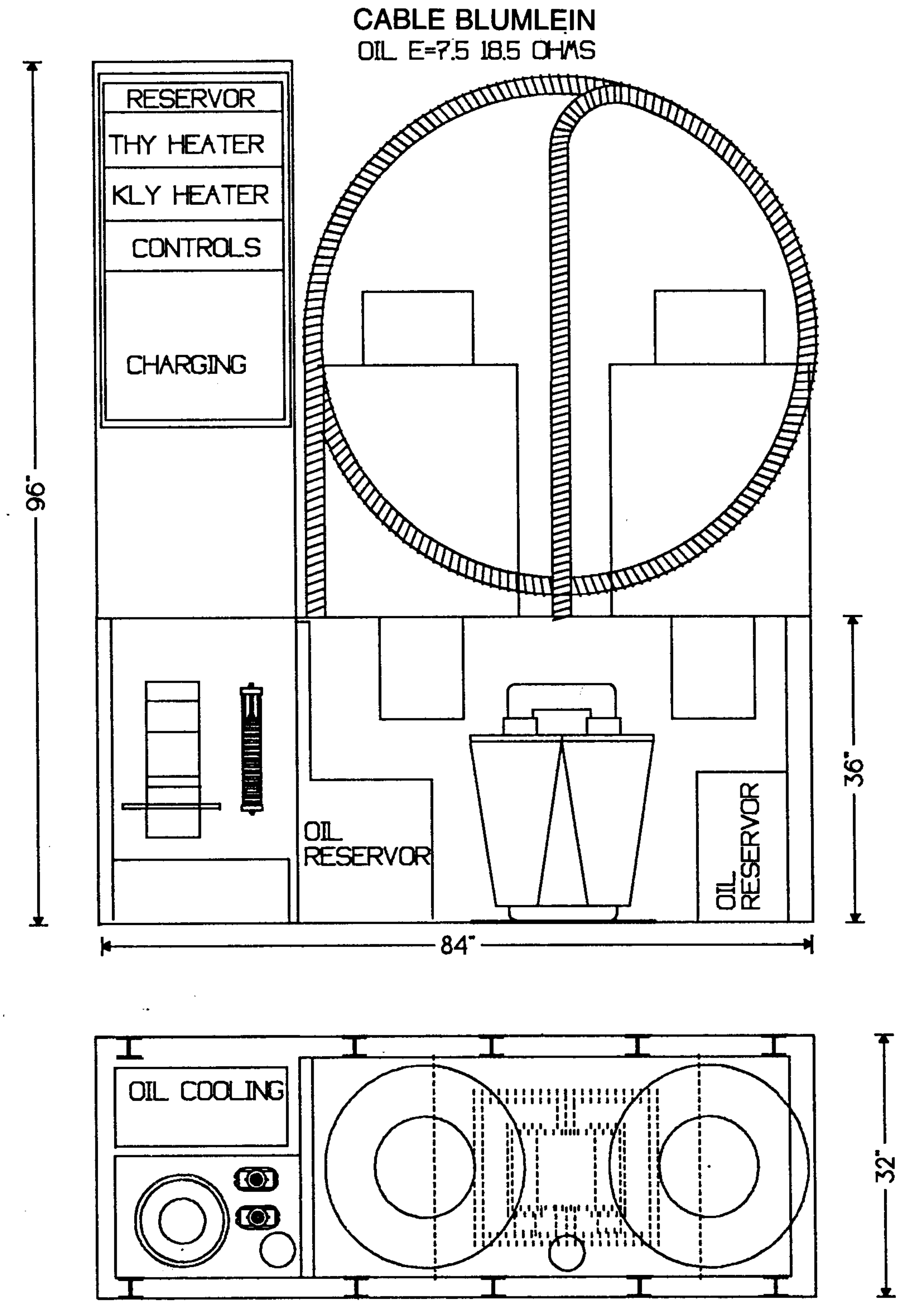

Klystron power supply
3 mhy inductor vs 20 mhy inductor
voltage, amps*2000
(Thousands)
time msec
Amps
ind charge volts
ind pfn volts
0
10
20
30
40
50
60
70
80
90
100
110
0
0.02
0.04
0.06
0.08


RESONANT CHARGING WITH DEQING
CHARGING INDUCTOR
COMMAND CHARGING DIODE/SWITCH
S2
S3
DEQING SWITCH
C0
RECTIFIER DIODE STACK
RECTIFIER TRANSFORMER
SCR PHASE CONTROLLED RECTIFIER
FILTER INDUCTOR

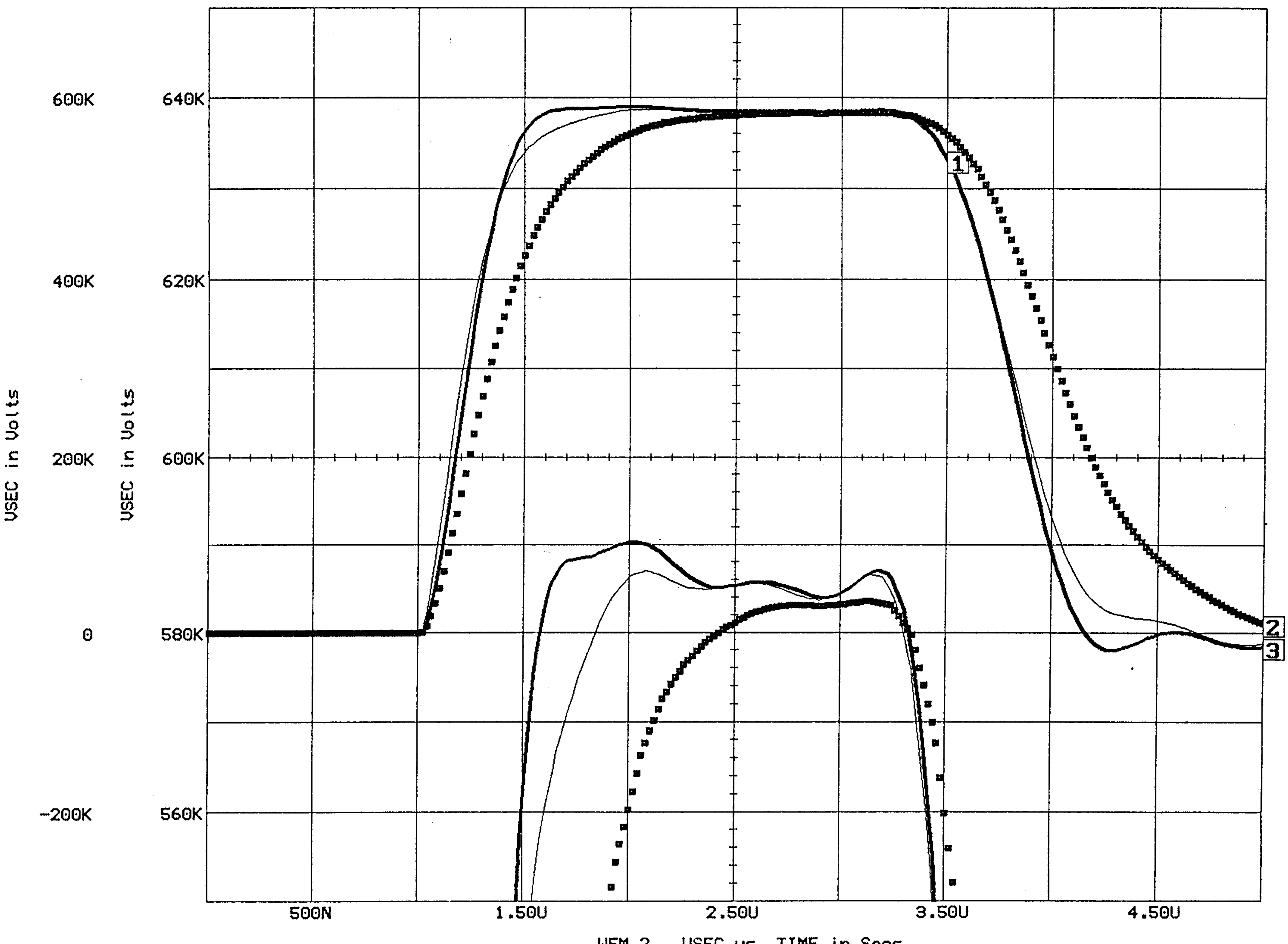


POSSIBLE COMMAND CHARGING POWER SUPPLY

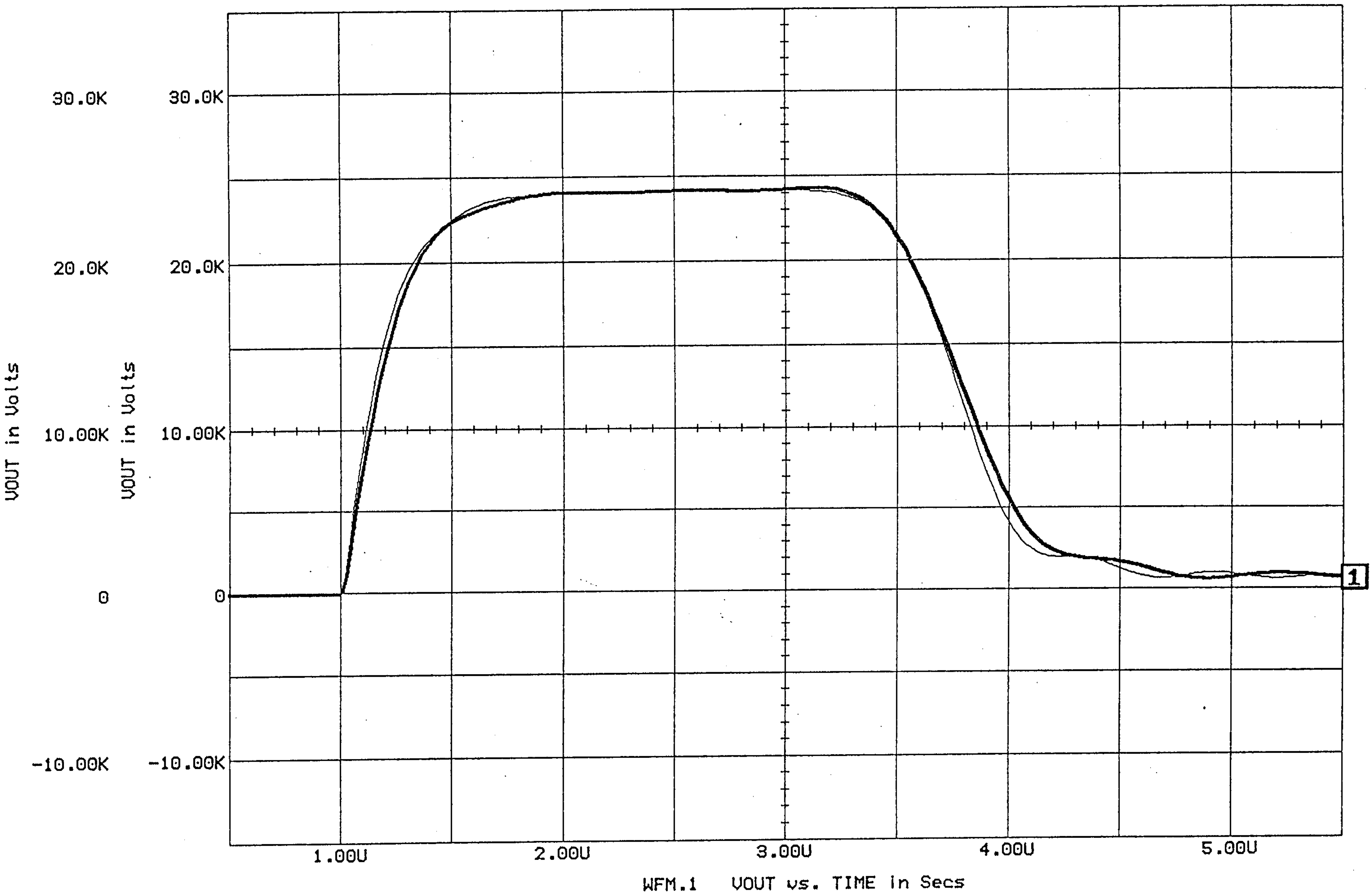
NLC MODULATOR



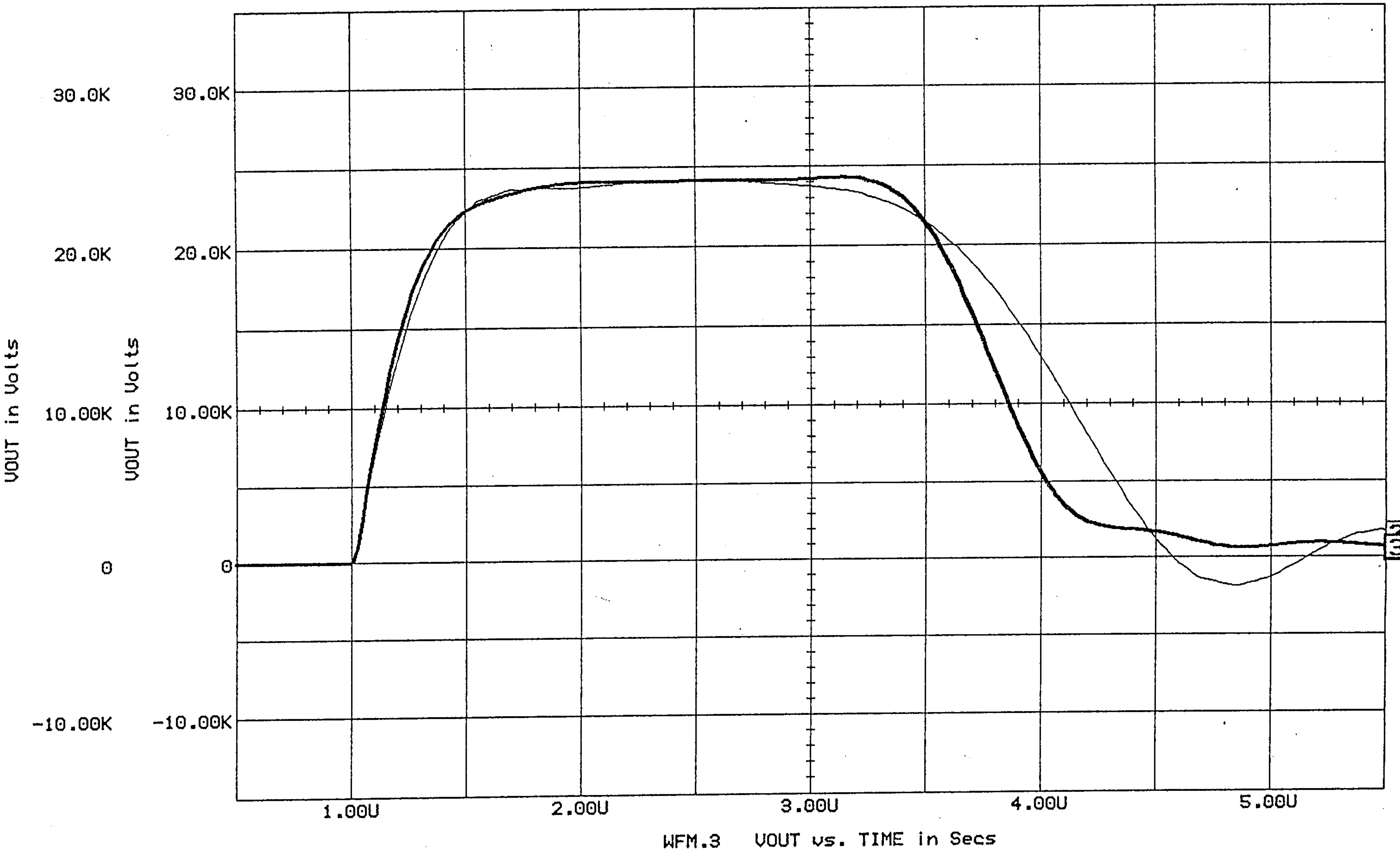
R CASSEL
12/2/94



Ls=.02uH, .1uH and .5uH, 4 x 6 Ohm lines



5-section and 8-section lines, with 25% coupling coefficients



5-section lines, with and without 25% coupling coefficients

NLCTA KLYSTRON MODULATOR

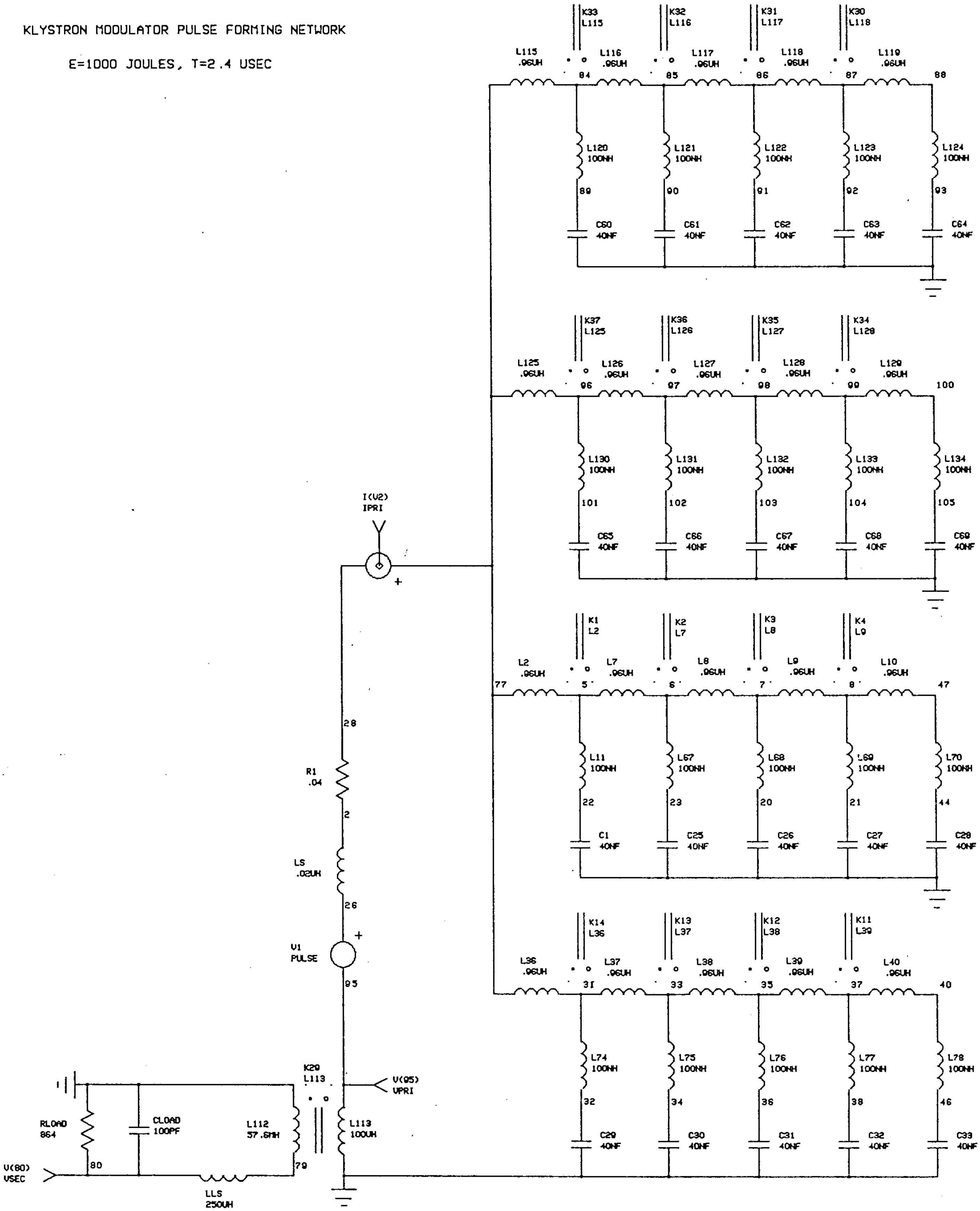
R. CASSEL
7/12/94

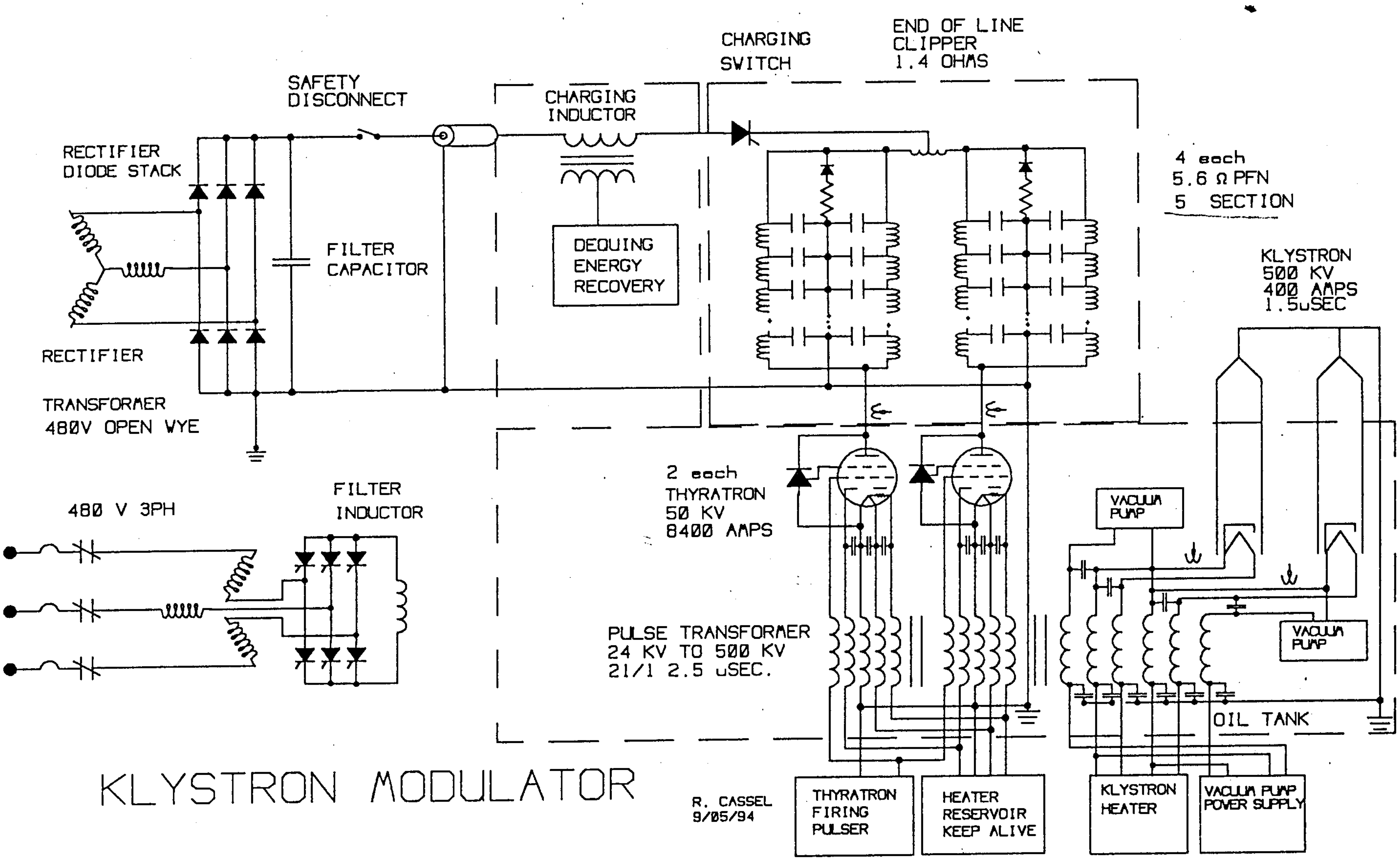
MANAGEMENT DECISION

- BUILD CONVENTIONAL TYPE MODULATOR FOR NLCTA
- ACCEPT SLOW RISE TIME MODULATOR
- ACCEPT RESULTING LOW EFFICIENCY
- USE AS MUCH AS POSSIBLE STANDARD SLAC DESIGN AND PROVEN COMPONENTS
- TWO KLYSTRONS PER MODULATOR 200 MW 1.5 μSEC (RF PULSE) 1000 JOULES IN PFN (i.e. efficiency <60%)
- 4 MODULATOR WITH TWO POWER SUPPLIES FOR 180 PPS OPERATION, OR 360KW PER POWER SUPPLY

KLYSTRON MODULATOR PULSE FORMING NETWORK

E=1000 JOULES, T=2.4 USEC





SAFETY DISCONNECT
CHARGING SWITCH
END OF LINE CLIPPER 1.4 OHMS
CHARGING INDUCTOR
RECTIFIER DIODE STACK
4 each 5.6 Ω PFN 5 SECTION
FILTER CAPACITOR
DEQUING ENERGY RECOVERY
KLYSTRON 500 KV 400 AMPS 1.5uSEC
RECTIFIER
TRANSFORMER 480V OPEN WYE
2 each THYRATRON 50 KV 8400 AMPS
480 V 3PH
FILTER INDUCTOR
VACUUM PUMP
PULSE TRANSFORMER 24 KV TO 500 KV 21/1 2.5 uSEC.
VACUUM PUMP
OIL TANK
KLYSTRON MODULATOR
R. CASSEL 9/05/94
THYRATRON FIRING PULSER
HEATER RESERVOIR KEEP ALIVE
KLYSTRON HEATER
VACUUM PUMP POWER SUPPLY

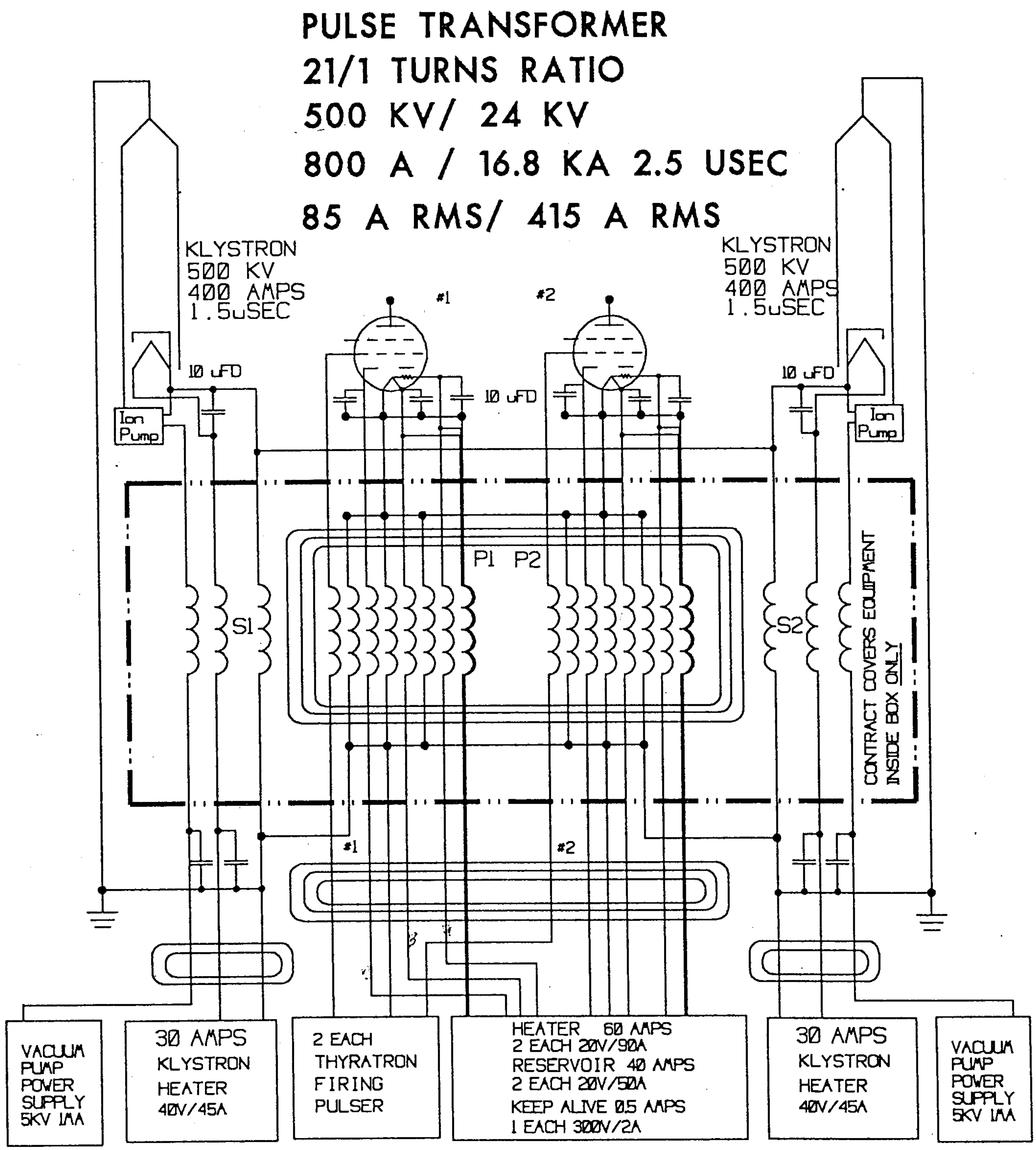

PULSE TRANSFORMER
21/1 TURNS RATIO
500 KV/ 24 KV
800 A / 16.8 KA 2.5 USEC
85 A RMS/ 415 A RMS
KLYSTRON
500 KV
400 AMPS
1.5uSEC
KLYSTRON
500 KV
400 AMPS
1.5uSEC
#1
#2
10 uFD
10 uFD
10 uFD
Ion Pump
Ion Pump
P1 P2
S1
S2
CONTRACT COVERS EQUIPMENT INSIDE BOX ONLY
#1
#2
VACUUM PUMP POWER SUPPLY 5KV 1MA
30 AMPS KLYSTRON HEATER 40V/45A
2 EACH THYRATRON FIRING PULSER
HEATER 60 AMPS
2 EACH 20V/90A
RESERVOIR 40 AMPS
2 EACH 20V/50A
KEEP ALIVE 0.5 AMPS
1 EACH 300V/2A
30 AMPS KLYSTRON HEATER 40V/45A
VACUUM PUMP POWER SUPPLY 5KV 1MA

FIGURE 2

PULSE TRANSFORMER

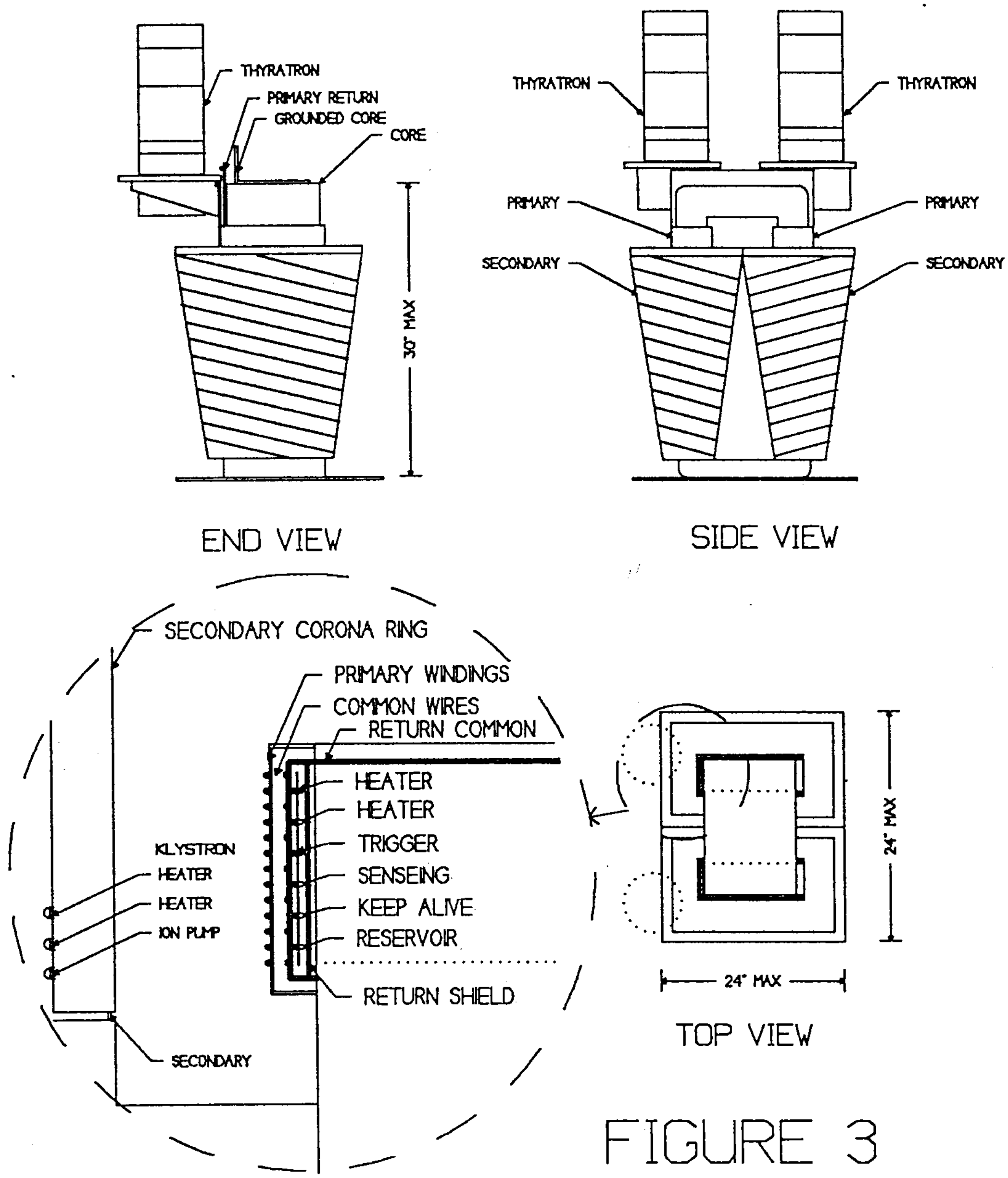
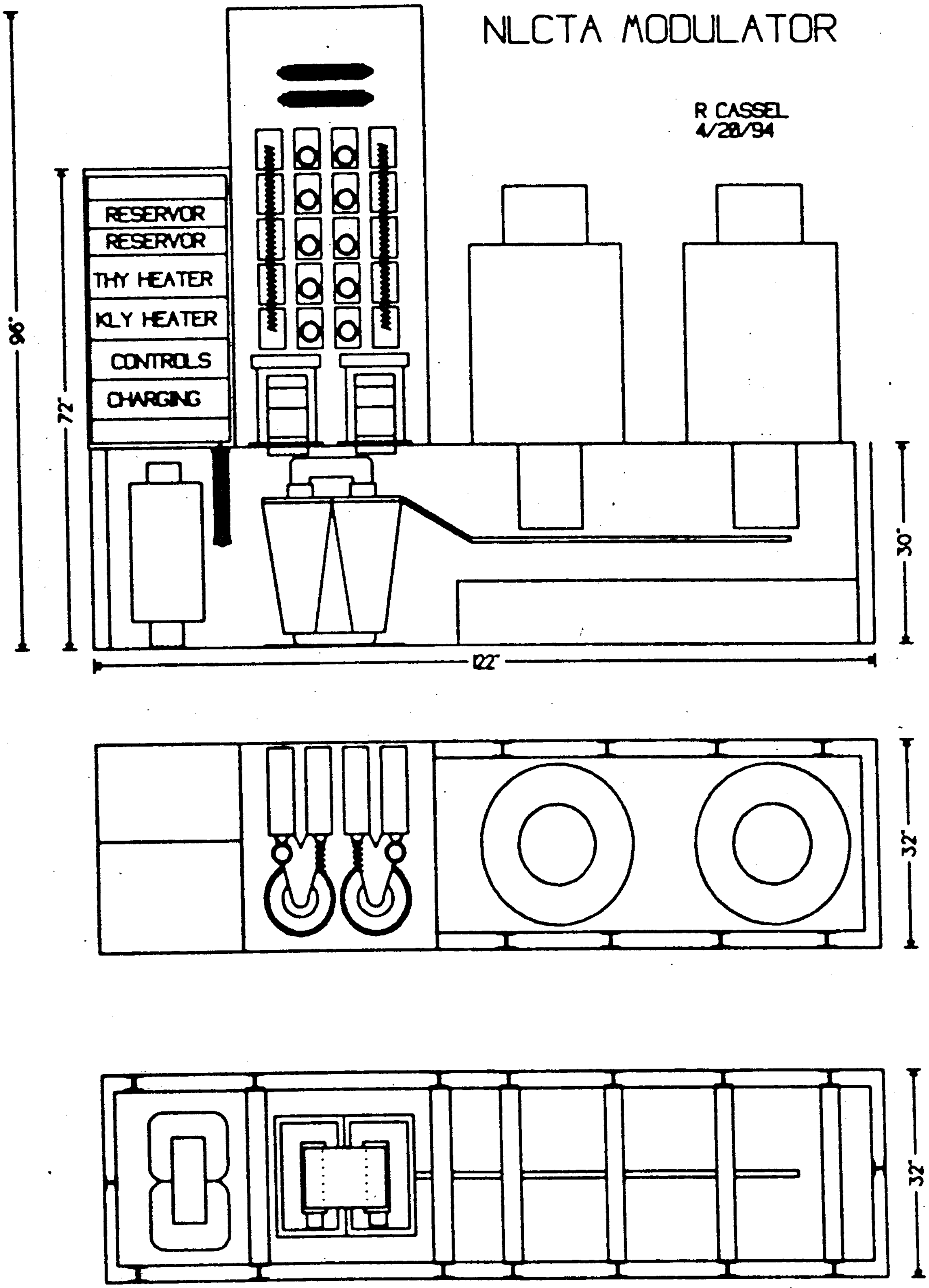


FIGURE 3


NLCTA MODULATOR
R CASSEL
4/28/94
RESERVOR
RESERVOR
THY HEATER
KLY HEATER
CONTROLS
CHARGING
96"
72"
30"
122"
32"
32"

Pulse Modulator using a PFL and Magnetic Switch

M. Akemoto (KEK/SLAC)

Our Dream is to make a

Long Lifetime
Compact
High Efficiency
⋮
Modulator.

One Solution

↓

Modulator using all-solid-state components.

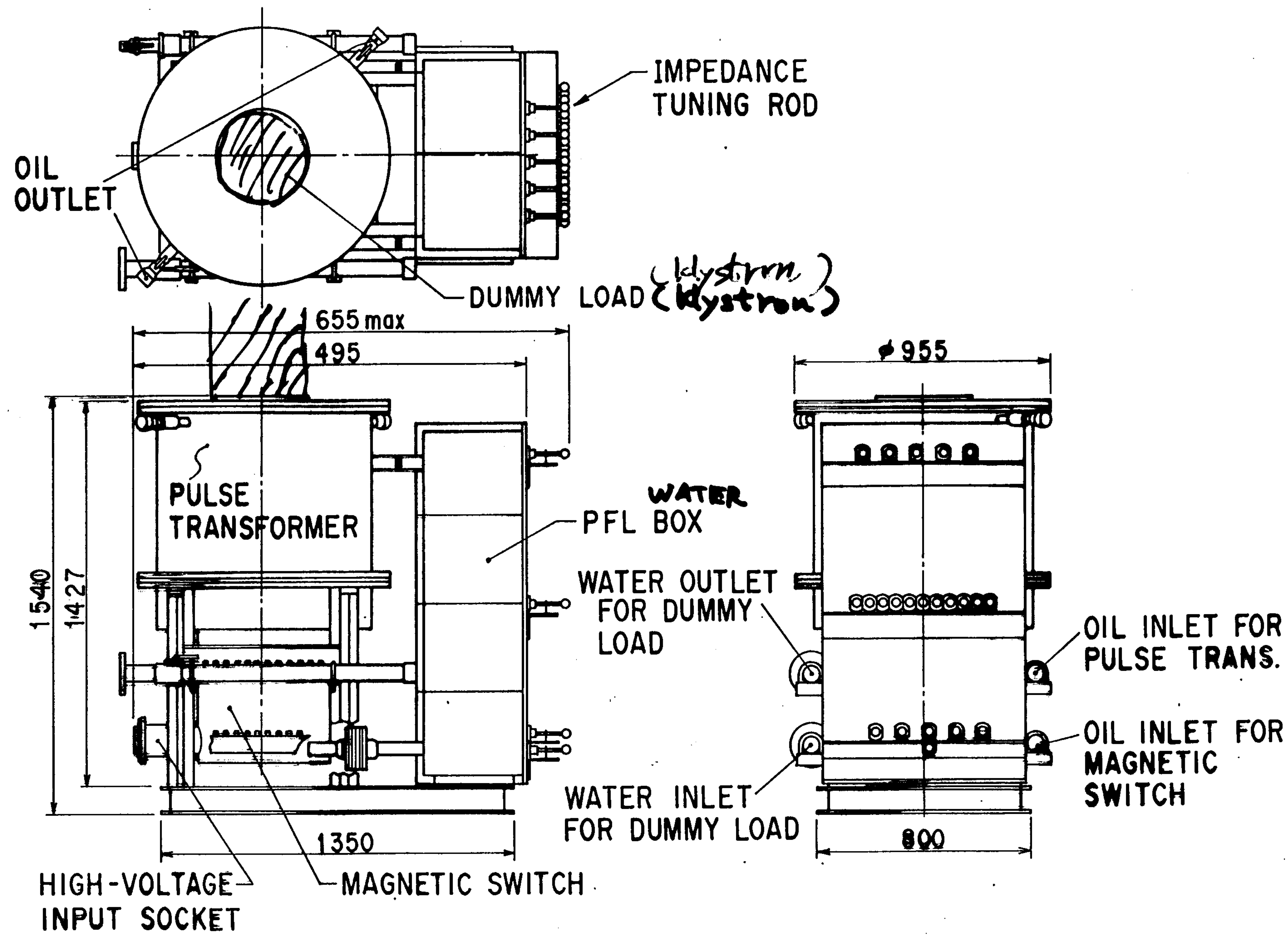
↓

We tested the modulator using a PFL and Magnetic Switch

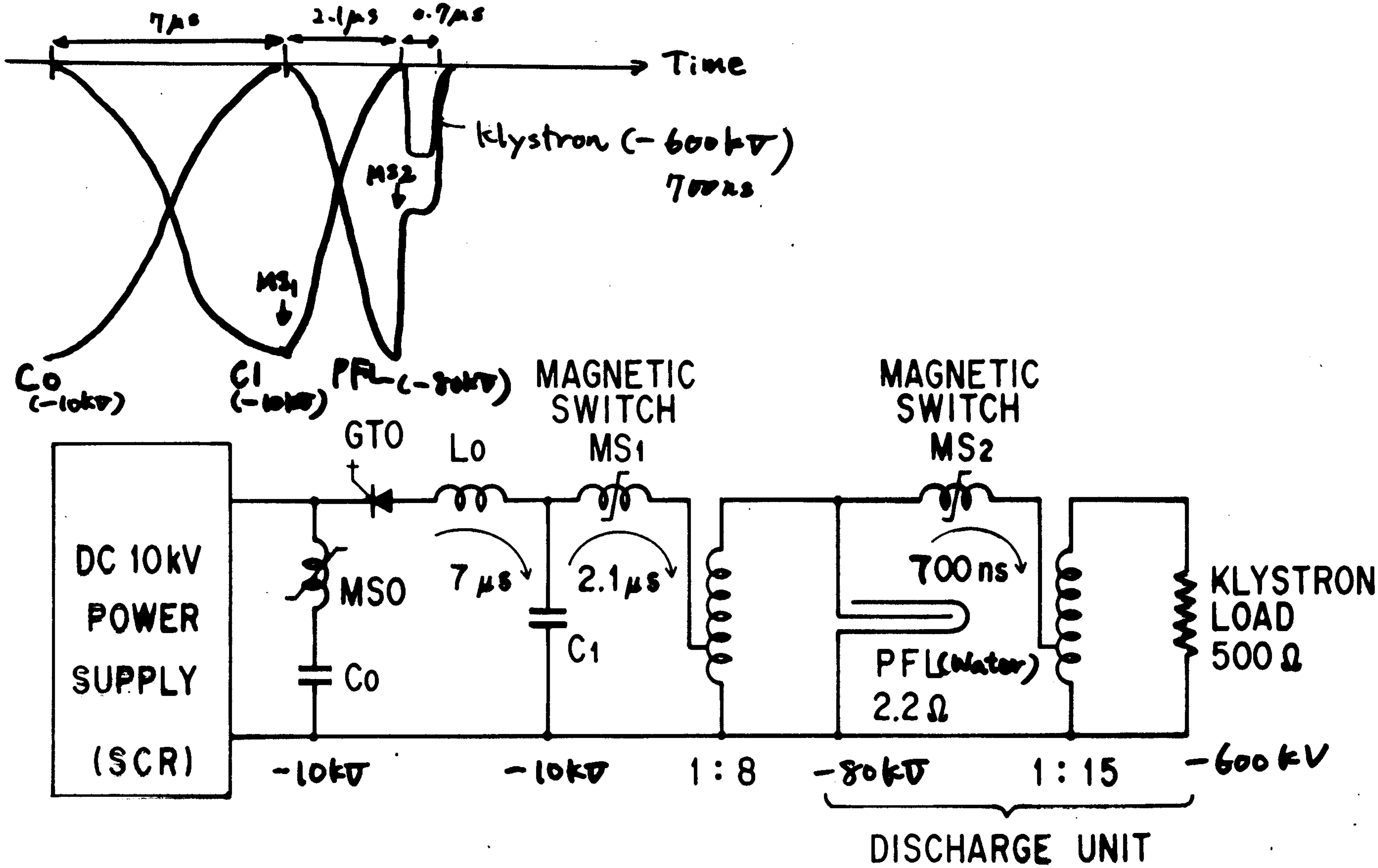
X-BAND KLYSTRON MODULATOR WITH A PULSE-FORMING LINE AND MAGNETIC SWITCH

Specifications

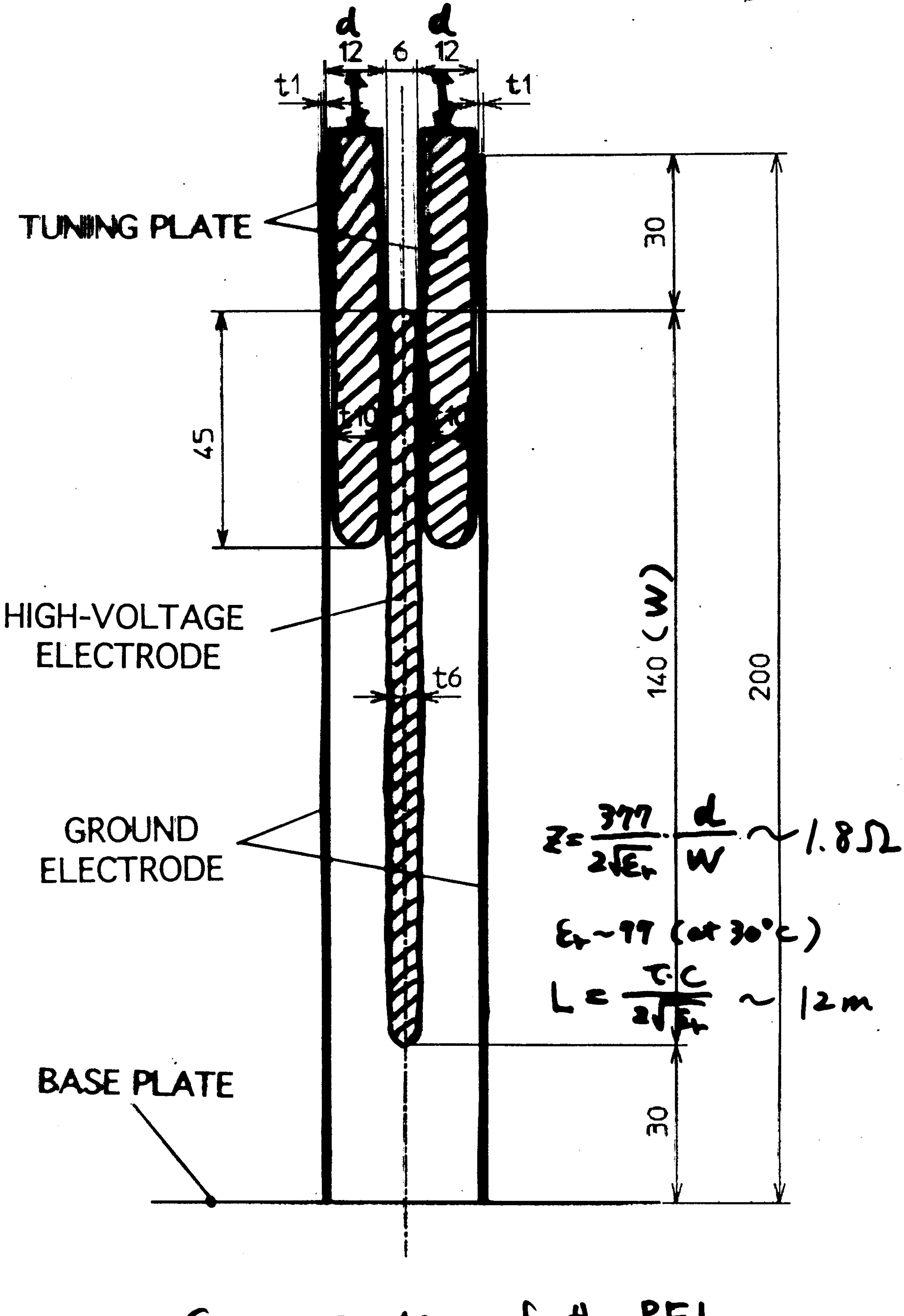
Output pulse voltage	600 kV
Output pulse current	1200 A
Output impedance	500 Ω (> 2 klystrons)
Pulse rise time	150 ns
Pulse length(flat-top)	400 ns
Pulse amplitude drift	< 1.0 %
Pulse repetition rate	50 pps



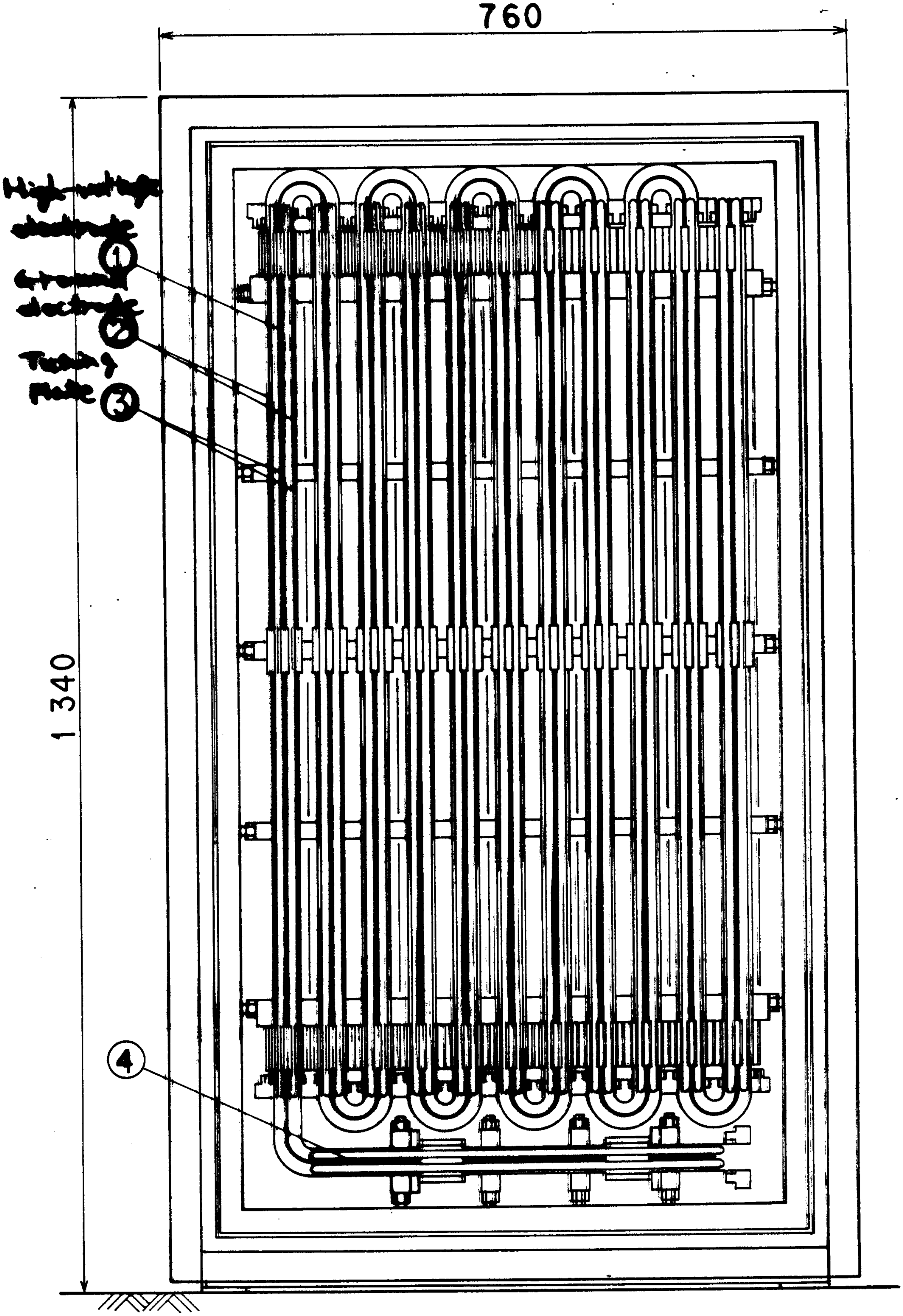
Overview of the discharge unit



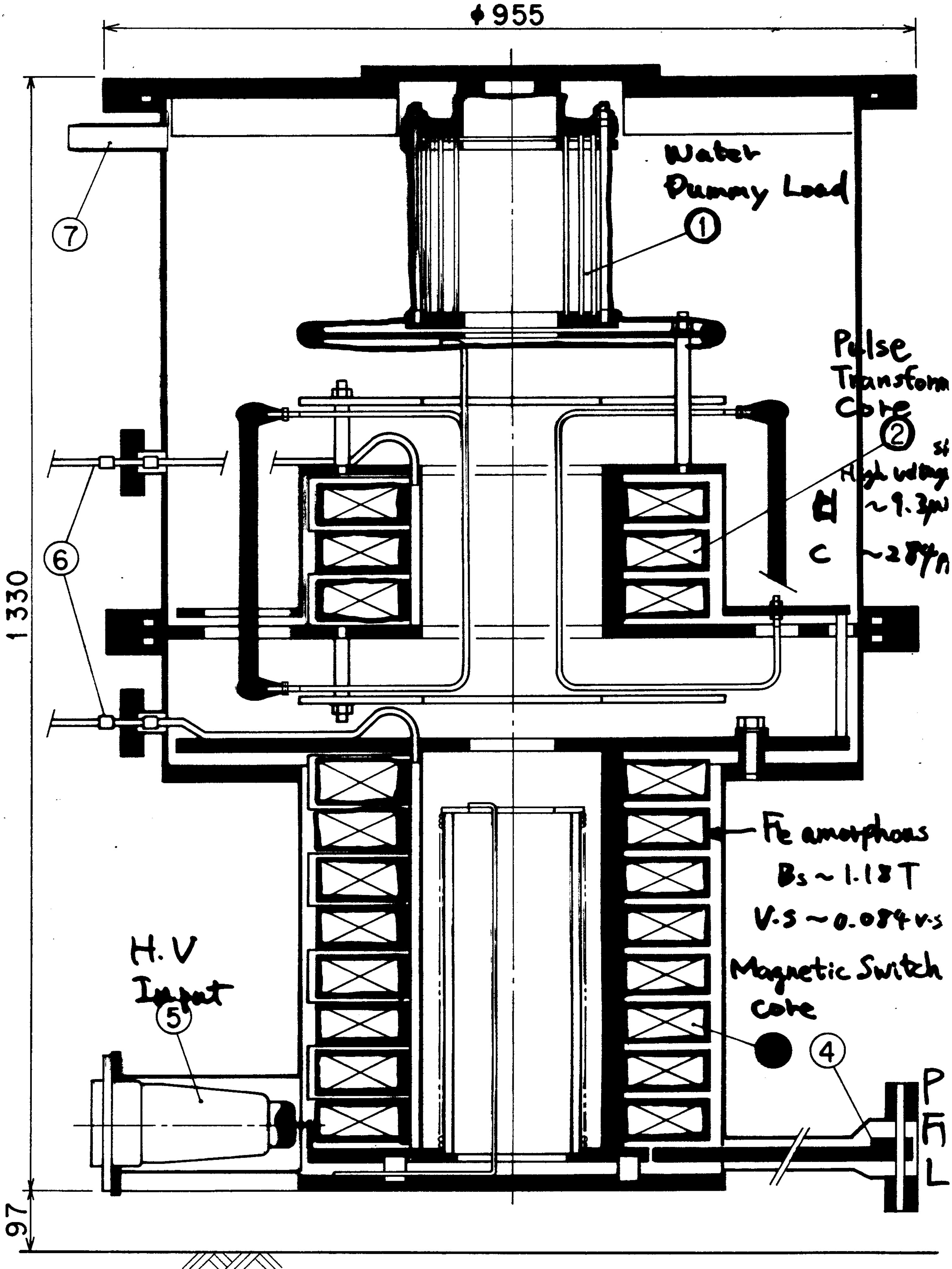
Simplified diagram of the MPC klystron modulator



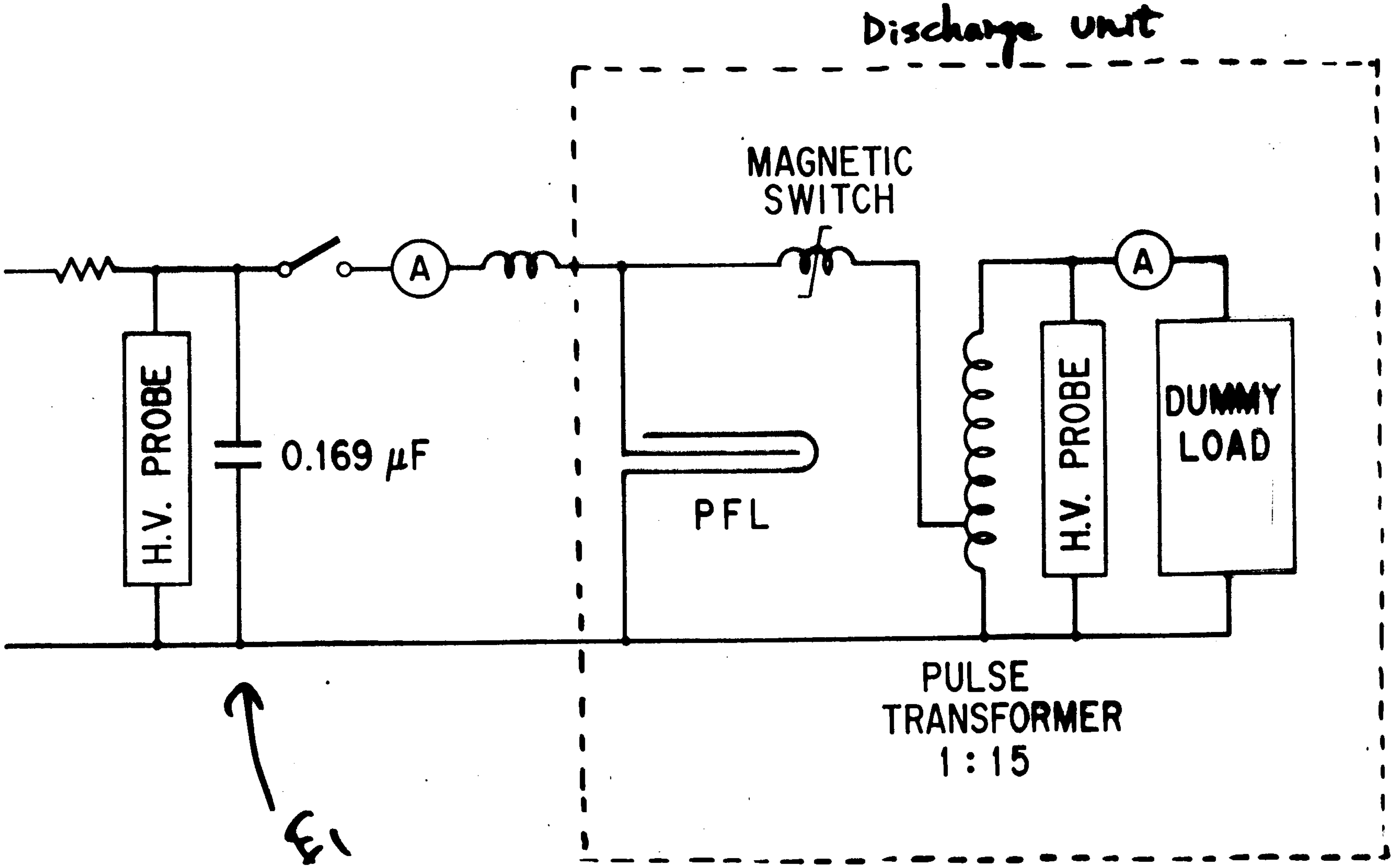
Cross section of the PFL



Structure of the PFL box



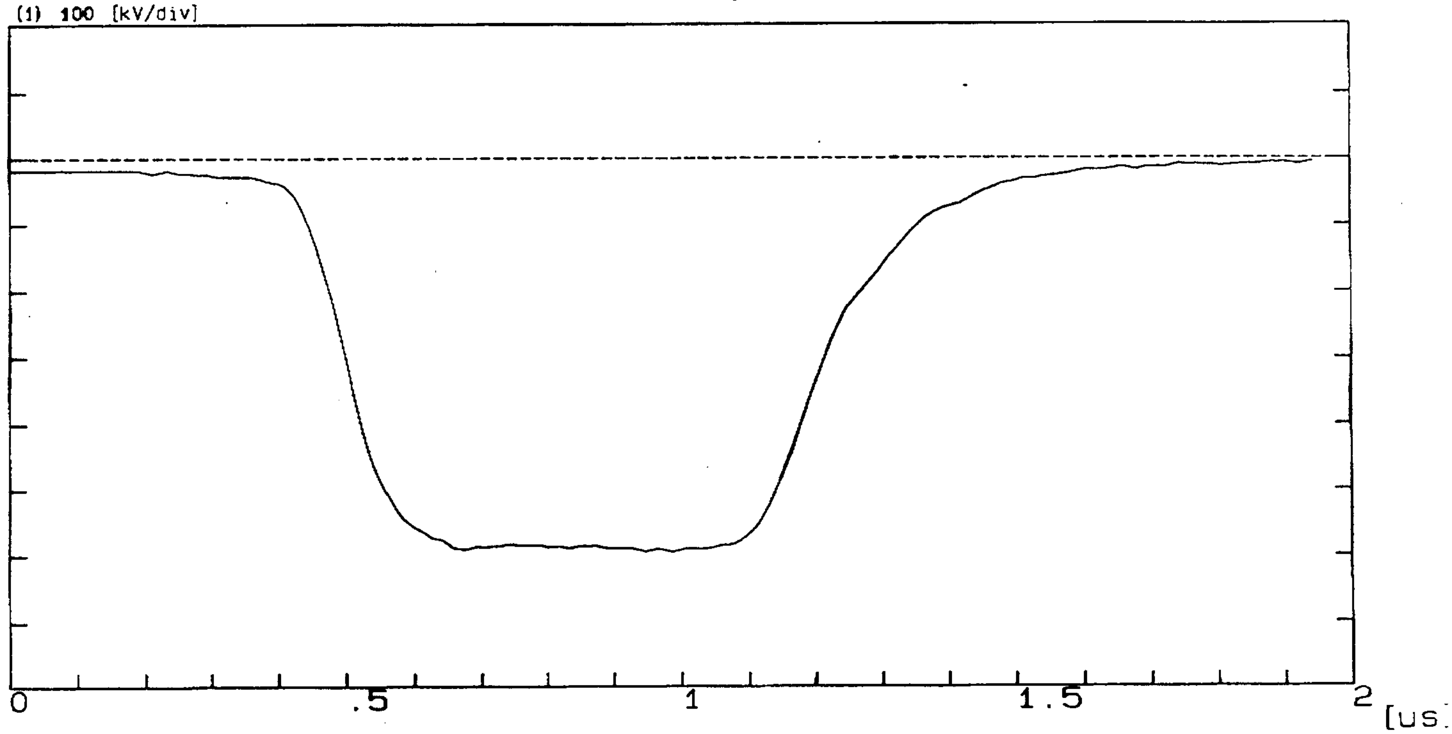
Cross section of the discharge unit



Test circuit.

$\eta = \frac{E_2}{E_1} \sim 80\%$

Output voltage waveform of the pulse transformer with damping resistors.



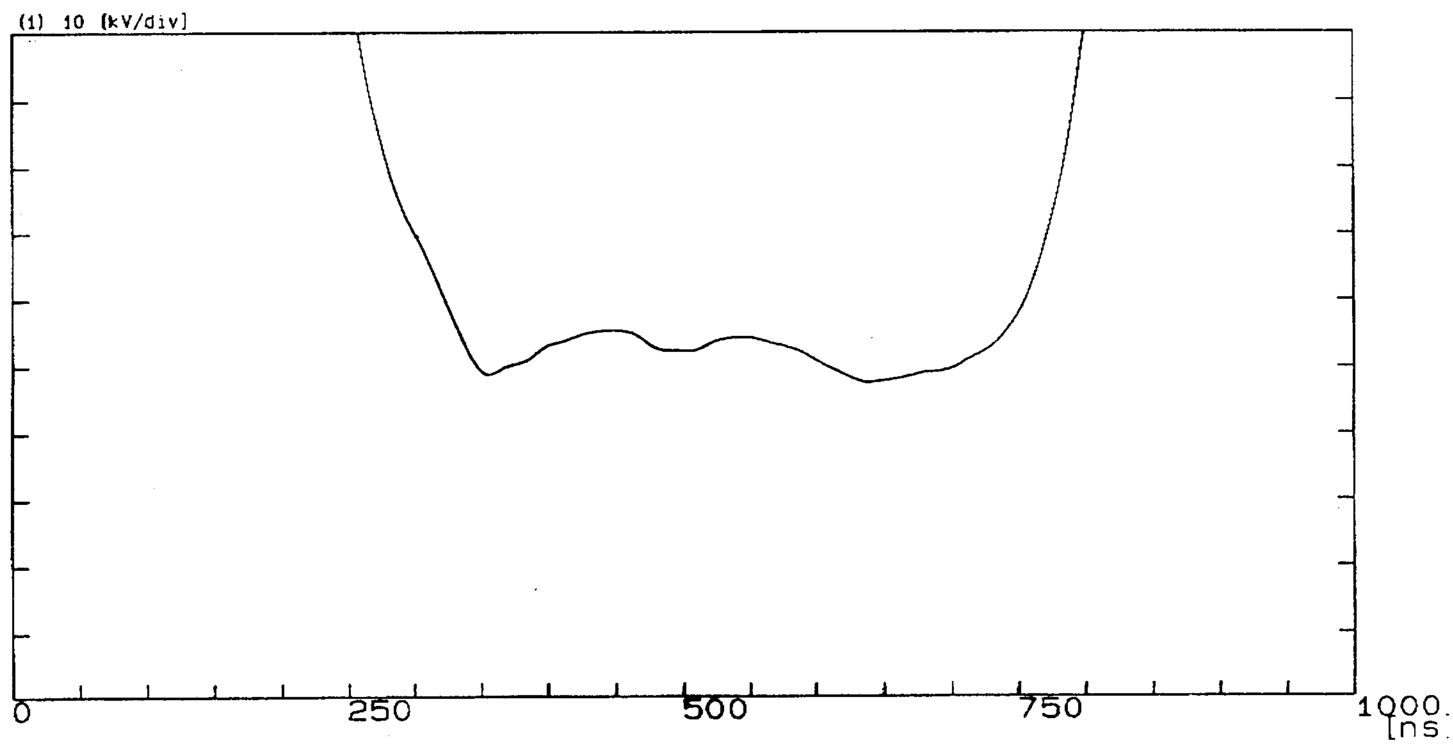
comment= Vc=90kV water out 31.4C in 31.2C
date = 93/06/17. time=14:26:07

File name: 93061705

Peak 590kV

rise time (10-90%) 154ns
Width (FWHM) 712ns

Expanded pulse top trace of the output voltage.



comment= Vc=90kV water out 31.4C in 31.2C
date = 93/06/17. time=14:26:07

File name: 93061705

Flat-top : 370ns Flatness : ±0.7%

M. AKEMOTO
(1/3)

New loss-free de-Qing System

Power loss of de-Qing system(P_{deQ})

$$P_{deQ} = \frac{1}{2} C_t V_{PFN}^2 \cdot f_r \cdot \frac{k}{1-k} \quad (k>0.5)$$

$$k = 1 - \frac{V_{PFN}(\text{regulated})}{V_{PFN}(\text{unregulated})}$$

C_t	: Total PFN capacitance(1.26μF)
V_{PFN}	: PFN charging voltage(50kV)
f_r	: Repetition rates(50pps)
k	: Regulation factor(5%)

Power loss for full-scale S-band JLC(C.M.S=500GeV)

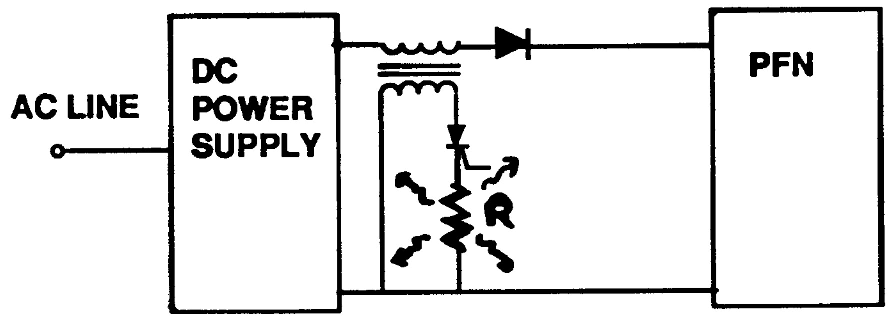
Total power loss=4.1kW x 1670=6.8MW (heat power)

Features:

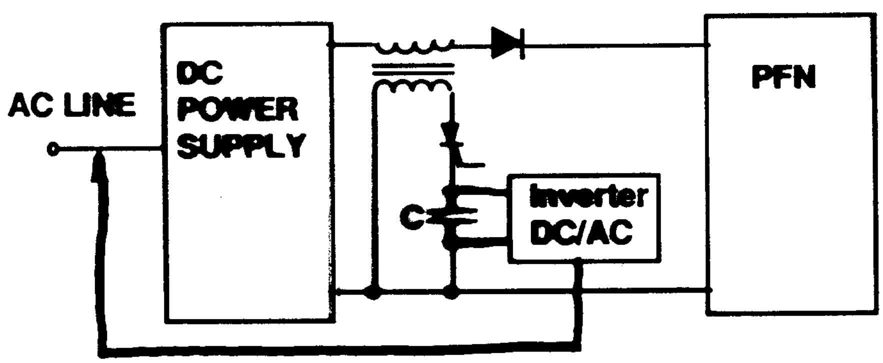
1. It is a simple circuit with low-voltage components.
2. It is high energy recovery because of its passive circuit.
3. It is possible to save 5% of wall plug power.

(2/3)

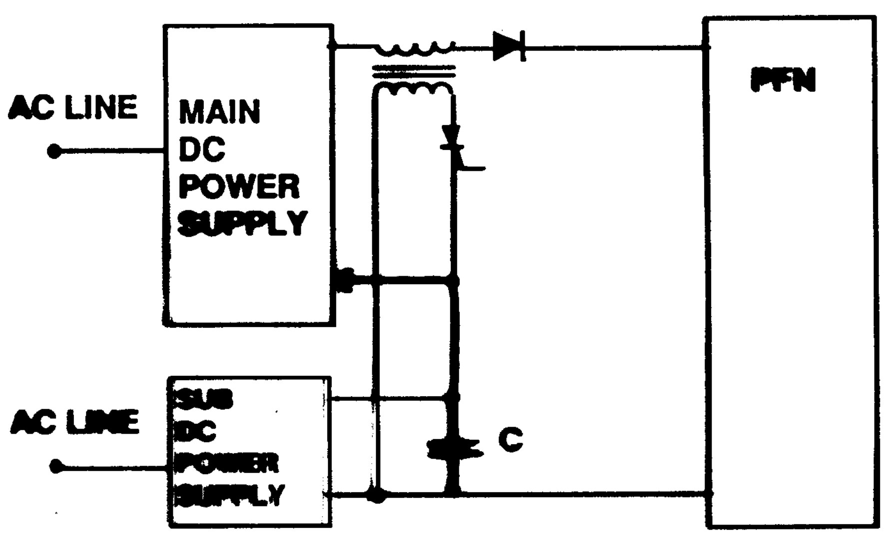
(1)Standard (Energy loss)



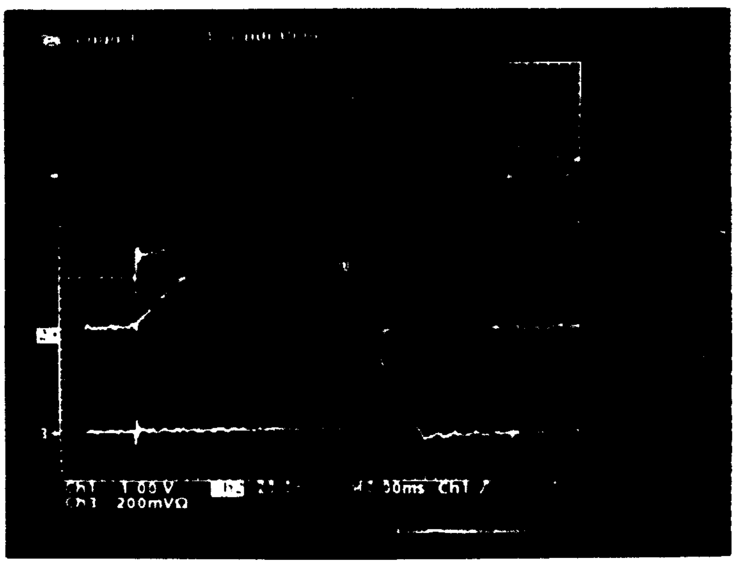
(2)SLAC inverter method (Energy loss-free)



(3)New method (Energy loss-free)



Loss-free de-Qing waveforms



Upper trace: de-Qing voltage (1kV/div)
Middle trace: PFN charging current (4A/div)
Lower trace: de-Qing current (20A/div)
de-Qing: 3.0%
Repetition rate: 50 pps
H: 2ms/div

R&D OF THE C-BAND KLYSTRON MODULATOR

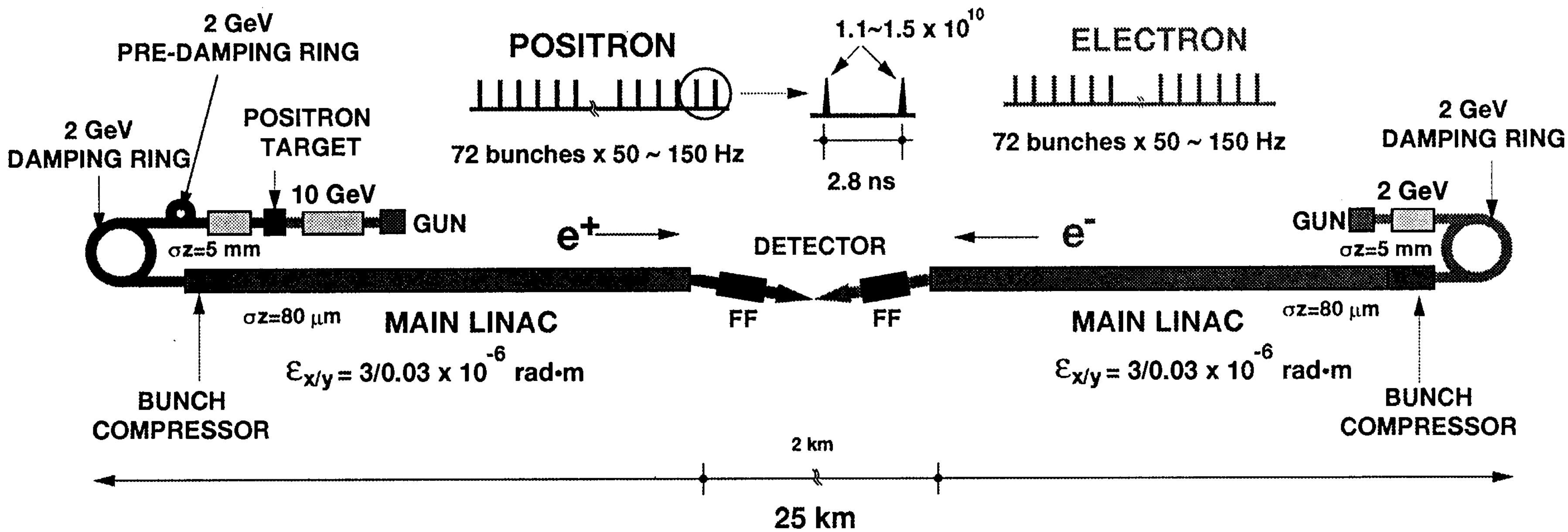
H. MATSUMOTO, H. BABA and T. SHINTAKE
KEK

K. WATANABE
TOHOKU UNIVERSITY

P. PEARCE
CERN

M. H. CHO, J. S. OH and W. NAMKUNG
PAL

LINEAR COLLIDER PROJECT



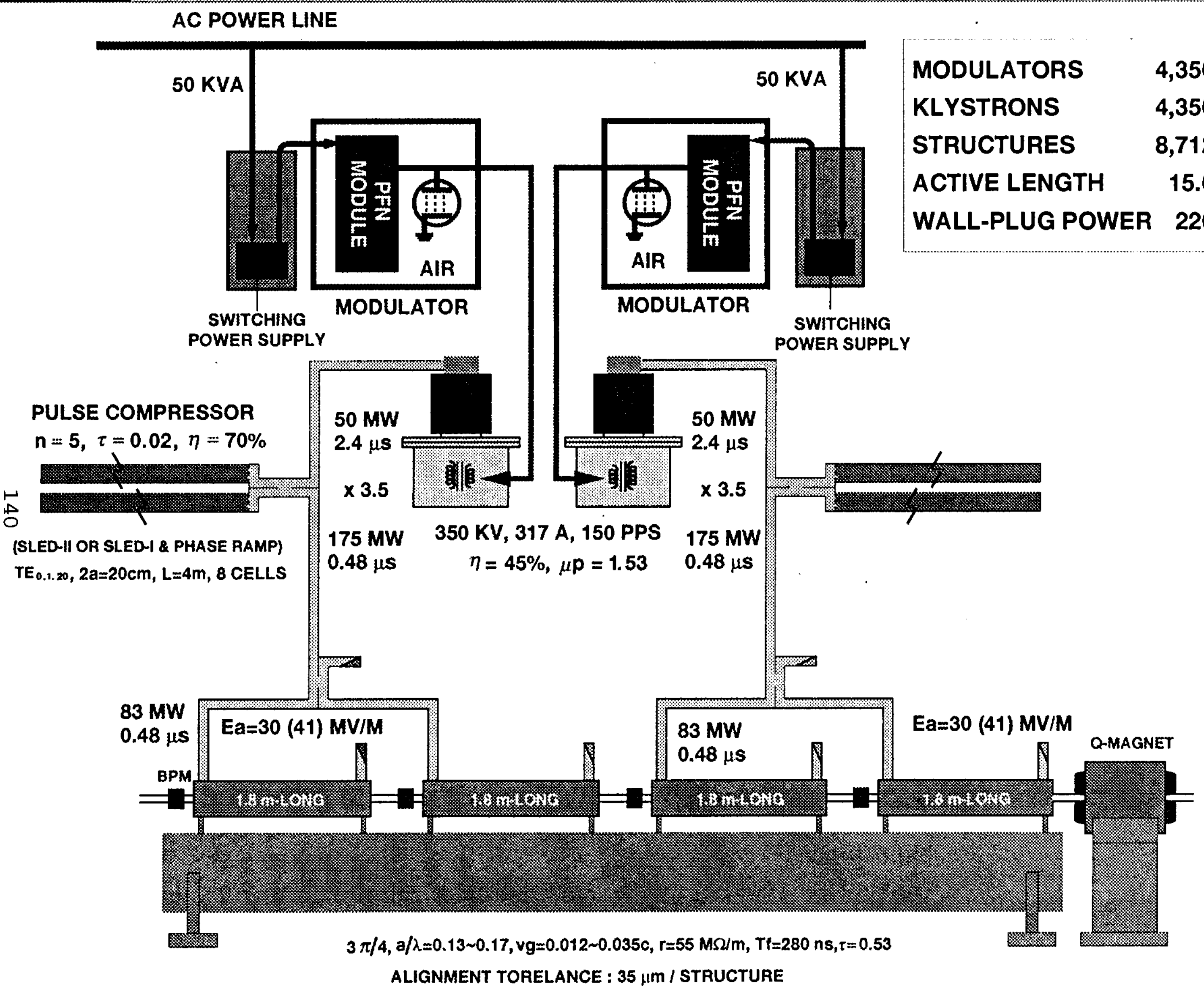
	LC1	LC2	
BEAM ENERGY (C. M.)	500	1000	GeV
LUMINOSITY	9.1	6.3	10^33/cm^2/s
TOTAL LENGHT	25	25	Km
NOMINAL ACC. GRAD.	41	58	MV/m
NET ACC. GRAD.	30	43	MV/m
TOTAL WALL PLUG POWER	220	220	MW
RMS BEAM SIZE AT IP (x/y)	260/3.0	372/2.2	nm
CROSSING ANGLE	6.0	6.0	mrad
DISRUPTION PARAMETER	0.20/17.5	0.067/11.3	Dx/Dy
NUMBER OF BEAMSTRAHLUNG PHOTONS	1.5	1.4	
ENERGY LOSS BY BEAMSTRAHLUNG	5.3	8.0	%
PINCH ENHANCEMENT FACTOR	1.6	1.5	

FINAL FOCUS
→ FFTB AT SLAC

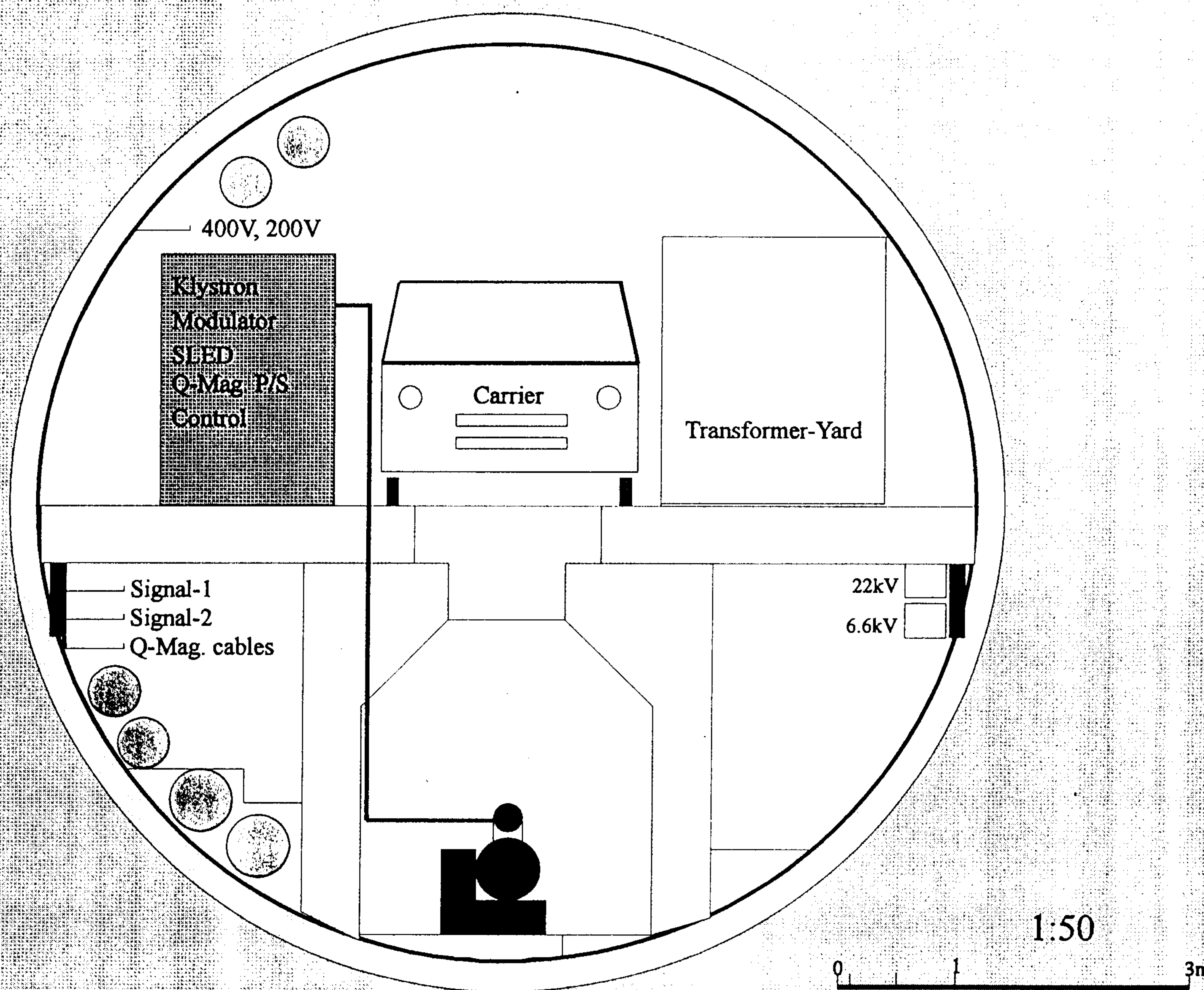
MULTI BUNCH DAMPING RING
→ ATF AT KEK

$\sqrt{S}$ = 500 GEV MAIN LINAC IN C-BAND CASE

MODULATORS	4,356	UNITS / 2LINACS
KLYSTRONS	4,356	TUBES / 2LINACS
STRUCTURES	8,712	UNITS / 2LINACS
ACTIVE LENGTH	15.6	KM / 2LINACS
WALL-PLUG POWER	220	MW / 2LINACS



MAIN LINAC


400V, 200V
Klystron
Modulator
SLED
Q-Mag. P/S
Control
Carrier
Transformer-Yard
Signal-1
Signal-2
Q-Mag. cables
22kV
6.6kV
1:50
0
1
3m

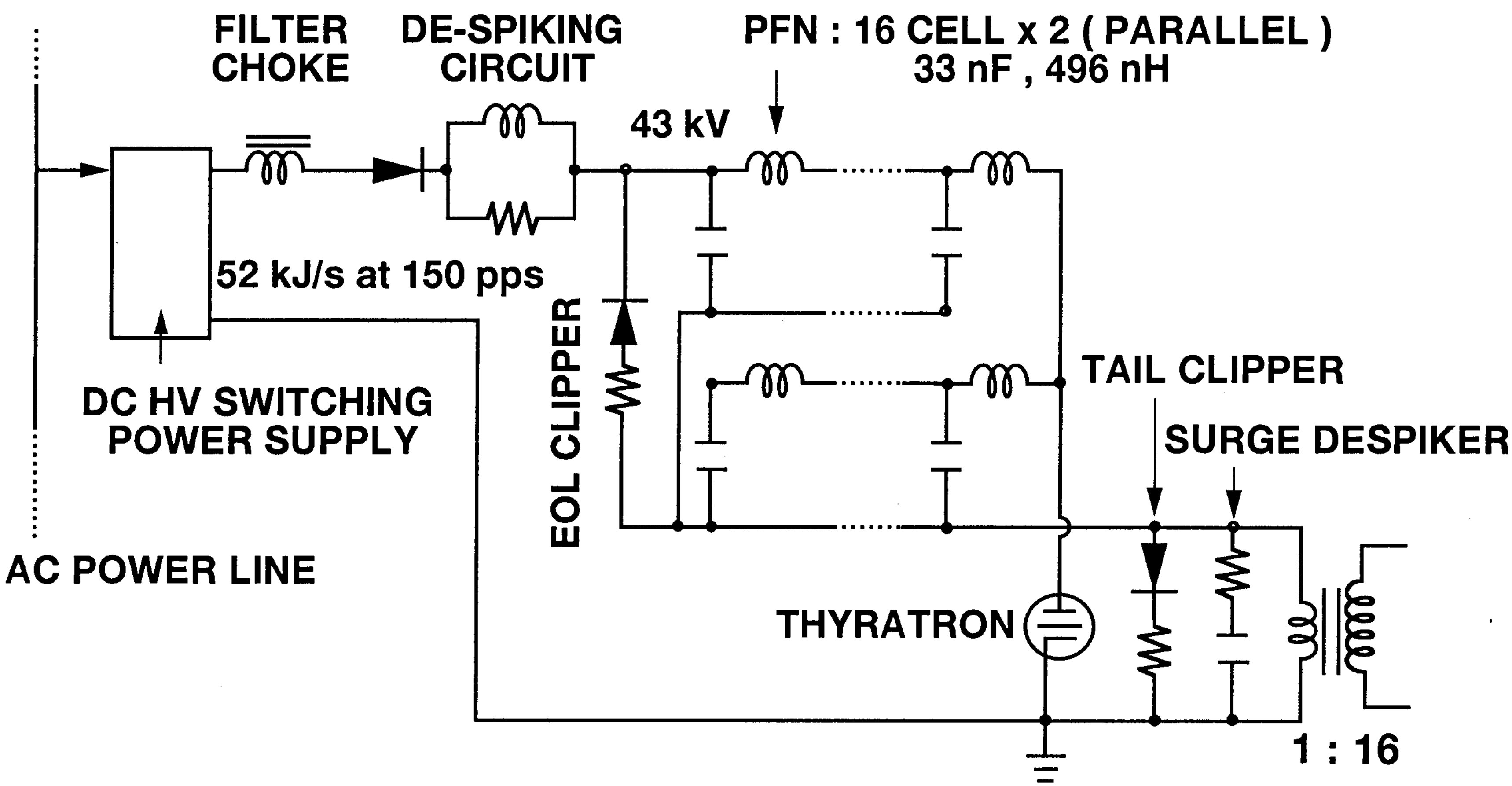
GENERAL CONSIDERATION OF THE MACHINE

VERY IMPORTANT DESIGN CONSIDERATION IS IMPROVING THE OVERALL SYSTEM SUCH AS

- RELIABILITY
- AVAILABILITY
- MAINTAINABILITY

BECAUSE, LINEAR COLLIDER SHOULD BE USE MORE THAN THE 4000 KLYSTRON MODULATORS AND TUBES

CIRCUIT OF THE C-BAND KLYSTRON MODULATOR



CAPACITOR CHARGING POWER SUPPLIES
20 kJ/s to 30 kJ/s

SPECIFICATIONS

MODEL	203	303
Output Voltages/Current		
0-1 kV	50 A	75 A
0-2 kV	25 A	38 A
0-4 kV	13 A	19 A
0-5 kV	10 A	15 A
0-10 kV	5 A	7.5 A
0-20 kV	2.5 A	3.8 A
0-30 kV	1.7 A	2.5 A
0-40 kV	1.3 A	1.9 A
0-50 kV	1.0 A	1.5 A
Charge Rate		
average	20 kJ/s	30 kJ/s
peak	25 kJ/s	37.5 kJ/s
Input Power		
340-460V or	50 A max	N.A.
432-528V 50-60 Hz, 3 phase	40 A max	60A max

Polarity
Positive or negative

Voltage Regulation
±0.5% to 200Hz

Efficiency
90% at full load

Inrush Current
Limited to below full power current

Protection
Short circuit, arc, over-temp, over-voltage, access interlocks, highly buffered I/O. Protected from excess voltage reversal.

Cooling
Water, 35 °C max at ≥ 2.0 gallons per minute.

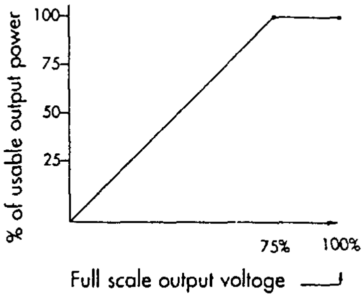
Temperature Range
Operating: 10 °C to 50 °C (Lower temperatures on special request)
Storage: −55 °C to 70 °C

Size
19 in. Standard rack mount
17 in. (430mm) Wide
12.25 in (7U) High
22 in. (560mm) Deep
5 in. for cables.
Other package configurations available on request.

Weight
185 lbs.

POWER REGULATION

Usable output power vs. output voltage setting

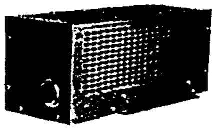


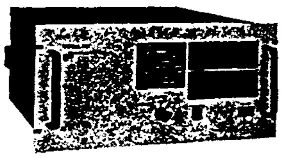
For a given capacitor and rep. rate, these models provide constant output power over the top 25% of the output voltage range. Below that it provides constant current.

ALE's unique control circuit maintains the constant output current independent of line voltage.

For High Voltage Capacitor Charging Supplies
From 500 J/s To 30 kJ/s

Advanced high voltage current sources specifically designed to charge capacitors in discharge driven applications.

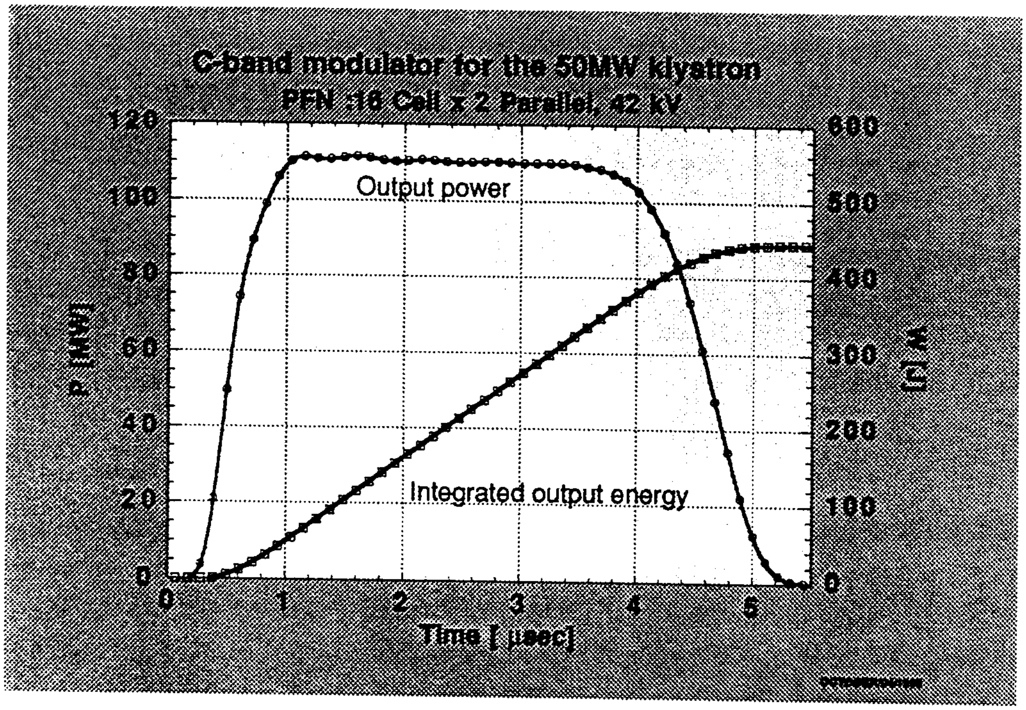


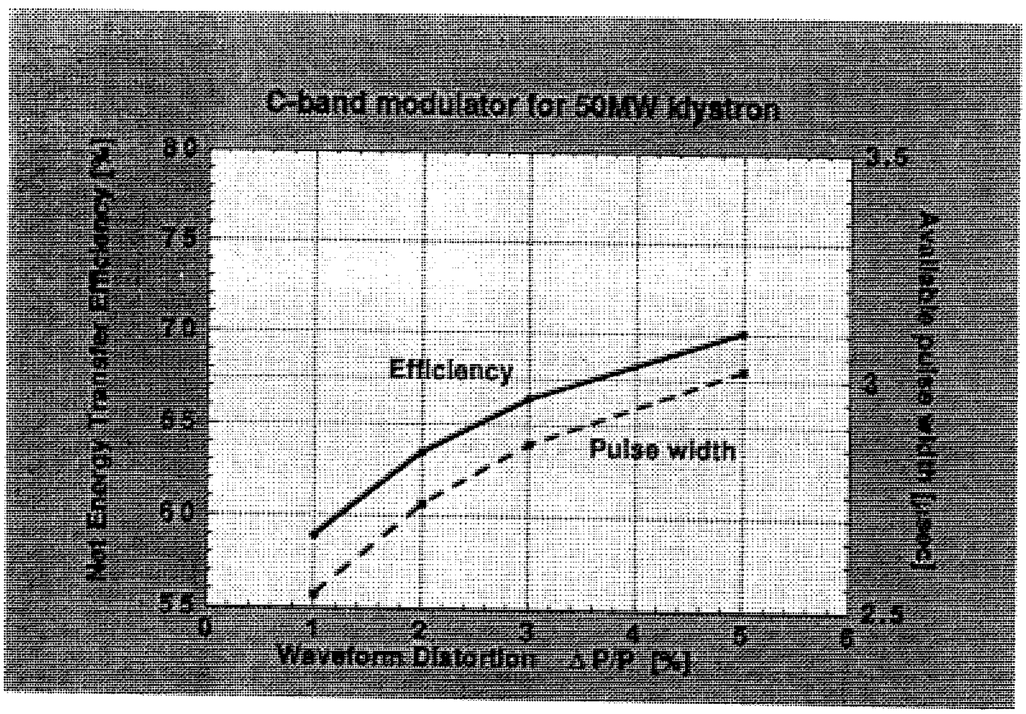


MODEL	CHARGE RATE
500	500 J/s
102	1000 J/s
152	1500 J/s

MODEL	CHARGE RATE
402	4000 J/s
802	8000 J/s

ALSO AVAILABLE
YAG DRIVE SUPPLIES
CW Arc Lamp Supplies
4kW to 8kW
CO_2
Ballastless CO_2 Supplies
250W to 1000W


C-band modulator for the 50MW klystron
PFN :16 Cell x 2 Parallel, 42 kV
Output power
Integrated output energy
P [MW]
W [J]
Time [μsec]
0
20
40
60
80
100
120
0
100
200
300
400
500
600
0
1
2
3
4
5

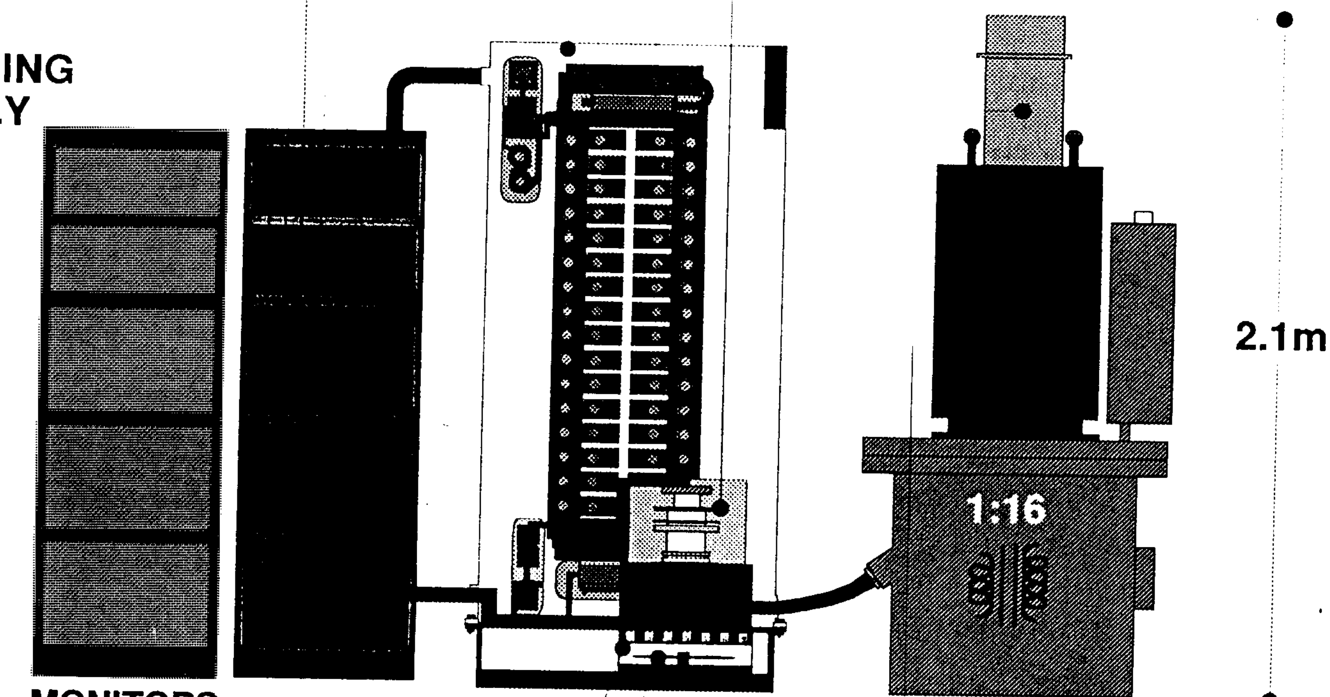

C-band modulator for 50MW klystron
Efficiency
Pulse width
Net Energy Transfer Efficiency [%]
Available pulse width [μsec]
Waveform Distortion ΔP/P [%]
55
60
65
70
75
80
2.5
3
3.5
0
1
2
3
4
5
6

C-BAND 50 MW KLYSTRON MODULATOR

INTER LOCK
RF CONTROL
FOCUSING MAGNET POWER SUPPLY
THYRATRON CONTROL

CABINET SIZE
: 2m (H) x 1 m (W) x 1.5 m (D)
PFN : 16 CELL-PARALLEL,
33 nF, 498 nH
THYRATRON : 43 kV x 5072 A

DC HV SWITCHING POWER SUPPLY



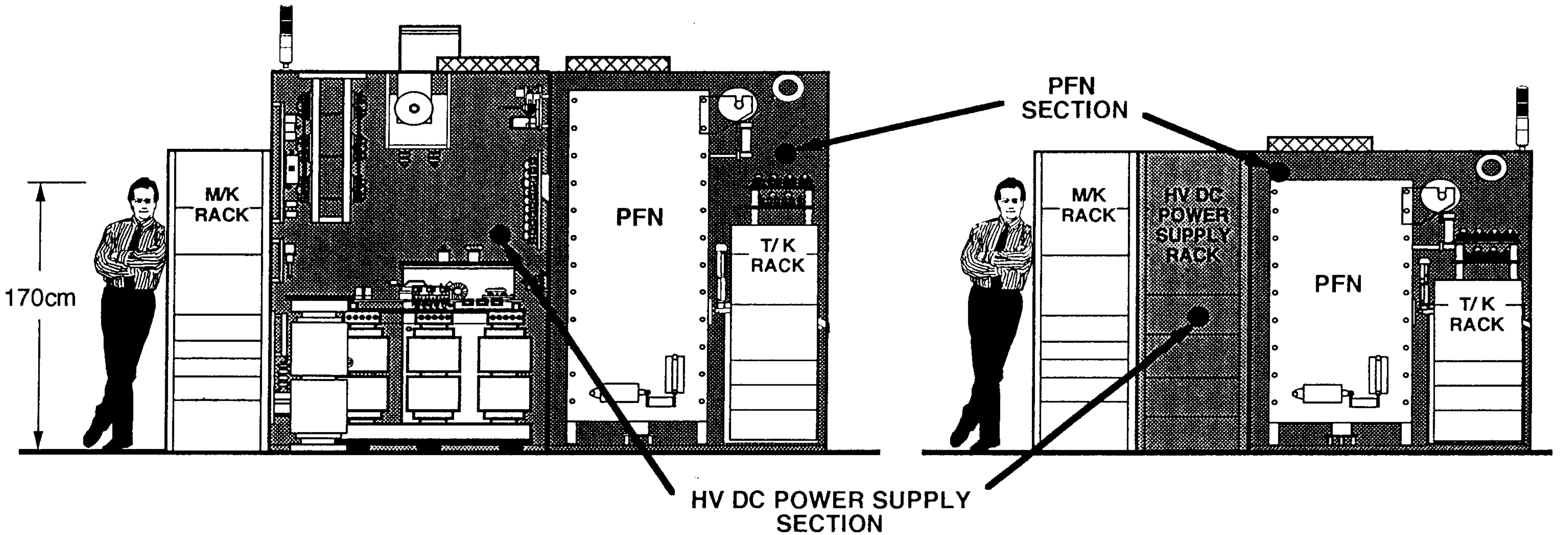
MONITORS

HEAT EXCHANGER
COOLING FAN

350 kV, 317 A, 150 pps
η=45%, μP=1.53

LINAC ← → PAL

PLS 200MW MODULATOR UPGRADE SYSTEM LAYOUT



MODULATOR SYSTEM

LC Resonant Charging
HV DC Power Supply
PFN Capacitor

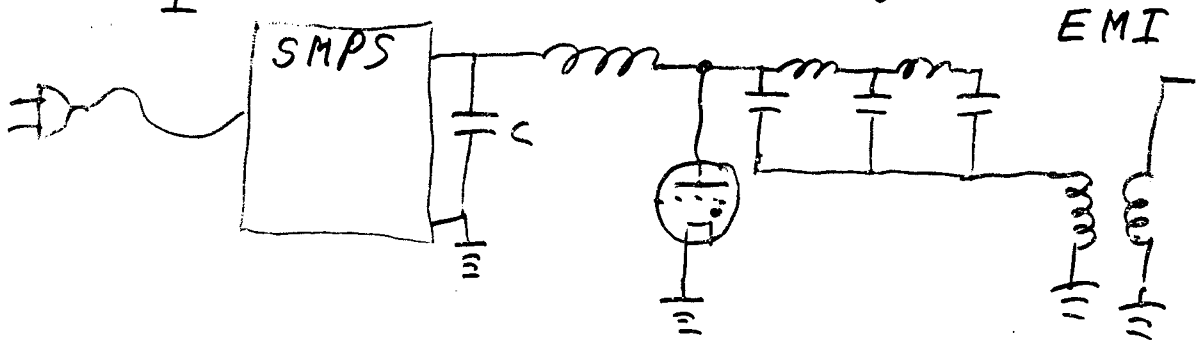
→

UPGRADE SYSTEM

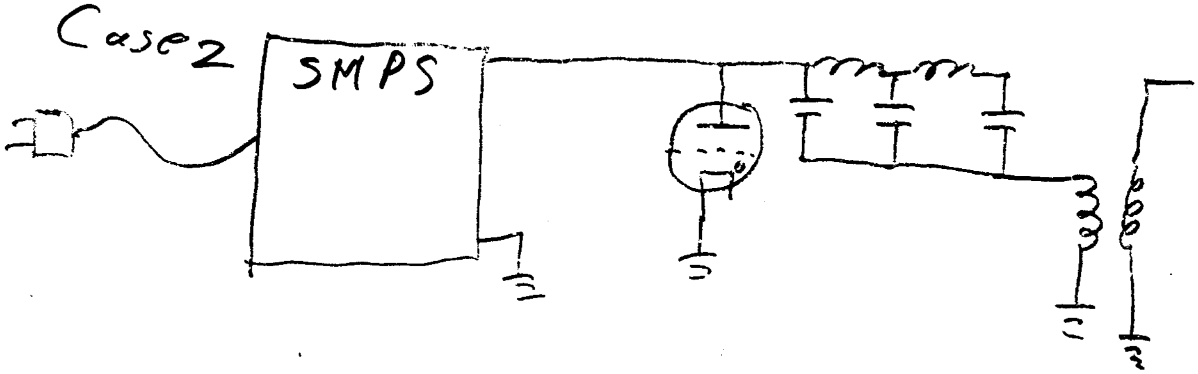
Command Charging
Inverter Power Supply
High Energy PFN Capacitor

Case 1

George Bees

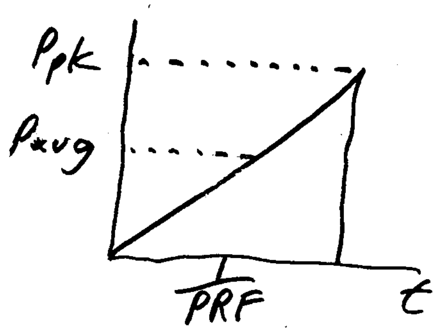


Case 2



Case 2

Peak Power



Direct Charge has ≈ 2X Losses due to higher peak power

Direct Charge avoids latching problem and could possibly reduce transformer turns ratio

George Bees
EMI

Advantage of SMPS

Small Size Can Exchange Failed Supply
Fast Response (No DeQ Network)
Modular Easy to Repair
Active Power Factor Correction
Inherently current limited
"Off the shelf" product

Cost

Today small Qty
0.8 to 1 $/J/sec direct charge
0.4 to 0.5 $/W resonant charge
Low Voltage SMPS
0.2 to 0.4 $/W

George Bees
EMI

8year old

Existing Supply Efficiency

303 Type
$12\frac{1}{4}$" rack mount
≈ 180 lbs
water cooled
480V 3Ø input

Pout Pk 37 KJ/sec

Pout Avg 30 KJ/sec

η Measured 82% in direct charge mode

Power Factor 92%

Room for improvment

Present design allows for 208 or 480
some comprimise made in switch loss

Parallel vs Series Resonant Topology

Active Power Factor Correction

Lower Losses in output transformer
through improved window usage

ELECTRONIC MEASUREMENTS, INC.

HV CAPACITOR CHARGING SUPPLIES

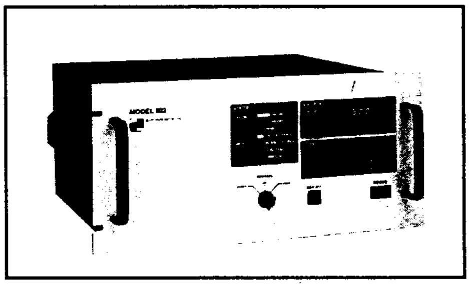
SERIES 402
SERIES 802

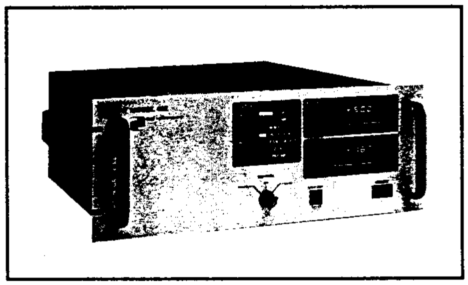
SERIES 402 • 0-1kV to 0-50kV 4,000 J/s ; 6,000 Watts Constant Voltage
SERIES 802 • 0-1kV to 0-50kV 8,000 J/s ; 10,000 Watts Constant Voltage

Producing voltage ranges between 0-1 kV to 0-50 kV, these supplies produce 4000 J/s (402) and 8000 J/s (802) average charging rates for direct capacitor charging of both repitition rate and high energy, single shot applications. They will also reliably drive constant Voltage Loads such as Magnetrons, TWTs and Electron Beam Sources.

All units incorporate IGBT inverter technology for trouble-free operation with protection against arcs, short and open circuit conditions.

- Fully adjustable output voltage
- Worldwide input voltages/frequencies
- Local/remote control as standard
- Complies with UL, CSA, VDE safety requirements
- Simple parallel operation for upgradeable increased power
- Positive and Negative polarity
- Repitition rates to 1 kHz and more
- Tight regulation





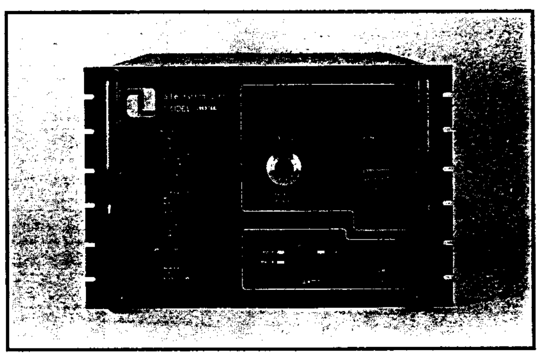
HV CAPACITOR CHARGING SUPPLIES
HV DC POWER SUPPLIES

SERIES 203
SERIES 303

SERIES 203 • 0-1kV to 0-50kV 20,000 J/s; 30,000 Watts Constant Voltage
SERIES 303 • 0-1kV to 0-50kV 30,000 J/s; 50,000 Watts Constant Voltage

FEATURES:

- Only an incredible 12¼" in 19" rack height
- Modular internal construction
- Full protection against open circuit, short circuit, Arc
- Remote and/or local control as standard
- High efficiency
- Parallel operation for increased power
- NEW! **High Voltage Engineers please note: In many applications the 203/303 Series can be used to generate 50kw average DC power! Contact our technical department for details.**



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ELECTRONIC MEASUREMENTS INC.

a.l.e. systems, inc.

CAPACITOR CHARGING

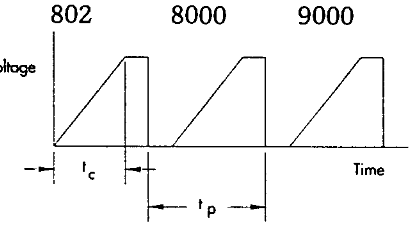
PRODUCT DESCRIPTION

This series of high voltage switching power supplies is designed to quickly charge capacitors and pulse forming networks. Advanced semiconductor technology, combined with high quality construction, yields exceptionally small and reliable power supplies. With many standard features and options, this series is useful in a wide variety of OEM and laboratory applications. Designed for continuous use in severe electrical environments, these air cooled power supplies provide an average charging rate of 4.0 to 8.0 kJ/sec over nine output voltage ranges from 1kV to 50kV, positive or negative polarity. Output control and status monitoring are easily accomplished with the standard remote interface or the optional front panel controls.

OUTPUT VOLTAGES

1kV to 50kV in the following ranges: 1,2,4,5,10,20,30,40,50

Model	Charge Rates (J/s) Avg.	Peak
402	4000	5000
802	8000	9000



$$\text{Peak charge rate} = \frac{1/2\ CV^2}{t_C}$$

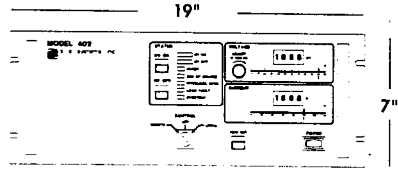
$$\text{Average charge rate} = \frac{1/2\ CV^2}{t_P}$$

APPLICATIONS

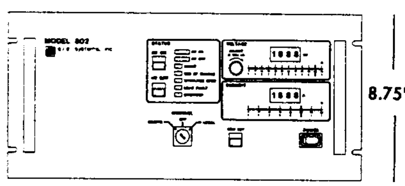
Laboratory Unit

402L and 802L have full front panel instrumentation for laboratory or prototype use. Includes voltage adjust, digital voltage and current meters, quick reference voltage and current bar graphs, high voltage ON/OFF, power switch, view-set switch which allows previewing of output voltage setting, status indicators.

402L CONFIGURATION



802L CONFIGURATION



OPTIONAL CONFIGURATIONS

Remote Control Only

For use as a stand-alone or in parallel with laboratory units for increased power. Has power switch and status indicators.

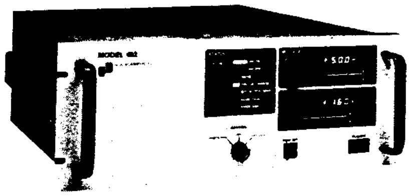
OEM Blank Front Panel

Remote operation only. Used in low cost high volume applications. User supplies all controls.

Consult factory for modifications to the standard configurations or custom requirements.

HIGH VOLTAGE POWER SUPPLIES 4 to 8 kJ/s

MODELS 402
802



- 5000 TO 9000 J/S PEAK CHARGE RATE
- COMPACT LIGHTWEIGHT DESIGN
- CONSTANT CHARGE RATES INDEPENDENT OF LINE VOLTAGE
- FULLY ADJUSTABLE OUTPUT VOLTAGE
- WORLDWIDE INPUT VOLTAGES
- MEETS UL, CSA, VDE SAFETY STANDARDS
- EXTREMELY LOW STORED ENERGY
- PROTECTED AGAINST OPEN CIRCUIT, SHORT CIRCUIT, ARC, OVER-TEMP, OVER-VOLTAGE
- SIMPLE PARALLEL OPERATION FOR INCREASED POWER

405 ESSEX ROAD, NEPTUNE, NJ 07753 • PHONE: 908-922-9300 FAX: 908-922-9334

CAPACITOR CHARGING POWER SUPPLIES
4 kJ/s to 8 kJ/s

SPECIFICATIONS

MODEL	402	802
Output Voltages/Current		
0-1 kV	10.0 A	18.0 A
0-2 kV	5.0 A	9.0 A
0-4 kV	2.5 A	4.5 A
0-5 kV	2.0 A	3.6 A
0-10 kV	1.0 A	1.8 A
0-20 kV	500 mA	900 mA
0-30 kV	333 mA	600 mA
0-40 kV	250 mA	450 mA
0-50 kV	200 mA	360 mA
Charge Rate		
average	4.0 kJ/s	8.0 kJ/s
peak	5.0 kJ/s	9.0 kJ/s
Input Power		
180-264V or	20 A max	40 A max
340-460V 50-60 Hz, 3 phase	15 A max	25 A max
Size		
19 in. rack mount by 17 in. deep	7 in. (4U) high	8.75 in. (5U) high
Weight	40 lbs., 18 kg	85 lbs., 40 kg

Polarity
Positive or negative

Regulation
±1.0% to 1kHz standard

Efficiency
85% minimum at full load

Power Factor
85% minimum with 180-264 VAC line

Cooling
Forced air, −20°C to 40°C inlet temp, 10% to 90% R.H. non-condensing

Options
Front panel controls, rack mount slides, AC contactor (OEM ONLY). Water to air external heat exchanger

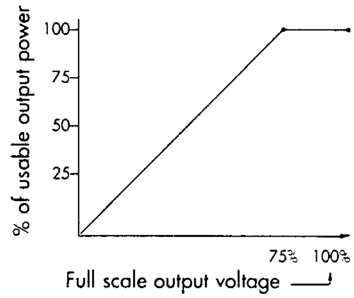
Inrush Current
Limited to below full power current

Protection
Open circuit, short circuit, arc, over-temp, over-voltage, access interlocks, highly buffered I/O

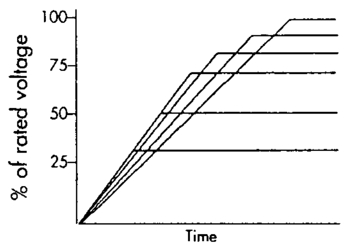
For a given capacitor and rep. rate these models provide constant output power over the top 25% of the output voltage range. Below that it provides constant current.

POWER REGULATION

Usable output power vs. output voltage setting

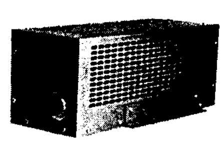


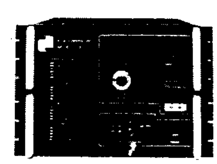
Variation of charge waveform with high voltage set point



ALE's unique control circuit maintains the constant output current independent of line voltage

For High Voltage Capacitor Charging From 500 J/s TO 30 kJ/s

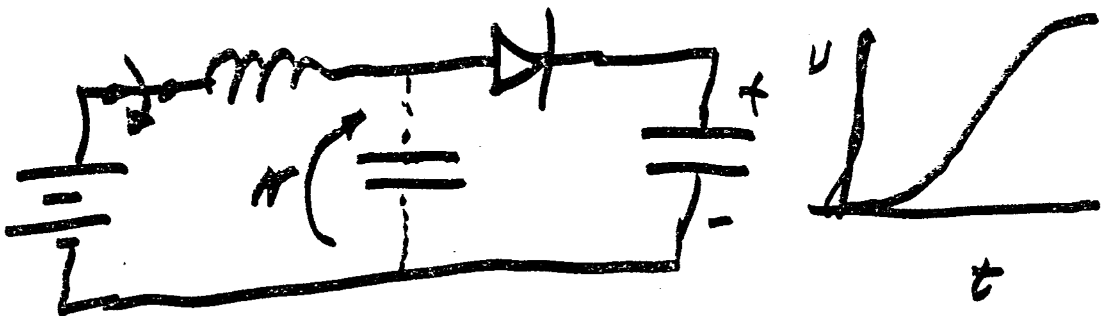


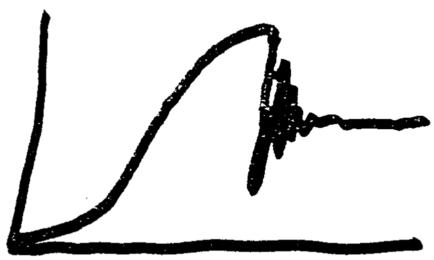


MODELS		MODELS	
500 FOR	500 J/s	203 FOR	20 kJ/s
102	1000 J/s	303	30 kJ/s
152	1500 J/s		

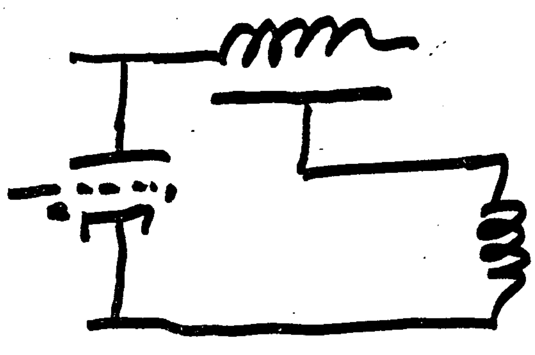
MODULATOR EFFICIENCY, RINGING, PFL's vs PFN's

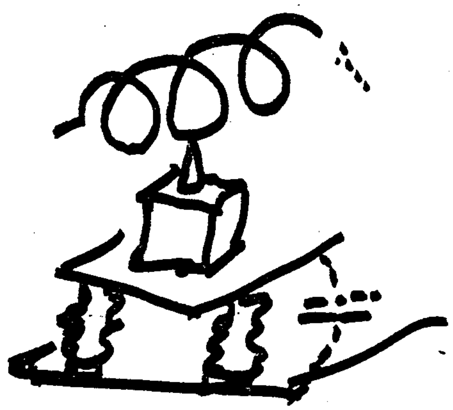
T. BURKES





Acoustic/Elect. Noise

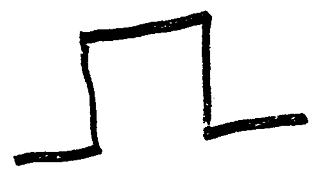




Low Loss → High Q

Lots of ringing

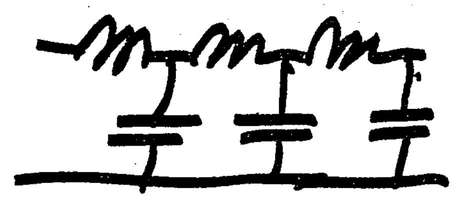
PFN Design

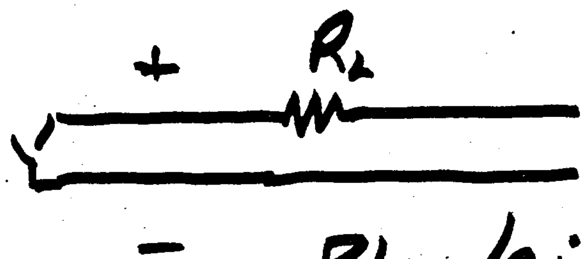


Fourier Series

- Least Mean Sq. Fit
- Max. Rise
- Max. Flat etc.
- # Sections not Harmonic
- Computer

PFL — PFN





Blumlein

$\frac{R_0}{2}, \tau$ $\qquad$ $\frac{R_0}{2}, \tau$

$I_s(\text{switch}) = 2 I_L$

Losses $\sim I^2 R$

Loss switched line = 4X

But " " → 1/2 τ

" " ~ X unswitched line

Losses " " 6X

Single	Blumlein
Losses 1X	~ 7X
$I_s = I_L$	$I_s = 2 I_L$
$\frac{di}{dt}$ =	$\frac{di}{dt}_s = 2 \frac{di}{dt}$ (load)

Inductance → Package

Hard	Harder

Pulse Xformer

~ Same

2 Volt Charge	1 Volt Charge

— recommendation

— Go for Voltage

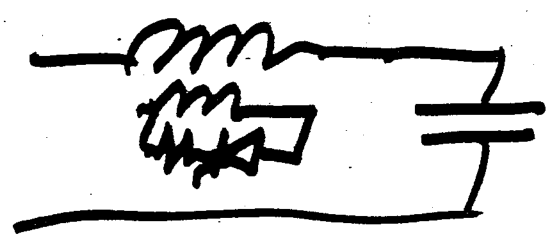
D'Qing

Lossless?

$$Q \equiv \frac{2\pi\,(\text{Peak Energy Stored})}{\text{Ave Diss. / cycle}}$$

$$\simeq \frac{\omega L}{R}$$

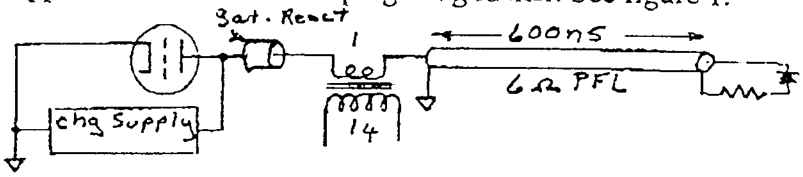
In' Qing



COMPACT AND EFFICIENT MODULATOR DESIGN

JOHN DINKEL

Basically, If you want efficiency, your system must be compact. Excess volume equates to leakage reactance in some form or other. The Blumlein approach certainly is not the best approach from an efficiency standpoint as Burkes pointed out. I suggest that you build the modulator using a variation on the approach used in the Damping Ring kicker. See figure 1.



If you use a 14/1 pulse transformer, the PFL can be operated at 75kV with a 6Ω impedance. If the PFL was made in the form of a stripline with slabs of strontium titanate($\in_r$ =232) as the dielectric, its length would be about 40 feet. To operate at 75kV the dielectric thickness would have to be no less than 1.5" thick on each side and would require several intermediate grading electrodes to maintain a uniform field across the dielectric, particularly at the edges. The width of the center conductor would be about 3" for a 6Ω PFL. The PFL could be made tunable over a limited range by using movable sides to adjust the inductance of the line. The whole works could be externally clamped to make good contact with the dielectric and filled with SF6 or a liquid dielectric. A flexible boot along the sides would contain this dielectric. The end-of-line clipper could be distributed into this structure by connecting diode wafers and resistors in between the grading electrodes. A PFL cross-section and clipper are shown in figure 2.

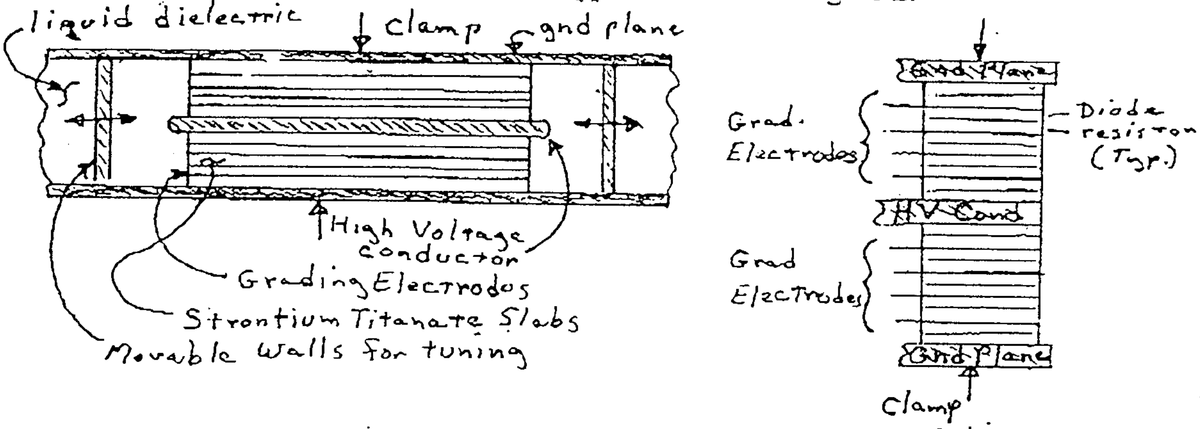


figure 2

End of Line clipper

Finally, to prolong thyratron lifetime, a saturable reactor can be made to help in two ways. First, it can be designed to limit thyratron current during turn-on to the reactor magnetizing current. Following the pulse, it will again limit any reverse current due to mis-match. This will eliminate the need for the reverse diode on the anode. To make this reactor function properly, it is reset by the PFL charging current (charging supply connected to the thyratron anode). The PFL discharge current resets the reactor in the opposite direction so that it can block reverse currents and the cycle repeats.

John Dinkel/Fermilab
October 16, 1995

SUMMARY OF MODULATOR EFFICENCY SESSION

G. Leyh

R. Cassel discussed the performance, cost, and efficiency requirements for the Next Linear Collider (NLC), and identified causes of inefficiency and expense in the existing SLAC modulator. Transparencies of conceptual designs for the NLC Modulator and simulated waveforms were presented.

Cassel stated that the performance specs of the existing SLAC modulator (efficiency < 50%, cost > 250k$) will not be sufficient to meet the construction and operating budgets of the NLC, and suggested a design goal of 80% overall modulator efficiency, a rise time of < 200 ns, and a per modulator cost of < 180k$.

The objectives for the NLCTA Modulator were presented as follows:

Klystron Test Modulator - 600kV, 560A, 1.2µSec

NLC Test Accelerator (NLCTA) Modulator - 480kV, 400A, 1.5µSec

Upgrade to 600kV, 560A, 1.5µSec

Development Modulator for future Linear Collider

Q: Regarding using Andrews cable as oil-filled Blumlein. Will there be a potential problem with surface breakdown between the plastic supports and the oil?

A: LLNL has successfully used this type of cable as a water-filled Blumlein, but at a lower voltage.

Q: Why don't you use water (higher dielectric constant) rather than oil?

A: The dielectric constant and strength of water varies significantly with temperature, and with the purity of the water. Also, pulse charging would be required with a water Blumlein scheme.

Q: Can magnetic shaping be used to improve the rise time?

A: Yes, but a non-trivial amount of energy would be reflected by the pulse shaping circuit in the process. How would you recover that reflected energy?

Q: Can the 100pF of 'stray' capacitance on the klystron cathode be incorporated into a lumped transmission line in order to reduce its effect on overall efficiency?

A: Much effort has gone into minimizing this stray capacitance, but the close cathode to anode spacing plus the proximity of irregular objects (such as ion pumps) place limits on how much the cathode capacitance can be reduced. Of greater importance is the cathode voltage, since the stored energy on the cathode structure is $^1/_2CV^2$.

George Bees introduced EMI's product line of switched-mode capacitor charging power supplies, and presented transparencies outlining the pros and cons of various modulator topologies, with and without switched-mode power supplies (SMPS).

The 3 topologies discussed were:

A. The SLAC-type modulator (60Hz PS followed by a resonant charger)

B. An SMPS capacitor charger followed by a resonant charger

C. An SMPS capacitor charger which charges the PFN capacitors directly

Topologies B and C were compared first, followed by a comparison of A and C. The claimed advantages of each topology are as follows:

B. - More efficient
SMPS costs about 0.4 to 0.5 $/W (Compare to scheme C at 0.8 to 1.0 $/W)

C. _ No large capacitor across PS to dump
PS latch-up avoided
Lower pulse transformer ratio may be possible

<u>Second Comparison</u>

A. - Well understood, reliability data available

C. - Modular, N+1 architecture
No De-Q'ing circuitry required
Active power factor correction available (>0.95)
Inherent current limiting, low stored energy
Available 'off-the-shelf'

Q: Has anyone ever used SMPS capacitor chargers in the direct charging scheme, in a real modulator?
A: Yes, John Kinross-Wright at LANL uses 5 of the model 303 cap chargers in parallel, in a modulator operating at 10Hz.

Fred Nylander talked about matching the pulse transformer to the PFN, and pointed out that if the impedance of the pulse transformer is set to 0.6 times the characteristic impedance of the PFN, then the overshoot on the output will be independent of the load impedance.

Magne Stangenes suggested a pulse transformer design using core bias in order to reduce the leakage inductance enough to meet this criteria.

ROUND TABLE DISCUSSION OF MODULATOR-KLYSTRON PARAMETERS

Responses compiled by G. Leyh

TOPIC 1:
Tony Donaldson asks the assembly, "So, will it be possible to build a machine with 2000 modulators, and 4000 klystrons?"
Harish Anamkath, Titan Beta - Expresses his position that reliability is more important than efficiency.
Chris Pappas, Brookhaven - Yes, if enough dollars are available. Energy recovery from the modulator will probably be necessary.
Dick Cassel, SLAC - Higher modulator efficiencies can be obtained, for more money.
Greg Loew, SLAC - The design tradeoffs that must be made will depend upon the country in which the Linear Collider is built, and the resources which will be available at the proposed site.
Chris Waters, Pearson - The pulse transformer losses can be made quite low, if enough research dollars are available. Present designs are almost optimum.
Jud Hammon, Physics International - Using a Blumlein at higher voltages will produce a better rise time. Jud described a modulator system that is in use, which operates at 500kV, 150 to 600 Joules/pulse, 100 pulses/sec, and has rise times of 150 to 500 ns.
Hugh Menown, EEV - Higher voltage thyratrons will allow faster rise times, and greater efficiency.
Ron Sheldrake, EEV - Use a 500 kV thyratron and eliminate the pulse transformer.
Tom Burkes, Pulse Power - A Blumlein is not a good choice for an energy efficient machine, since the switch current is much higher than the load current. Higher voltages on the thyratron would be better. Tom states that he has had good experience with switched-mode capacitor chargers, and that they offer better diagnostics and adjustability than conventional supplies.
David Turnquist, Litton - Agrees with Burkes. Double the switch voltage rather than use a Blumlein.
Mitsuo Akemoto, KEK - Showed transparencies outlining a scheme for recovering the De-Q'ing energy back into a 'Sub PS', which bootstraps the main supply. The main advantage of this scheme is that no AC inverter is required in order to return the energy back to the AC line.
Hank Grunwald, Triton, - Agrees with Menown. Recommends a 100 kV thyratron and a PT.

TOPIC 2:
Donaldson asks for suggestions on how to produce a modulator with an 80% efficiency.
James Weaver, SLAC/SSRL - Use SMPS's. He states that he has used a Maxwell capacitor charger with a modulator powering an XK5 klystron.
Stefan Choroba, DESY - Suggested the use of switch tubes in order to power the klystron cathode directly from a HVDC bus. Says that Multiple Beam Klystrons (MBK's) are appealing, due to the lower voltage requirements.
Ron Koontz, SLAC - MBK's offer several advantages, such as better perveance, lower cathode voltage, and they might be accept a control grid.
Dick Cassel, SLAC - since $\frac{1}{2}CV^2$ determines the rise and fall times, lower V is better. The topology of the modulator and the klystron should be considered simultaneously.
Tom Russel, ANL, - Use SMPS for line charging and avoid de-Q'ing.
Len Genova, SLAC - Suggested using a combination of a coarse HVDC supply and a SMPS for charging the PFN. In this hybrid approach, the SMPS would top off the PFN only, and provide the fine control of the PFN voltage.
Hiroshi Matsumoto, KEK - Showed transparencies outlining a scheme for reducing the core loss and leakage inductance in the pulse transformer during the rise and fall time by surrounding the standard tape wound core with an outer layer of high dB/dt ferrite material.

The ferrite would support the magnetic field during the rise and fall time, and would resist the formation of eddy currents on its surface, thus reducing the leakage inductance.
Gary Wait, TRIUMF, - Use a 100 kV switch and minimize the PT turns ration. But why not just make the pulse longer so that rise and fall times don't dominate efficiency?
Greg Loew, SLAC - Explained that if the peak power is increased, then the accelerating gradient is higher, and therefore the machine can be shorter in order to achieve the required beam energy.
Lou Reginato, LBL - Increase thyratron voltage. Going from a 6:1 to a 4:1 ratio on the pulse transformer cuts the rise time in half. Don't use water dielectric pulse forming lines, and avoid high dielectric oils. Try to improve existing capacitor technology, and use SMPS charging supplies.
John Dinkel, Fermilab, - Try to match the klystron cathode to the PFN with a coaxial configured PT. Consider metglass rather than iron core material.
Iosif Yampolsky, Integrated Applied Physics - Eliminate the pulse transformer. Use 6 switches in series, the first one being a 40kV thyratron. Use saturated cores for flat-topping.
Richard Adler, North Star, - Use a gridded klystron rather than the modulated gun. He states the best efficiency from a gun modulator is ≈ 70%.

TOPIC 3:
Donaldson asks if a lower ratio on the pulse transformer will improve efficiency.
Magne Stangenes, Stangenes Industries - The core loss doesn't improve much, but the rise time improves due to a lower leakage inductance. Half of the cost of the transformer is the core cost. More core material reduces core loss.
Andrew Erickson, LANL - Keep the design simple. Reliability increases with fewer parts. Use a SMPS for direct charging of the PFN. Operate at 100 to 150kV.

H. Pffeffer/Fermilab

1. **Efficiency vs Cost**

$0.05/kw hr times 6 kW hr=$300/yr

Three year payback period = $900~$1000/kW

EXAMPLE: 50 kW charging supply cost = $50k

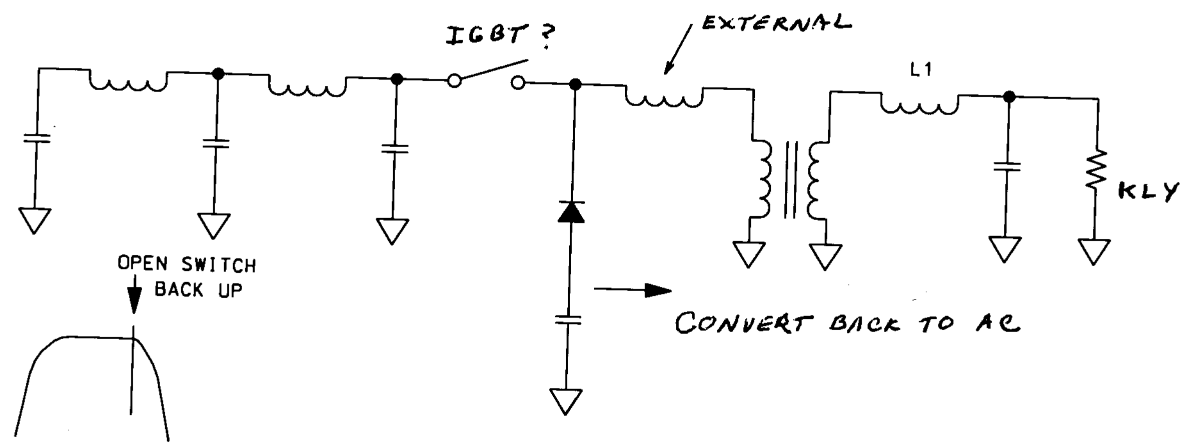
A. 10% inefficiency------>5kW

make 5% inefficient by paralleling units

-------->Saving 2 kW by spending $50k is no good.

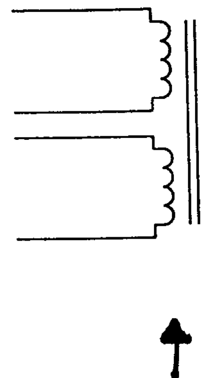
B. Solenoids ~ 5kW?

If ppm system costs more than $5k greater than solenoid system, is it worthwhile?



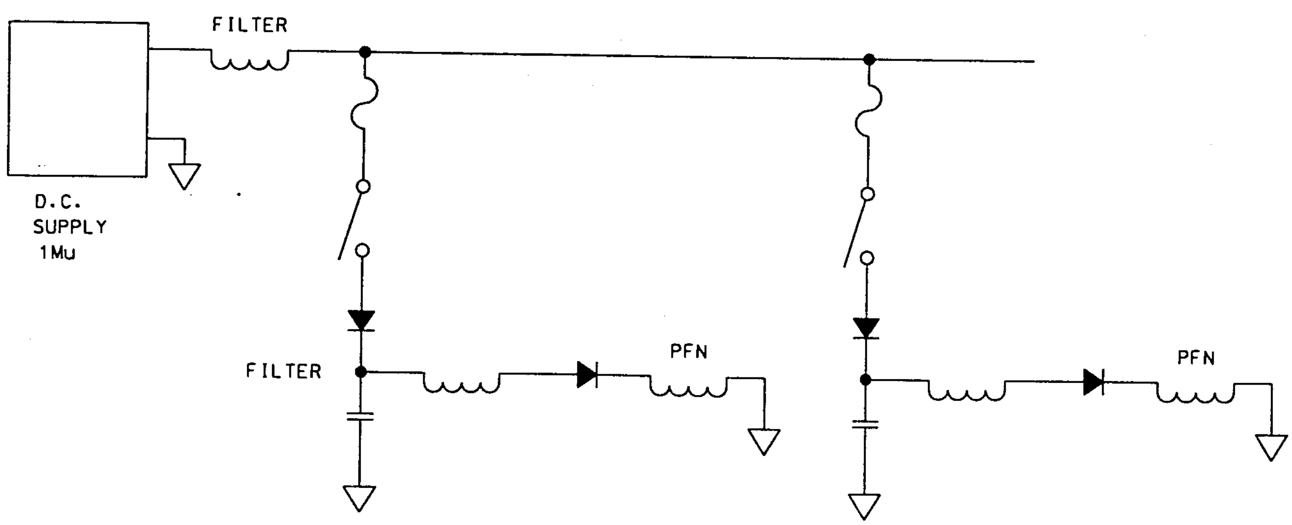
(1)Recapture some stored energy
(2) Don't fully discharge PFN.

2) Is rise time vs. turns ratio relationship really true.



Primary winding. What is difference between driving it in series or in parallel?

3) Large scale changing supply?



NLC MODULATOR PARAMETERS

AND

CONSTRUCTION

R. KOONTZ

S. GOLD

4. 5. 2. Pulse Modulator Design Outline (R. Koontz)

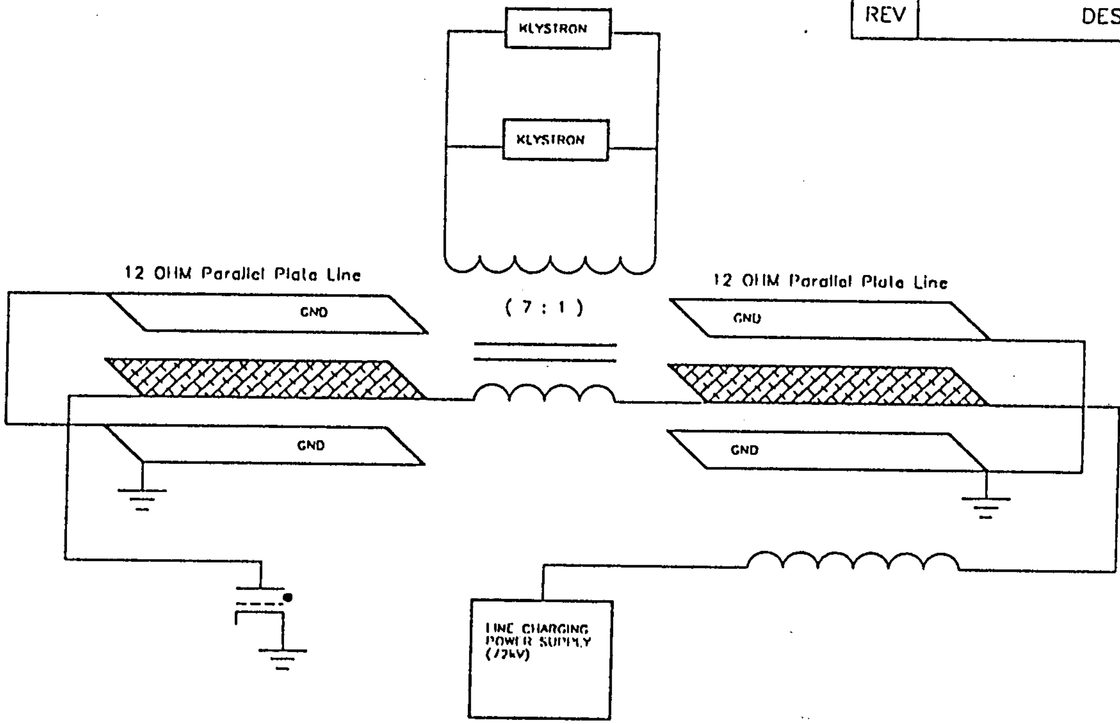
The station klystron modulator drives two PPM focused klystrons. The modulator is of the Blumlein type, and uses as its energy storage elements distributed type transmission lines rather than lumped element artificial lines. The design is driven by the need to synthesize the klystron cathode pulse with the highest efficiency consistent with reasonable cost. In a modulator, the major areas where energy is lost are in the rise and fall times of the cathode pulse where energy is dissipated, but no useful RF energy is produced, and in the IR drops and capacitive and inductive energy storage that is dumped out after the pulse is finished. There is also the power lost in the thyratron voltage drop, and the energy necessary to operate the thyratron heater and reservoir.

In a good thyratron-PFN modulator design, the rise time determining element in the modulator is usually the pulse transformer. Because of the voltage holdoff necessary between the primary and secondary of the transformer, there is always leakage flux generated by the primary that does not couple to the secondary. This shows up as leakage inductance in series with the primary which limits the voltage rise time of the secondary. There is a minimum stray capacity associated with the klystron cathode, and the high voltage secondary of the pulse transformer. This capacity must be charged each pulse, and the charging energy is lost every pulse in the pulse fall time. The transformer core does not have infinite μ, and so a real inductance which is not infinity appears across the primary of the transformer which has the effect of lowering the load impedance as a function of pulse length. The transformer leakage inductance can be minimized by keeping the pulse transformer ratio as low as possible. A low ratio dictates a high primary pulse voltage, and the primary voltage is limited by the switching capability of the thyratron, and the voltage holdoff of the pulse forming line.

In the standard design modulator a single pulse forming line switched by a single thyratron drives a high ratio (typically 23:1) pulse transformer. A modulator using this conventional design was optimized for efficiency and minimum rise time in the Test Stand 13 position in the SLAC Klystron Test Lab. Rise time was less than 600 nanoseconds. This is about the limit of conventional design technology. A modulator design in which two PFN's are used, charged in parallel, and discharged in series (called the Blumlein design) allows the use of a low ratio (7:1) pulse transformer and a reasonable voltage holdoff thyratron. In a lumped element PFN, internal inductance in the capacitors limits the shortness of the rise time that can be obtained. If a distributed transmission line is used instead of the LC lumped line, this limit can be circumvented. Fig 8.5. 3 shows the simple Blumlein modulator concept using two 12 ohm distributed lines, a 75 kV thyratron, and 7:1 ratio pulse transformer. This circuit can provide a pulse rise time of less than 350 nanoseconds delivering a 450 kV pulse of 455 amps to drive two klystrons.

The Blumlein pulser circuit as shown in Fig. 8.5.3 operates as follows:

1. A pulse charging power supply charges both inner plates of the two lines to a DC potential of +72 kV. The two inner plates and the primary of the pulse transformer now are at a +72 kV potential.



BLUMLEIN MODULATOR
FIG 8.5.3

REV	DESCRIPTION	DRN	CHK	APP	DATE

ITEM NO	PREF	BASE	SUFF	TITLE OR DESCRIPTION	QTY
	STOCK OR PART NO				

NEXT ASSEMBLIES:

SCALE:

DIMENSIONING AND TOLERANCING IS IN ACCORDANCE WITH ANSI Y14.5M-1982.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES, TOLERANCES:
BREAK EDGES .005-.015
INTERNAL CORNERS .015 R MAX
FRACTIONS ±
DEC .XX ±
.XXX ±
.XXXX ±
ALL SURFS ✓

DO NOT SCALE DRAWING

STANFORD LINEAR ACCELERATOR CENTER
U.S. DEPARTMENT OF ENERGY
STANFORD UNIVERSITY STANFORD, CALIFORNIA

ENGR R. KOONTZ DATE APPROVALS
DRWN Z. WILSON
CHKD

CAD FILE NAME:

NLC
MODULATORS
BLUMLEIN SCHEMATIC

B SH OF

2. The thyratron is triggered and presents a short circuit to the left end of the left transmission line. The 12 ohm transmission line presents to the thyratron a voltage source of 72 kV in series with an internal impedance (line characteristic impedance) of 12 ohms. The current in the thyratron is thus 6,000 amps. The 6,000 amp wavefront travels to the right on the transmission line, and when it reaches the end of the line connected to the pulse transformer, it reverses the polarity of the voltage as seen looking into the right end of the transmission line to -72 kV.

3. We now have -72 kV with an internal impedance of 12 ohms presented to the left side of the primary pulse transformer winding, and +72 kV with an internal impedance of 12 ohms presented to the right side of the pulse transformer winding. There is the sum of these two voltages, 144 kV, driven from the series impedanace of the two pulse lines, 24 ohms, presented to the primary of the pulse transformer.

4. The dynamic impedance of two klystrons approximates 1,200 ohms. The 7:1 turns ratio pulse transformer transfers this impedance to the primary presenting a primary impedance of 24 ohms to the two pulse lines.

5. The two pulse lines see impedances matched to their characteristic impedances, and in this situation, each of the two lines discharges its full energy into the pulse transformer primary for a period equal to twice the electrical length of each line. The primary sees a total of 72 kV driving 3,000 amps in the form of a square, smooth pulse.

Distributed energy storage lines are most familiar as coaxial cables. There are many low power applications where coaxial cables are used for smooth pulse energy discharge. At high power, there is a good technology development in water filled pulse lines for very short pulses at low impedance. These water filled energy storage lines make use of the very high dielectric constant of pure water, e_r =100+, but they must be charged very rapidly because water as a dielectric cannot withstand high E fields for more than a few hundred μseconds before it before it becomes lossy. An oil filled line with high dielectric oil (e_r=7) can in principal hold off a high voltage, but the support structure of the inner coaxial element is subject to creepage breakdown. For the NLC application, physically realizing a 12 ohm distributed line as a coaxial cable requires a very large diameter cable, in excess of 6 inches, and the high voltage creepage across the inner support insulator would limit the charging voltage. Any breakdown inside the cable would be irreparable without replacing the whole line structure.

An old filled five layer parallel plate transmission line as shown in Fig. 8.5.4 is physically realizable and relatively easy to manufacture and repair. The structure as shown contains two lines each of 12 ohm impedance. The dielectric constant of the oil is just that of normal transformer oil, 2.6. The oil containment for the transmission line is shown separate from the klystron and pulse transformer oil so that high dielectric (e_r=7) oil can be considered in the design development or upgrade. Note that with normal transformer oil, e_r=2.6, the transmission lines shown support klystrons of 0.6 μperv. By just increasing the dielectric constant of the oil, lower impedance lines result that can support higher perveance klystrons. These lines would also be electrically longer by the square root of the dielectric constant ratio.

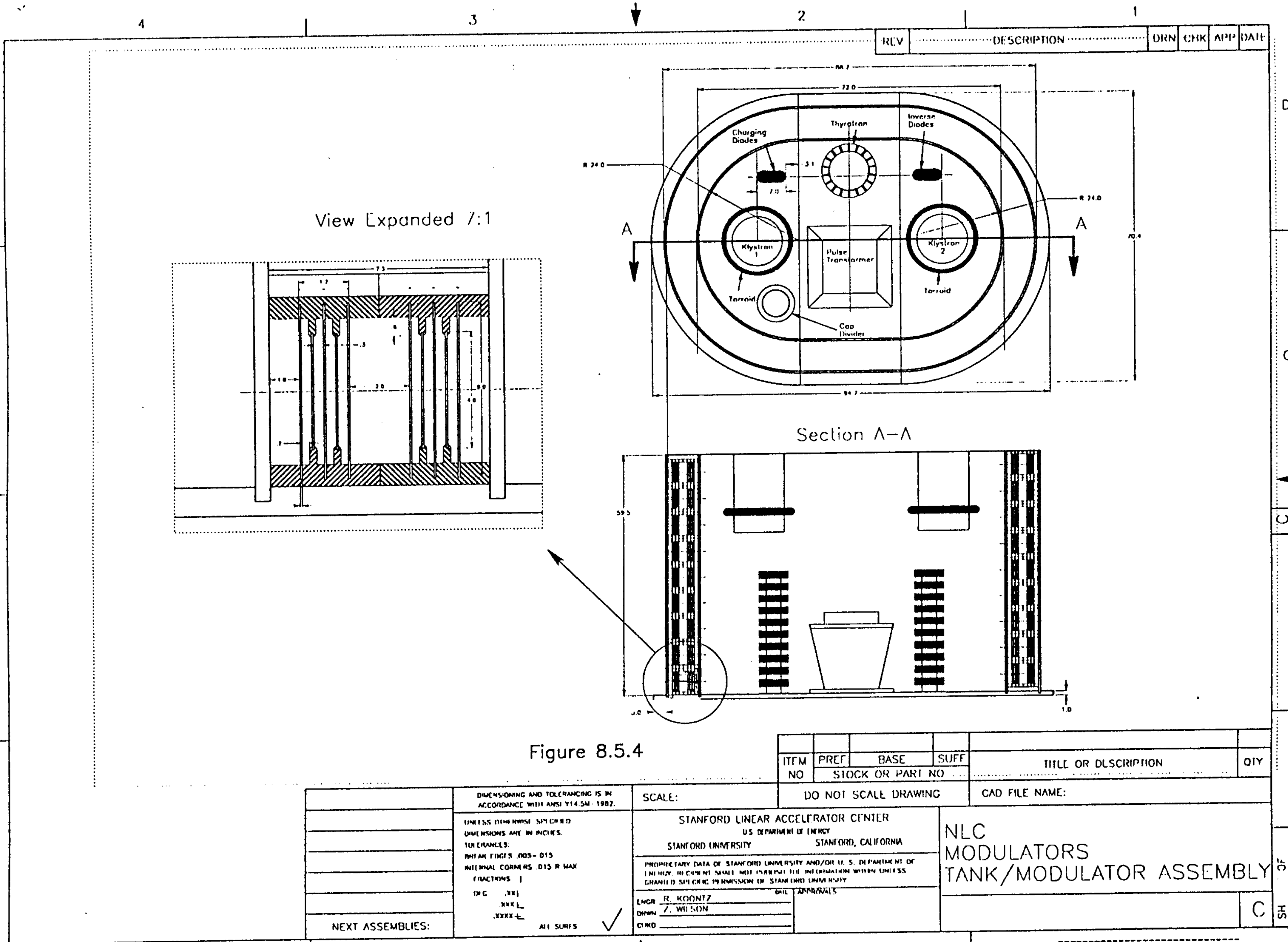

REV
DESCRIPTION
DRN
CHK
APP
DATE
View Expanded 7:1
Section A–A
Charging Diodes
Thyratron
Inverse Diodes
Klystron 1
Klystron 2
Pulse Transformer
Torroid
Cap Divider
A
A
R 24.0
ITEM NO
PREF
BASE
SUFF
STOCK OR PART NO
TITLE OR DESCRIPTION
QTY
DIMENSIONING AND TOLERANCING IS IN ACCORDANCE WITH ANSI Y14.5M - 1982.
SCALE:
DO NOT SCALE DRAWING
CAD FILE NAME:
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES.
TOLERANCES:
BREAK EDGES .005-.015
INTERNAL CORNERS .015 R MAX
FRACTIONS
ALL SURFS
NEXT ASSEMBLIES:
STANFORD LINEAR ACCELERATOR CENTER
US DEPARTMENT OF ENERGY
STANFORD UNIVERSITY
STANFORD, CALIFORNIA
ENGR R. KOONTZ
DRWN Z. WILSON
CHKD
APPROVALS
NLC
MODULATORS
TANK/MODULATOR ASSEMBLY
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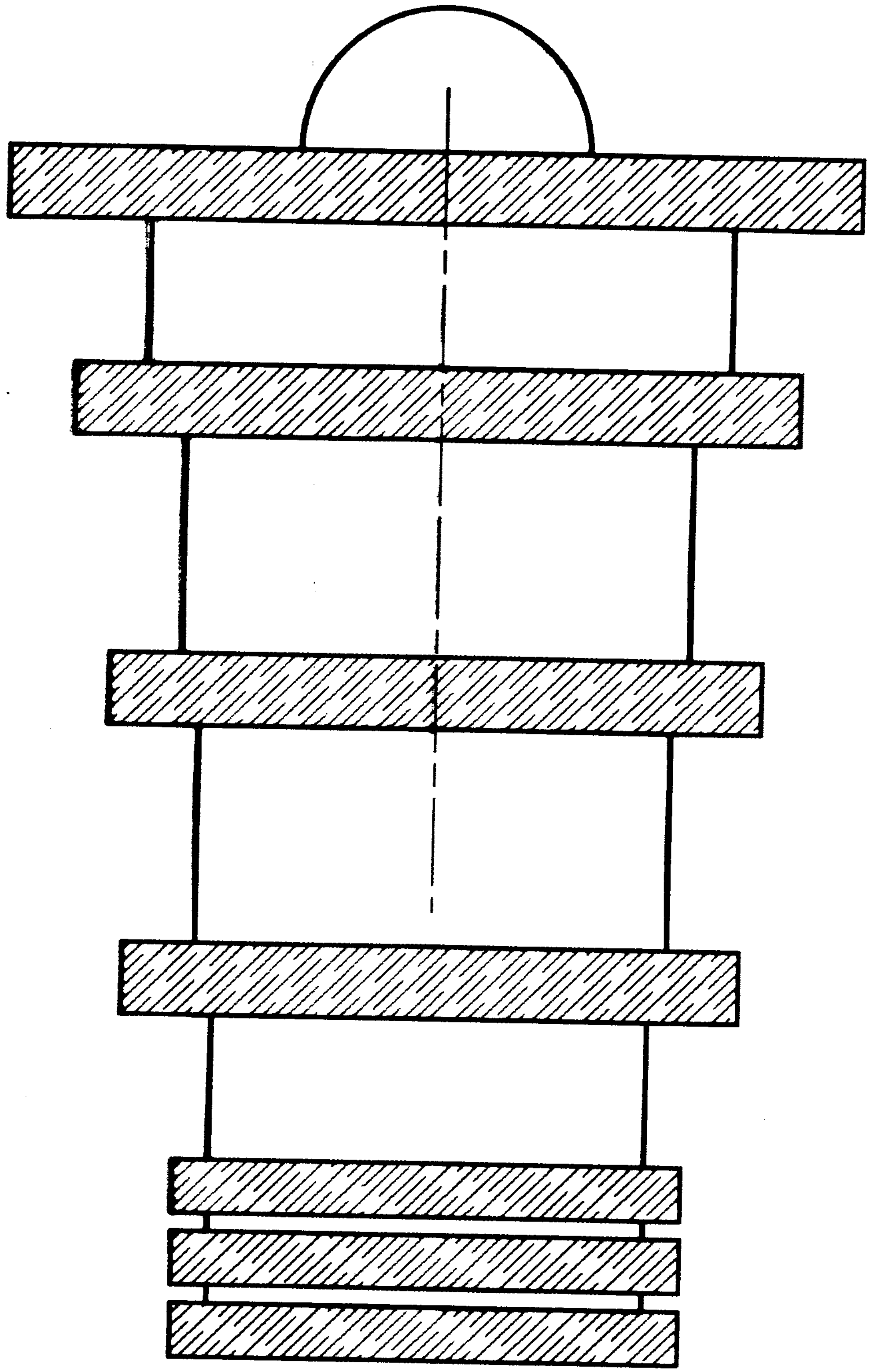
Figure 8.5.4

Concentric Plug-In 3-Gap Thyratron



EXAMPLE

8.5. Klystron Pulse Modulator: (R. Koontz, S. Gold)

The Klystron Pulse Modulator is the principal electronic system of the RF station. Fig. 8.5.1 shows a block diagram of the RF Station. The RF station contains the following sub-systems:

1. Low level RF controls and monitors Section 8.7.)
2. 500 watt to 1 kW Klystron or TWT RF Driver (Section 8.6.4.)
3. Dual PPM focused 50 to 75 MW klystrons (Section 8.4)
4. A single thyratron Blumlein modulator driving two klystrons (Section 8.5.2.)
5. The modulator power supply (Section 8.5.3)
6 The modulator, klystron, and structure monitor & protection system (Section 8.6.)
7. The Station cooling system and oil circulation (Section 8.5.4)

Sections 8.5 and 8.6 are discussed in detail below.

8.5.1. Modulator Requirements (P. Wilson)

Specifications for the NLC modulator are given in Table 8.5.2. These specifications are driven by the requirements of the NLC klystron, as listed in the first seven rows of the table. Although the initial design goal for this klystron is an output power of 50 MW, as required by the 500 GeV NLC design, an improvement program is in progress which will eventually increase the power output to the 72 MW required for the 1 TeV upgrade. The modulator must therefore be capable of driving two klystron at this higher power level. The repetition rate for the initial 500 GeV NLC design is 180 Hz. To save AC power, this drops to 120 Hz for the final 1 TeV machine. However, during the transition to the higher energy, there may be a mix of 50 MW and 72 MW klystons on the linac, operating at 180 Hz. In fact, the higher power tube may be available even at the time construction begins on the 500 GeV collider. In any case the modulator must be capable of driving the higher-power tube at the 180 Hz repetition rate.

The first column in Table 8.5.2 lists the design goals for the 72 MW NLC klystron, and a corresponding set of parameters for a modulator capable of driving two such klystrons. However, as mentioned above, both klystron and modulator must be capable of operating at a 180 Hz repetition rate, as reflected in the second column of Table 8.5.12. Also, the klystron efficiency may fall short of the 60\% efficiency goal, at least initially. To be conservative, the modulator parameters have therefore been chosen so that it can drive a klystron with an efficiency as low as 50\% to the required 72 MW output power.

A key consideration for a modulator in a linear collider application is the efficiency with which power is transferred from the AC line to klystron beam power in flat-top portion of the high voltage output pulse. A 1% decrease in efficiency at any point in this efficiency chain results in an increase by between one and two megawatts in the AC line power for the NLC RF system. An important component in this efficiency is the ratio of the useful energy in the flat-top portion of the pulse to the total pulse energy, including the energy in the rise and fall-time portions of the pulse. This rise/fall energy efficiency is given (very roughly) by T_k (T_k + 1.1 T_R), where T_k is the flat-top pulse width and T_R) is the rise time (the constant 1.1 depends on the precise definition of rise time). In turn, it is well known that the rise time is determined primarily by the turns ration n of the pulse transformer (very roughly, T_R) is proportional to the turns ratio and to the square root of the pulse length). However, a low transformer turns ratio implies a high value for the charging voltage for the pulse forming network (PFN) or pulse forming line (PFL), and a correspondingly high hold-off voltage for the thyratron and other high voltage components. For a modulator using a standard PFN design which can deliver a 500 kV output pulse this charging voltage would be about 150 kV for the 7:1 transformer turns ratio listed in Table 8.5.2. However, by going to a Blumlein type of PFN, the charging voltage can be reduced by a factor of two to about 72 kV. Although a Blumlein PFN design is somewhat more complex, it makes possible both a low transformer turns ratio and a reasonable value for the charging voltage.

In a standard modulator design with output pulse lengths longer than a microsecond or so, lumped elements (capacitors and inductors) are used for the pulse forming network. Such a lumped network has the advantage that it can be readily tuned to adjust the pulse shape, although it is still difficult to eliminate all of the ripples to attain a truly flat pulse unless a very large number of elements are used. Also, it is difficult and expensive to manufacture pulse capacitors with a very low series inductance and long life, especially when the polarity must reverse during the pulse, as required by the Blumlein configuration. For these reasons, the use of lengths of smooth transmission line is being proposed for the NLC modulator. The major disadvantage of such lines (long length) can be ameliorated by choosing an appropriate packing geometry and good mechanical design (see Sec. 8.5.2)

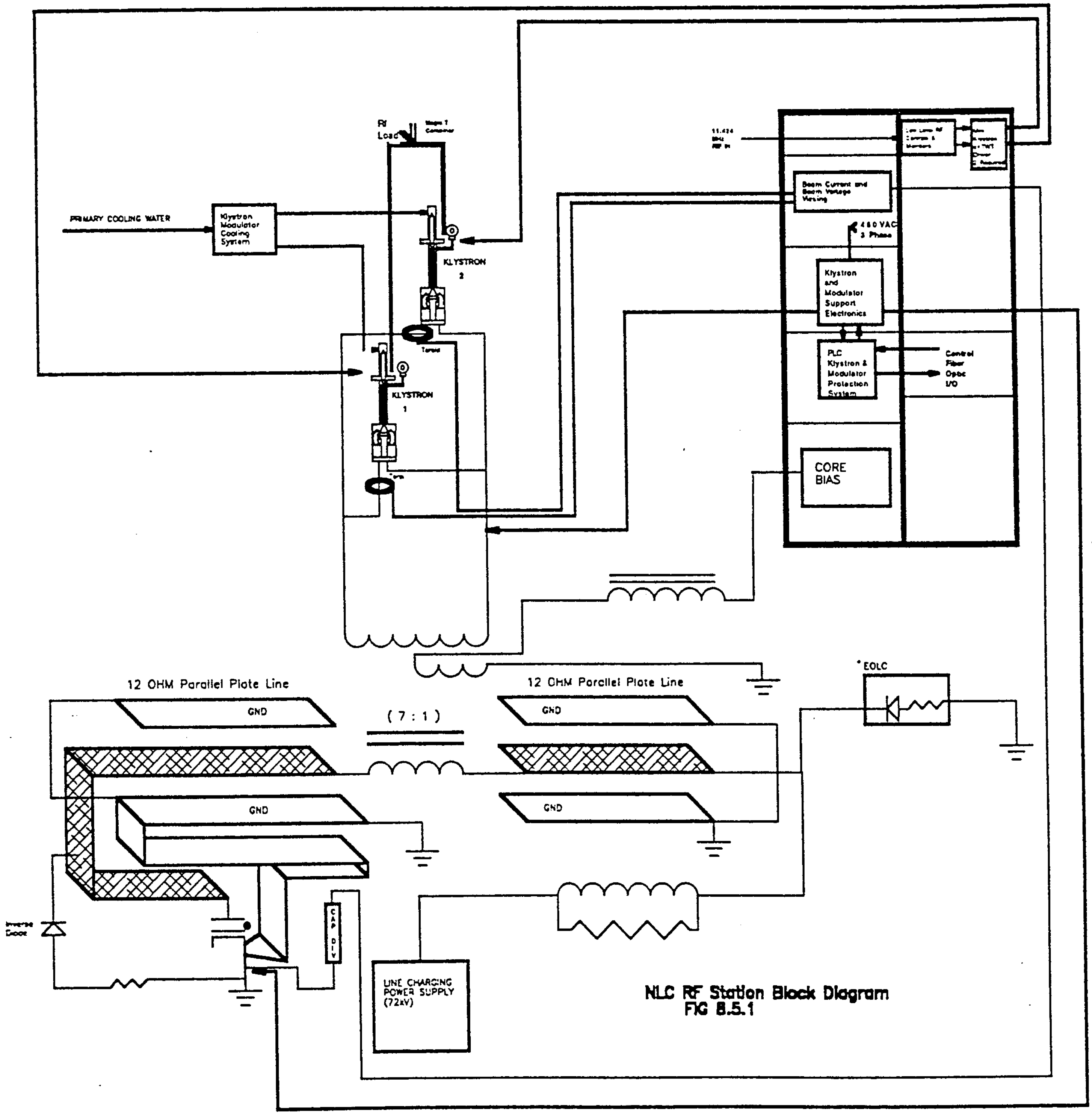
The rise/fall-time energy efficiency, just discussed, is the major component which determines the over-all modulator efficiency. In addition, a voltage drop across the thyratron and eddy currents in the pulse transformer core lead to an additional energy loss of about 3%. The charging voltage on the PFL must be about 1-1/2% higher to compensate for these losses. The corresponding loss efficiency (97%), multiplied by the rise/fall efficiency, gives the net efficiency with which energy stored in the capacitance of the PFL is transferred through the pulse transformer into the useful flat-top portion of the output pulse. A detailed discussion the projected efficiency for the NLC modulator design is given in Sec. 8.5.5

Table 8.5.2

Klystron - Modulator Specifications

(Two klystrons per modulator)

Description:	**Design Goal**	**Design Max/Min**
Klystron Output Power (MW)	72	70 Min
Klystron Microperveance (μperv)	0.6	0.65 Max
Klystron RF Pulse Width (μsec)	1.20	1.20
Klystron Pulse Voltage (kV)	480	517 Max
Klystron Repetition Rate (PRF)	120	180 Max
Klystron RF Pulse Flatness (%)	1	1.2 Max
Klystron Efficiency (%)	60	50 Min
Modulator Type: (drives two klystrons)	Distributed Network Blumlein with individual capacitor charger power supply.	
Distributed Pulse Forming Network Voltage (kV)	72	75 Max
Rise/Fall time (nanoseconds)	300	400 Max
PFN energy storage 2 klystrons (J)	360	461 Max
Auxiliary AC Power Input (kW) (Thyratron heater, reservoir, control)	1.5	2.5 Max
Avg. AC Input Power (kW)	50	460 Max
PRF (Hz)	120	180 Max
Flat Top Pulse Width (μsec)	1.2	1.2
Output pulse voltage (kV)	480	505 Max
Output pulse current (kA) (2 klystrons)	400	430 Max
Pulse transformer ratio	7:1	7:1
Thyratron pulse current (kA)	6.0	6.5 Max



NLC RF Station Block Diagram
FIG 8.5.1

A proposed modulator tank supporting two klystrons is shown in Fig. 8.5.4. The parallel plate transmissions lines are shown mounted in the space between the inner oil tank, and the outer containment tank. The total length of this double transmission line assembly is about 460 feet. The oil is contained in a polypropylene racetrack shaped tank that also serves as the support for the transmission line assembly. The transmission line assembly consists of continuous aluminum strips supported by molded nylon support insulators approximately one inch thick spaced at 12 inch intervals. This construction allows easy servicing and repair of the pulse line if an arc destroys one of the support insulators. By supporting the parallel plates from the end of the aluminum strips, the creepage path between the plates can be made long enough to prevent discharge while still keeping the plate to plate gap small enough to take advantage of the 20 kV+ per tenth inch breakdown properties of the oil.

There are a number of secondary elements also housed in the modulator tank: the end-of-line clipper diode stack, the charging diode (if one is used), the current viewing transformers and voltage viewing capacity divider, the core reset inductor, and the thyratron inverse clipper diode. All of these elements are contained in the inner tank adjacent to the thyratron and pulse transformer.

A double rack enclosure adjacent to the modulator tank contains all the support electronics for the modulator, and the RF drive electronics. The support electronics includes: the klystron cathode heater supply, the thyratron cathode supply, the thyratron reservoir supply, the control power distribution, the RF low level driver and interlock system, the one kW klystron input driver (a special small klystron or TWT), and a custom designed PLC (programmable logic controller) that provides the control and monitor functions for both the pulse modulator and the klystron RF drive and protection systems.

8. 5. 3. Charging Power Supply Design Outline (L. Genova)

8.5.3.1 Specifications (500 GeV Operation)

Charging Voltage	72 kV
Pulse Forming Line Capacitance	0.124μF (PFL)
Joules/pulse, 2 klystrons	320
Repetition Rate	180 PPS at 500 GeV
Charging Voltage Regulation	(0.1 %)
AC Line	480 V, 3 phase, 60 Hz
AC Line Stability	3%
Power Supply Efficiency	93%

8.5.3.2 Conventional Charging System

Traditionally, the power supply that charges the PFL capacitance consists of an AC to DC power supply, a filter capacitor bank, a charging choke, a charging diode or a command charging SCR circuit, and a DQing circuit that regulates the PFN charging voltage (See Fig 8.5.5)

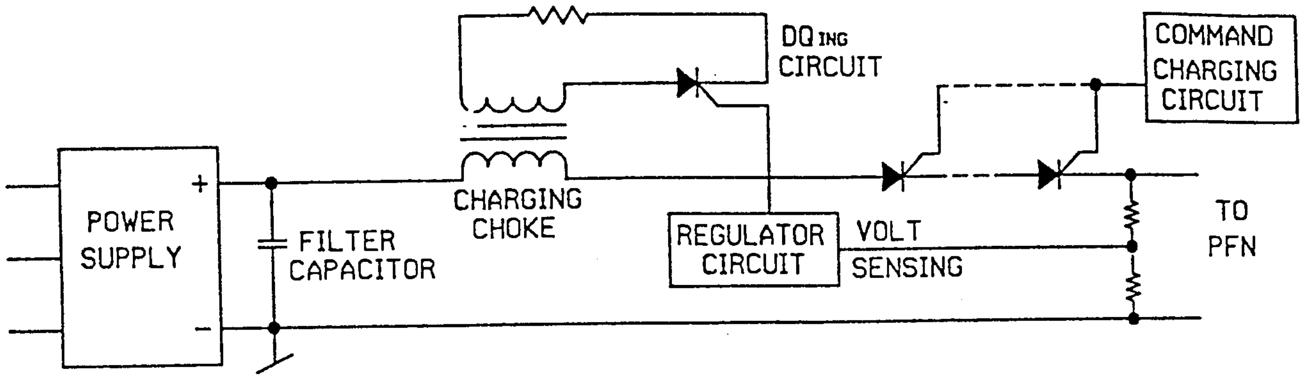


FIG. 8.5.5 CONVENTIONAL PFN CHARGING PS

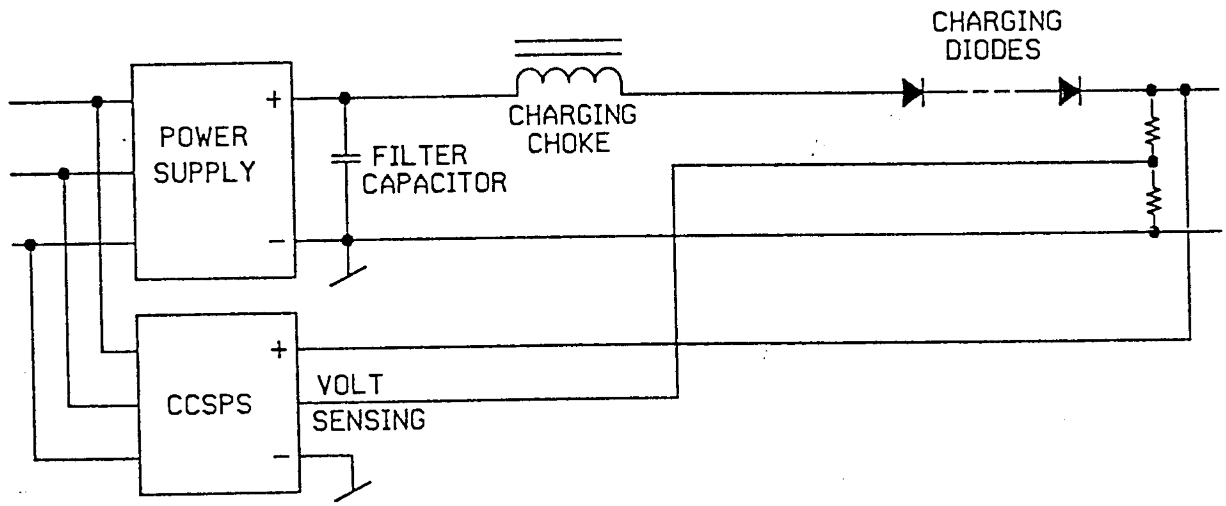


FIG. 8.5.6 HYBRID CIRCUIT CONSISTING OF CONVENTIONAL PS AND SMALL CAPACITOR CHARGING SWITCHING PS (CCSPS) IN PARALLEL

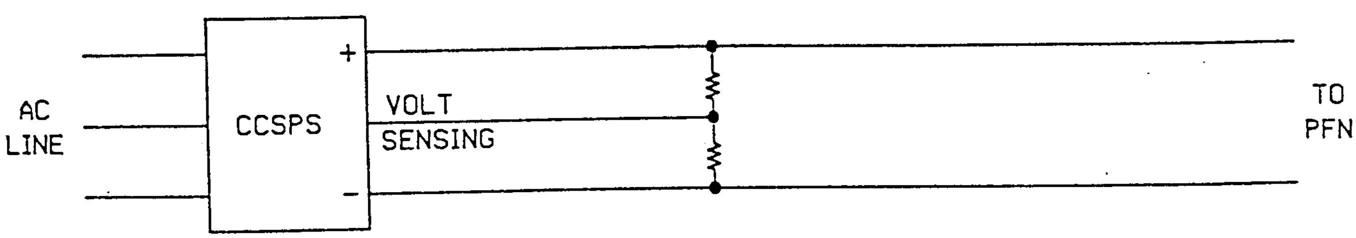


FIG. 8.5.7 CAPACITOR CHARGING SWITCHING POWER SUPPLY (CCSPS) SCHEME

If we assume an AC line stability of (3%, then we must DQ at least 6% to meet the regulation parameter. If the DQing power is dissipated, the efficiency of the power supply charging system is diminished. An energy recovery scheme could be developed to recover the energy and feed it back to the power lines, but it would be expensive and would only recover a portion of the energy. With energy recovery, we could only achieve a total power supply efficiency of 90%.

8.5.3.3 Hybrid Charging System

A better scheme would be to use a small capacitor charging switching power supply in parallel with the charging choke output (Fig 8.5.6 At the lowest line voltage, the PFL would then be charged to 94% of its peak voltage by the charging choke, and the switching power supply would be used to charge the final 6% of the voltage. What we have done is substitute an additive process for a subtractive one with a resulting increase in efficiency. With this additive scheme, power supply efficiency could be as high as 93%.

8.5.3.4 Capacitor Charging Switching Power Supply System

An even more attractive idea is to use a capacitor charging switching power supply (CCSPS) to charge the PFL directly (Fig 8.5.7) The charging cycle starts with the PFL capacitor at zero volts. The CCSPS starts charging the PFL at constant current until the desired voltage is reached. At that time the supply becomes a constant-voltage power supply and keeps the PFL charged at the desired value. The charging waveform looks like a linear ramp which flattens out at the desired voltage.

The CCSPS supplies are becoming commercially available now and will be more common in the near future. A single 50 kW power supply is presently available which will charge the PFL to 50 kV at 120 PPS, will tolerate a voltage reversal of 20%, and has an efficiency of 93%. Research is required to increase the charging voltage to a minimum value of 72 kV. In order to be able to charge at 180 PPS, two CCSPSs, operated in parallel using master/slave connections, are required.

This solution greatly simplifies the charging circuit topology since there is no need for a filter capacitor bank, charging choke, command charging circuit and high voltage blocking SCR strings. The elimination of the filter capacitor bank reduces the amount of energy storage and the possibility of thyratron damage in a latch-up condition. With a filter capacitor bank, a false trigger or a thyratron breakdown will cause the filter bank to discharge completely through the thyratron and then the power supply will short circuit itself through the thyratron. With the CCSPS, a thyratron breakdown would only result in a maximum current equal to the nominal charging current since the CCSPS reverts to constant current operation when it is short circuited. In addition, the CCSPS is much more compact than a conventional power supply. For example, the 50 kW supply cited is rack mountable, 19" wide, 22" deep, and only 12.25" high.

Since we are planning to connect many power supplies across the same AC lines (480V, 3 phase, 60 Hz), it is important that the power factor be as close to one as possible. The rated power factor of the CCSPS is 0.9. There is a need to add power factor correction circuitry to increase it to at least 0.98.

8. 5. 4. Station Cooling System and Oil Circulation (R. Koontz)

There are several cooling circuits that remove heat from the klystron and modulator. The klystron has just one cooling circuit that is a combination of all the passages on the passages on the klystron. Temperature monitor points on parts of the klystron (body, anode, collector, etc.) provide interlocking for over temperature conditions. The modulator contains two oil systems, one for the transmission lines oil which may have a higher dielectric than the main tank, and the other for the low dielectric oil for the klystron guns, the thyratron, the EOLC and charging diodes, and the pulse transformer. Each of these systems will have a small oil circulation pump and an oil to water heat exchanger appropriately interlocked.

There is no cooling required in the RF system support racks unless the charging power supply is mounted in these racks and it needs water cooling, but there may be a need for water temperature stabilization if RF components cannot be designed phase stable with temperature changes.

8. 5. 5. Modulator / Charging Power Supply Efficiency Projections:

At the time of this writing, the efficiencies of the various components and sub-systems are being analyzed, but there are no definitive efficiency projections available as yet. The numbers will become clearer as R&D progresses.

8. 5. 6 PFN / Pulse Transformer Network Simulations

There have been several preliminary SPICE network simulations run to date which show the general waveshapes on the Blumlein as shown in Fig. 8.5.3. More detailed simulations are planned to look at waveshapes using more detailed equivalent circuits that approximate real lines and pulse transformers. All the secondary parameters such as klystron stray capacity, the real characteristics of the various diode stacks and monitor elements, and the actual characteristic of a switched thyratron will be added to the model to get a better picture of what the real pulse response will be.

The dielectric constant of the various normal and high dielectric oils must be characterized as a function of frequency including dielectric losses as the propagation of the wavefront on the lines will be limited by these parameters. High frequency losses limit the wavefront rise time, and dielectric constant variations with frequency can smear out the rise time, and cause pulse overshoot if all frequency components of the wavefront do not arrive at the end of the line at the proper times. It will take a little bit of development work with a simulation program to allow the dielectric constant to have a real and imaginary part corresponding to loss and propagation velocity,

8. 5. 7 Existing prototype modulator performance

At the present time, there is very little experimental data to check design ideas. In the Klystron Test Lab, there are two modulators which can give some experimental check points to simulations. Test Stand 13 is a high power conventional modulator which contains close coupled PFN's and a direct connection to a 23:1 pulse transformer. It produces 500 kV pulses driving a perveance 2 klystron for a 3 μsecond flat top pulse.

Test Stand 3 contains a 1.5:1 PFN they modulator driving a 6:1 pulse transformer with all elements in one large oil tank. It also is designed to produce 500 kV pulses, but it has not run at full voltage in oil as yet. The capacitors that make up the three PFN's that constitute the Blumlein have too much series internal inductance to allow a very fast rise time, flat top pulse. Additional testing will be done on this modulator to get better data. This test stand will be used as the location of new R&D work on distributed pulse line modulators.

8. 5. 8 Modulator / Power Supply R&D Development

As the paper design of a possible NLC modulator evolves, the R&D areas where the new ideas must be tested start to surface. At the present time, we can divide the R&D effort into two categories, component and subsystem development, and system concept testing.

In the component and subsystem area, R&D programs are needed to develop the oil immersed parallel plate pulse lines, a new three gap thyratron that is long life and easy to manufacture, the whole general field of pulse transformers including manufacturing cost minimization, economical and rugged diode stacks, a new pulse charger for this application, and the general simplification and cost optimization of the support electronics.

For system concept testing, a parallel plate transmission must be constructed and tested to prove the principal. This can be done using the various pulsed energy facilities of the Klystron Test Lab.

8.6. RF Unit Protection, Monitor, and Drive Systems

Protection systems are all serviced by the PLC plus some additional faster protection circuitry. This protection system combines the logical protection and operating functions of the modulator, the klystron, and the waveguide and structure systems. It includes the water cooling system, the temperature monitoring system, the various electronic monitors of the klystron support power supplies and the modulator electronics, the related vacuum systems, and the high power RF protection. While all of these various protection and interlock systems are serviced by one PLC, the functions will be discussed separately in the sections below.

Much of the monitor system is part of the protection system in that if monitoring is necessary, it is probably because some protection interlock is essential to the safety of the system. Because of the large number of RF stations, monitors that provide information into the general linac operating system must be kept to an absolute minimum to limit costs.

Each RF system has associated with it a klystron RF drive package that consists of some low level RF processing and phase programming to make the SLED compression operational, some RF interlocks, and a kilowatt driver to provide input to the klystron. In this section, the RF interlocks are discussed, and the kilowatt driver. The other low level RF processing is covered in Section 8.7.

8. 6.1. RF Monitor & Protection System

RF Structures: Structure protection includes all of the high power X-band waveguide, the SLED II energy compressors, and the disc loaded waveguide. Other than accelerated electron beam interception damage over which this interlock system has no control, the primary causes of potential component damage are arcing brought on by poor vacuum and loss of cooling. Because of the limited pumping speed of small waveguide, the high power RF distribution system contains many individual ion pumps. It is expected that these ion pumps will be serviced by a small number of multiple output ion pump power supplies that will be interlocked with the RF system module.

There will be a limited number of reflected energy pickup points, especially in the output arms of the klystrons that will detect reflected energy due to arcs or SLED II mistuning, and will operate through the PLC to inhibit either the drive RF to the klystron, or the klystron pulse modulator.

Klystrons: Klystron protection is accomplished by providing monitoring and interlocks on the systems which provide power and cooling water to the Klystron, the Klystron vacuum and the RF systems including the system vacuum. These monitoring and interlock signals are both analog and digital.

Most of the interlocking is done through the use of a Programmable Logic Controller (PLC) which provides the interlocking and sequencing logic for the Klystron system. Local control and human interface for status readout is planned as a touch screen panel. Critical interlocks such as Klystron Output Reflected Power, which require faster response time, are also direct, hard wired.

The water system is designed for two klystrons per station with separate water circuits for each klystron. Each klystron will have a water circuit for its anode, its body and window and its collector. The separate water lines will be protected for minimum flow by a flow switch. The flow switch also puts out a signal which can be used to read flow. This water manifold will provide the cooling water for the klystron/ modulator oil tank and it will also have a flow switch for minimum flow protection. A summary water interlock from the PLC will signal the main computer system of the failure.

Each Klystron is separately instrumented for window temperature and body delta temperature. The body delta temperature, which increases if beam interception increases, is fed to the PLC compared to a pre-determined level. Exceeding this level causes the PLC to turn off the Klystron beam. Window temperature, also read by the PLC as an analog signal will cause the RF drive to be removed if a maximum temperature is exceeded. The main computer can interrogate the PLC through a communication link and read the interlock status and window temperature.

The klystron Vacion pumps will be paralleled into two Vacion controllers for each klystron. The controllers will have an internal vacuum pressure limit interlock which will be manually set. An excessive vacuum pressure interlock will turn off the klystron beam through the PLC. A vacuum fault indication will be sent to the main computer system.

The Klystron heater circuit, separate for each klystron, is equipped with an interlock for minimum heater current and a warm-up time delay is provided by the PLC once the minimum current is exceeded. Klystron beam is inhibited until these interlocks are cleared. Analog signals for heater voltage and current are read by the PLC and transferred to the main computer system via the communication link.

Klystron peak cathode voltage and peak cathode current are digitized in the Klystron and Modulator Support Electronics and read into the PLC for Overcurrent and Overvoltage interlocking and into the main computer system for data taking and storage. The Klystron and Modulator Support Electronics includes the circuitry and connectors to attach a PC, running LabVIEW, for special data taking during diagnosis and analysis. This system can be easily configured to look at any of the analog and digital signals, for a station, on a very frequent time scale, record and visually present the data.

Klystron Heater and High Voltage operating hours will be totaled in the PLC.

The RF Output waveguide transport system, which is under vacuum, contains Vacion pump supplies with manually set high vacuum pressure interlocks. These feed into the modulator and klystron PLC to remove RF drive for an excess pressure condition.

The RF Output waveguide transport system also has various forward and reflected monitor points. An example of one of these monitor points is at the output of the klystron. These signals are each shipped through a four port coupler. One of these ports feeds a crystal detector into a Video Amplifier system which provides buffered video outputs, a peak and hold detected output and a comparitor circuit. The comparitor circuits with manual adjustment can be used to interlock any of these detected signals. The output of the interlock is sent to the PLC for action. Klystron reflected power is one of the critical interlocks which will also be hard wired from the Video Amplifier interlock to directly remove RF drive.

8. 6. 2. Modulator & Support Electronics Sensing & Protection

The modulator control, sequencing and protection is also accomplished through the PLC. The main protection interlocks are excessive End of Line Clipper (EOLC) current (for a klystron arc) and High Voltage Power Supply Overcurrent (HVOC). The modulator local interface is also through the Touch Screen Panel.

The modulator protection system contains discharge solenoids, barriers and door interlocks for protection of both personnel and equipment. It is connected into the overall accelerator Personal Protection System (PPS).

Thyratron warm-up time delay will be started in the PLC after the thyratron electrodes are energized. Thyratron heater hours will also be totaled in the PLC.

8. 6. 3. The Klystron / Modulator Logic Controller

At the present time, PLC's are being used for monitor and interlock functions in the Klystron Test Lab. On the NLCTA, two PLC's are used at each klystron station to provide modulator interlocking and control, and to monitor the operation of the klystron RF system and the various interlocks that protect the RF station. It is expected to use this same technology for the NLC RF station, but the general PLC will be replaced by a dedicated logic controller that is designed and optimized for NLC RF station operation.

8. 6. 4. The Klystron RF Driver (TWT or small Klystron)

There are various schemes for providing the approximately 1 kW of pulsed RF that is the drive source for each high power klystron. It is useful to have individual drivers as the various phase manipulations that go into the operation of the RF compressors are best done at milliwatt level. Power programming of the two klystrons on the single modulator is done by differential phase modulating the two klystron inputs which has the effect of steering the power summation either into a dummy load or the RF pulse compressor.

There exists extensive TWT technology at this frequency and power level as a product of military applications. The available TWT's are reliable, but fairly complex to manufacture and operate. They have already been pretty extensively cost optimized, and are still very expensive.

A small x-band klystron design of fairly narrow bandwidth and gain is not too difficult to design and build. In construction, it is relatively simple compared to a TWT. It is possible that after the initial engineering models are tested, a modest program of redesign for automatic manufacturing could reduce the unit cost to something approximating microwave oven power source scale. A little early R&D effort in this area would be useful.

8. 6. 5. Monitor & Control Electronic Interfaces

Almost all of the monitor and control for the RF station can be handled with a low data rate interface between the station logic controller and the central computer. There are a few signals that require fast response including some diagnostics, but with 4,000 RF stations in the NLC system, fast, broad band data retrieval will be very limited. More on this interface subject will be written as the system develops.

Klystron Development Overview, NLC ZDR

Esoteric Designs:	Gridded Klystrons, Hard Switch Tubes, Quasimodulators, High Voltage Switching and other ideas needing major development
NLC ZDR Modulator	ZDR (Zero Design Report) Modulator making use of existing and short term development technology.

Modulator Development in Future

The Players:

I. Component Manufacturers
   a. Energy Storage Devices - Capacitors, Lines
   b. Switches - Thyratrons, etc.
   c. Pulse Transformers
   d. Power Supplies
   e. General Electronics

II. Big Labs capable of supporting R&D programs
   a. SLAC
   b. KEK
   c. DESY
   d. CERN
   e. Other ?

III. Small Business (SBIR's) New good ideas, low cost development

IV. Main Line, High Volume Manufacturers
   (Not represented here)
   Examples Auto Industry General Motors, Ford, etc.
   High volume electronics, IBM, Apple, Packhard Bell, etc.
   Electric Power Industry, Westinghouse, GE,?

Modulator Development in Future

The Charge:

Get started on serious R&D on Components

Evaluate and settle on base modulator design

Get prototype(s) built - running - evaluate and optimize efficiency

Re-engineer for minimum cost, maximum reliability large volume construction

Watch for breakthroughs in klystron and modulator design concepts that could improve efficiency, reliability, and reduce cost.

RECENT PERFORMANCE OF KLYSTRON TESTING MODULATORS IN THE SLAC KLYSTRON TEST LAB*

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Abstract

The mix of klystrons being designed and operated in the SLAC Klystron Test Lab continues to expand and now includes large klystrons, CW and pulsed, from UHF to X-band. To support these developments, a number of new pulse modulators and power supplies were designed from scratch, or upgraded from existing laboratory test systems. This paper presents recent experimental performance of these modulators and describes a quasi-line power supply that could efficiently support a high-power gridded klystron with a special isolated collector.

400 MW Peak Power Modulator (DESY)

A 400 MW peak power modulator was designed and constructed to power and test a 150 MW S-Band klystron for DESY. The basic approach, first described at PAC '93, is a straightforward SLAC modulator except that four parallel lines and two thyratrons are used to obtain the low line impedance and high discharge current. The voltage is obtained by using a pulse transformer with a turns ratio of 23 to 1. A simplified schematic of the modulator is shown in Fig. 1.

Specific attention was paid to minimizing inductance in the primary current path. This stray or wiring inductance and the pulse transformer leakage inductance are the limiting factors in the output voltage rise time. Therefore the connection from the PFN to the pulse transformer was made using 6-inch parallel-plate copper bus and kept as short as practical by directly connecting the pulse tank to the PFN cabinet. Connections from the PFN to the thyratrons are copper tubing. The four ten-section PFNs are packaged in a single rack with half of the coils on one side and half on the other producing a compact, symmetrical assembly. The thyratrons are located on either side of the PFN and the output to the pulse transformer is between the thyratrons.

Earlier this year the modulator was brought into operation and used to test and process a beam diode to 550 kV, 700 amps, 3.5 µs, and 60 Hz PRF. Figure 2 shows the beam voltage and current waveshapes obtained with this diode load. The peak beam voltage in this waveshape is 532 kV, and the current is 673 amps peak. The rise time of the beam voltage pulse is 0.8 µs from 10% to 90%. This measured rise time compares with the simulated 0.7 µs rise time for the pulse transformer and a primary estimated lead inductance of 0.5 µH. Figure 2 also shows the primary rise time of the PFN-thyratron combination to be very fast, less than 80 ns. Even with this fast rise time and a primary discharge of over 15 kiloamps, the ringing is minimized because of the close coupling of the modulator elements and the minimum-inductance, minimum-stray capacitance design.

200 MW Peak Power Simple Modulator

Another modulator, which we like to call "conventional", was constructed in the Klystron Test Lab this last year to power an X-band klystron that drives a resonant ring. This compact design is capable

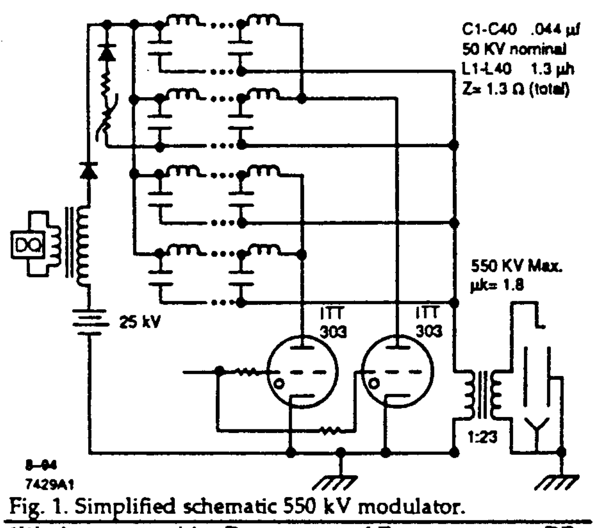


Fig. 1. Simplified schematic 550 kV modulator.

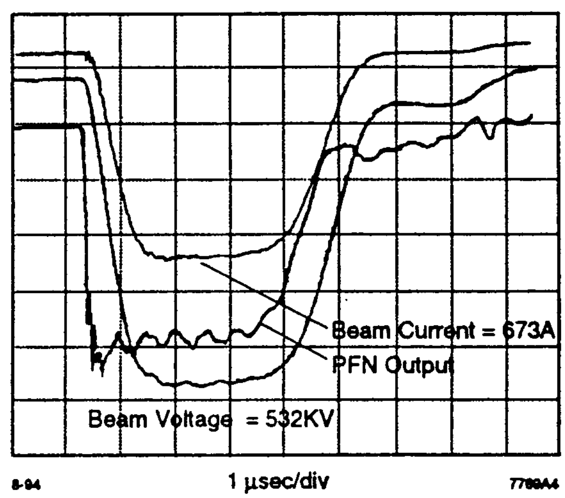


Fig. 2. 400 MW modulator voltage and current waveshapes.

*Work supported by Department of Energy contract DE-AC03-76SF00515.

Presented at the 1994 International Linac Conference
Tsukuba, Japan, August 21-26, 1994

of driving any klystron from 350 kV to 430 kV at a perveance from 1.2 to 1.9 μperv. The pulse width can be adjusted from 1 μs to 4 μs by selecting the number of PFN segments in the network. The pulse capacitors are 0.044 μfd, 50 kV each, and the tunable inductors are 2 μH each. A standard ITT 241 thyratron is used for the switch element or the corresponding EEV, or Litton thyratrons may also be used.

One and 3 MW CW Test Stands (B Factory)

CW low-frequency klystrons are being produced and tested in the Klystron Test Laboratory for use on the *B* Factory. At present, there is one 500 kW, 476 MHz klystron in place on the one megawatt test stand that is used for component testing. The power supply in this test stand operates at 67 kV, 15 amps. A second, higher voltage and power test stand is under construction that will deliver 97 kV, 30 amps to a new design 1.1 MW CW 476 MHz klystron. The power supply is designed to provide three intermediate stages of voltage that can be used to bias a depressed collector for energy recovery. The test stand is instrumented to operate a depressed collector klystron, although a depressed collector klystron is still in the preliminary design stage. The 3-MW test stand uses a programmable logic controller (PLC) for the interlock system. The test stand will be in operation in December 1994.

Quasi-line Power Supply for Gridded Klystron with Isolated Collector

Because of the very large rf power demand of all proposed NLC systems, it is most important to maximize the efficiency of rf delivery systems. Energy is dissipated when large amounts of charge are moved into and out of the system stray capacities. In addition, the klystron electron beam dissipates energy during the rise and fall times of the beam pulse when no rf energy is produced. As klystron voltages go higher, and pulse widths grow shorter, there is pressure to build faster and faster rise- and fall-time pulse modulators to minimize these losses. The fast rise and fall times, however, do not change the energy lost in charging stray capacity, or left over in stray inductance. This energy is lost independent of the pulsed power rise and fall times.

It has been recognized for some time that the cathode of a klystron need not be moved in voltage if there were some other way to control the current emitted from the cathode. Some klystrons at low power have been built using either full or partial voltage-swing modulating anodes. These designs limit the amount of stray capacity that must be moved to produce pulses, but the voltage swing necessary to switch on current is high, and the cathode voltage must come from a DC supply that contains much stored energy. The gun area of the klystron must be designed to withstand this DC voltage without arcing, and arc protection in the form of a high power crowbar must be incorporated in the design to discharge the high stored energy of the DC supply. Until now, conventional wisdom has dictated that high power, short pulse klystrons be built with diode guns driven by pulse modulators, usually line type with step-up pulse transformers.

It is time to revisit the idea of high-voltage gridded guns for klystrons. New cathode technology that allows emission at a lower temperature makes possible the use of a conventional intercepting grid in front of a klystron cathode that can have a transconductance approaching 50,000 μmhos. This will allow the klystron beam to be switched by a fast grid pulser of only about 5,000 volts. Such pulsers are available in solid-state components with rise times of less than 5 ns. The beam optics of such a klystron gun is difficult, but not impossible. A serious problem, however, is the DC voltage holdoff, and the minimum stored energy required in the DC supply to deliver the klystron beam current without excessive cathode voltage droop.

To make a high-voltage, fast-grid pulsed klystron feasible, a limited energy storage, high voltage pulse line can be used with a specially designed klystron incorporating an isolated collector. Figure 3 shows a block diagram of a unique quasi-line power supply-klystron system that is almost circuit loss free. For this example, a klystron of low perveance (0.6 μperv), high voltage (500 kV) is switched with a 5 ns rise- and fall-time grid drive pulse (1.5 μs pulse duration). The klystron cathode is connected to one terminal of a high-voltage lumped element PFN, which in this example has a characteristic impedance of 500 ohms. The unique part of this design is that the other end of the PFN is connected to the isolated collector of the klystron. Note that this configuration allows the klystron cathode to be held at a fixed 500 kV potential by a low current sustaining power supply which can also be used to maintain intermediate voltages on the multi-element DC klystron gun. In operation, this sustainer supply delivers only the klystron cathode current that is lost to the klystron body.

The uniqueness of this design is the voltage swing on the klystron collector. Assume that the PFN has been resonantly charged to 600 kV from an unregulated, multiphase 500 kV power supply with no capacitor energy storage. There is 500 kV across the cathode-body gap, and this voltage is held fixed by the sustainer power supply. With no beam in the klystron, the voltage that is present across the

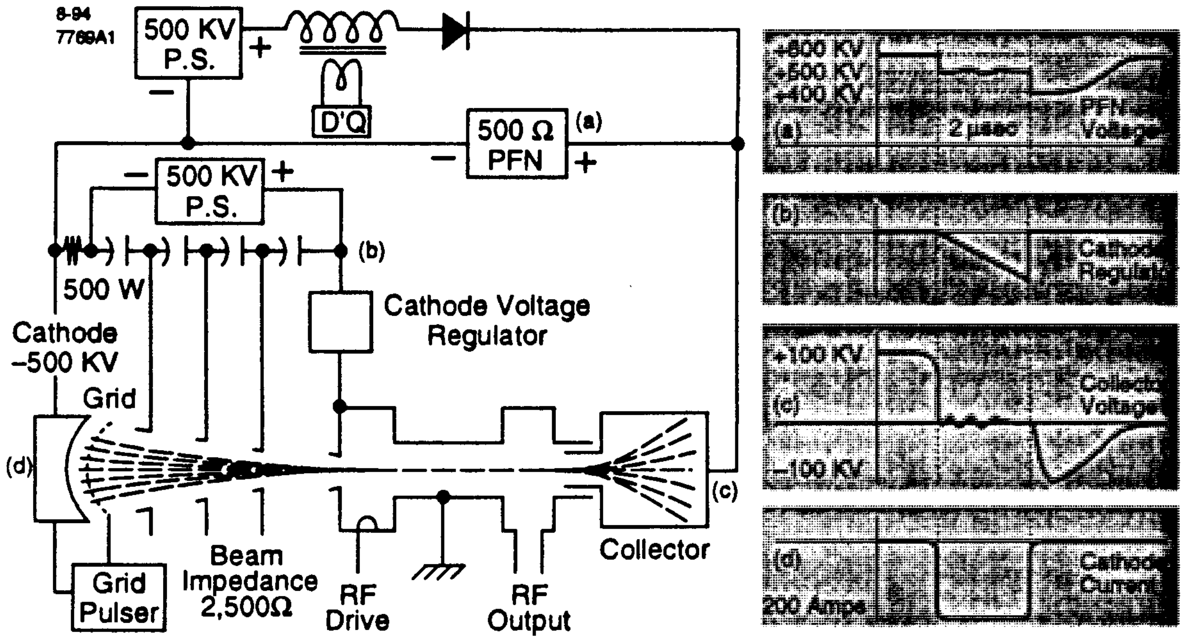


Fig. 3. Quasi-line klystron and power supply system.

klystron collector-body gap is +100 kV. The grid pulser now turns on the klystron cathode to 200 amps. The PFN sees a real beam load of 2,500 ohms between the klystron cathode and collector. This 2,500 beam load on the PFN reduces the PFN voltage to 500 kV where it stays for one discharge period of the PFN. The voltage on the klystron collector goes to zero with respect to the klystron body. At the end of one discharge period of the PFN, the grid drive is turned off, the beam current stops, and the voltage on the PFN drops to 400 kV. This applies a -100 kV voltage to the klystron collector. The resonant recharge returns the PFN to 600 kV over the interpulse recharge period, and the klystron is ready to pulse again.

This system design allows a DC-grid pulsed gun to be mated to a mismatched high-voltage PFN of limited energy storage without the gun having to withstand the overvoltage of a charged PFN. The over and under voltage swing has been transferred to the collector of the klystron. During the actual klystron beam pulse, the voltage on the collector is zero, or close to zero. The "close to zero" statement is important as the PFN network ripple and capacitive charge and discharge voltage appear here during the klystron beam pulse rather than on the klystron cathode. Within limits, these voltage variations at the collector do not affect the beam efficiency of the klystron. The resonant charging of the PFN is self regulating during normal operation, but on initial startup some dQing of the charging choke is necessary to limit the initial inrush current from overvoltaging the network.

The block diagram shows a capacitor stack, and an active makeup voltage regulator in the sustainer power supply circuit. Since the klystron body current can be as much as 1% (2 amps) during the beam pulse, the capacitor stack is necessary to deliver this current. Low value capacitors are used in this capacitor stack to minimize energy storage, and an active regulator is used in the bottom of the stack to maintain and regulate the cathode voltage during the klystron beam pulse. Intermediate gun electrodes are also fed from this stack, and the high impedance nature of the sustainer stack provides a measure of arc protection for the gun. An arc between any two electrodes causes the voltage between these electrodes to collapse with the lost voltage being distributed among the other gaps. The arc extinguishes, and no energy from the main PFN is dissipated in the arc.

This scheme of klystron power system development requires primary R&D work in several areas. A few are listed below.

1. Low temperature klystron cathodes mated with high transconductance grid structures.

2. High voltage, compact, low lead inductance PFN's operating in a common oil tank.

3. High vacuum, low perveance, high voltage multielement electron guns with good beam optics.

4. Medium voltage holdoff isolated collectors with low impedance rf choke joints.

5. Periodic, permanent magnet focused klystrons.

With much R&D and component development, this type of high power rf delivery system has the possibility of realizing the high efficiency needed for a future NLC accelerator.

Blumlein PFN's

for

100MW class X-Band Klystrons

95-10-08 H. Mizuno

500 ~ 800 ns Pulse Width.

600kV Output

1.2 μP Klystrons.

Use only Currently available Parts

(SW. Tube, Capacitor etc)

*. X-Band Linac
但し "VLEPP" は 14GHz

表一1） 主リニアックパラメータ

Table 2.3.1

General RF Design Parameters for Main Linac

	TESLA	SBLC	JLC*	NLC*	TBNLC	VLEPP*	CLIC
RF frequency (GHz)	1.3	3.0	11.4	11.4	11.4	14	30
Accelerating Gradient							
Unloaded/Loaded (MV/m)	25/25	21/17	73/53	50/37	100/74	100/91	80/78
Active Linac Length[1] (km)	20	30.2	9.5	14.2	7.1	5.8	6.3
Total Linac Length[2] (km)	29	33	10.3	15.6	7.8	7.0	9.4
Peak Power per Meter (MW/m)	0.206	12.2	100	50	200	120	144
Structures per Power Unit	32	2	4	4	1	4	2
Structure length per PU (m)	33.2	12	5.2	7.2	1.8	4.0	0.56
Total Number of Power Units[3]	604	2517	1804	1970	3938	1400	11233
Total Number of Klystrons	604	2517	3608	3940	—	1400	—
Total Number of Modulators[4]	604	2517	3608	1970	26	140	2
Repetition Rate (Hz)	10	50	150	180	120	300	2530/1210
RF Pulse Length at Str. (μs)	1315	2.8	0.23	0.240	0.242[5]	0.11	.0116
Peak Beam Current[6] (A)	.0083	0.30	0.80	0.74	1.49	SB	SB/1.94
Total Ave. RF Pwr. at Str. (MW)	54	51.6	32.4	30.5	41	22	26.5

1) Active length = [(500 GeV − 2 × injection energy)/(loaded gradient)] × [factor for BNS damping and energy management].

2) Total linac length = Active length plus allowance for beam line components, including cryostat.

3) Number of power units = number of klystrons for TESLA, SBLC and VLEPP, = number of pulse compression units for JLC and NLC, = number of transf structures for TBNLC and CLIC. For VLEPP there are two pulse compressors per power unit.

4) Number of drive beams for TBNLC and CLIC and number of high voltage sources (supermodules) for VLEPP.

5) Equivalent length for a rectangular pulse.

6) SB = single bunch acceleration.

表一2）高周波システム仕様

Table 2.3.2

RF System Efficiencies and AC Power Requirement: Design Goals

	TESLA	SBLC	JLC	NLC	TBNLC	VLEPP	CLIC
Klystron Electronic Efficiency [1](%)	70	50	45	60	92	60	75
Klystron Auxiliary Power[2] (MW)	2.4	2.5	7	1	—	1.4	—
Pulse Compression Efficiency (%)	—	—	98	77	—	74	—
Power Transmission Efficiency (%)	96	97	95	94	98	95	90
Modulator Efficiency[3] (%)	86	80	82	72	44	95	55
Modulator Auxiliary Power [4] (MW)	—	3.5	5	3	3	0.4	1
Cryogenic Power (MW)	58	—	—	—	—	—	24
Total Aux. plus Cryo. Power (MW)	62	6	12	4	3	2	25
RF System Efficiency Excluding Auxiliary & Cryogenic Power (%)	58	38	34	31	40	40	35
AC Power Excluding Auxiliary and Cryogenic Power (MW)	94[5]	133	102	98	103	55	75
Total AC Power (MW)	154[5]	139	114	102	106	57	100
Net Efficiency for Production of RF Power[6] (%)	35	37	30	30	39	39	26
Efficiency for Conversion of RF Power to Beam Power (%)	21	10.4	5.6	7.4	16.7	8.3	1.6/8.0

1) For TBNLC/CLIC: efficiency for conversion of drive beam power to rf.

2) Cathode heater plus solenoid power.

3) Drive beam production efficiency for TBNLC/CLIC.

4) Thyratron cathode and reservoir heater power (drive beam focusing for CLIC).

5) Does not include regulation reserve.

6) Including cryogenic power for TESLA and CLIC.

表一3）クライストロン駆動電源仕様

Table 2.3.4

Modulator Parameters: Design Goals and Achieved to Date

	TESLA		SBLC		JLC		NLC		VLEPP	
Modulator Type[1]	Storage cap. with bouncer		PFN		Blumlein PFN		Blumlein PFL		Gridded Gun	
	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d	Design	Ach.'d[5]	Design	Ach.'d
Flat Top Pulse Length, $T_k(\mu s)$	1314	2010	2.8	3.0	0.5	0.7	1.2	1.5	0.50	0.50
PFN Voltage (kV)	9	10	65	43	120	80	[illegible]	[illegible]	1000	960
Transformer Ratio n	1:13	1:13	1:18	1:23	1:5	1:7	1:7	1:20	—	—
Rise/Fall Energy Efficiency (%)			86.5	≈ 65	89	70	80	≈ 60		
Scaled Energy Efficiency[2] (%)	99	—	70	65	79	70	81	58	—	—
I^2R/Thy./Core Loss Efficiency (%)			97	95	97		97			
Energy Stored on PFN[3] (J)			1000	1650	174		258			
Power Supply Fficiency (%)			95	90	95		93	≈ 90		
Mod. Eff. without Aux. Power (%)			79.5	≈ 60	82		72	≈ 52	95	
Auxiliary Power[4] (kW)			1.5	3	1.5		1.5	1.5	0.3	
Net Modulator Efficiency (%)	86	86	77.5	59	80		70		92.5	5
Ave. AC Input Power (kW) (Including Auxiliary Power)	155		54.2	88	29		51.5		40.5	

1) PFN = lumped element pulse forming network; PFL = pulse forming line (transmission line).

2) See text.

3) Energy switched per pulse from storage element for TESLA and VLEPP.

4) Includes thyratron cathode heater, reservoir heater and other control power.

5) Standard (not Blumlein) PFN.

Modulator は使用しない

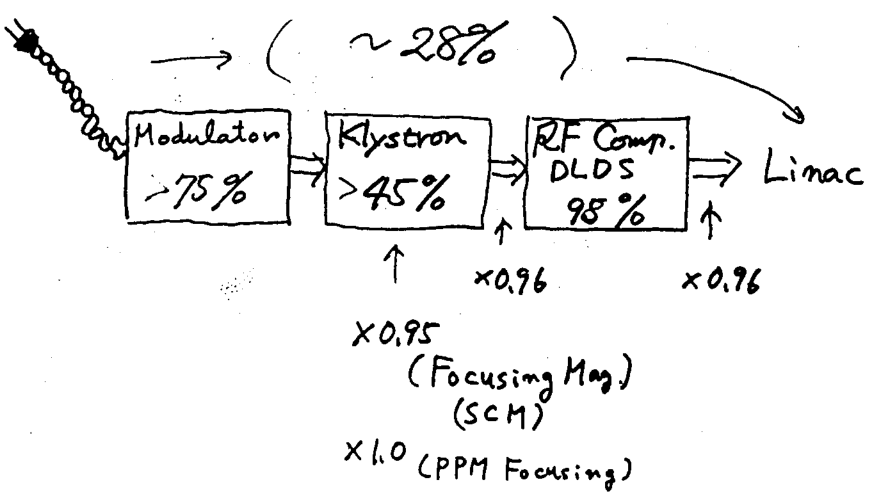
× JLC : ×2 Blumlein

× NLC : ×3 Blumlein

The prototype RF power source for JLC(Ec=1Tev)

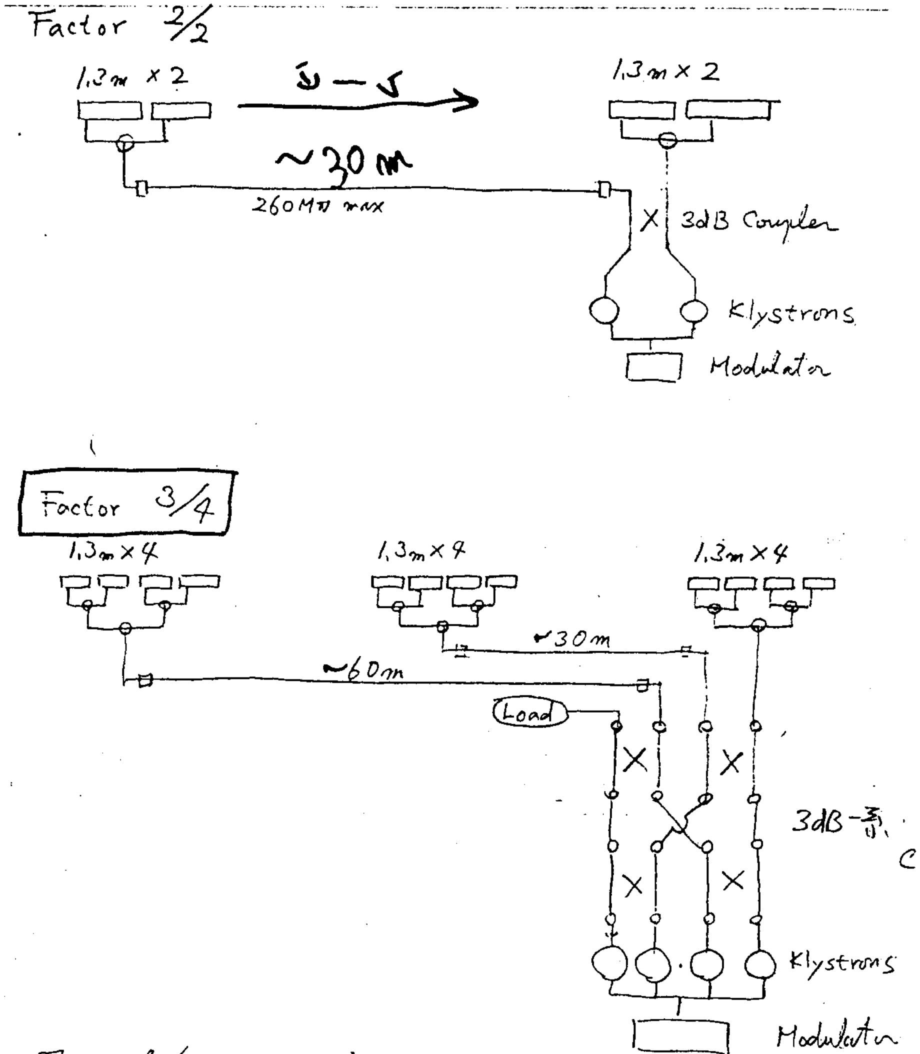
	Designe	Achieved (95/Sumer)
(1)Klystron(XB72k)		
RF out	130MW	97MW (400ns)
Pulse width	500ns	
Efficiency	42%	36% (27%)
Focusing	Super cond.Mag.	(unit test OK)
(2)x2 or x3 RF pulse compression system		
RF input	500ns 130MW	(Design stage)
RF out	240n 250MW	
Efficiency	>96%	
(3)Blumlein modulator		
Output pulse	600kV 500ns(flattop)	~~500kV~~ 430kV 700ns
Effiency	75%	
Pulse trans.	1:5	1:7
Rise &Fall time	150ns 200ns	250ns(rise)
	(PFN in an oil tank)*	(PFN in air)

*This oil tank version will be tested 1994-Dec.



Energy Efficiency of JLC RF system

DLDS-系 (RF Pulse Compression) ③



Factor 4/4 以上の場合
非実用的

2^n [2^n ↑ 0]

DLDS

	Factor	Factor
	2/2	3/4
Unit Length/klystron	2.6 m (1.3×2)	3.9 m (1.3×3)
No. of Acc. Str/Klystron	2	3
Length of D.L/Klystron	15 m (7.5 m/1 unit) (30 m)	22.5 m (7.5 m/unit) (90 m)
No. of TE_{01} モード Convertor/klystron	1 (0.5/1 unit) (2)	1 (0.33/unit) (4)
No. of 3dB coupler/Klystron	1/2 (0.25/1 unit) (1+2)	1 (0.33/unit) (4+9)
続く.		

Modulator (1:5 step up Blumlein Type) 550 kV

Impedance (Secondary)	520 Ω	260 Ω
(Primary)	21 :	10.4 :
(PFN)	11.5 :	5.2 :
DC H.V 55 kV	55 kV	同左
Charging Voltage	110 kV	110 kV
PFN Vout	550 kV	550 kV
I total	1,050 A	2100 A
Pulse Width	550 ms (250×2+50)	800 ms (250×3+50)
Pulse Energy	3.18×10^2 Joule	9.24×10^2 joule

④

Blumlein #1. (with USA Capacitors)

① PFN Spec's

Impedance	23 ohms	
Charging V.	80 kV	
Pulse Width (total)	700 ms	
N. of Stages	9 stages	(12 for Japanese Capacitors
L (/stage)	460 mH	
C (:)	3.5 mF	

② Pulse Transformer

Step Up Ratio	1:7
Leakage L	830 mH
Stray C	4 mF
Loss (Hys. 200 pps)	100 W
〃 (Eddy I. 200 pps)	1 kW
Rise Time	~100 ms
Fall Time	~200 ms
Sagging (500 ms)	2.8%
Core (Si Fe)	25 μm

Blumlein #2 (in the Oil Tank)

① PFN' Spec's

Same as #1 PFN

but

<u>16 stages of LC Network.</u>

② Pulse Transformer

Almost Same as #1 PFN case,

but.

2nd. Winding is 2-layers

C↓ L↑

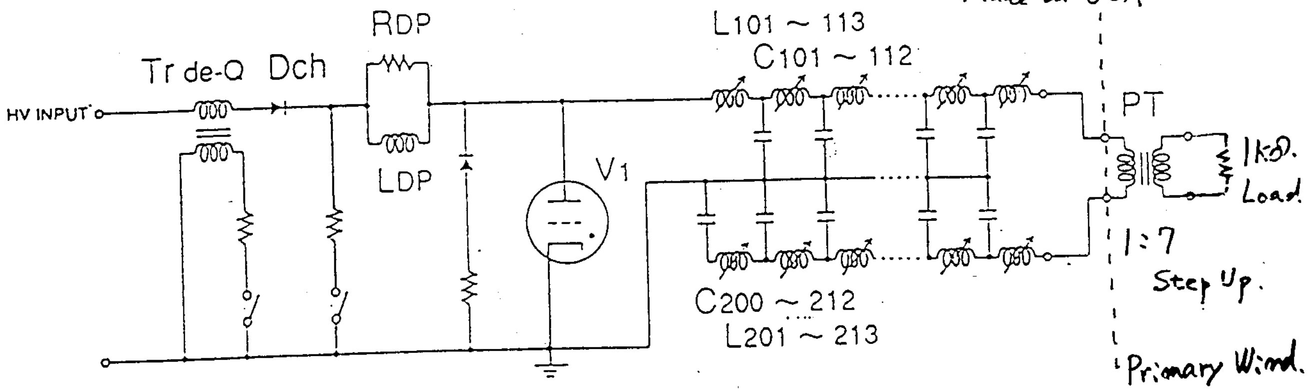
(4)

2 · Types of PFN were Tested (1993-Oct)

① 12 Stages of "Nichi-Con" Capasitors Made in Japan

OK? ② 9 Stages of "Maxwell" Capacitors Made in USA

Fig-1) Blumlein PFN

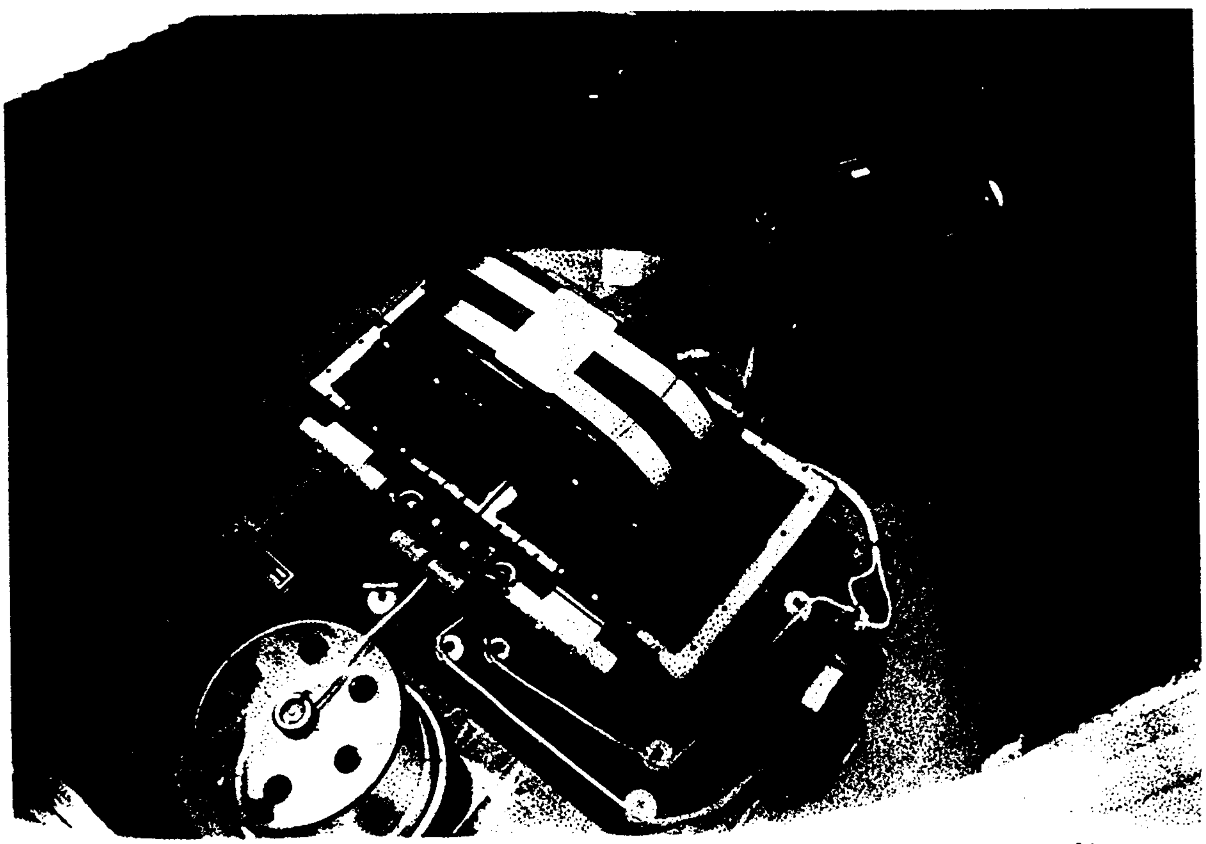


L101-103=340nH. C101-112=2.9nF
L201-213=340nH. C201-212=2.9nF

V1 Thyratron(CX1937A; EEV)

3

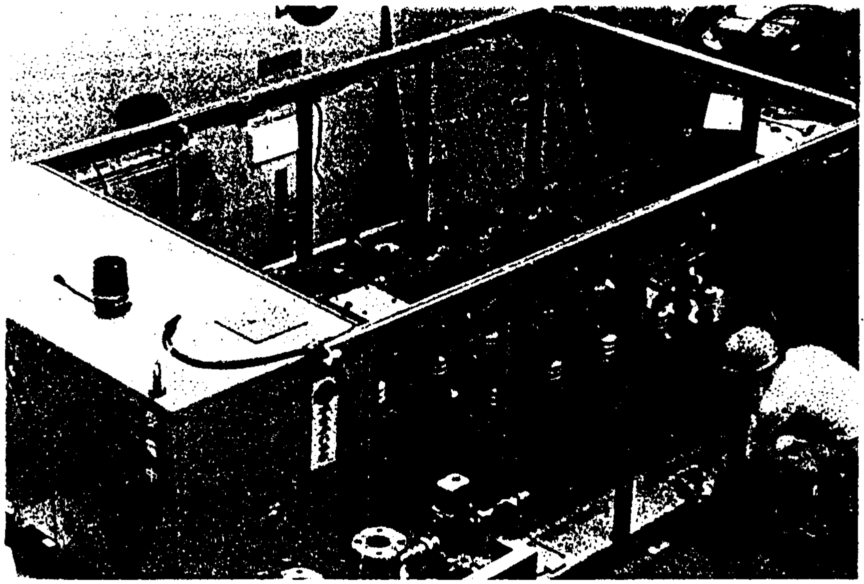
1994-March. H. Mizu...

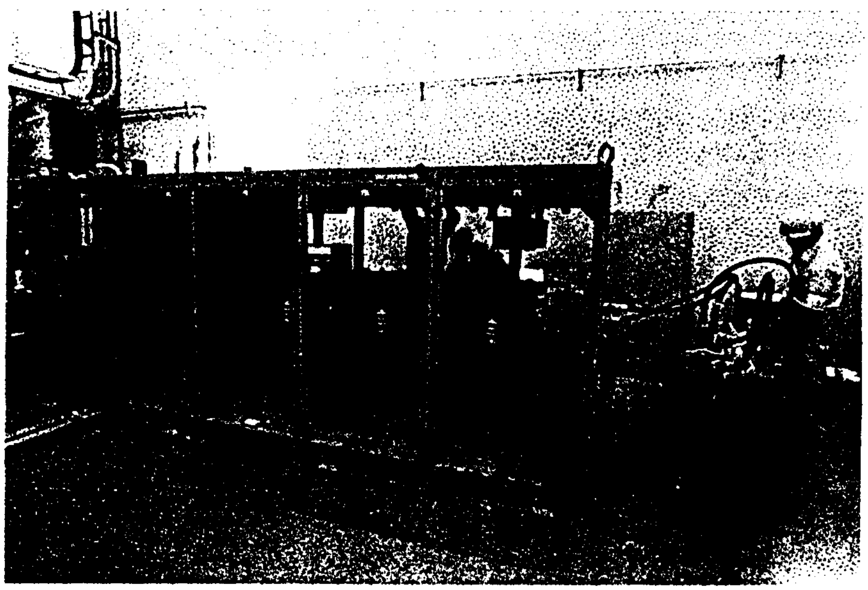


1993-Sept

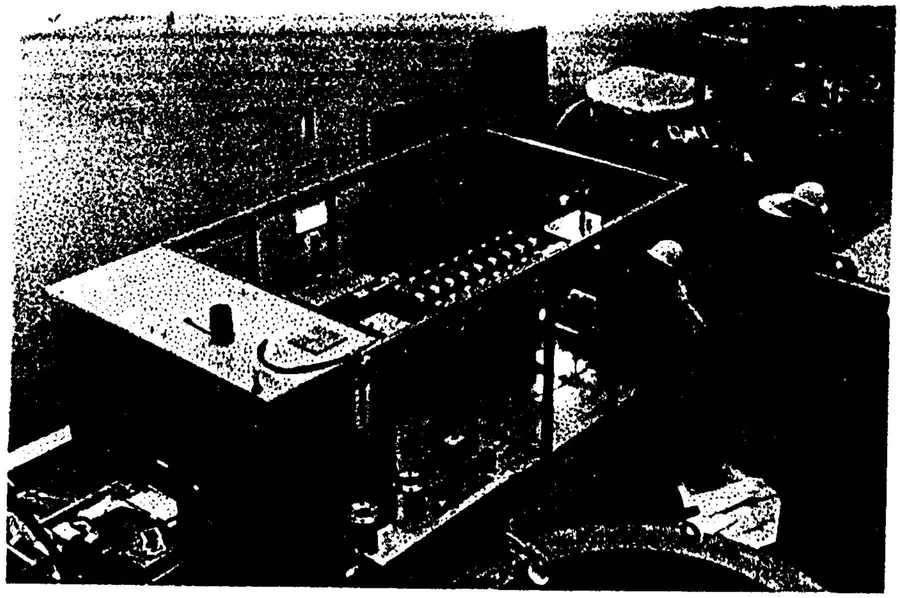
Blumlein [illegible] Pulse [illegible]

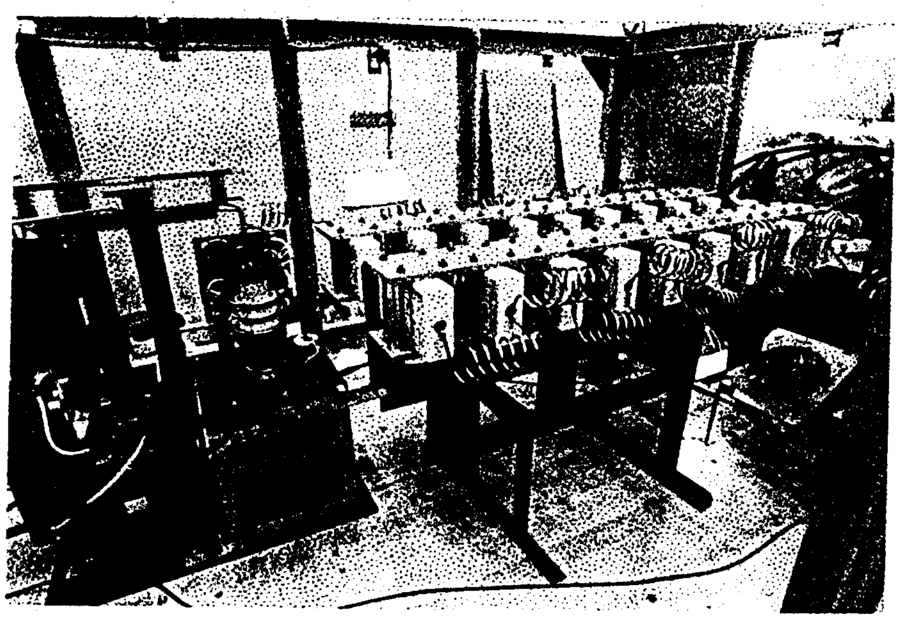
⑥





93-Oct. Blumlein PFN "Nichi-Con"
12-Stages.
25Ω-Load

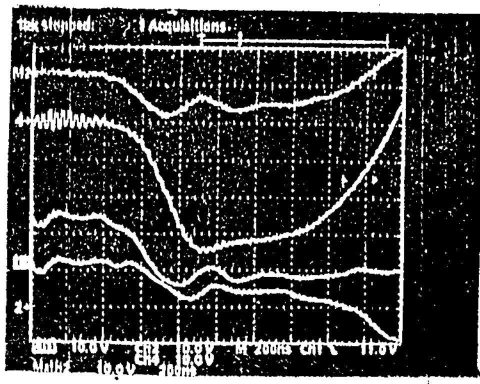




(5)

(a) $I_{P\text{-}BIAS}$ = 15A

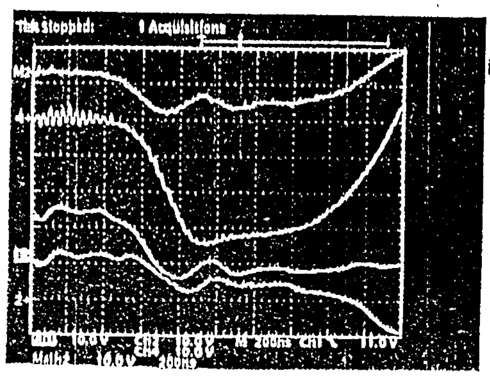
Bias Current = 15A



Blumlein #1 HV テスト結果

(b) $I_{P\text{-}BIAS}$ = 20A

= 20A



限界、
① 寸法効果
配慮した
分布 L, C
等

1993-Nov.

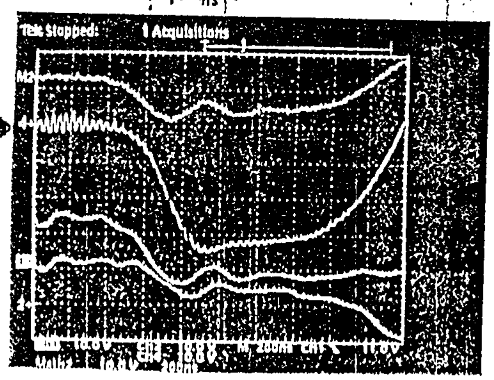
(c) $I_{P\text{-}BIAS}$ = 25A

→| 400ns |←

V_c ~ 450kV →

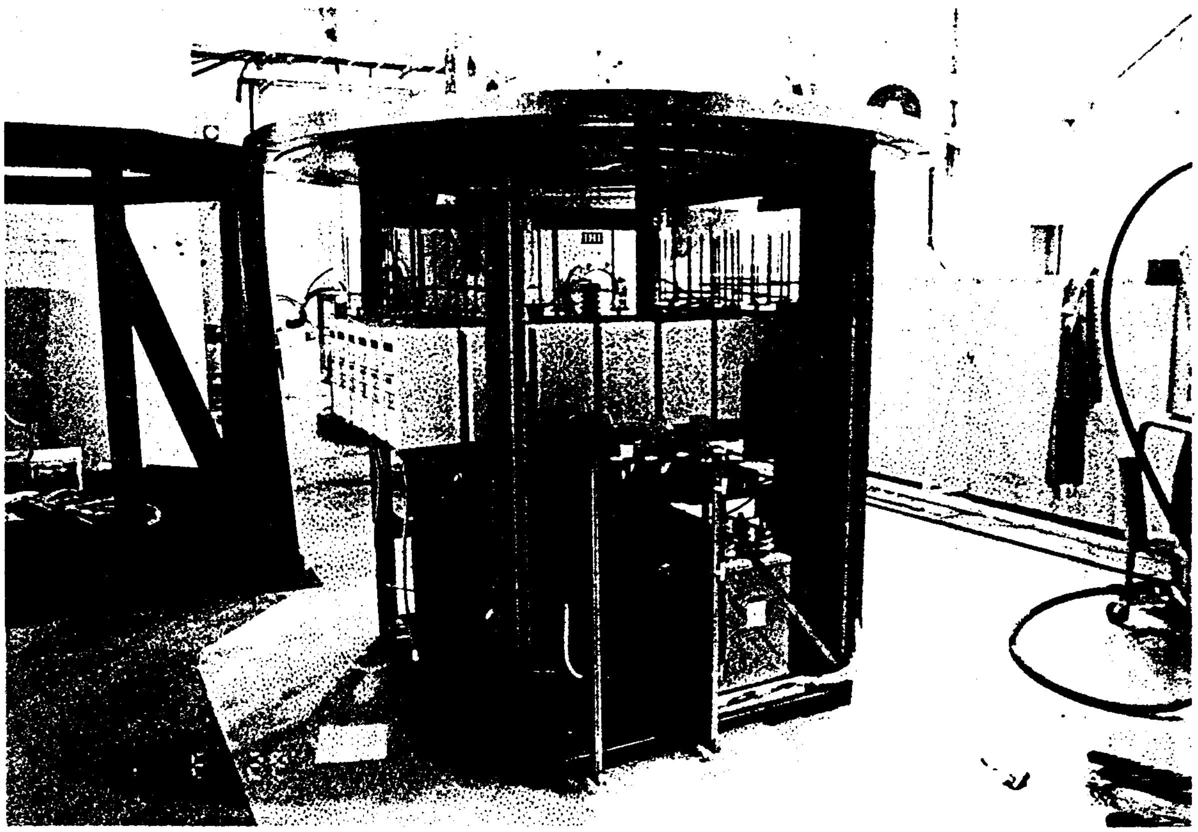
= 25A

T_{rise} ≒ 250ns

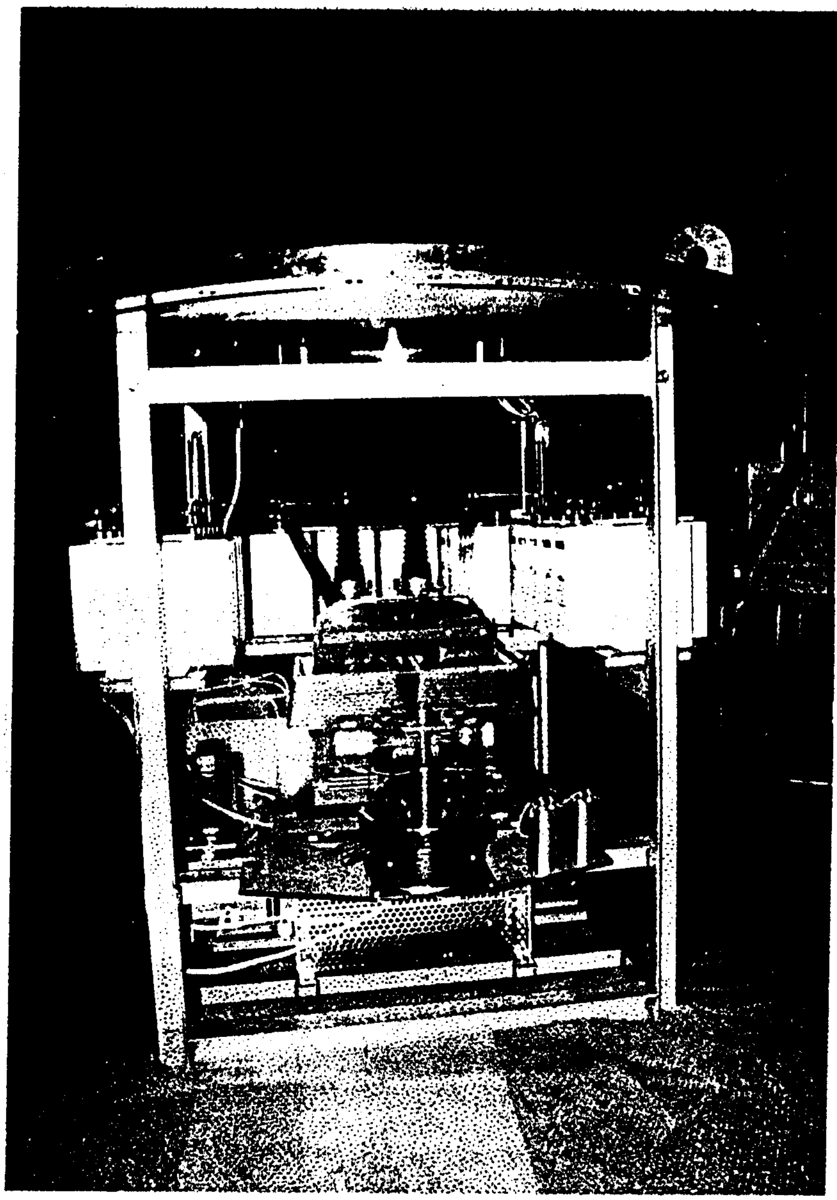


今回のほぼ Best
但し Injector
若干すれ…
出力電圧に
若干問題あり
Impedance

Blumlein #2 (油タンク型)(IHI) 94年製. Low Voltage テスト完



(8)



1.6m

1.6m

Blumlein #2 (IHI.) ~~1994. Sept~~ 1995. March

Blumlein Type PFN Tests in KEK.

(for XB72K (600kv 1.2μF))

H. Mizuno

H.V Test Results.

① Blumlein #1 (air)

× i) 12-Stages of "Japanese Capacitors" PFN
"L" was too Large.

○ ii) 9-Stages of "USA" Capacitor PFN

$\tau_{rise} \doteqdot 250$ns 400 kV output

1:7 Trans. with ~~2~~ 1000Ω Resistor Load

② Blumlein #2 (Oil Tank)

16-Stages of "USA" Capacitor PFN's

Low Voltage Tests were finished

(TR. SW) and 1000Ω Resistor load

Air Environment (no-Oil)

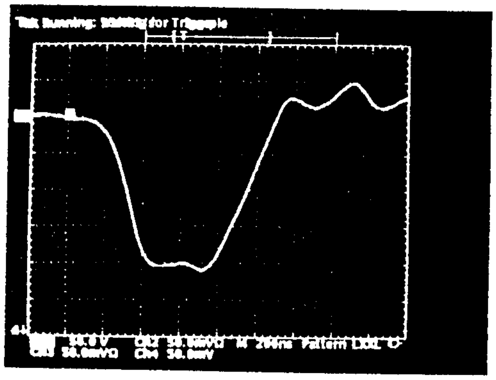
$\tau_{rise} \doteqdot 200$ns ~100V output

H.V Test is currently scheduled within 6-months.

(9)

Low Voltage Test 95-03-23

(Transistor B SW. 1?)

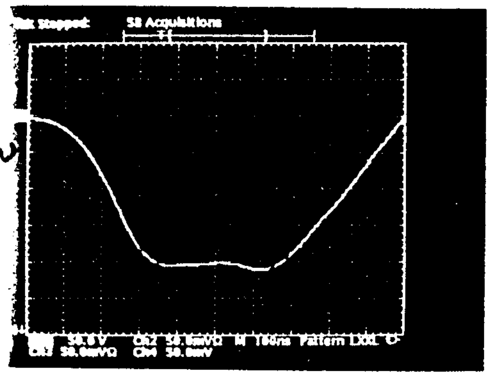


Before change

RL = 1074Ω

tr = 200ns

100ms/div



RL = 1kΩ

After change

RL = 1074Ω

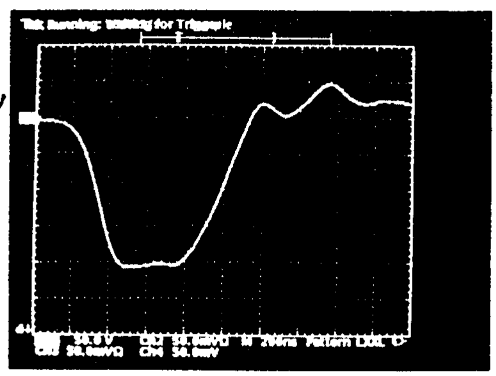
flat top is better

tr = 200ns

T(rise) = 200ms

400ms Flat To.

200ms/DIV



(10)

What is to be Done?

① H.V Tests of Blumlein #2 (Oil tank)
with XB72k Klystron. (Next 6 months)

② Blumlein #2 Development.

- 120 kV Charging
- 1:5 Transformer.

(preparing some parts) (Schedule ?)

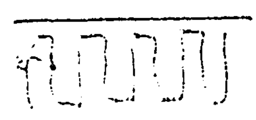
③ Designe Study of "2 or 4 Klystrons
Parallele Drive"

- 800ns Pulse
- Faster Rise Time
- Cost

etc.

④ Designe Study of "Stripline PFN"

- Ohmic Loss ? ~4% 800ns ⟷ Faster Tr. (trade off)
- How to adjust ?

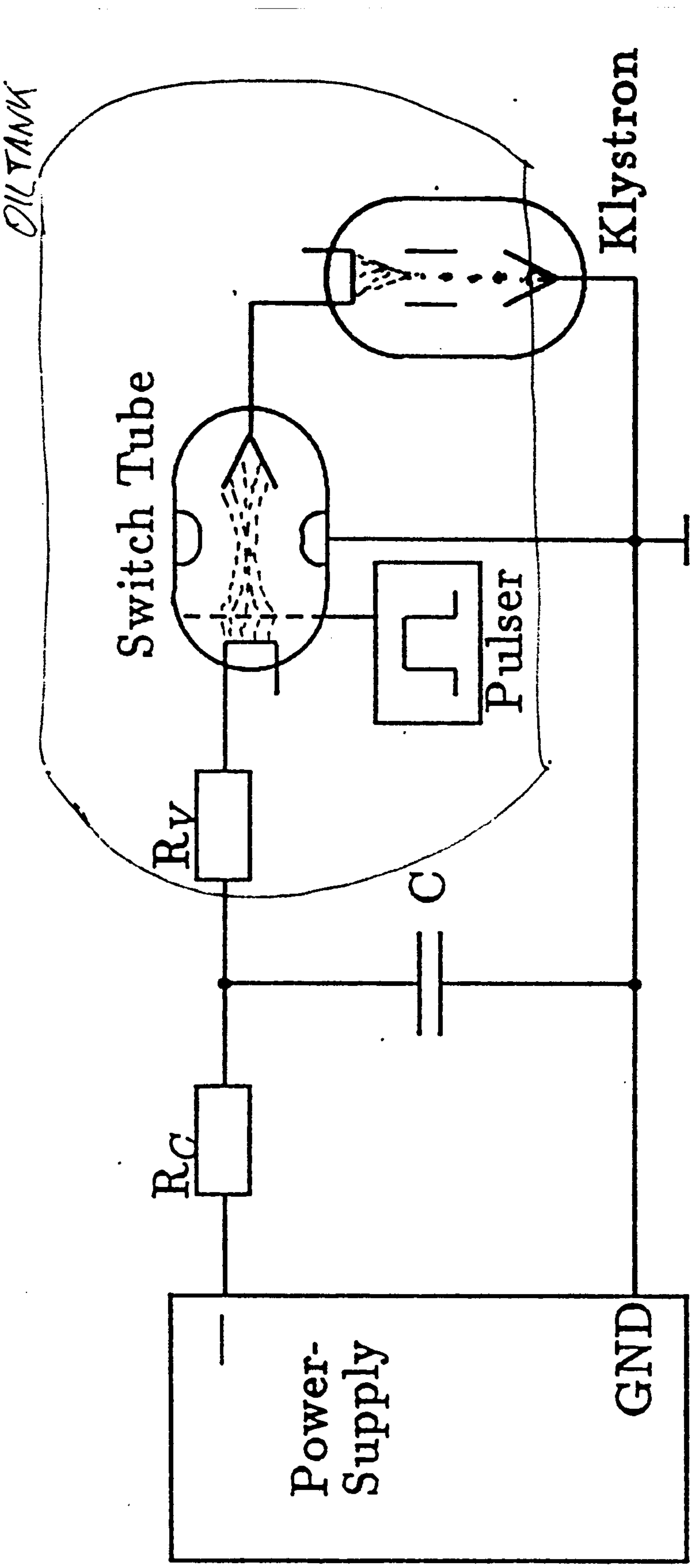


DESY HARD TUBE MODULATOR TEST

S. CHOROBA

Comparisons of SLAC Tubes

Item	5045	150MW (1985)	DESY
Frequency (MHz)	2856	2856	3000
Beam Voltage (kV)	350	475	535
Beam Current (A)	393	622	700
Perveance (u)	1.9 nom.	1.9	1.8
Max. Gun Gradient (kV)	201	208	150
Peak RF Power (MW)	65	150	>150
Pulsewidth (us)	3.5	1	3
Rep Rate (Hz)	180	40	50
Average RF Power (kW)	43	6	27
Single Pulse RF Energy (J)	210	150	>450
Tunnel Diameter (in.)	1.25	1.476	1.25
Efficiency (%)	>40	50	>40
Gain (dB)	50 nom.	59	>55
Magnetic Field (Gauss)	1400	1800	2100



OILTANK
Klystron
Switch Tube
Pulser
R_V
C
R_C
Power-
Supply
—
GND

DESIGN PARAMETERS FOR 25MW HTP TEST SETUP

KLYSTRON: THOMSON DOD 2002

OUTPUT POWER	:	25 MW
FREQUENCY	:	3 GHz

BEAM VOLTAGE : 250 kV
BEAM CURRENT : 250 A
PULSE DURATION : 3 μs
PULSE REP. RATE : 50 Hz

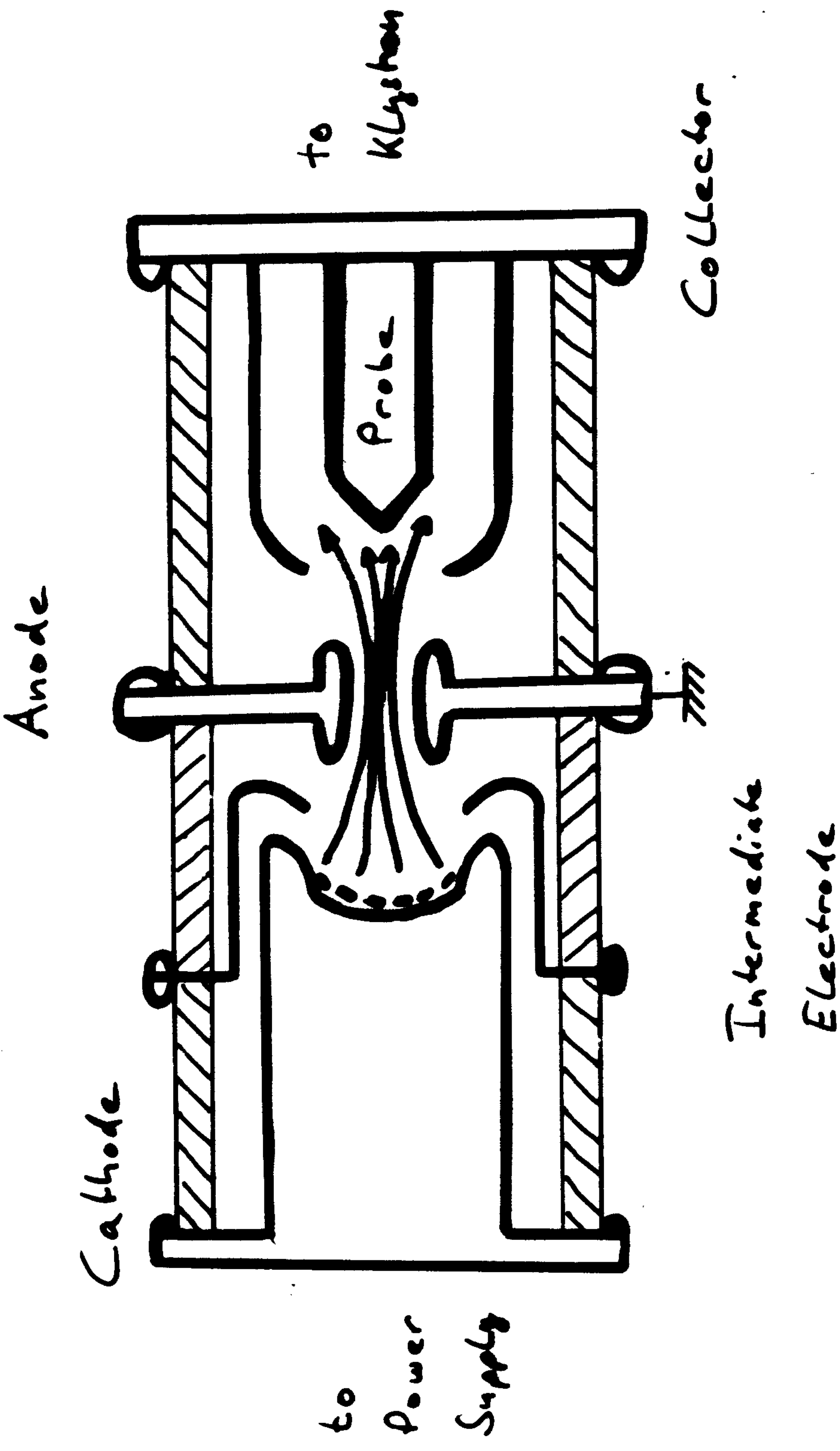
PS OUTPUT VOLTAGE : 300 kV
AVERAGE CURRENT : 50 mA
CHARGING RESISTOR : 240 kΩ (120 kΩ)
STORAGE CAPACITANCE : 50 nF (100 nF or 150 nF)
CURRENT LIMITING RES : 30 Ω
STORED ENERGY : 2.25 kJ (4.5 kJ or 6.75 kJ)

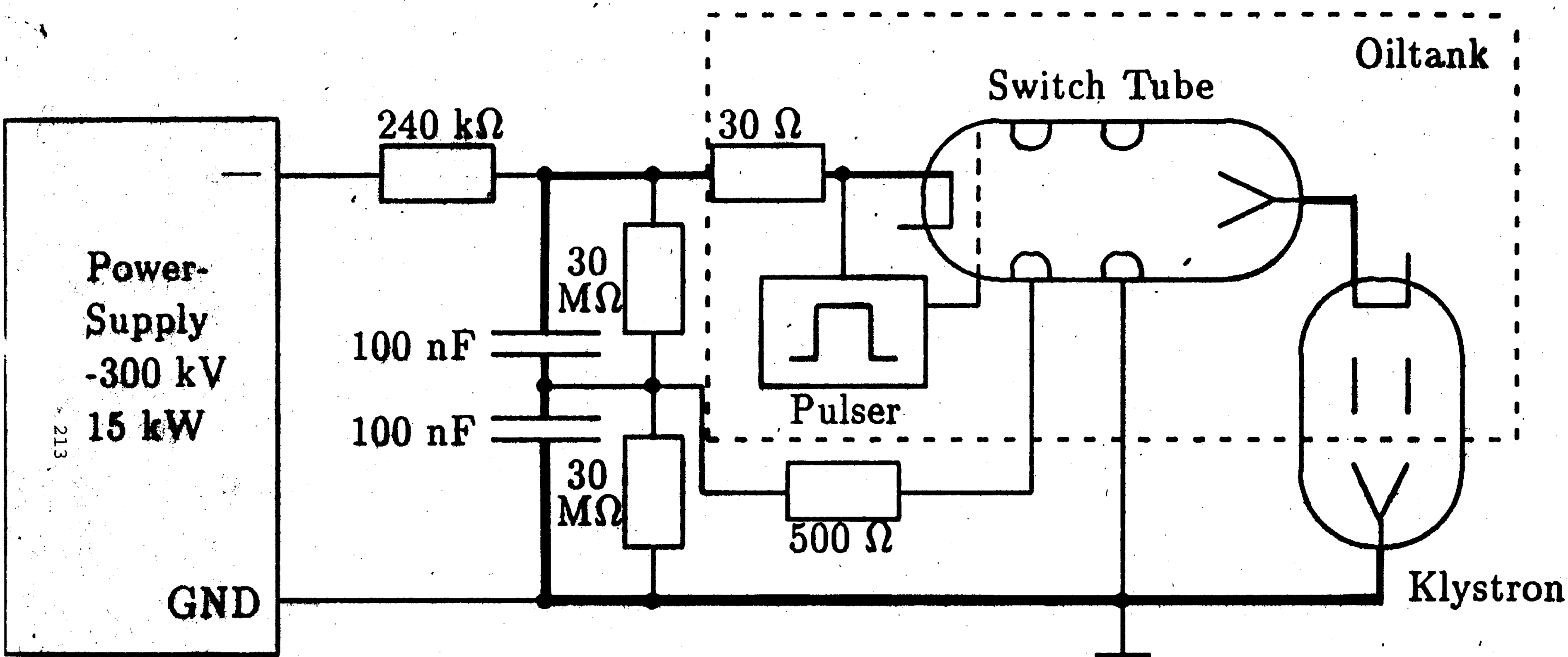
GRID PULSER

OUTPUT VOLTAGE : 10 kV
BIAS VOLTAGE : −2 kV
PULSE WIDTH : 3 μs ADJUSTABLE

Switch Tube

Varian VKW-8273

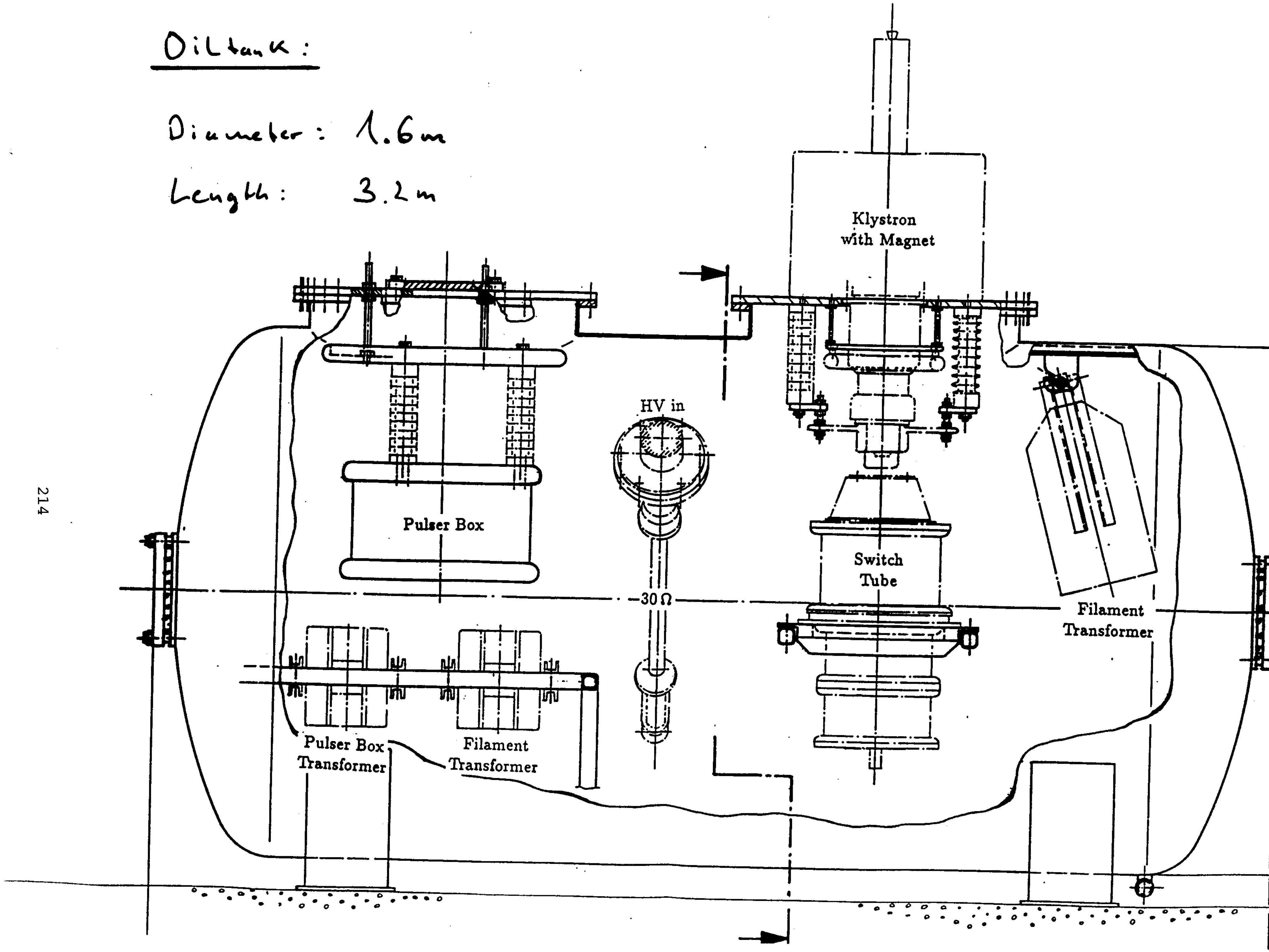


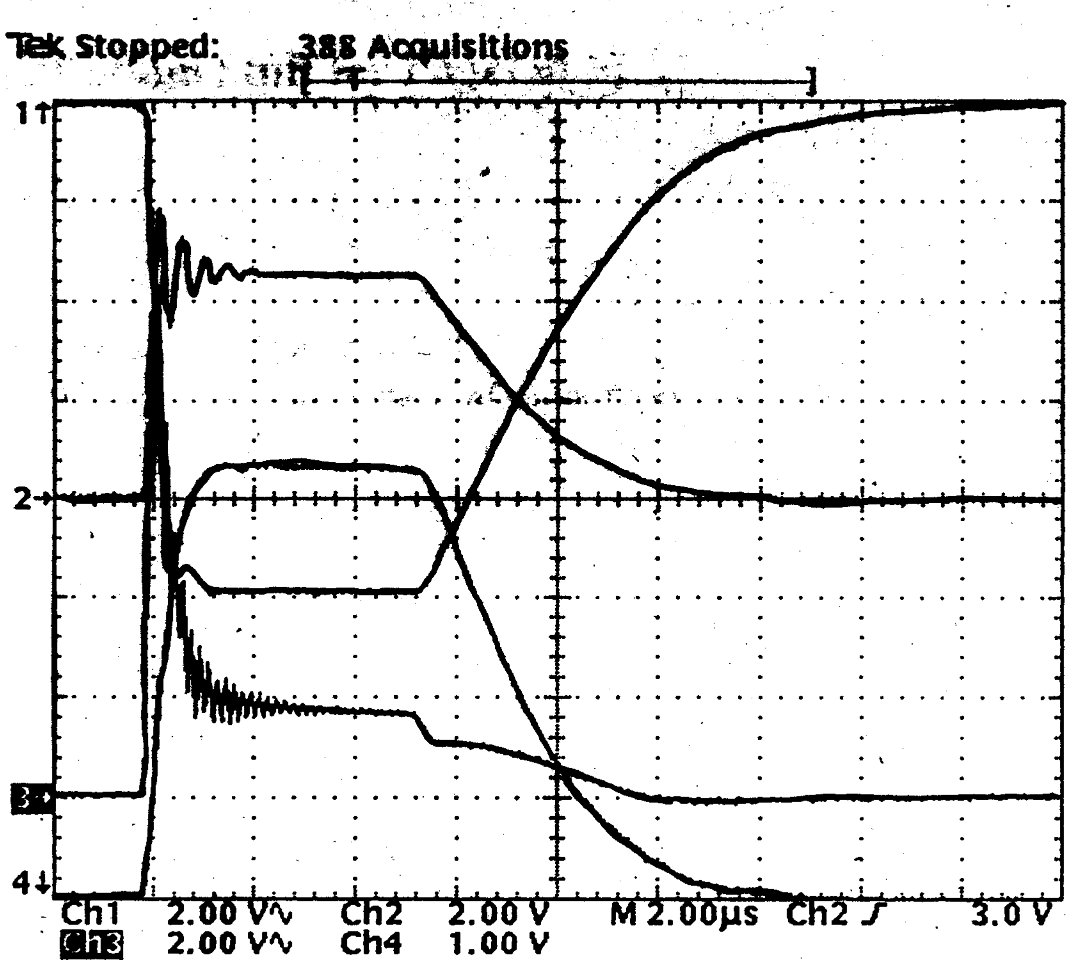

Oiltank
Switch Tube
240 kΩ
30 Ω
Power-
Supply
-300 kV
15 kW
30
MΩ
100 nF
100 nF
Pulser
30
MΩ
500 Ω
GND
Klystron

Oiltank:

Diameter: 1.6m

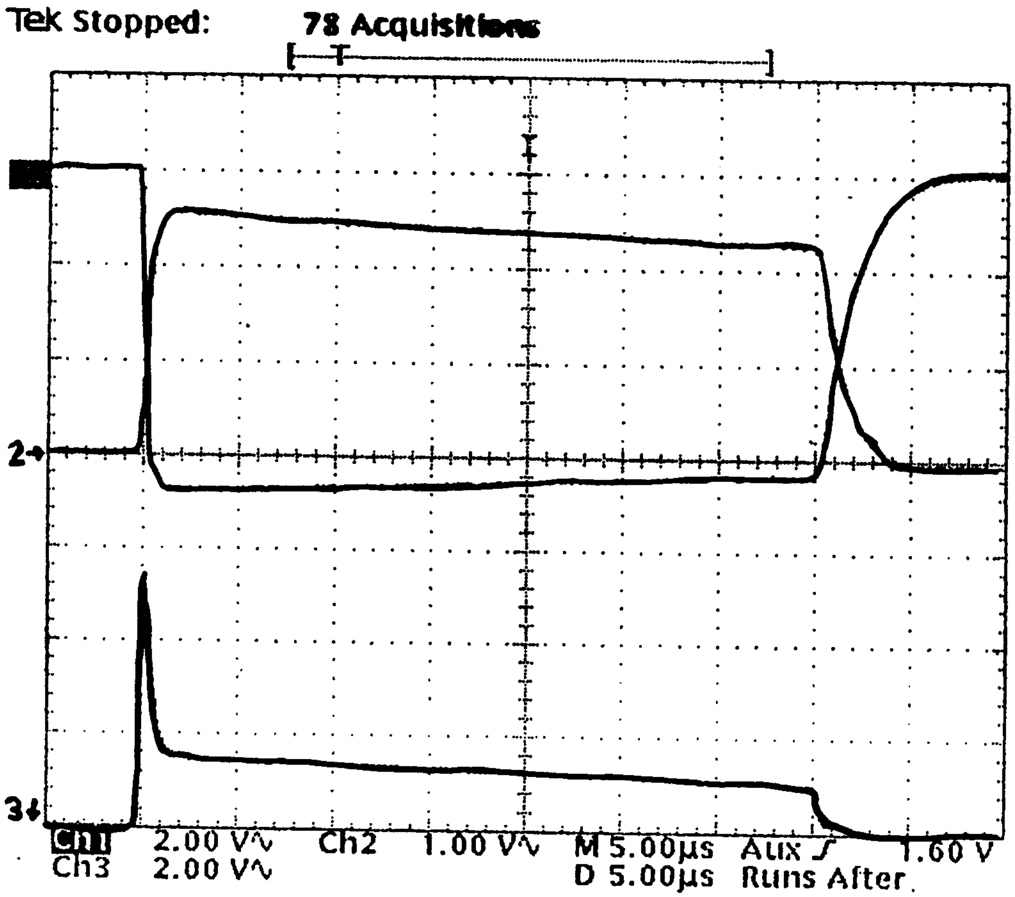
Length: 3.2m





CH1: Klystron Voltage, 17,66 kV/div   86kV
CH2: Power Supply Current, 20 A/div
CH3: Anode Current, 0,72 A/div
CH4: Klystron Current 10 A/div
Time: 2 µs/div

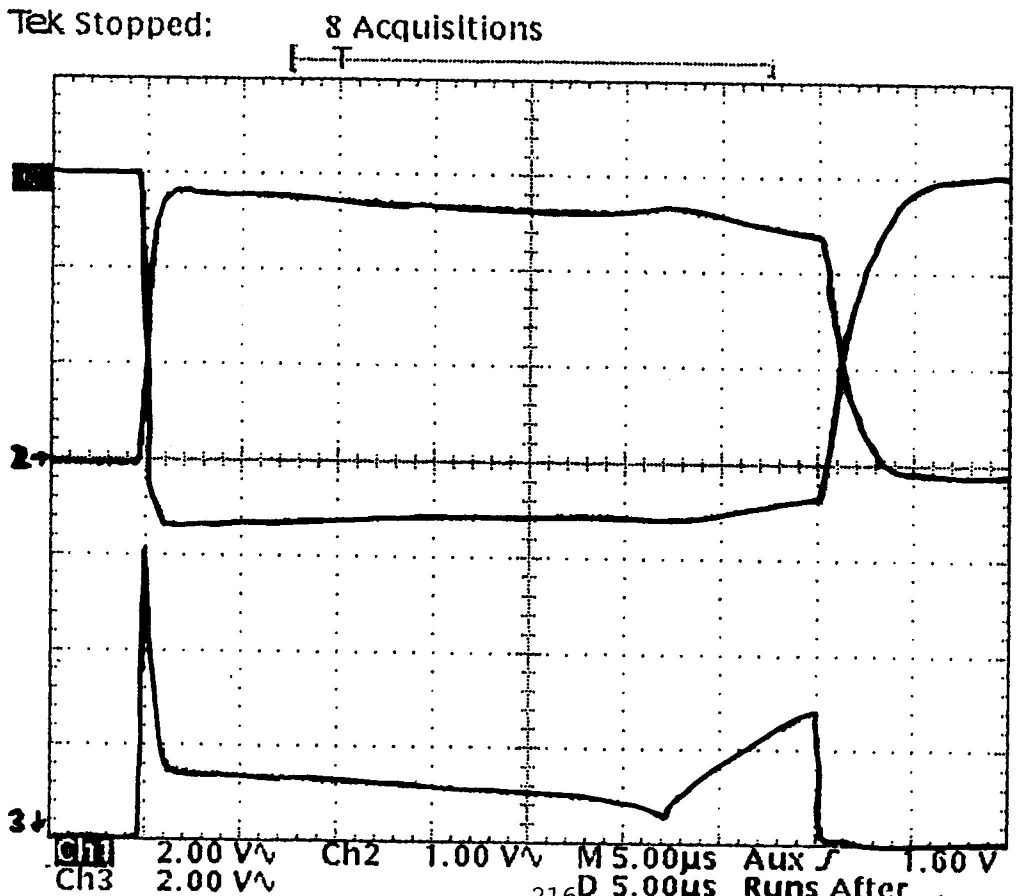
Power Supply Voltage: 100 kV
Bias Voltage: 1400 V
Pulse Voltage: 4300 V



Power Supply Voltage: 79 kV

Bias Voltage: 1200 V

Pulse Voltage 2420 V

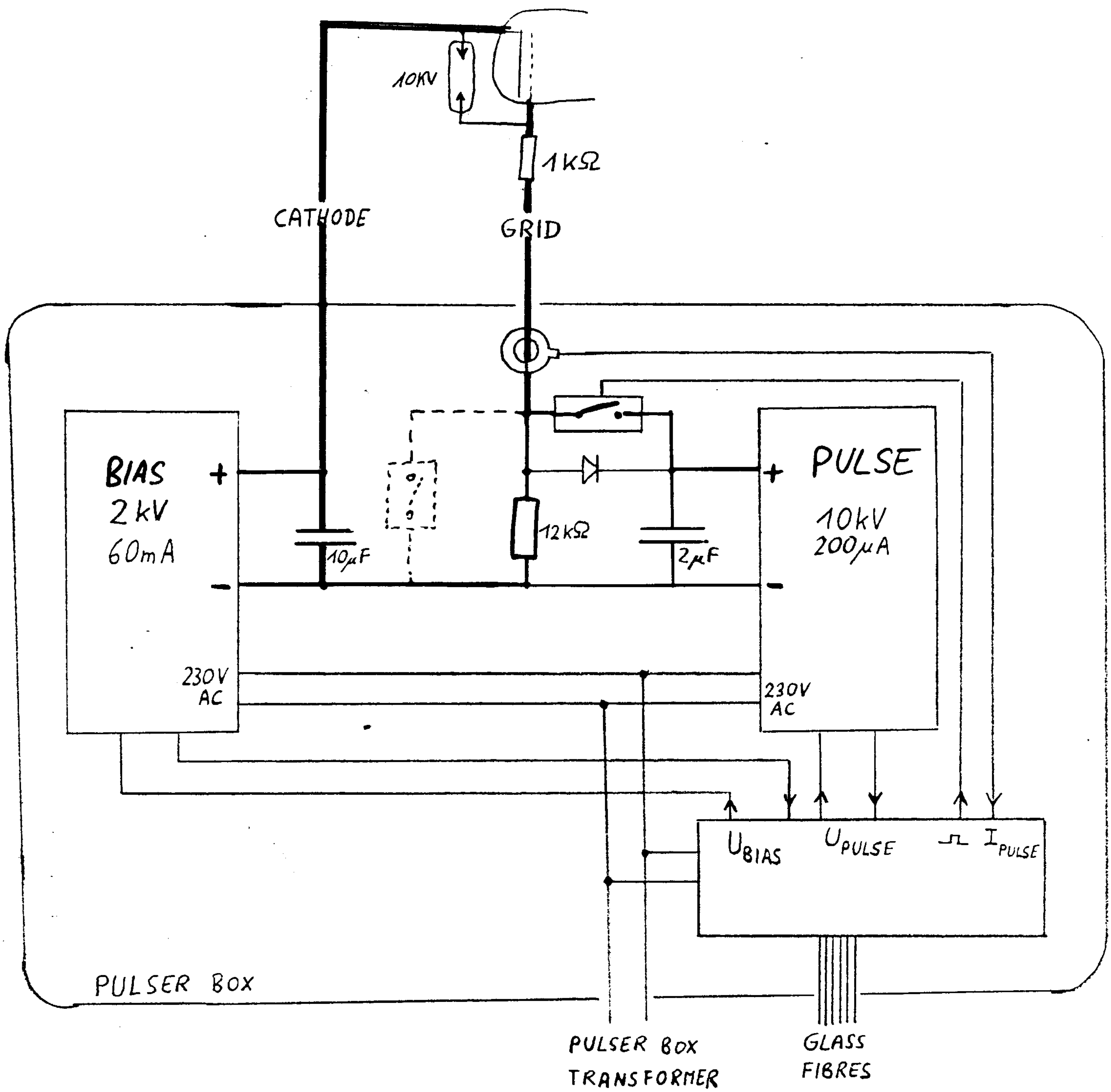


Pulse Voltage 2530 V

CH1: Klystron Voltage: 17.66 kV/div time: 5µs/div

CH2: Klystron Current: 10 A/div

CH3: Anode Current: 2 A/div


10KV
1 kΩ
CATHODE
GRID
BIAS
2 kV
60mA
+
-
10μF
12 kΩ
2μF
PULSE
10kV
200μA
230V
AC
230V
AC
U BIAS
U PULSE
I PULSE
PULSER BOX
PULSER BOX
TRANSFORMER
GLASS
FIBRES

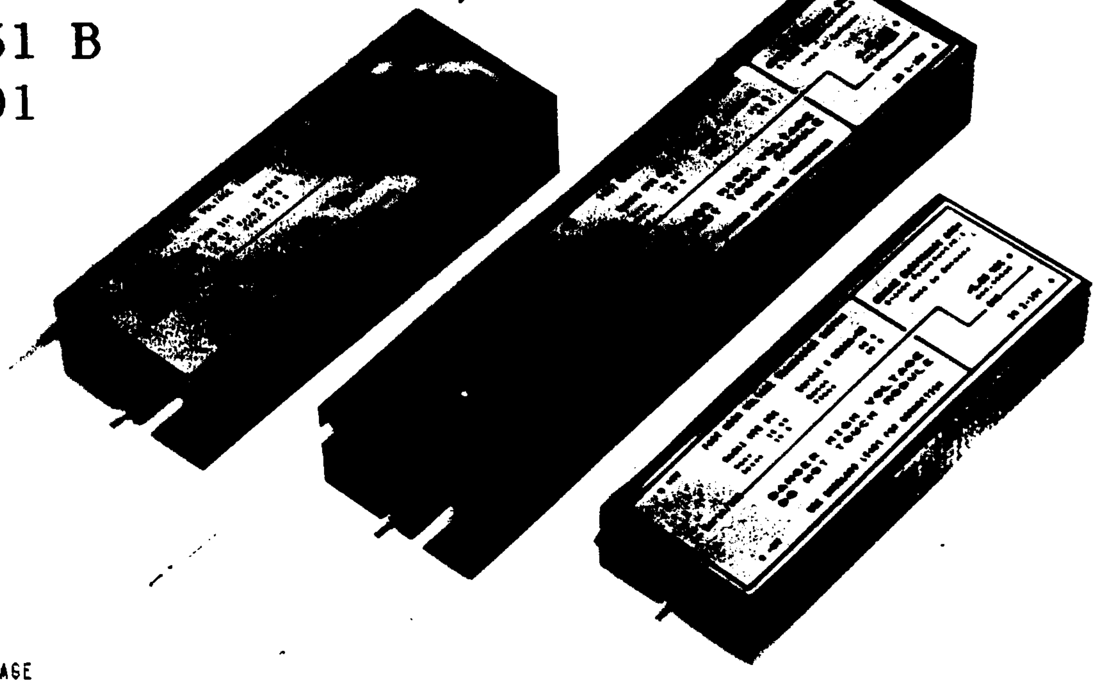
FAST HIGH VOLTAGE TRANSISTOR SWITCHES

HTS 151 A
HTS 151 B
HTS 301

Patent pending.

15KV, 15A

30KV, 15A



- 15/30 KV VOLTAGE
- FAST SWITCHING
- LOW TURN-ON JITTER
- SHORT DELAY TIME
- LOW INPUT CONTROL VOLTAGE
- GALVANIC ISOLATION
- POSITIVE AND NEGATIVE VOLTAGES
- RELIABLE SWITCHING
- EASY INSTALLATION AND CONNECTION

- ACCELERATION AND DEFLECTION GRID DRIVERS
- POCKELS CELL DRIVERS
- NANOSECOND PULSE GENERATORS
- HV TEST EQUIPMENT
- IONS OPTICS
- ELECTRO OPTICS

INTRODUCTION

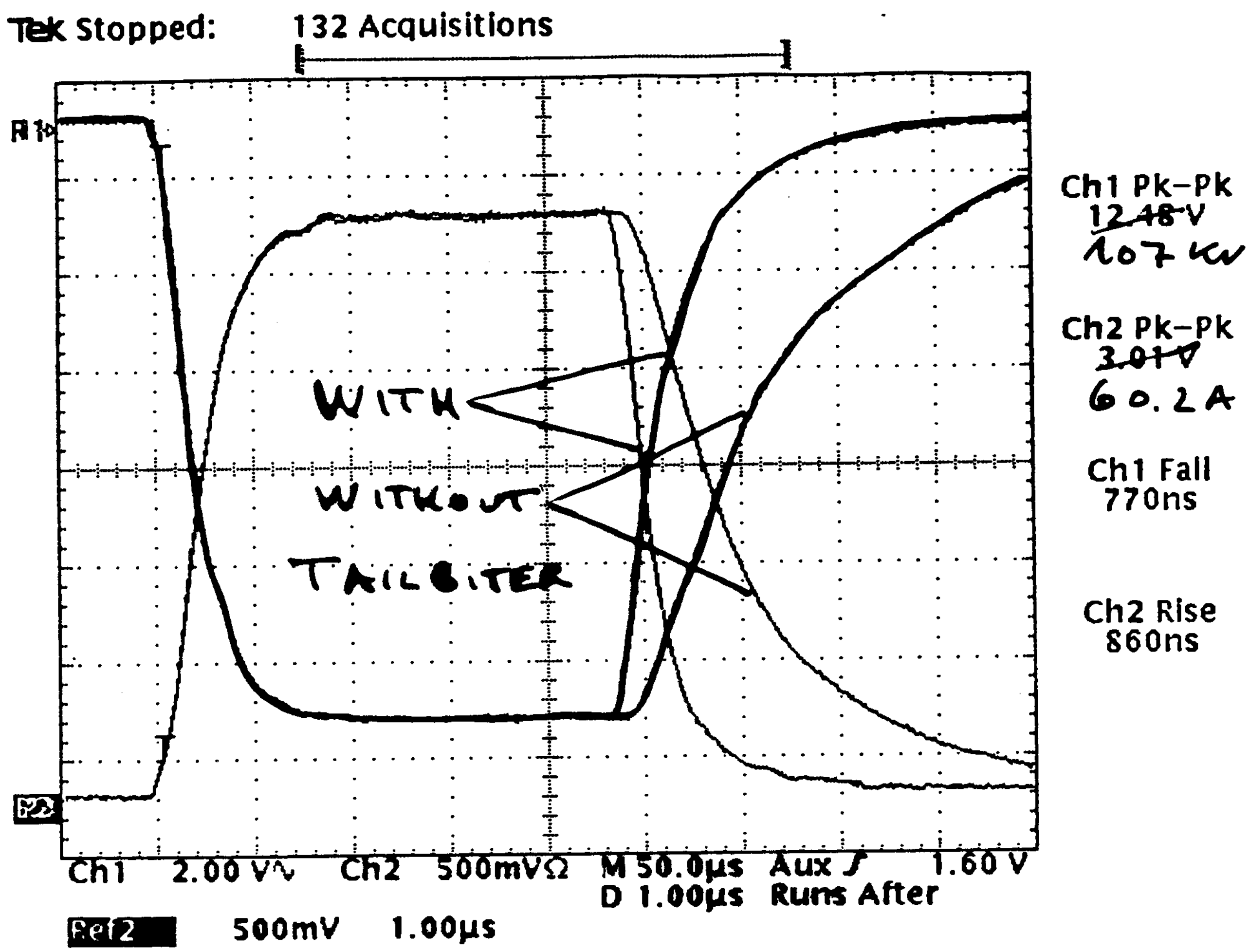
These switches has been designed for high voltage, high speed switching applications such as acclera- tion- and deflection grid drivers, pockels cell drivers and nanosecond pulse generators. Because of their simple control and high voltage strength, the models HTS 151 and HTS 301 can be used as direct replacement for high voltage tubes in many switching applications. In contrast to the conventional tubes, HTS transistor switches do not require heating power or high auxiliary voltages and the live times are typical for semiconductor devices. The switches are constructed with a multitude of synchronous controlled MOSFETs, which are highly isolated against earth and control circuit. Turning-on will be effected by a control signal of 2 to 10 Volts amplitude. The turn-on rise time depends essentially on the operating voltage, stray- and load capacitances. Rise times in the order of 10 to 20 nanoseconds will be achieved with optimized circuit designs. Because of the galvanic isolation, positive as well as negative voltages can be switched on or off. The switches may be floated also at high potentials, if the sum of working voltage and floating voltage does not exceed the specified isolation strength.

CIRCUIT DESIGN CONSIDERATIONS

Since HTS-switches can generate extremely rapid rates of voltage and current change, the circuit design should be in accordance with the typical requirements of RF-circuits. That means all leads should be kept as short as possible, part components must be low inductance types (No wirewound resistors!) and power supplies should be decoupled, as well as ground leads must be connected as short as possible to a common ground point. The use of shielded coaxial cables with proper termination is recommended for the connection of control input. To avoid electromagnetic interferences, the complete set-up should be placed in a shielded housing. If the circuit is not designed according to the above mentioned RF circuit principles, wild oscillations and undefined switching may occur, which can cause a switch overloading, especially in case of loads with low impedances. To keep the risk of oscillations as low as possible, a connection between logic ground and HV-ground is often necessary. This connection should be kept very short. For this purpose there is a third terminal at the HV-side of module, which is internally connected with the logic ground. In a floating set-up, the connection of the ground points will be made by means of a coupling capacitor Cc.

Behlke Electronic GmbH Mainzer Landstraße 276 | Postfach 190249 D-6000 Frankfurt 1 | Telefon 069/733215 Telefax 069/733179 | Tlx 0402/6101602 beh lu Btx 069733215000 1+

BEHLKE

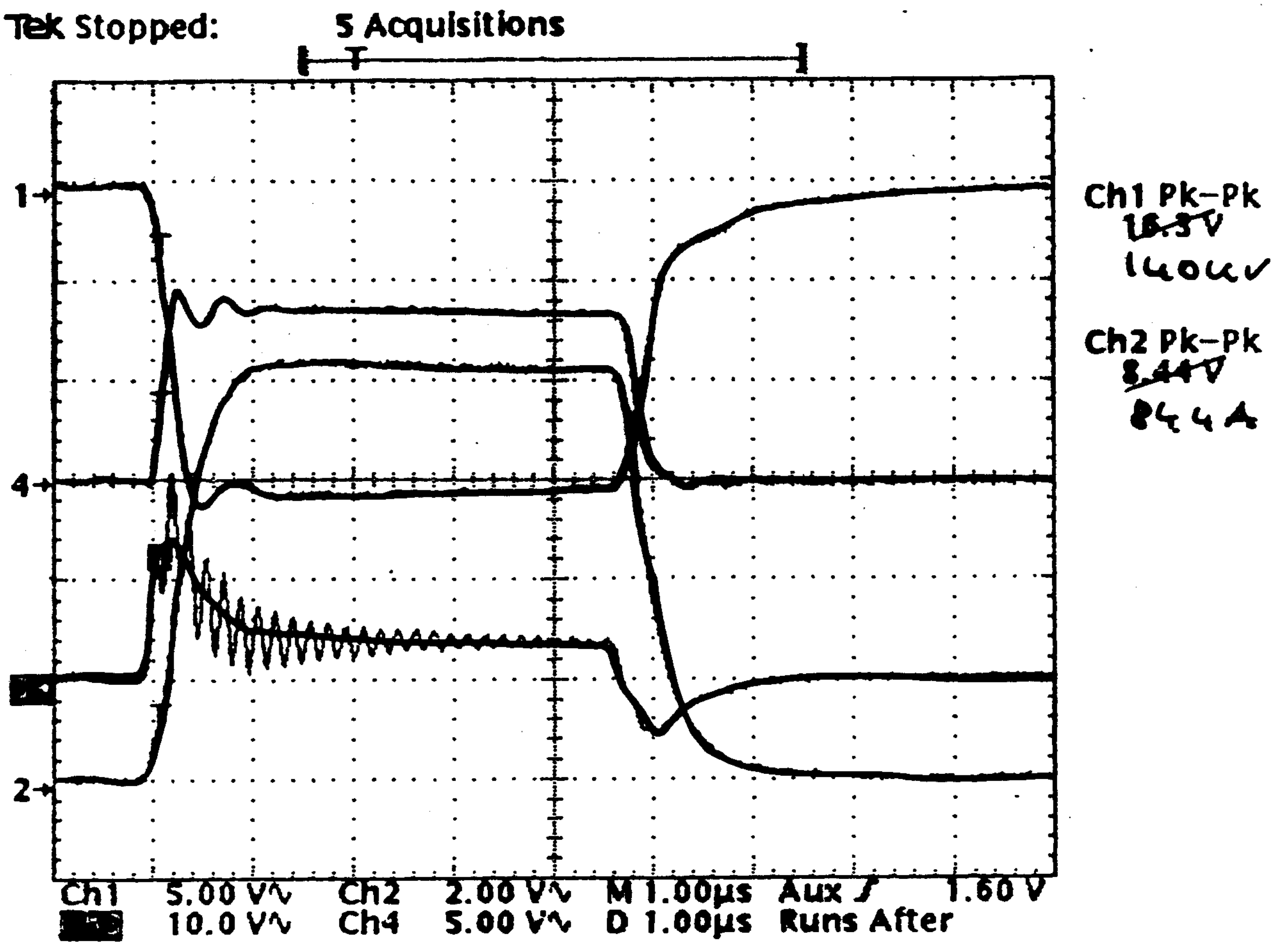


CH1: KLYSTRON VOLTAGE 17.2 kV/div

CH2: KLYSTRON CURRENT 10 A/div

TIME: 1µs/div

PS VOLTAGE 122 kV



CH1:	KLYSTRON VOLTAGE :	43kV/div
CH2:	KLYSTRON CURRENT	20A/div
CH3:	ANODE CURRENT	2A/div
CH4:	TOTAL SW TUBE CURRENT	50A/div

TIME: 1µs /div

PS VOLTAGE : 162 kV

BIAS VOLTAGE : 2.5kV

GRID PULSE VOLTAGE: 5.4kV

Commissioning of the Hard Tube Pulser Experiment at DESY

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R. Giebeler*, S. Gold**
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22603 Hamburg, Germany
*Private Consultant, **On leave from SLAC

Abstract

The development of adequate modulators for high peak power klystrons is one of the focus points for linear collider R & D programs. For the DESY/THD S-band linear collider study 150MW rf-pulse power at 50Hz repetition rate and 3μs pulse duration is required [1]. Instead of the conventional method of discharging a pulse forming network through a transformer to the klystron, a hard-tube pulser (HTP), which switches the high voltage directly from a storage capacitor to the klystron, offers a simpler design and a better pulse quality. A 25MW rf-power test version of a hard-tube pulser has been built up at DESY. Circuitry and the results of the commissioning of the switch tube are reported.

1 TEST SETUP

A test setup of a HTP capable of powering a 25MW-klystron (Thomson-CSF, TV 2002 DoD, 3GHz) has been built up at DESY.

1.1 *Circuitry*

Figure 1 shows the circuitry of the HTP test setup. The modulator is designed to produce a high voltage of up to 250kV at a current of 250A. The pulse duration is 3μs at a repetition rate of 50Hz. The rise time of the pulse is mainly determined by the klystron cathode/filament transformer stray capacitance. Assuming a capacitance of 100pF one calculates a 10%-90% rise time of 175ns. During the pulse the voltage at the storage capacitor only drops by 6%, which can be estimated by $\Delta U = U(1-\exp(\tau/RC))$, where R is the resistance of the klystron of 1000Ω, τ the pulse duration of 3μs and C the storage capacitance of 50nF. Due to its tetrode characteristics the switch tube delivers a nearly constant current to the klystron. According to the relatively low storage capacitance of 50nF the stored energy can be hold relatively small. At U=-300kV it is only 2.25kJ. This limits the danger of damaging the switch tube by arcing. In this case most of the stored energy goes into the current limiting resistor of 30Ω. Assuming an arc resistance of 100mΩ only 7.5J are dissipated in the tube, which should be safe. The charging resistor of 240kΩ decouples the power supply (and the mains) from the rest of the HTP. It limits the charging current to 75mA peak and reduces voltage ripple caused by the the power supply.

1.2 *Hardware*

Our power supply is capable of delivering a high voltage of U=-300kV at an average current of 50mA. It is an air insulated power supply consisting of lumped elements. In order to give the ability to change parameters of the HTP as fast as possible, charging resistor and storage capacitors are under air as well. We also have additional high voltage capacitors and resistors, which allow us to change parameters of the HTP to longer pulses or lower voltage drop during the pulse. Via a HV-cable the HV is fed into an oil tank (diameter 1.6m, length 3.5m) containing about 6m^3 oil.

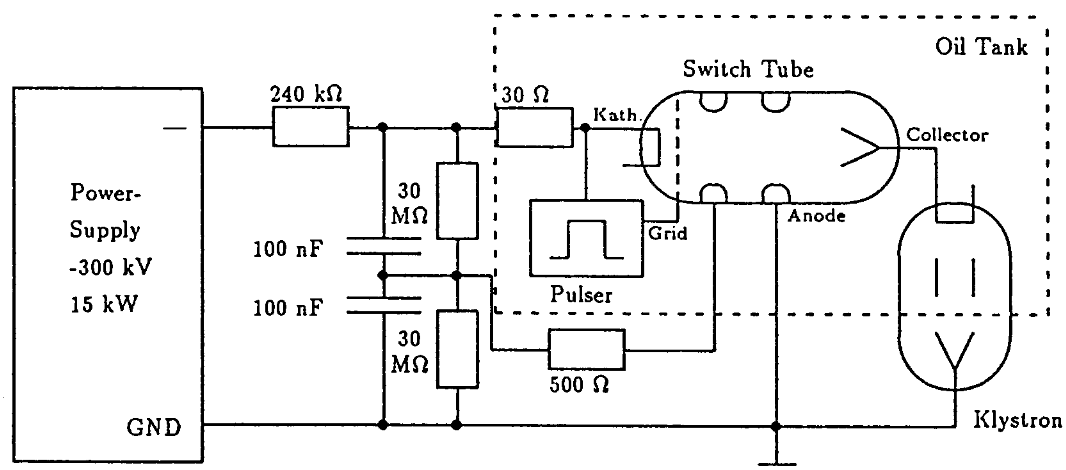


Figure 1: Circuitry of the Hard Tube Pulser

The current limiting resistor, switch tube and klystron kathode are housed in this tank. Also the filament transformers, diagnostic elements and the grid pulser are inside the tank. All these components are accessible through flanges. A lot of feed throughs, electrical and optical, serve for diagnostics and the control of the HTP. An oil circulating systems is needed for cooling, especially the electrodes of the switch tube. The whole system is sited in concrete shielding ($8.5 \cdot 6.5\text{m}^2$, 4m high) to protect people from HV and x-rays. It is driven and controlled from a separate control room.

Figure 2 shows the interior of the oil tank.

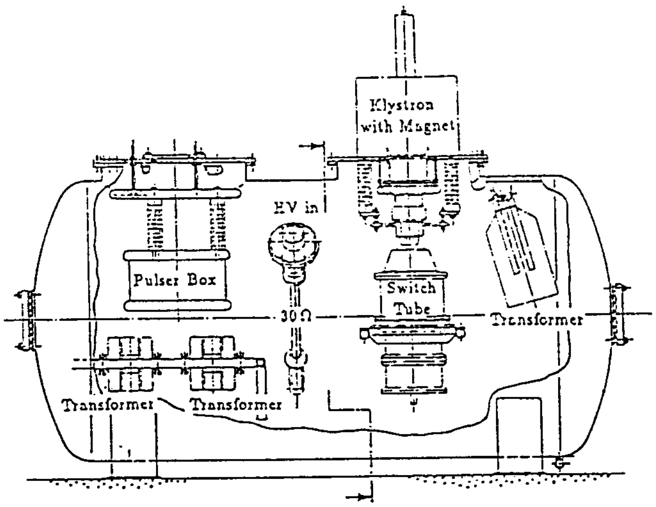


Figure 2: Sketch of the Modulator Tank

2 FIRST TESTS

First tests of the system began in spring 93. The whole system, consisting of the power supply, the switch tube, the klystron, the grid pulser, the control system, the cooling system and the interlock system came into operation without major problems. However, as the switch tube was an unconditioned tube, it had to undergo several procedures such as highpotting and heater aging.

Figure 3 shows typical pulse forms of the hard tube pulser.

The pulse forms were recorded at a power supply voltage of 81kV, a bias voltage of 1200V and a grid pulse voltage of 2800V.

Channel 1 shows the klystron voltage (17.66kV/div). The flat top voltage is 71.7kV, the risetime (10-90%) is about 400ns, the ripple on the flat top is below 1%. Due to the very long fall time of the grid drive pulse, the fall time of the klystron voltage is above $5\mu s$. For the next test run this was improved by adding a tail biter to the grid pulser circuitry.

Channel 2 shows the klystron current (10A/div).

Channel 3 shows the current from the switch tube anode to ground (2A/div). The spike at the beginning of the pulse is caused by secondary electrons, emitted from the collector. The first electrons coming from the cathode are accelerated by the full power supply voltage when they reach the collector. The secondary electrons created by these high energy electrons are emitted towards the anode. By leaving the collector they lower its potential. This effect limits the risetime of the klystron voltage and could be minimized by an improved collector design.

The timebase for all channels is $1\mu s$/div.

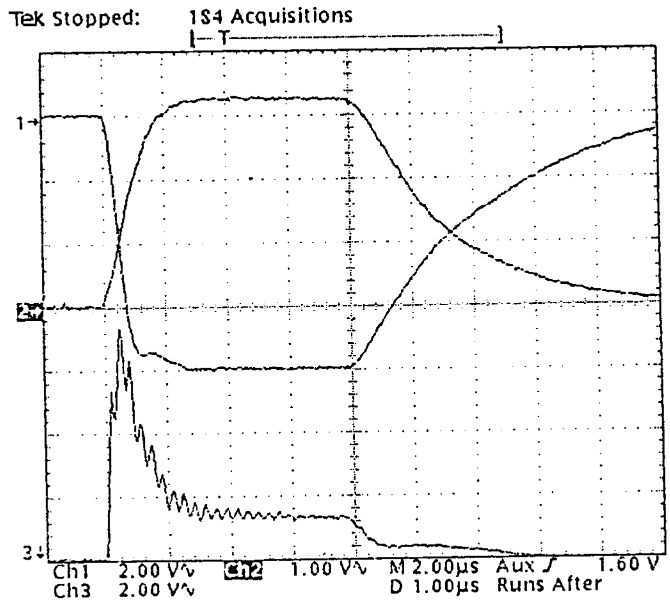


Figure 3: Typical Pulse forms of the HTP.
Chan.1: Klystron Voltage, 17.66kV/div
Chan.2: Klystron Current, 10A/div
Chan.3: Anode Current, 2A/div
Timebase: $1\mu s$/div

2.1 *Saturation*

Figure 4 shows pulse forms that were taken under the same conditions as those in figure 3, but at an increased grid pulse voltage. The pulse forms were recorded at a power supply voltage of 81kV, a bias voltage of 1200V and a grid pulse voltage of 2920V.

Channel 1 shows the klystron voltage. Here the flat top voltage is 77.7kV.

Channel 3 shows the current from the switch tube anode to ground (2A/div). The timebase for all channels is $1\mu s$/div. At the end of the pulse there is a slight increase in the anode to ground current. At this point the cathode voltage, which is decreasing during the pulse due to the small storage capacitor, has reached the level of the collector voltage. Some of the electrons, that were emitted from the cathode, do not reach the collector and turn back to the anode, causing the increased ground current. The collector voltage decreases, the switch tube is driven into saturation. To avoid saturation, the anode to ground current has to be monitored carefully.

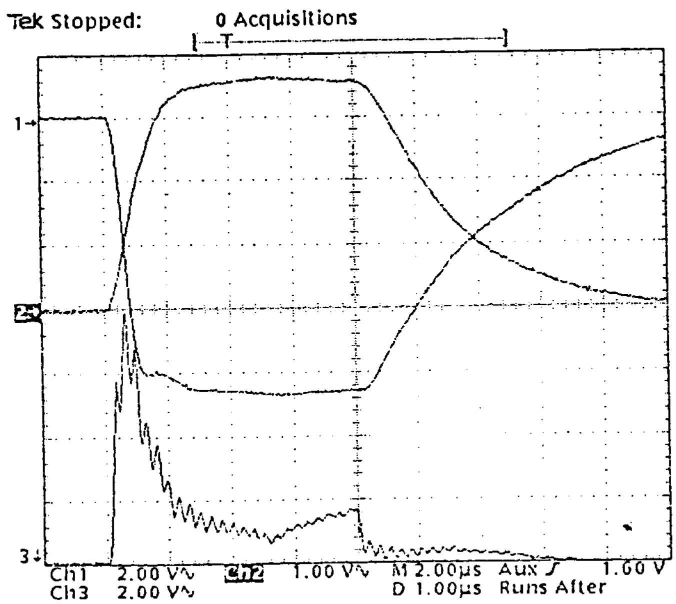


Figure 4: Increased Grid Pulse Voltage, Saturation.
Chan.1: Klystron Voltage, 17.66kV/div
Chan.2: Klystron Current, 10A/div
Chan.3: Anode Current, 2A/div
Timebase: 1μs/div

2.2 *Long Pulse Application*

Figure 5 shows an example for a long pulse application of the hard tube pulser.

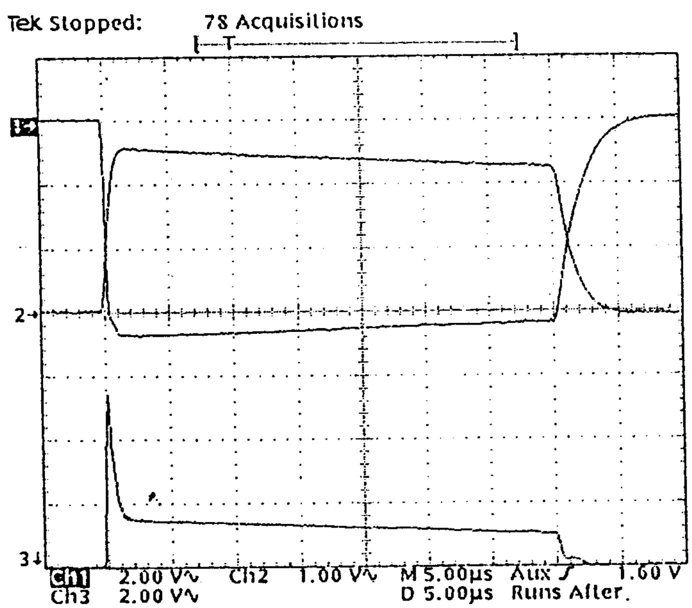


Figure 5: Long Pulse Application.
Chan.1: Klystron Voltage, 17.66kV/div
Chan.2: Klystron Current, 10A/div
Chan.3: Anode Current, 2A/div
Timebase: 5μs/div

The pulse forms were recorded at a power supply voltage of 79kV, a bias voltage of 1200V and a grid pulse voltage of 2420V. The pulse length was increased to 35μs.
Channel 1 shows the klystron voltage. Here the peak voltage is 60.4kV.
Channel 2 shows the klystron current.
Channel 3 shows the current from the switch tube anode to ground (2A/div).
The timebase for all channels is 5μs/div.
Klystron voltage and current show a drop during the pulse, caused by a drop of the storage capacitor voltage during the pulse. The capacitance of the storage capacitor was originally chosen for a pulse duration of 3μs. At 35μs pulse duration the voltage at the storage capacitor and so the switch tube cathode voltage drops by about 20% of the initial charging voltage. The tube can not compensate for this large voltage drop, the current through the tube decreases and so does the klystron voltage. Since the switch tube cathode voltage drops significantly during the the pulse, but has to be kept well above the klystron voltage in order to avoid saturation at the end of the pulse, the switch tube has to be operated with a relatively large voltage drop across the tube at the beginning of the pulse. For long pulse applications a larger storage capacitance, which allows smaller voltage drops, must be chosen. For our application with a pulse duration of 3μs a storage capacitance of 50nF is absolutely sufficient.

2.3 *Operational limits of the switch tube*

During the commissioning of the Hard Tube Pulser the operating voltage was limited to about 120kV by breakdown in the switch tube. A relatively high gas pressure in the cathode region caused breakdown between grid and cathode. The bias voltage broke down and the subsequently emitted high electron current caused a high voltage breakdown in the tube.
To improve this situation the tube was shipped back to the vendor, the cathode heater package was redesigned and an additional vacuum pump was mounted on the cathode flange. The rebuild of the tube is finished, the tube is back in the modulator tank and ready for a new test.

3 REFERENCES

[1] K. Balewski et.all., Status Report of a 500 GeV S-Band Linear Collider Study, *DESY 91-153*, December 1991

Triaxial Helical Blumlein Type Modulator

T. SHIDARA
KEK-PF-LINAC

Motivation: Realization of a klystron modulator with a shorter rise time (~100 ns)
Efficiency

Required to reduce C_D, L_ℓ, $L_{unknown}$ (stray), C_K (if possible)

⇓

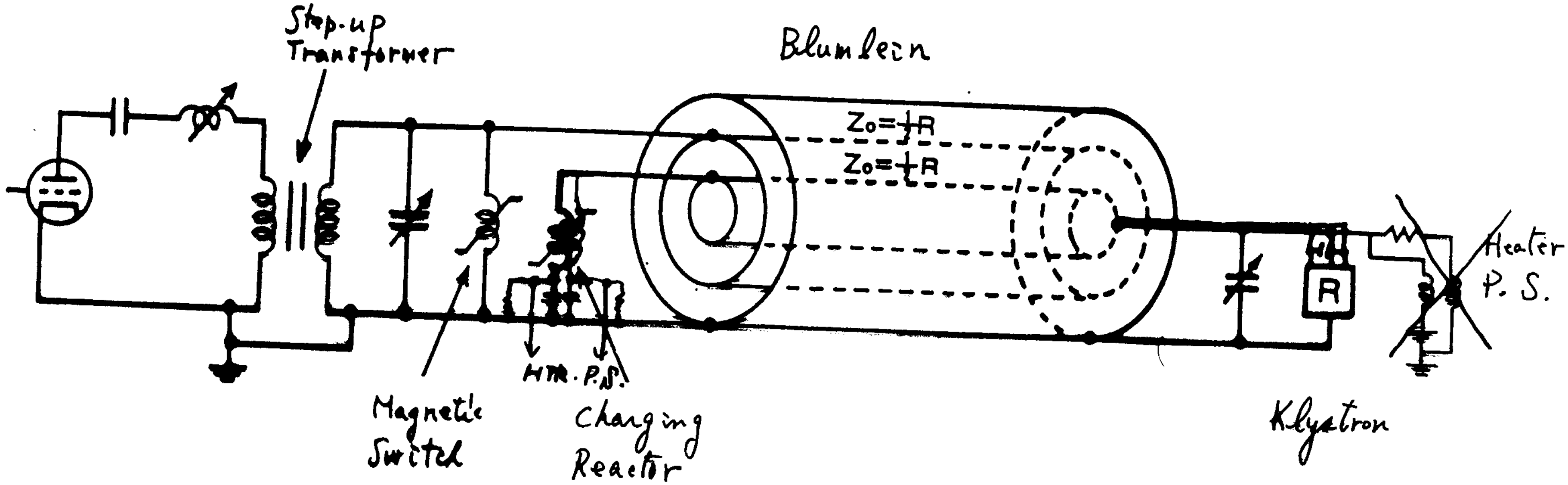
Output transformer-less modulator

※ Switch was a key issue

⇓

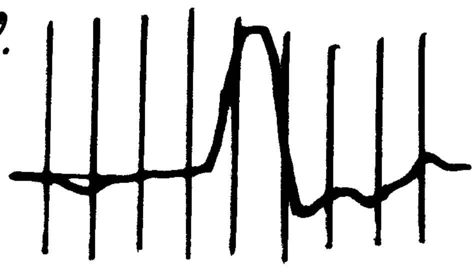
Magnetic switch

HEACC-1992
HAMBURG



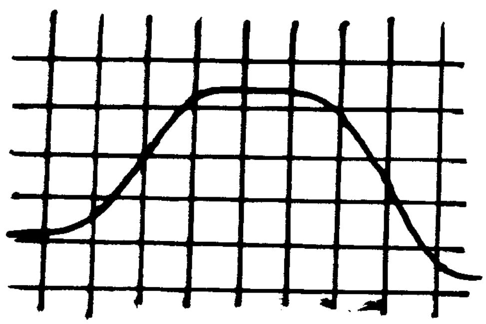
Conceptual Drawing of Blumlein Type Modulator

539 kV peak vol.

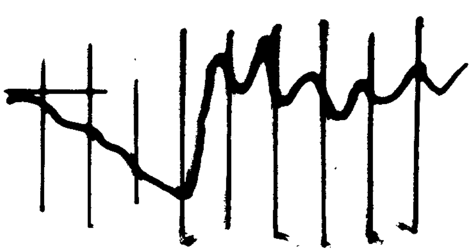


Output voltage of the Blumlein
(↑ 160kV/div. ↔ 248ns/div.)

107 ns flat-top
128 ns trise



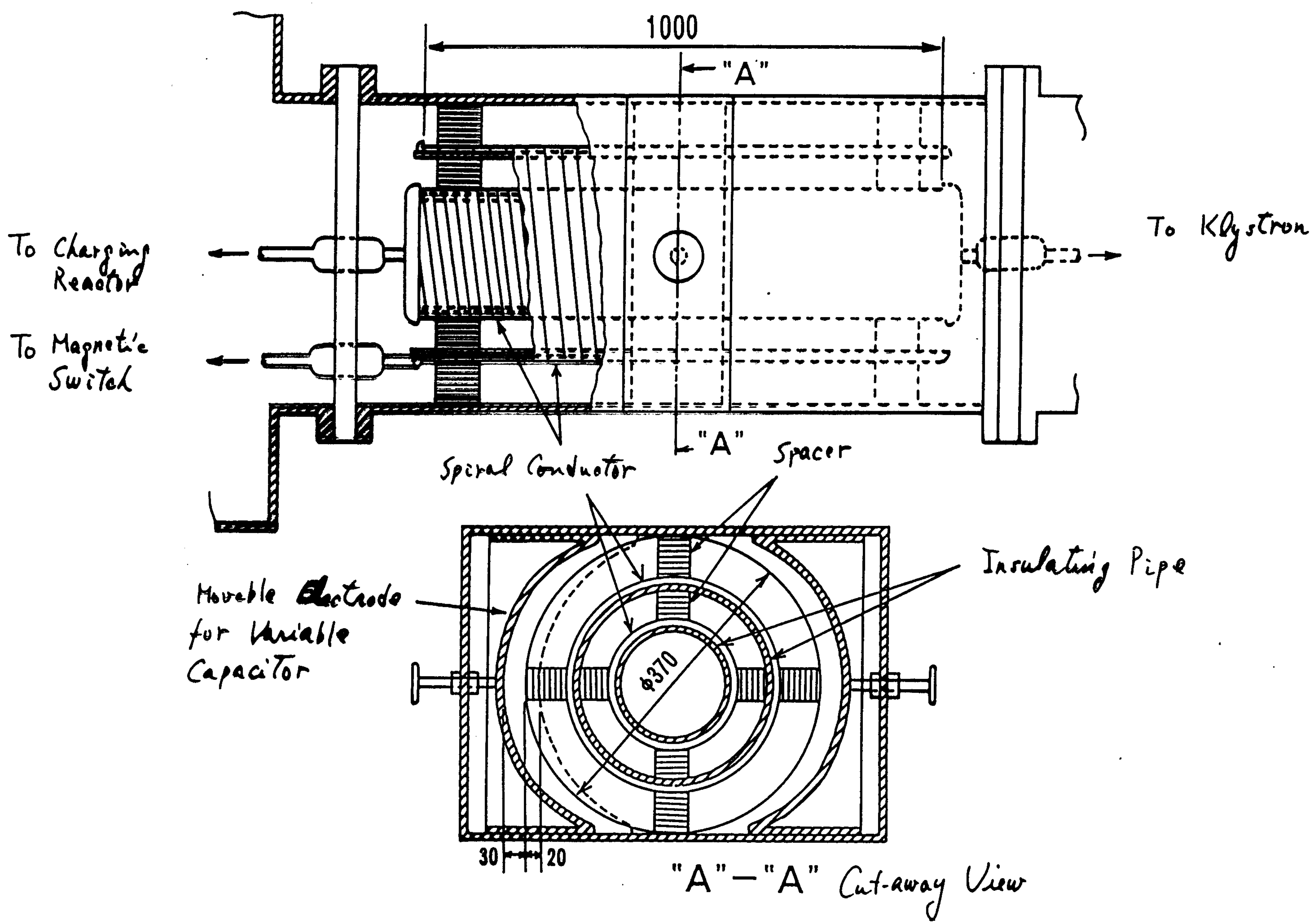
Expanded output voltage of the Blumlein
(↑ 160kV/div. ↔ 62ns/div.)



~860 ns pulse
600 kV peak

Input voltage of the Blumlein
(↑ 200kV/div. ↔ 248ns/div.)

Rough Sketch of Blumlein Structure



MODULATOR CONSTRUCTION SESSION SUMMARY

J. M. Grippe

Howard Pfeffer made some general comments about design trade-offs available. Special emphasis was placed on the cost effectiveness of the use of multiple capacitor charging power supplies versus a single power supply.

Ron Koontz discussed the general requirements of the NLC Modulator including the need for high efficiency from the prime power line through the klystron. The requirement of a fast rise time and to limit stray capacitance and inductance was also discussed. A proposed design using transmission lines in a Blumlein configuration and Capacitive charge power supplies was shown and discussed. The parameters of the NLC Klystron were also shown and discussed.

Questions were raised during this session as to the possibility of load, line mismatches due to the non adjustable impedance of transmission lines, and the number of capacitor charge power supplies needed to support the required klystron energy using a two klystron modulator.

Saul Gold discussed the present NLCTA klystron design including the plans to upgrade the present magnetic focused klystrons to 72 MW PPM Klystrons. Gridded klystrons and the use of linear beam tubes in place of the line type modulator was also discussed. The challenges presented to the modulator designer in regards to efficiency, cost, reliability and other factors was also shown. A review of R&D programs needed to support the NLC program was given.

Hajime Mizuno discussed the design and test results of the Blumlein Modulators at KEK. Design requirements for the klystron, Blumlein Modulator and RF pulse compression system were given. Test results including efficiency, capacitor data (U.S. vs Japanese), and pulse transformer data was also shown.

Stefan Choroba discussed the Modulator work being done at DESY. The layout and design of a Hard Tube Modulator using a Varian VKW-8273 Linear Beam Switch Tube was shown. Test data taken on this modulator was discussed.

T. Shidara discussed the design of a Triaxial Helical Blumlein Type Modulator at KEK with the goal of a fast rise time and high efficiency. A conceptual drawing of this modulator was shown along with some test data.

THOMSON TUBES ELECTRONIQUES

R. LECHATELLIER

TDH - DP/EQM
Vélizy le 4 octobre 1995

KLYSTRON MODULATOR TECHNICAL MEETING

OCTOBER 9TH TO 11TH 1995 - SLAC STANFORD

THOMSON high stability and large duty cycle modulator

11 MW peak - 350 kW average

Réf. 055.95/RL/JBe

ABSTRACT

A modulator for high power klystron has been built by TTE as a part of a CEA development program on a high-peak power FEL.
The RF amplitude stability during the macropulse is very important for this application.
To be able to control the plateau, via a feedforward feedback loop, we have developped a hard-tube modulator by which the voltage droop caused by the capacitor bank is compensated by varying the switching tube "on" voltage. The grid voltage of the modulator tube is controlled by a computer through an analog waveform synthetizer. The waveform is corrected from macropulse to macropulse using a recurrent algorithm.

SUMMARY

1. GENERAL VIEW OF TTE EQUIPMENTS

1.1. For TTE tubes tests

- To run super-power CW klystrons
- To run gyrotrons during development and in ligne production processes
- To run super-power pulsed klystrons
- To run high-power travelling waves tubes

1.2. For TTE customers

- To feed a collision ring (INFN - ITALY)
- To run super-power klystron with a HV pulse amplitude stability better than ± 0.3 % (CEA - FRANCE)

2. HARD-TUBE MODULATOR

2.1. Klystron specifications

FOR TYPICAL OPERATION	TH 2118	
Frequency	433MHz	
Pulse length	180µsec	(220 µsec max)
Duty cycle	0.033	
RF output power peak	6MW	
avg.	200kW	
RF input power peak	60W	(100 W max)
Beam voltage peak	165kV	(188 kV max)
Beam current peak	65 A	(75 A max)
Heater power (25 V 25 A)	625 W	(900 W max.)
Efficiency	57 %	
Impedance	2540 Ω	
Gain	50 dB	
Output	On waveguide window	
Focusing	Electromagnet	

2.2. Hard-tube modulator specifications

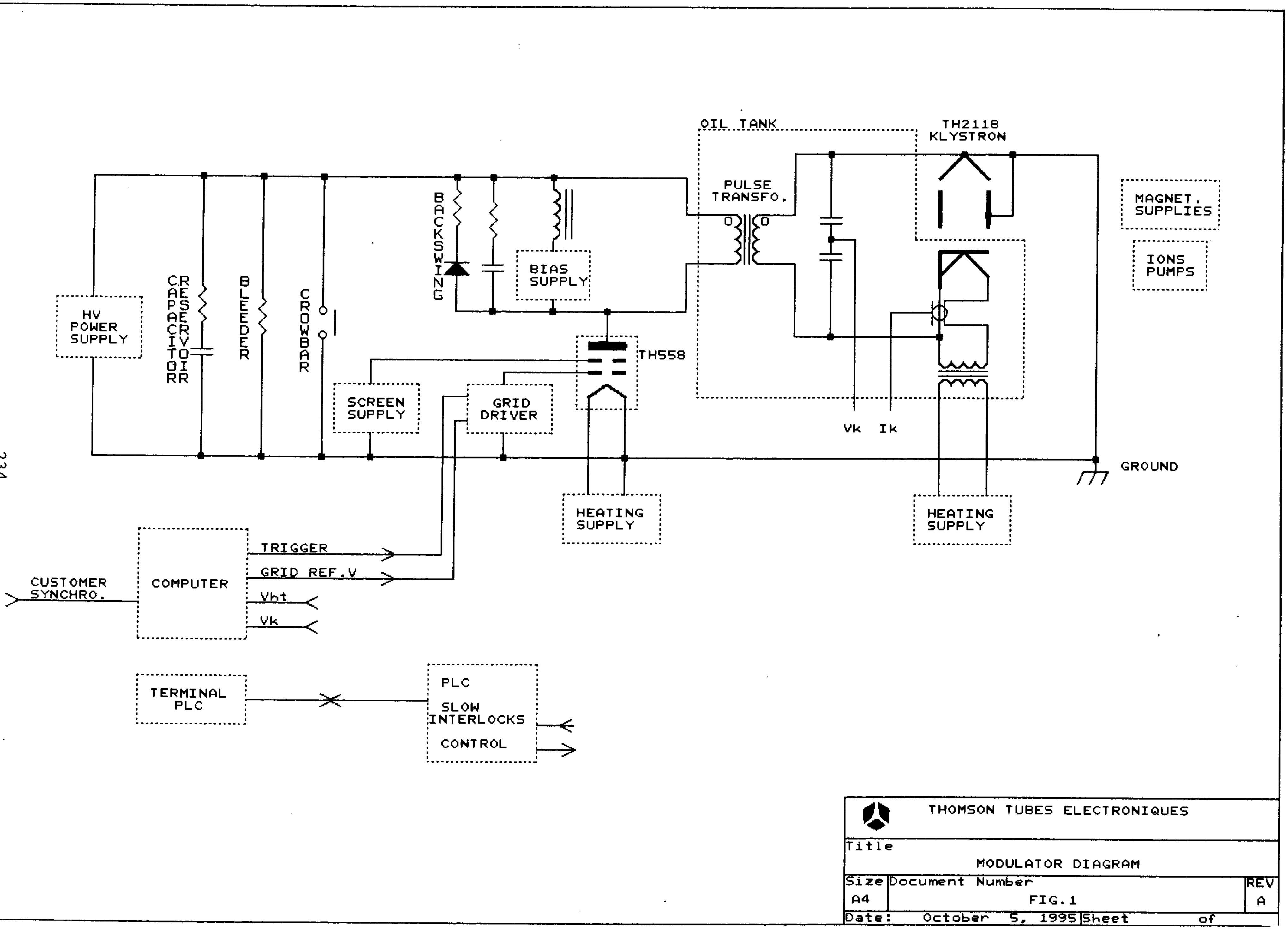
See modulator diagram figure 1

	Max	
RF peak power	6 MW	
Mod peak power	13,5 MW	
Cathode voltage	190 kV	(1)
Cathode current	75 A	(1)
Repetition rate	150 Hz	
Pulselength (flat top)	180/280	(2)
Rise time	< 12 µsec	
Fall time	< 20 µsec	
Voltage flat top ripple & droop	< ± 0.5 %	(3)
Voltage amplitude jitter	< ± 0.5 %	(3)
Storage capacitor	150 µF	
Stored energy	77KJ	
Max. energy/pulse	4.7 KJ	
Pulse transformer ratio	1 : 7	
Max. primary current	525 A	
HV power supply	32 kV/ 15 A	

(1) : Non simultaneous maximal specifications
(2) : With bias voltage
(3) : Target ± 0.1 %

HVPS efficiency ($\rho 1$)	90 %	
Hard-tube modulator efficiency ($\rho 2$)	84 %	(4)
Klystron efficiency ($\rho 3$)	57 %	
Global efficiency ($\rho 1 \times \rho 2 \times \rho 3$)	43 %	

(4) : Without taking into account the auxiliary supplies average power


OIL TANK
TH2118 KLYSTRON
PULSE TRANSFO.
MAGNET. SUPPLIES
IONS PUMPS
HV POWER SUPPLY
CAPACITOR RESERVOIR
BLEEDER
CROWBAR
BACKSWING
BIAS SUPPLY
TH558
SCREEN SUPPLY
GRID DRIVER
Vk Ik
GROUND
HEATING SUPPLY
HEATING SUPPLY
CUSTOMER SYNCHRO.
COMPUTER
TRIGGER
GRID REF.V
Vht
Vk
TERMINAL PLC
PLC
SLOW INTERLOCKS
CONTROL
THOMSON TUBES ELECTRONIQUES
Title
MODULATOR DIAGRAM
Size
A4
Document Number
FIG.1
REV
A
Date: October 5, 1995
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2.3. Hard-tube modulator switching tube

See tetrode control figure 2

2.3.1. Main circuit

Klystron pulse	165 kV/65 A
Pulse transformer	1 : 7
Switch current (peak)	455 A
Storage capacitor voltage	32 kV
Max. switch anode dissipation	55 kW avg.
→ 1 TH 558	

2.3.2. Solid state driver circuit

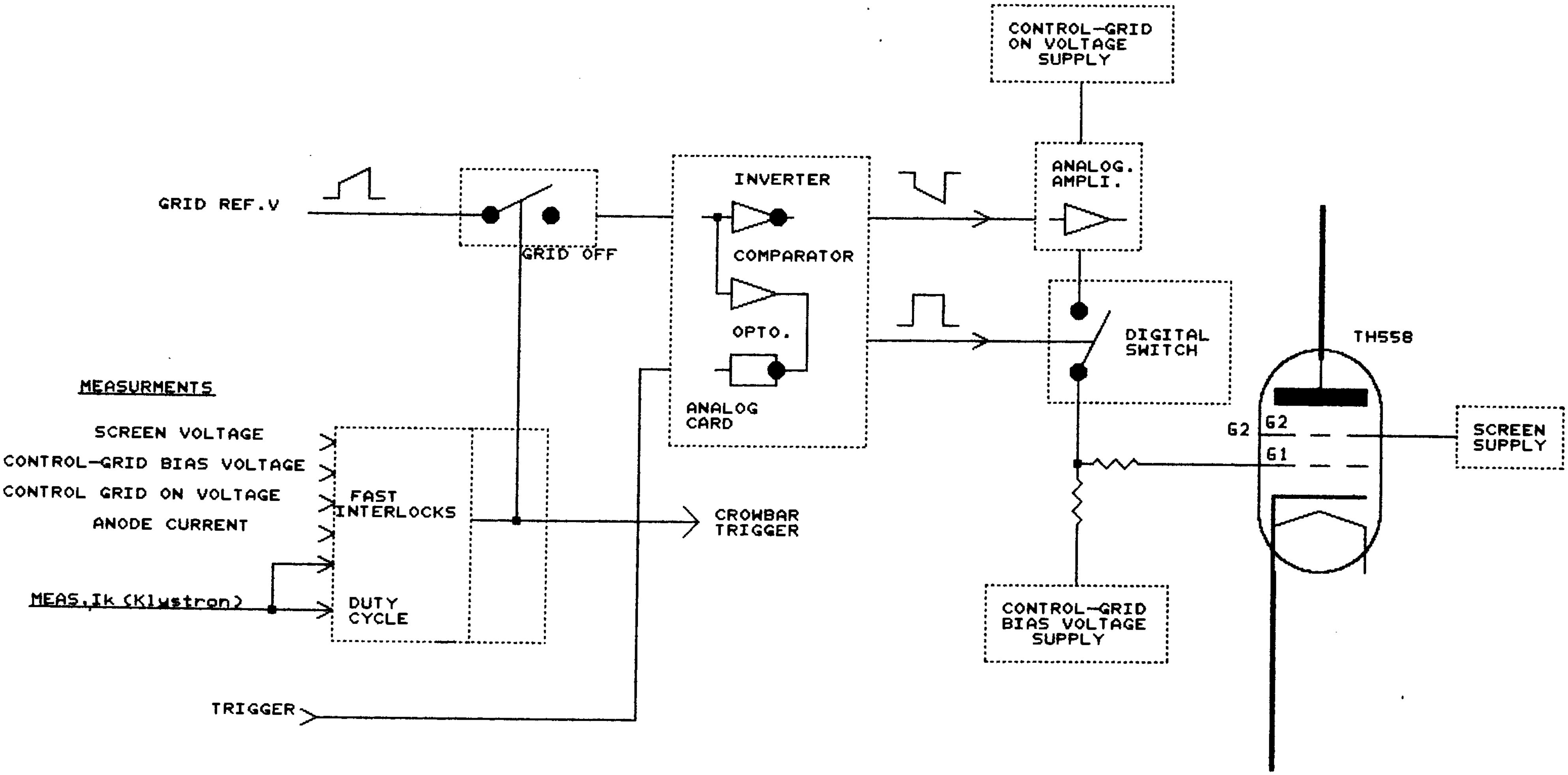
- Analogic amplifier

  . Voltage amplifier stage
  . Impedance adaptation and voltage amplifier control circuit (local feedback)
  . Current amplifier stage without voltage gain

- Digital switch

- Analogic card

- Supplies (control-grid bias and on voltage, screen)



THOMSON TUBES ELECTRONIQUES			
Title: TETRODE CONTROL			
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A4	FIG.2		A
Date:	October 6, 1995	Sheet	of

2.3.3. Hard-tube specifications (TH 558)

Operating conditions

Anode voltage continuous	35 kV
Control-grid bias voltage	-1.2 kV
Control-grid on voltage	+350 V
Screen voltage	2 kV
Peak anode current	525 A
Anode dissipation	55 kW
Filament voltage	23 V
Filament current	500 A

3. PULSE SHAPE CORRECTION

3.1. Pulse shape distortion due to

- Tank capacitor voltage droop (2 %)

- Pulse transformer transient response (rise time : 12 µsec)

⇨ **Versatility of hard-tube modulator**

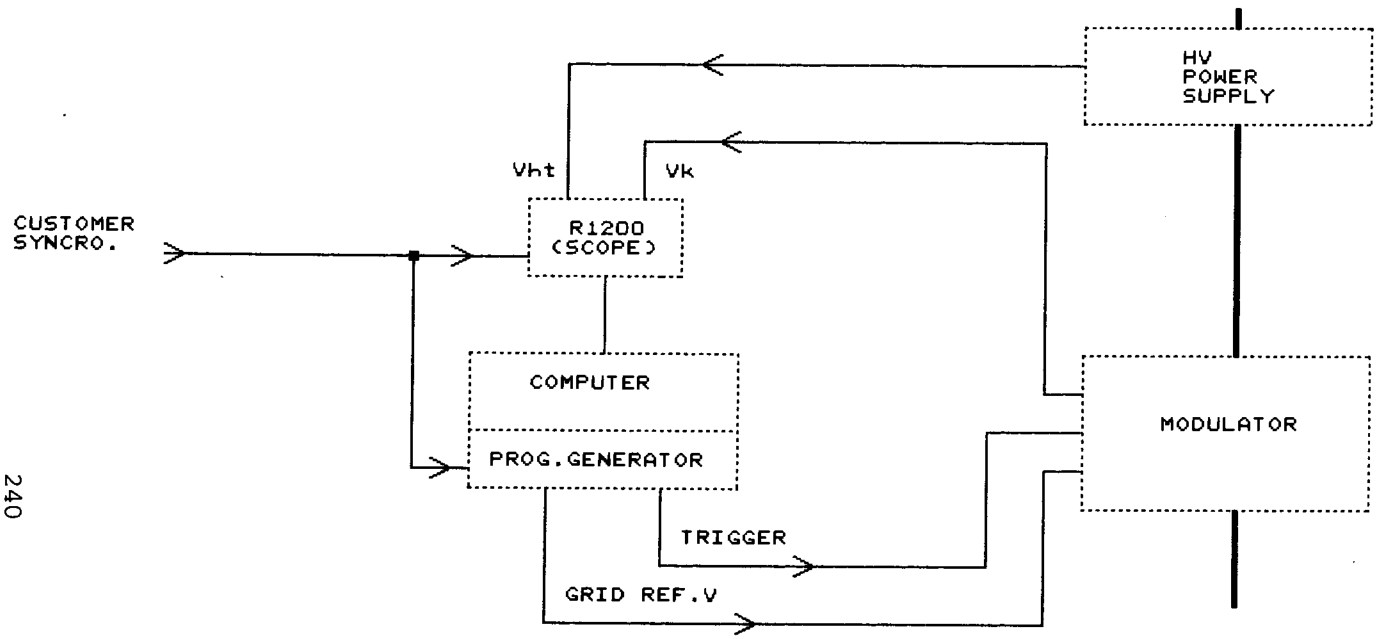
- Changing pulse amplitude
- Pulse length
- Droop compensation at low voltage level
- pulse shaping
- Feedforward feedback loop

3.2. FEEDFORWARD FEEDBACK LOOP

This method is based on the errors evaluation between the klystron pulse and the theorical reference pulse.
The theorical reference pulse takes into account the theorical limits of the system (finite rise time).
A specific shape is elaborated with the following parameters :

- pulsewidth (CD)
- reference voltage (CV, CN)
- rise time (CT)
- angle of phase difference (leading)
- correction parameters
- synchronisation mode

The klystron pulse is acquired by an numerical oscilloscope.
A computer calculates the voltage new reference which will be applied to the control grid by a programmable waveform generator.
The hardware (fig.3) and software (fig.4) architectures represent a complete system to control the modulator operating in remote modes.



THOMSON TUBES ELECTRONIQUES		
Title: COMPUTER SYNOPTIC		
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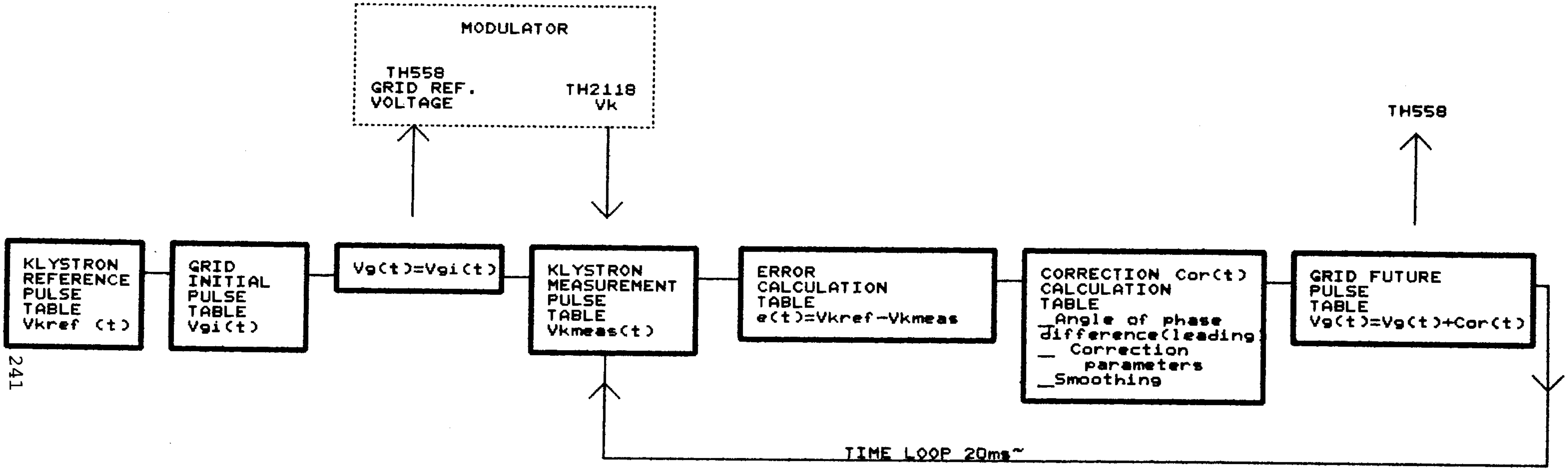

241

THOMSON TUBES ELECTRONIQUES

Title
REFERENCE PULSE TABLE ELABORATION

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A4	FIG.4	REF

Date: October 6, 1995 Sheet of

3.3. CONCLUSION

Results of experiments are presented on figure 5 for a nominal power operation at 25 Hz.

. ± 0.06 % on the plateau

. ± 0.3 % on the total pulse

These values are in good agreement with the hard-tube modulator specifications. The target value of ± 0.1 % is obtained on the plateau. Two main perturbations remain :

- The voltage droop at the end of the pulse
- The rise time oscillations

The first perturbation is due to the transformer and tetrode saturation.
The first point could be improved by a premagnetizing circuit and the second one by raising the control-grid on voltage supply provided that the tetrode cross voltage stays superior to the tetrode saturation voltage.

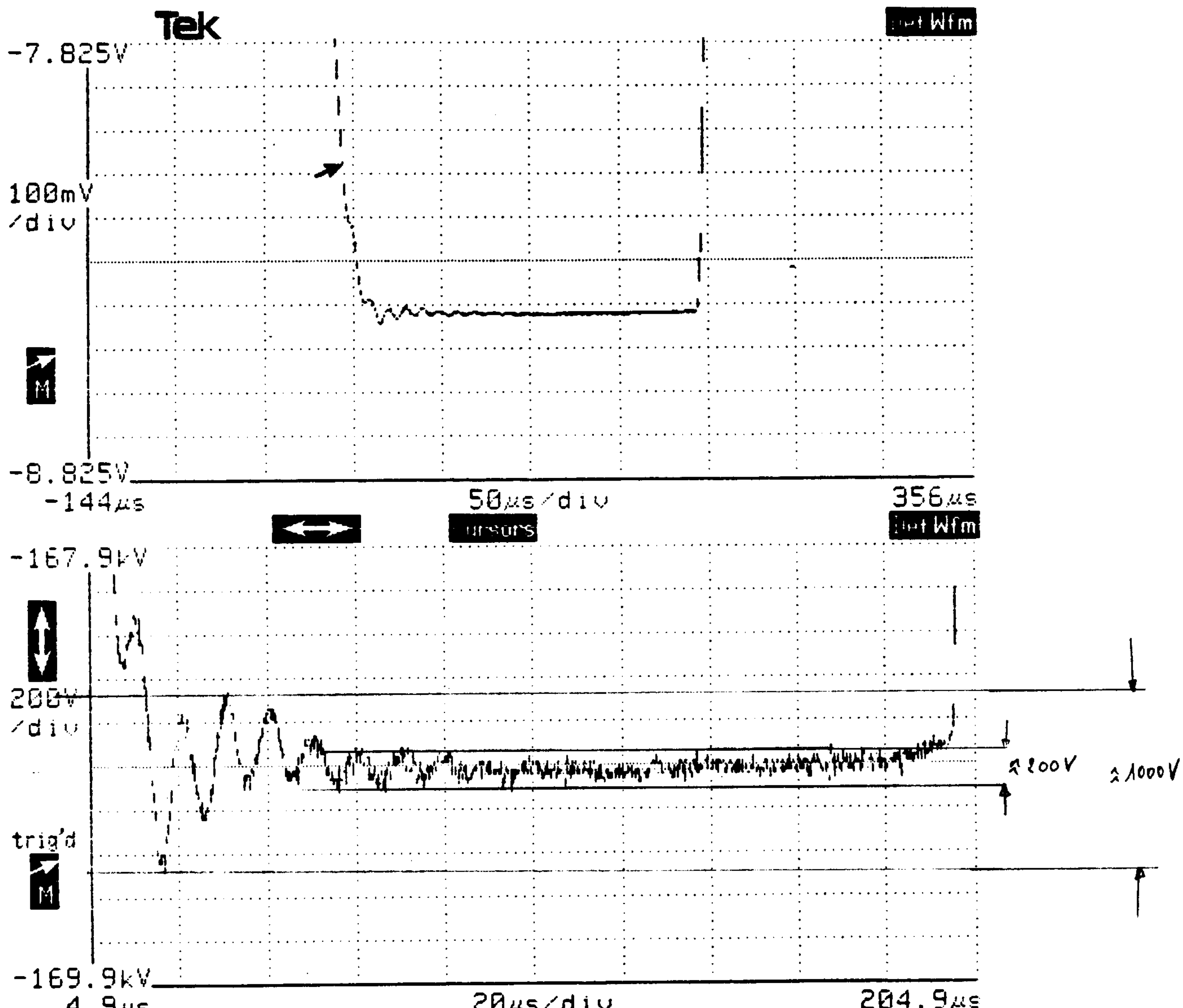
The second perturbation is due to the digital switch which stores energy into the transformer parasitic elements (leakage inductance and capacitors). Some solutions exist and have to be analysed to prove their faisability :

- To raise the cathode pulse rise time by :
  - Raising the rise time of the digital switch
  - Using an analogic amplifier with a larger dynamics (-1200V to 350V) instead of 0 to 350V

Results Fig. 5

$f = 25\,Hz$

11401 DIGITIZING OSCILLOSCOPE {exp:3.8,dig:3.91,dsy:3.3}
date: 20-MAR-91 time: 14:35:36 Instrument ID# B021121



Vertical Desc	Horizontal Desc	Acquire Desc	Lower Graticule	Vert Mag: Wfm
				200V
L2*20000 High Prec	Window @ 1024 pts	Continuous	Linear	Vert Pos: Wfm
				-168.9kV

Impedance	Coupling	BW Limit	Page to	Remove Wfm 3	Chan Sel
1MΩ	DC	20MHz	All Wfms Status	L2*20000 Window 1	Calcd Wfm

Upgrading the CTF modulators to a peak output power of 45MW for the Compact Linear Collider Test Facility CTF-2

P. Pearce

1. Introduction

The present CTF modulators are copies of those used in the LIL pre-injector for LEP and are designed to operate with 35MW S-band klystrons at 100Hz and with an RF pulse width of 4.5μs. The new CTF-2 test facility requires 45MW peak RF power pulses at a 10Hz rate. The low power RF synchronisation scheme must inject drive power into new 45MW klystrons every 10th modulator power pulse so not to over-drive the RF gun of the test facility, or the modulators made to work at 10Hz. In order to make a significant demonstration of the CLIC two beam acceleration scheme, a new layout requiring higher RF power is proposed for the new probe beam, the drive beam sections and for the new beam loading compensation cavities. This new test facility layout is shown in Figure 1.

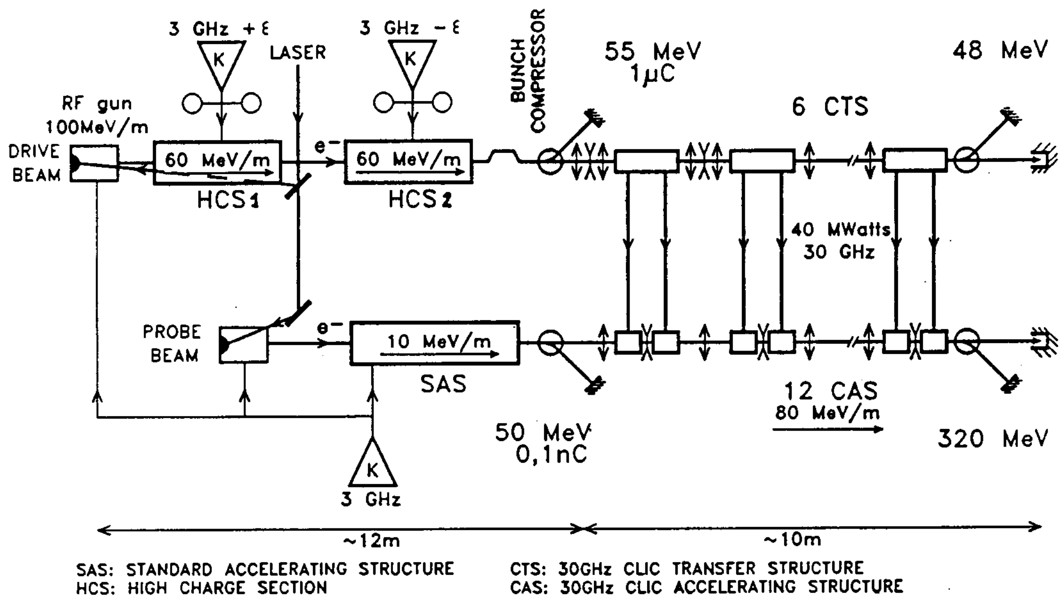


Figure 1. CTF2 test facility

2. Klystrons for 45MW operation

Two European 45MW S-band pulsed klystrons are available from Thomson and Valvo-Philips the present suppliers of LIL klystrons. The Thomson 45MW klystron (TH2132) is already in use with the Sincrotrone Trieste laboratory who have 10 modulators with these klystrons operating in their 10Hz repetition rate linac. The Valvo-Philips klystron (YK1645) is a derivative of their 35MW tube and is at the present in development. Both of these tubes are mechanically and electrically compatible with the present 35MW models such that they are plug replaceable without major mechanical changes. As well, the same focal coil assemblies can be used for both the 35 and 45MW klystrons. Each model of the new 45MW klystrons have two horizontal arms from the output cavity so that a recombiner is required when connecting up these klystrons to the machine. The Thomson recombiner operates in vacuum whilst its RF windows are for use with SF6 gas. Two additional RF windows are then needed between the klystron windows and the recombiner for the accelerator vacuum to be independent from the klystron. The Valvo-Philips recombiner works with SF6 gas so that only one extra 45MW RF window would be required between the recombiner output and the accelerator vacuum system. Both recombiners will be fitted with arc detectors. These different arrangements are shown in Figure 2.

Paper presented at the 2nd Klystron-Modulator workshop at SLAC for Future Linear Colliders 9th to 11th October 1995.

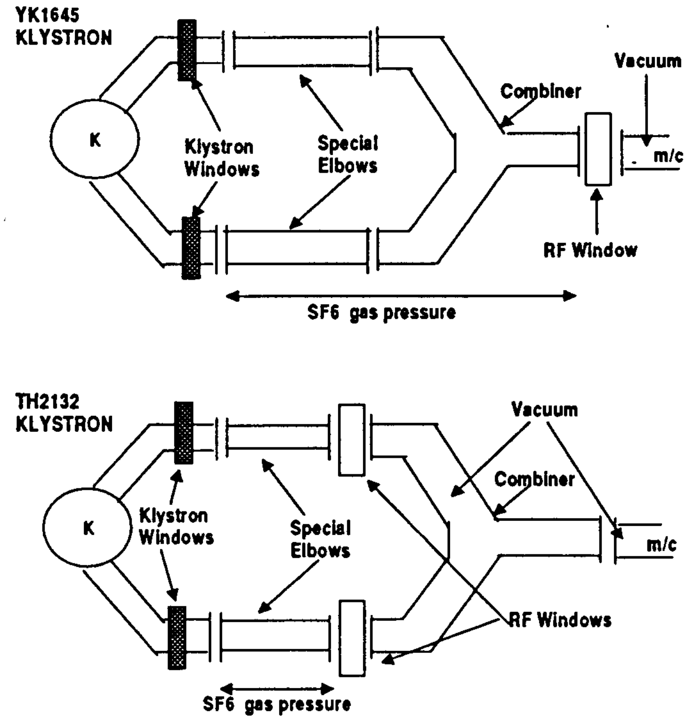


Figure 2 45MW Klystron outputs

The typical operating data for these two klystron types are given in Table 1 below.

PARAMETER	UNITS	THOMSON TH2132	VALVO YK1645
Peak beam voltage	kV	310	300
Peak beam current	A	328	327
Microperveance	A/V3/2	1.9	1.9
Heater voltage	V	28.5	20
Heater power	W	680	420
Focusing currents	A	3 x 200 max	3 x 200 max
Peak input drive power	W	80	170
RF pulse width	µs	4.5	4.5
Peak output power	MW	45	45
Average power	kW	20	20
Gain	dB	57	54
Efficiency	%	44.5	46
Pulse repetition rate	Hz	100	100
SF6 gas pressure on windows	bar	4.5	5.0
Peak inverse voltage	kV	75	75

Table 1. Preliminary operational klystron parameters

3. Klystron performance for beam loading compensation

The 45MW klystron central frequency is 2998.5MHz for normal operation. When the klystrons are used for the beam loading compensation scheme they will generate up to 45MW RF pulses at side frequencies close to the central frequency at 2998.5 ± 8 Mhz. The Thomson tube TH2132 has been tested fully at 45MW peak output over this frequency range, where the input power has been adjusted to maintain a saturated condition. The Valvo RF structure to be used in their 45MW tube has been tested for this bandwidth in a YK1600 35MW klystron. It should then be possible to use either types in acceleration or beam compensation positions within CTF-2. The power-bandwidth data for the Thomson tube is shown in Figure 3.

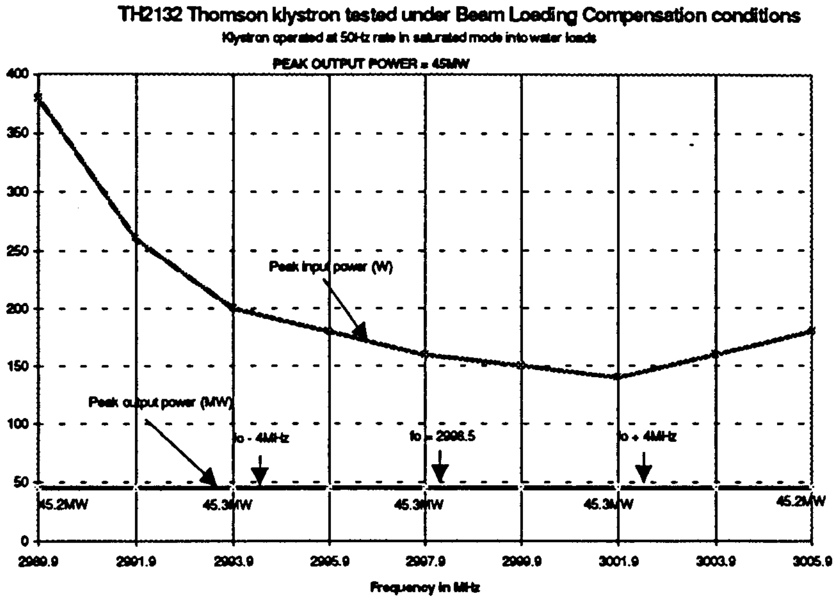


Figure 3. Thomson TH2132, 45MW klystron

4. Klystron Rf output phase stability versus high voltage stability

The output phase stability is dependent on the stability of the high voltage pulse applied to the klystron. The phase shift over the active klystron length, between input and output cavities, can be written as in (1) where θ is in radians and d is the length between the klystron input and output cavities in metres.

$$\theta = \frac{2\pi f d}{c}\left(1 - \frac{1}{\left(1 + \frac{Vk}{Eo}\right)^2}\right)^{-\frac{1}{2}} \text{ radians} \qquad (1)$$

The electrical phase shift per kilovolt of change has been calculated below for a klystron operating at two voltages corresponding to 40 and 45MW output power using data from a TH2132 klystron. The Valvo klystron should have a very similar performance.

$$\Delta\theta/\Delta Vk \cong 1.8 \text{ degrees per kV variation}$$

The pulse to pulse voltage accuracy of the D'qing system is about ± 0.1% giving about 0.56 degrees variation at 310kV. The periodic voltage ripple created by the PFN's 25 lumped impedance cells also contribute to the overall beam energy fluctuations and phase stability. The typical measured voltage ripple from a PFN is about ± 0.25% or 1.4 degrees of phase jitter. If both pulse to pulse stability and PFN voltage ripplé add, the total phase variation is about 2 degrees with the PFN contributing a larger proportion. Therefore good PFN adjustment is important to reduce this ripple to a minimum.

5. Pulse transformer and load matching

The present 35MW klystrons operate with a maximum pulse voltage of 270kV, and a PFN voltage of about 41kV for a new klystron of this type. There is a positive 10% mismatch between the klystron load and PFN impedances. To obtain a 310kV pulse either a higher ratio transformer can be used or the primary PFN voltage can be increased. From these two options a larger turns ratio pulse transformer has been chosen for the 45MW design upgrade. The choice of the turns ratio is linked to the referred klystron impedance, the PFN impedance, the amount of mismatch desired as well as the maximum primary PFN voltage. To optimize this, a voltage mismatch expression (2) derived from these parameters and using the simple equivelant circuit of Figure 4, is obtained.

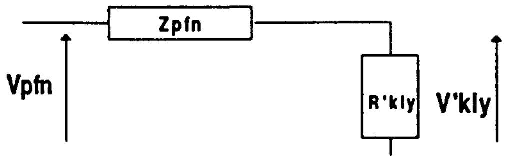


Figure 4. **Equivelant output circuit**

The mismatch is $m = \frac{v}{V'kly}$ (Figure 5) at the klystron, and the mismatch equation using a step-up transformer of ratio N and efficiency η is:

$$Vkly = \frac{Vpfn \cdot N \cdot \eta}{(2-m)} \qquad (3)$$

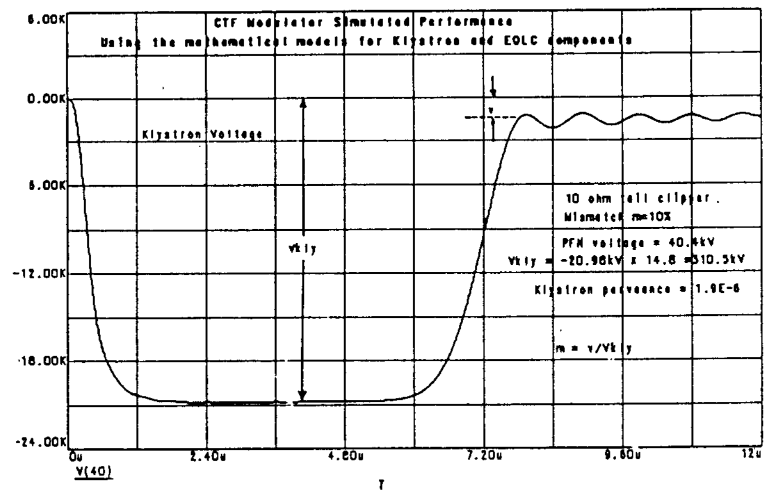


Figure 5. **Percentage voltage mismatch**

The ratio $\frac{Vkly}{Vpfn}$ is plotted against mismatch in Figure 6 for three transformer turns ratios. This shows that to maintain the centre of the design at 10% impedance mismatch and generate a voltage pulse of 310kV for 45MW operation a transformer ratio of 1:14.8 is needed with the PFN charged to 40.4kV. The present 1:13 ratio pulse transformer would require a PFN voltage of 47kV for the same conditions and is close to the peak rating of the present PFN capacitor reducing overall reliability.

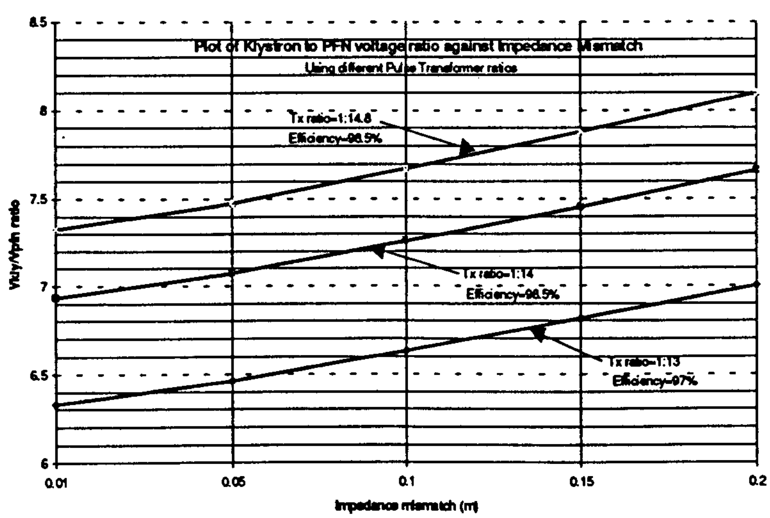


Figure 6. **Impedance mismatch**

6. The Thyratron switch

The thyratron switch used in the 35MW modulators is the EEV CX1836A. This tube has a maximum peak current capability of 10kA and will operate up to 50kV anode voltage. The conditions in the upgraded design will require a maximum 5kA anode current with approximately 41kV maximum anode voltage. The peak thyratron current as a function of positive mismatch is given below:

$$\hat{Ithy} = \frac{Vpfn}{R'kly(2-m)} \text{ Amps} \tag{3}$$

At the 45MW operating conditions where the klystron perveance $\rho = 1.9 \cdot 10^{-6}$ $A/V^{1.5}$, the PFN voltage 40.4kV, N= 1:14.8 and with m = 10% gives a peak thyratron current of 4926A. The average current is 3.2A so that the RMS current is about 125A. The thyratron parameters for the upgraded modulator design are shown in Table 2 below.

Parameter	Units	CX1836A thyratron	CTF upgrade
Anode voltage (max)	kV	50	41
Anode current (max)	kA	10	5.2
Average current	A	10	3.2
Anode heating factor	VAHz	$300 \cdot 10^9$	$21 \cdot 10^9$

Table 2. Thyratron requirements

7. The Pulse Forming Network (PFN)

The present PFN has 25 cells each having an inductance L = 0.625µH and capacitance C = 25nf with an adjusted impedance of about 5 ohms and 10% mismatch. To maintain a pulse flat-top width of at least 4.5µs in the upgraded design, the pulse width at 70% must be about 6.3µs. With the larger transformer step-up ratio the new PFN impedance must be a lower value to match the new referred klystron resistance of about 4.32 ohms. The adjusted value of the new PFN impedance, with 10% mismatch, will be about 3.9 ohms. This amount of change is not possible with the tuning inductors alone, and the PFN capacitor value has been increased to bring it into this range. Taking into account the capacitor tolerances of ±6.5% and the maximum tuning range on the cell inductor, a 32nf value for the cell capacitance was chosen.

8. End-of-line and inverse voltage protection

The end-of-line diode -resistor network in parallel to the PFN absorbs negative voltage reflections on the line and at the thyratron anode. These reflections can come from intermittent short circuits in the klystron or its tank assembly. The front end snubber network fitted across the sending end of the triaxial pulse cable is used to damp out the fast reflections that are generated when the rising edge of the thyratron pulse hits the pulse transformer inductance. These voltage spikes travel up and down the triaxial cable and could cause problems to it and the thyratron if the snubber network was not present.

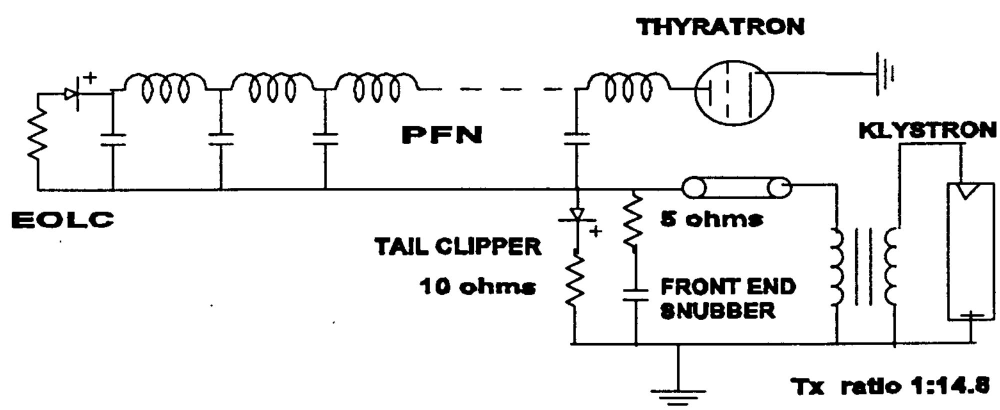


Figure 7. Basic modulator circuit

A new tail clipper circuit protection element has been added, as in Figure 7, because of inverse klystron voltage faults that have occurred in the present modulators. If during the high voltage pulse the thyratron ceases to conduct the magnetic energy stored in the pulse transformer creates a large positive voltage pulse at the klystron cathode. Figure 8 shows the normal klystron voltage pulse and an inverse klystron voltage fault that has occurred without a tail clipper. This inverse voltage can cause internal breakdowns in the klystron gun structure. The tail clipper network will prevent this happening and does not have an adverse effect on the positive mismatch, but must be designed so not to affect thyratron recovery conditions.

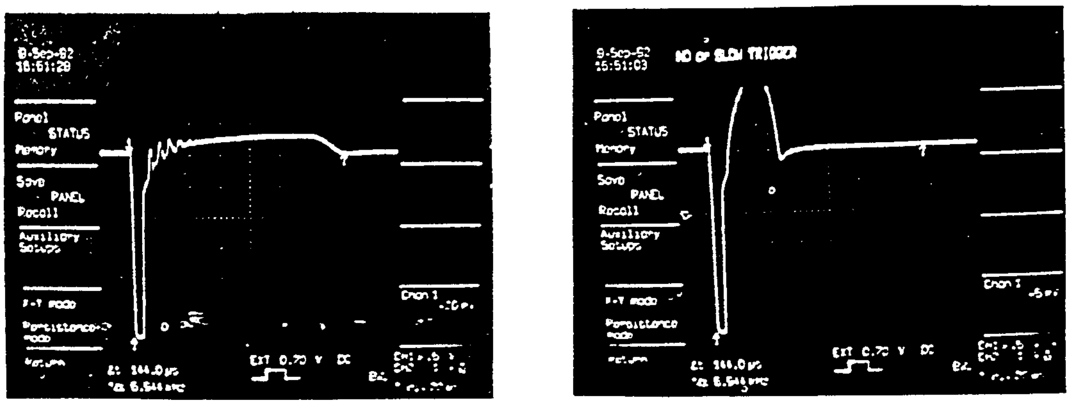


Figure 8. **Normal and inverse fault voltage klystron pulses**

9. Summary.

All components described have been designed and integrated into the present modulator structure. The modulator performance with these new components has been simulated under normal and fault operating conditions successfully. An SCR command charging system is being developed for the resonant (charging time t=4ms) high voltage supply. This will enable the modulator to operate at rates between 10 and 100Hz without having to maintain high voltage on the thyratron anode for long periods, and avoid PFN voltage droop at the low 10Hz repetition rate. The project schedule requires that the first of the three modulators be upgraded for an early 1996 operation of the CTF-2 test facility.

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Power Modulators Based on Advanced Transformer Line Methods

I. Yampolsky and M. Choi
Integrated Applied Physics
M. Gundersen
U.S.C.

An approach to modulator design is described that has the following advantages:

- Overcome rise time limitations imposed by switches and transformers, for high voltage, high power transfer operation
- Reduce dependance on high voltage switch-transformer combination
- Produce a design so that each stage has no reflected energy
- Optimize efficiency of energy transfer

Support for this work has been provided by the Department of Energy, the Office of Naval Research, and IAP IR&D funding.

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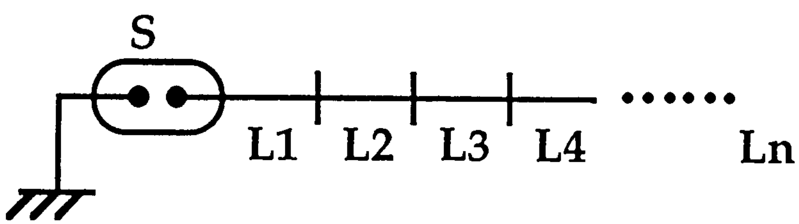
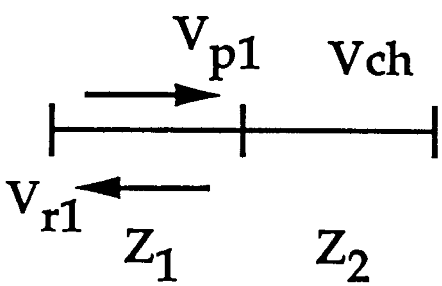
General Concept (1)

— Smith Approach





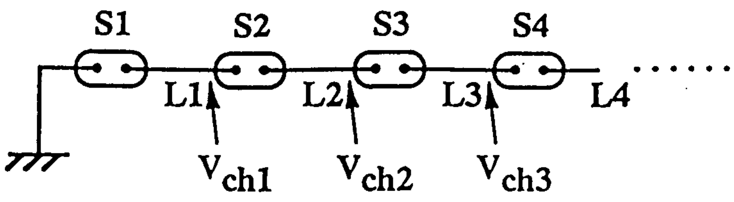
S – Switch
Ln – Pulse Forming Line

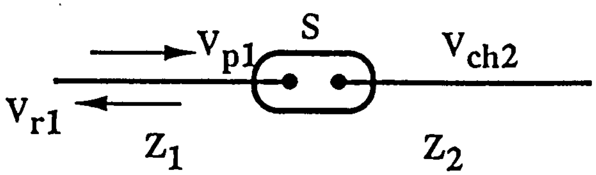
Line Number Ln	Relative impedence of the line R(Ln)/R(L1)	Relative charging voltage of the line Vch(Ln)/V(S)	Relative pulse voltage in line Vp(Ln)/V(S)
1	1	1	-0.5
2	3	1	-1.0
3	6	1	-1.5
4	10	1	-2.0
5	15	1	-2.5
6	21	1	-3.0
7	28	1	-3.5
8	36	1	-4.0
9	45	1	-4.5
10	55	1	-5.0
11	66	1	-5.5
12	78	1	-6.0

The charging voltage and pulse voltage are given relative to the switch voltage.

General Concept (2)

— New Approach





$$V_{r1} = \frac{V_{ch2} - V_{p1}\,(1 - Z_2/Z_1)}{1 + Z_2/Z_1}$$

S – Switch
L – Pulse forming line
V_{ch} – Switch charging voltage
V_p – forward wave
V_r – reflected wave

Line Number Ln	Relative impedence of the line R(Ln)/R(L1)	Relative charging voltage of the line Vch(Ln)/V(S)	Relative pulse voltage in line Vp(Ln)/V(S)	Over voltage on switch
1	1	1	-0.5	
2	5	2	-1.5	3
3	15	3	-3.0	6
4	35	4	-5.0	10
5	70	5	-7.5	15
6	126	6	-10.5	21
7	210	7	-14.0	28
8	330	8	-18.0	36
9	495	9	-22.5	45
10	715	10	-27.5	55
11	1001	11	-33.0	66
12	1305	12	-39.0	78

The charging and pulse voltage are given relative to the switch voltage. The over voltage is given relative to the switch closing voltage.

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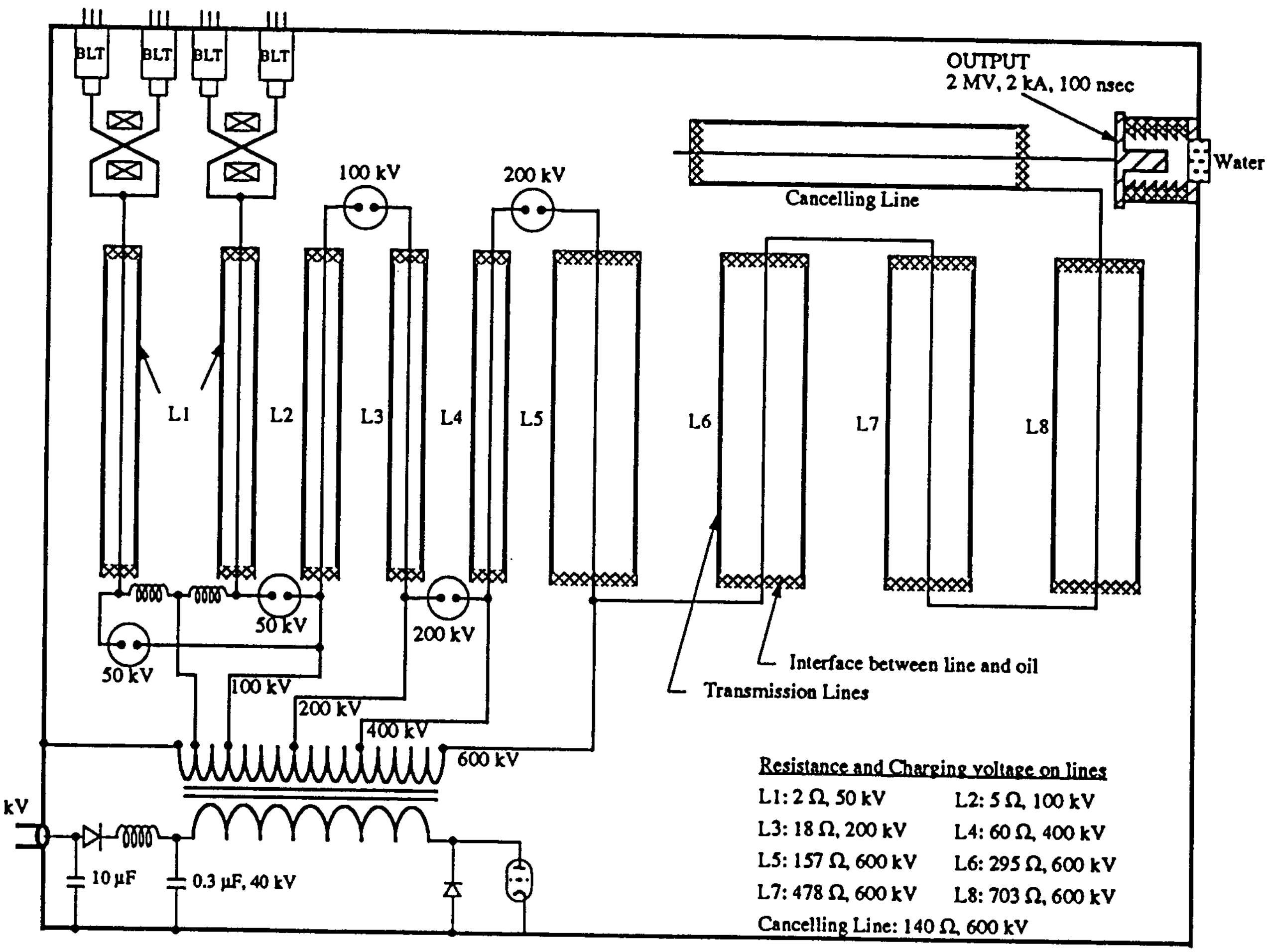
Application Example (2)

– 2 MV, 2 kA, 100 nsec Accelerator



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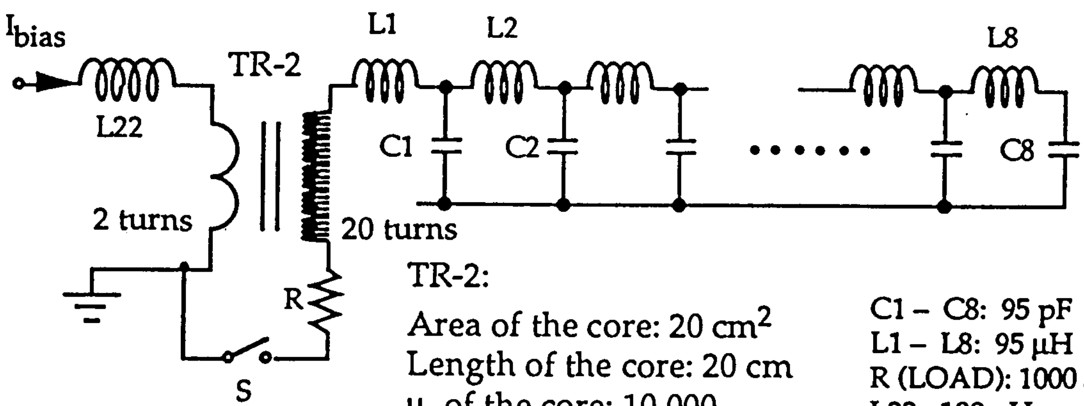
Magnetic Pulse Flattener – Simulation

Simulation circuit configuration

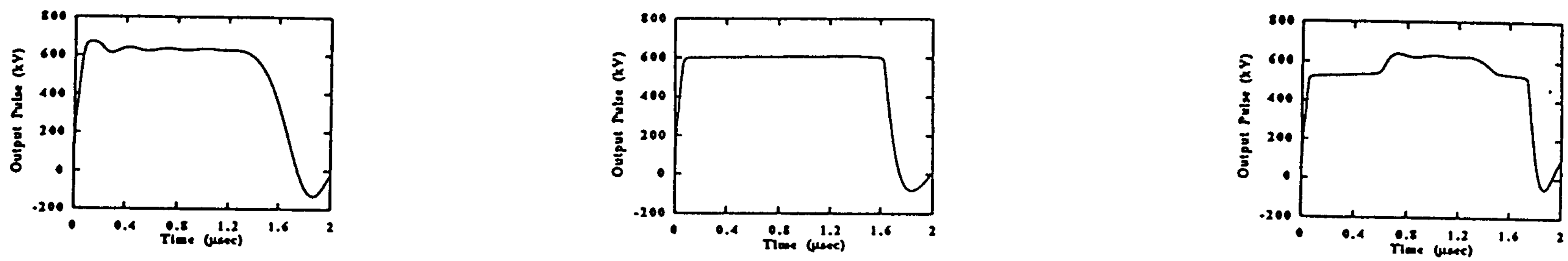
I_{bias} = 5250, 6000, 6750 A   Charging Voltage: 1.26 MV



TR-2:
Area of the core: 20 cm^2
Length of the core: 20 cm
μ of the core: 10,000

C1 – C8: 95 pF
L1 – L8: 95 μH
R (LOAD): 1000 Ω
L22 : 100 μH

Simulation results



(a) High bias current   (b) "Just right" bias current   (c) Low bias current

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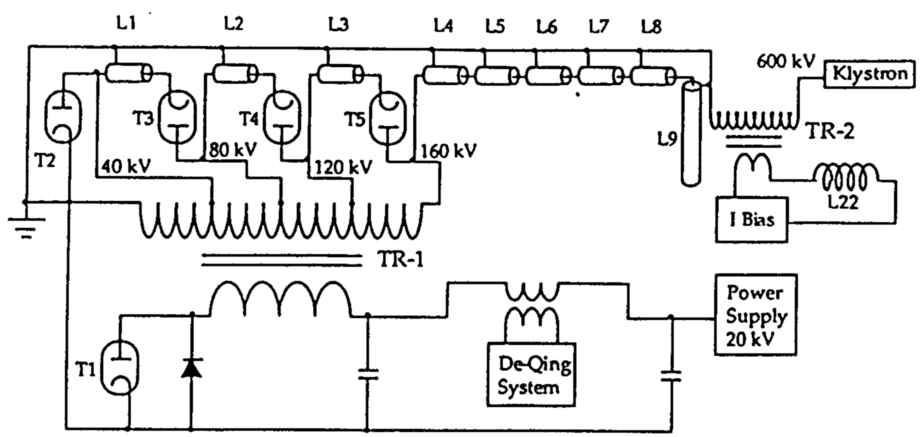
Application Example (1)

– 600 kV, 600 A, 1.5 μsec Klystron Driver

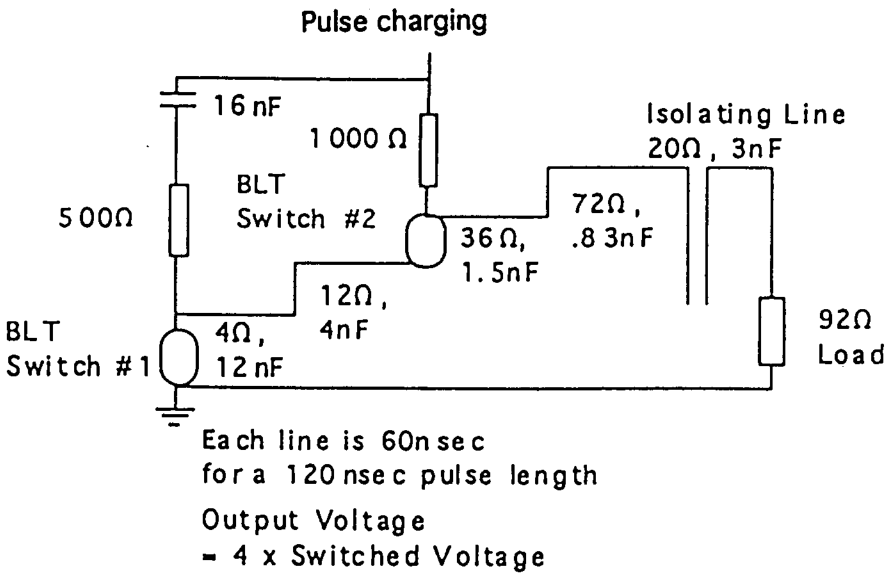


Line	Voltage (kV)	Impedance (Ω)	Capacitance (nF)
L1	40	4.5	155.00
L2	80	22.5	31.00
L3	120	67.5	10.30
L4	160	157.5	4.45
L5	160	283.5	2.47
L6	160	445.5	1.57
L7	160	643.5	1.08
L8	160	877.0	0.79
L9	-160	123.0	5.70

Circuit diagram

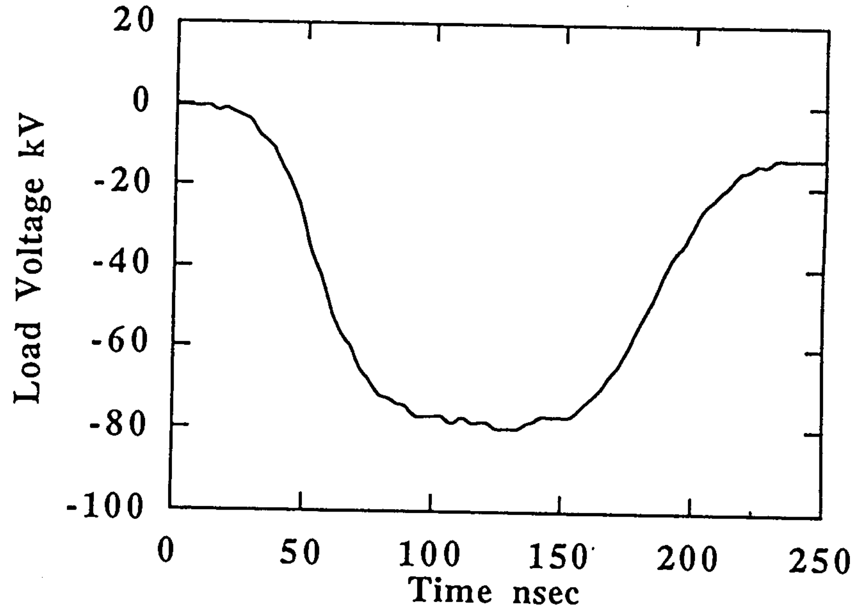
Design of the lines

The Demonstration Model and the Result



Circuit diagram of two-switch high voltage pulse modulator

Output voltage at 22 kV switch voltage and 800 A load current



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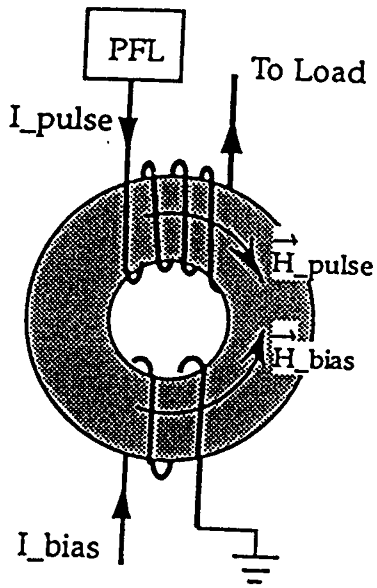
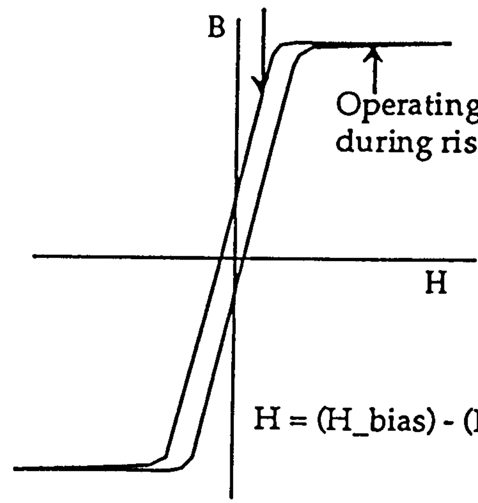
Magnetic Pulse Flattener





Using bias current on the magnetic core to obtain:

Fast pulse risetime – Saturated core (low inductance)
Flat pulse top – Unsaturated core (high inductance)

THYRATRON LIFETIMES, A BRIEF REVIEW

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1 Mandate for Thyratron Section

For a good overview of the NLC modulator requirements see references [9, 17]. Tony Donaldson has posed the following points for consideration during the thyratron section of the Modulator Switch Session. The NLC modulator switches must reliable, fast and long lived. If we were to build a LC today with 3000 modulators, we would end up replacing thyratrons at the rate of one every two to three hours. Even with a MTTF = 30 khrs, we would loose a thyratron every 10 hours. The Thyratron Switch session will consider the present specifications for the NLC (SLAC style) modulator that follows:

Epfn	= 360 to 461 Joules, modulator will drive 2 parallel klystrons
Vpfn	= 72 to 75 kV
ib	= 3 kA thyratron anode current
tr = tf	= 300 to 400 ns
tpw	= 1.2 us
PRF	= 120 and then at a later time 180 Hz
PT ratio	= 7:1
Klystron cathode voltage	= 480 to 505 kV
Klystron beam current	= 400 to 430 A for 2 parallel klystrons

• Oxide cathode thyratrons at SLAC
current density = 30 A/cm2
240 modulators for 5 years [SLC Era] at 5000 hours/year
performance: epy = 46 kV (2 gaps) , ib = 6 kA, tpw = 3.5 us, f = 120 Hz
reasonable lifetime: MTTF = 8 khrs
reasonable cost: = 8 k$ for hundreds
power consumption: typical heater power = 420 W upto 700 W
typical reservoir power = 90 W

• Dispenser cathode thyratrons for NLC
(current density ~150 A/cm2)
performance: epy = 72 kV (3 gaps), ib = 3 kA, tpw = 1.2 us, f = 180 Hz
lifetime: MTTF > 30 khrs
cost: < 8 k$ for thousands

power consumption: < 500 W

2 Experience on Thyratron Lifetimes

1. CERN PS

Average lifetime in 200 thyratrons in CERN PS >20,000 hours (low Hz) (approx 10^8 pulses?), which was probably determined by filament hours[11]. Tests done at EEV[15] on a CX1171 for 9 x 10^6 shots resulted in a requirement to raise the reservoir voltage by 50 mv. After a change of about 1 volt the tube would have to be replaced. This implies a life of 2 x 10^8 shots for a CX1171.

2. SLAC

Thyratron experience at SLC with 120Hz operation was described at PAC in 1991 in reference [16] show lifetimes averaging

- 5200 hrs at 120Hz = 2.2 x 10^9 pulses

In a 1992 Power Modulator Symposium paper there were lifetimes quoted[8] as

- 16,000 hours at 60 Hz = 3.5 x 10^9 pulses
- 12,000 hours at 120 Hz = 5.2 x 10^9 pulses

Also thyratron lifetimes based on 243 modulators were extracted from a 1994 paper [12]. We assume 66% operation of SLAC per year, based on the age of the oldest tube compared to its operating hrs. There are a few exceptional tubes which have exceeded 100,000 hrs but it is difficult to tell how many shots this corresponds to.

Rate (pps)	Tube Replacements (per month)	Life (hours)	Life (pulses)
10-60	4.5	26,000	3 x 10^9
60	7.5	15,000	3.2 x 10^9
120	14	8,000	3.4 x 10^9
180	(21?)	(5,300?)	(3.4 x 10^9?)

3. LANL

In a 1990 paper[4] thyratrons were operated for 10^{10} shots with and without reverse current.

4. Rutherford Appleton Labs

They have converted to hollow anode CX1725 which have dispenser cathodes and an increased reservoir volume. They operate at 50Hz and should have some useful data on lifetimes by now.

3 Methods for Improving Thyratron Lifetime

1. Select a thyratron manufacturer [EEV, ITT/Triton, EG&G, or Litton].

2. Saturable reactors
The heating of the anode will be a maximum if the electrons that impinge on the anode have full energy. If the peak current flow is delayed until the voltage across the tube is collapsed (i.e., low energy electrons) then the energy deposition will be substantially reduced.

Since the relative magnitudes of the erosion for different electrode materials can be closely predicted by the energy required to melt or vaporize the material[6], it is thus important to reduce the beam energy.

Measurements were performed at CERN[10] on an EEV CX1171 thyratron with saturating ferrites mounted on the anode in a 15 Ω system. The measurements showed that, with ferrites, the commutation losses are reduced by a factor of 7. PSpice calculations done at TRIUMF[1, 2, 3] shown in Fig 1, show reasonable agreement with the CERN results. The calculated commutation losses are reduced by a factor of 5.3 with the CERN configuration.

Fig 2 shows the calculated effect on the pre-pulse cathode current with and without a saturated ferrite mounted on the anode or on the cathode. When the 72 cm^2 ferrite is connected there is an extra displacement current peak whose magnitude is dependent on the stray capacitance of the anode and the ferrite (to ground).

Fig 3 shows the mechanical arrangement of the saturating ferrite which was installed in the modified coaxial thyratron housing. Fig 4 is a photograph of the ferrite assembly before installation in the modified thyratron housing. Fig 5 and Fig 6 show the measured pulses without and with a 72 cm^2 ferrite respectively. The measured anode displacement current peak is too large since we had overlooked the stray capacitance of the ferrite when designing the housing. The high anode displacement current will significantly increase the anode power dissipation and thus reduce the effectiveness of the ferrite.

Fig 7 shows the calculated instantaneous power in the 30Ω system with two different CMD5005 ferrite areas. The calculations showed that 80% of the total switching loss occurs in the anode with no ferrite and that about 40% of the total switching loss occurs in the anode with 72 cm^2 of ferrite installed on the anode of a CX1171. Note that the power dissipation on the first and second grids are not effected by the presence of ferrite.

Fig 8 shows the measured voltage rise time as a function of reservoir voltage with and without a saturable ferrite. The rise is independent of reservoir voltage within the normal operating range with the ferrite installed.

We noticed two problems with our design. One is that if the ratio of the ferrite outer diameter to inner diameter is large then the inner portion will saturate before the outer portion, thus slowing the reactor switching times. The other problem that we had was that the capacitance to the ground in the coaxial housing was too high and thus we obtained some smaller O.D ferrite for the next series of tests.

The pulser was modified to accept a CX2171 (an upgraded CX1171 with a dispenser cathode and a high volume deuterium gas reservoir) which was borrowed from EEV and life tests were to be done but all further tests were terminated last year along with KAON. However TRIUMF now plans to do a limited series of tests to extend this work for LHC studies.

Measurements done recently at SLAC[14] with a thyratron and a klystron modulator do not give such encouraging results. The saturable ferrite mounted on the anode resulted in only a 10% reduction in the anode temperature rise.

There were some measurements done at LANL in about 1990 with 10^{10} pulses[4] without saturable reactors and there were plans to extend the tests using a saturable reactor but we have not seen the results.

3. Improve electrode materials and design
Oxide surface coated vs impregnated tungsten cathodes (dispenser coated). Porous tungsten impregnated cathodes in test devices have led to an order of magnitude increase [5] in the following parameters;

- Switch lifetime
- Peak and average switch current
- Rate of rise of current

6. Reverse current
Hollow anode tubes reduce damage caused by reverse current. The effects of reverse current on a thyratron anode after 10^{10} limit reverse current is shown in reference[4]. There are papers which address details in circuitry to improve impedance matching by modifying details in the pulse transformer circuit[7, 13] and thus minimize reverse current.

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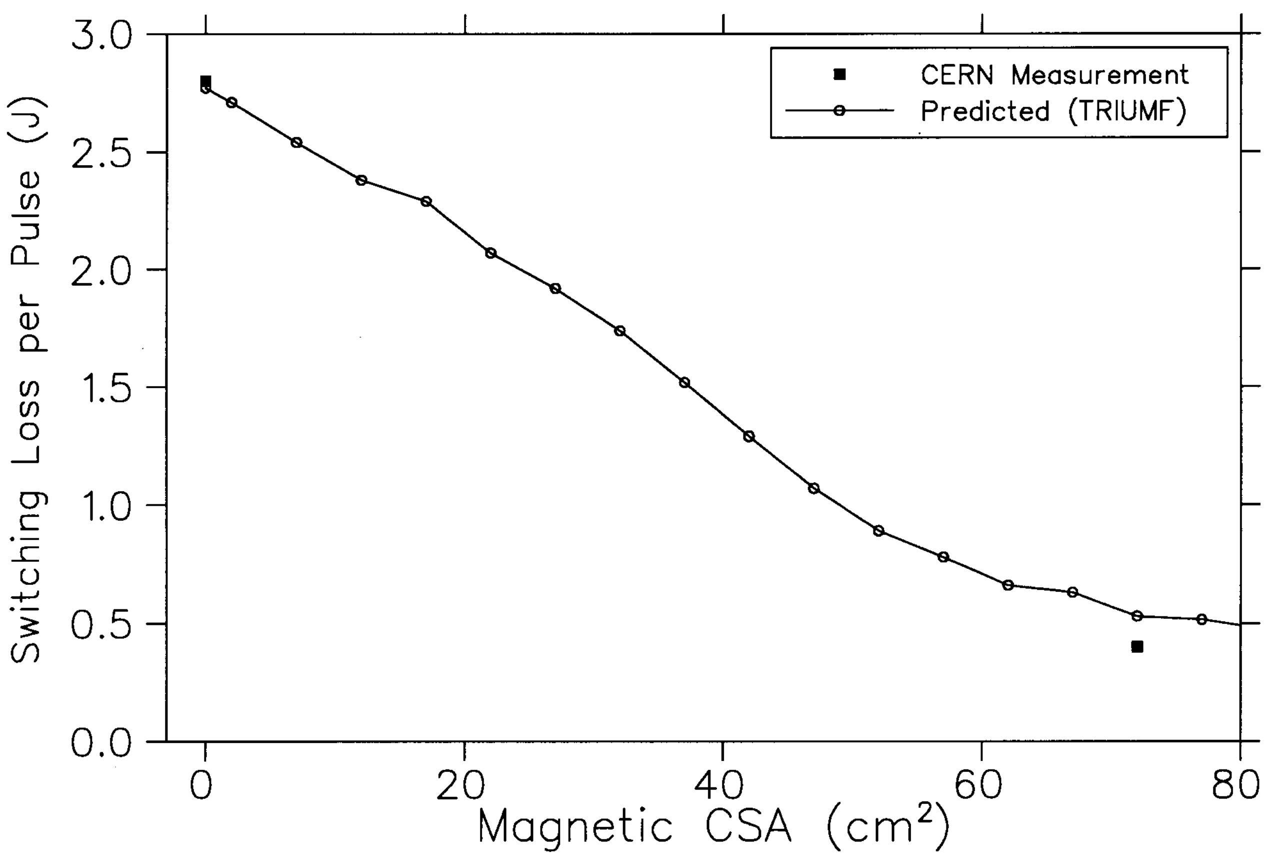

Fig. 1: Comparison of PSpice model with CERN Measurements.

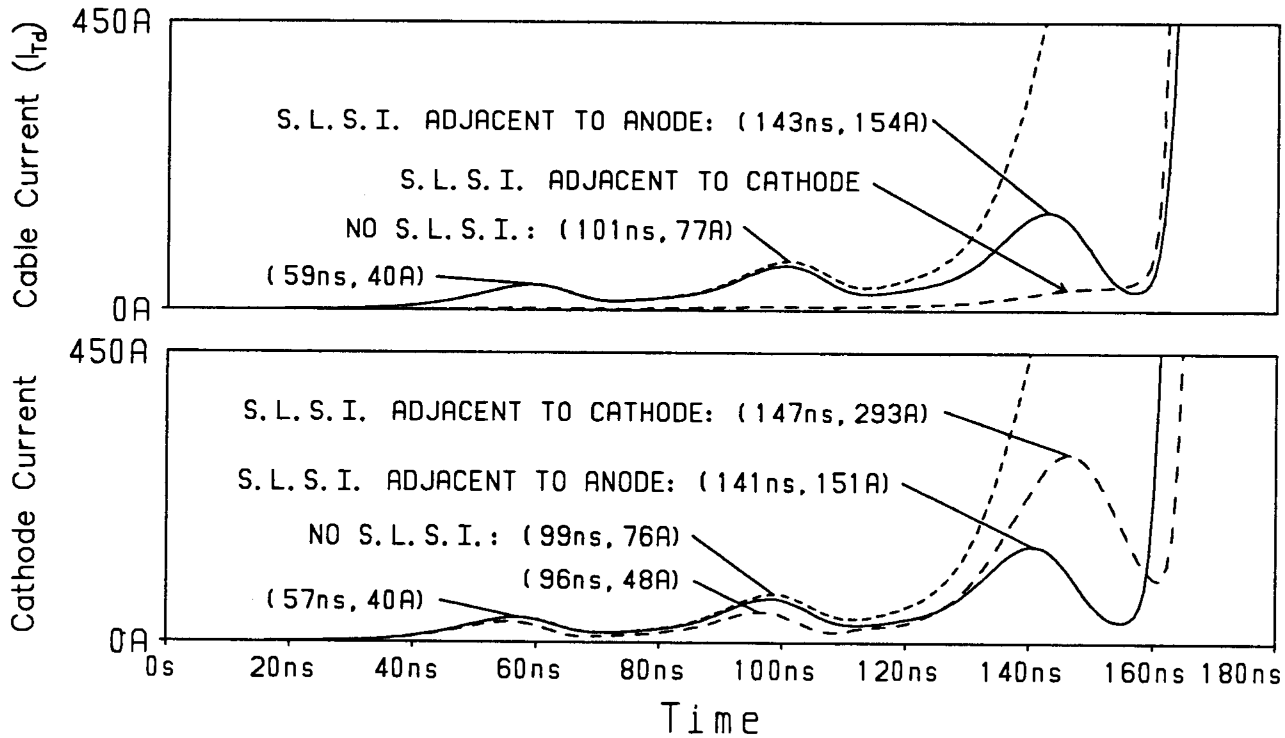

Fig. 2: Calculated effect of ferrite (72 cm^2 of CMD 5005) on prepulse peaks.

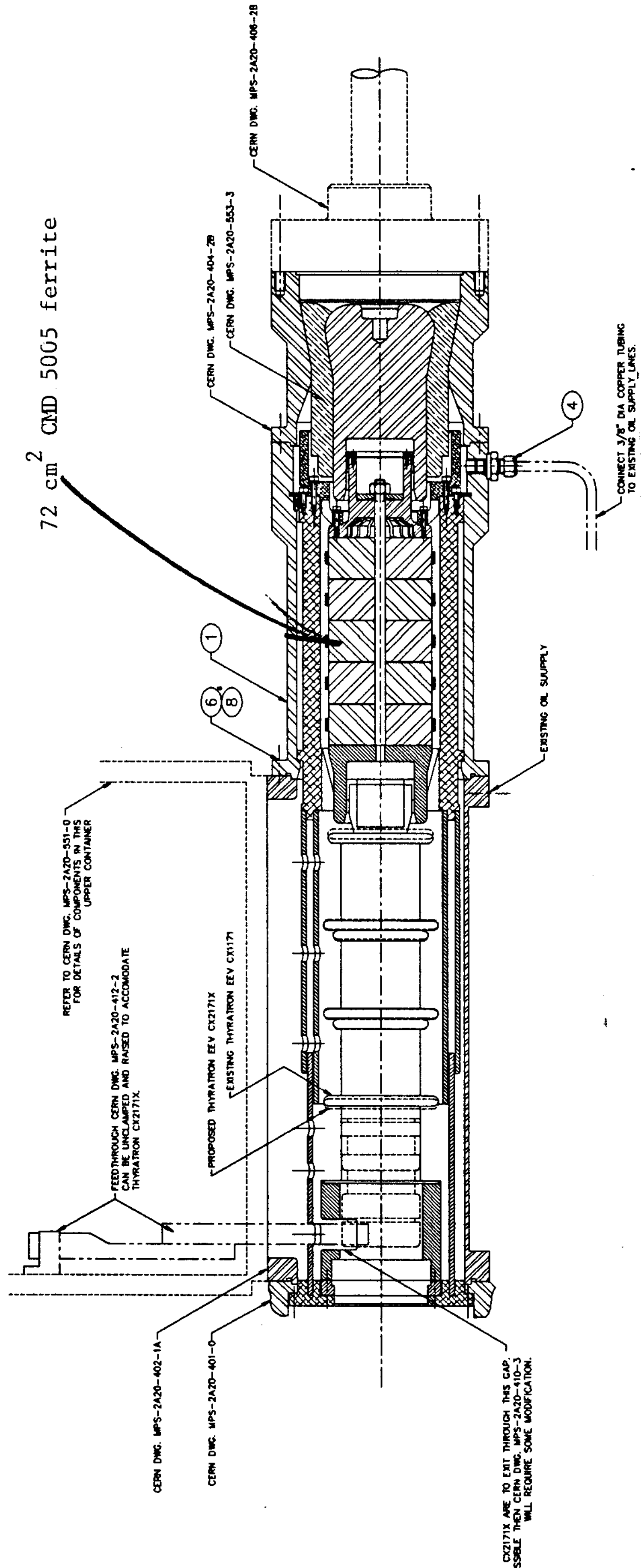

Fig. 3: 72 cm^2 CMD 5005 on CX 1171.

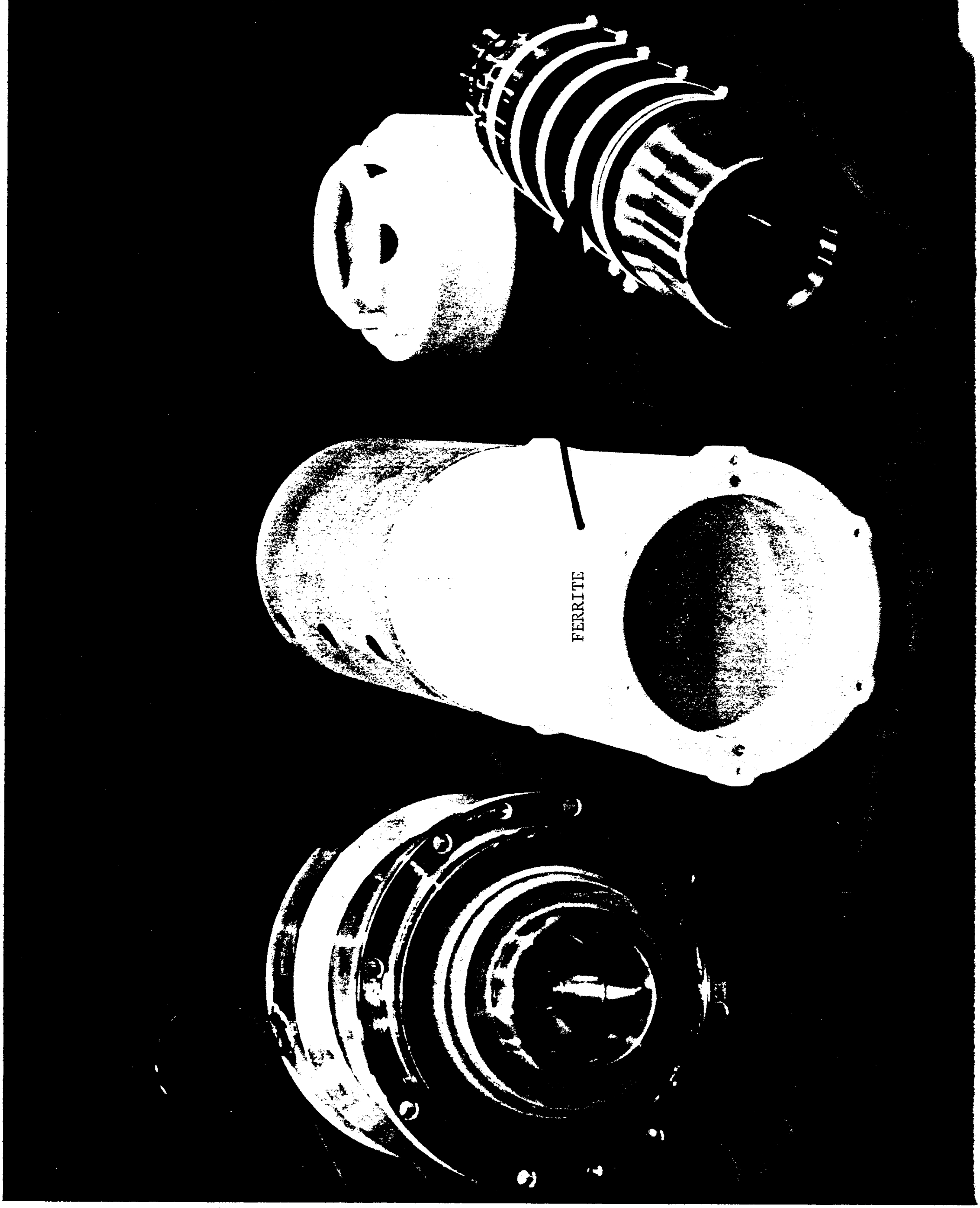

Fig. 4: 72 cm^2 CMD5005 Ferrite Mechanical Assembly.

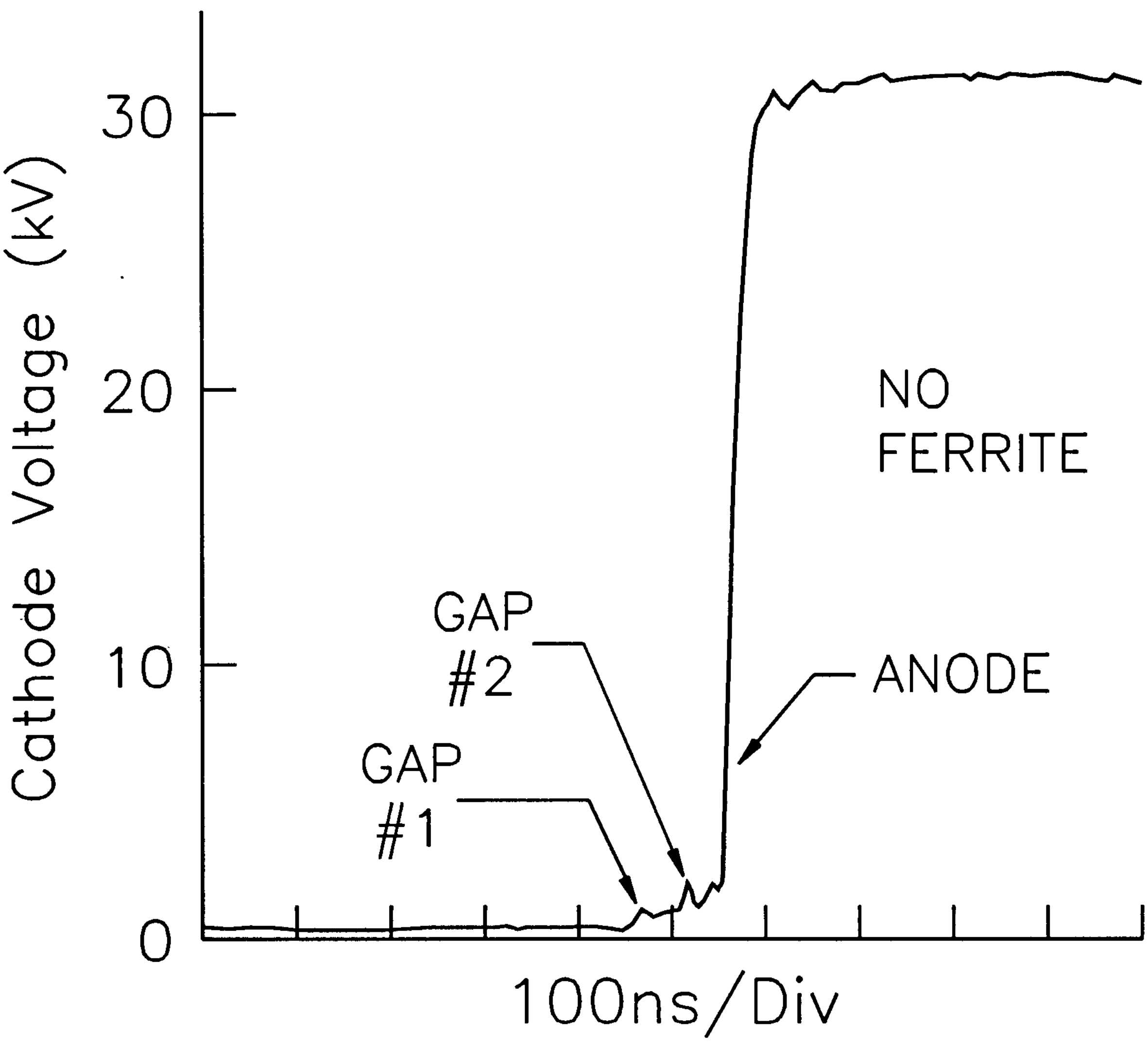

Fig. 5: CX1171 Cathode Pulse with no Ferrite on Anode.

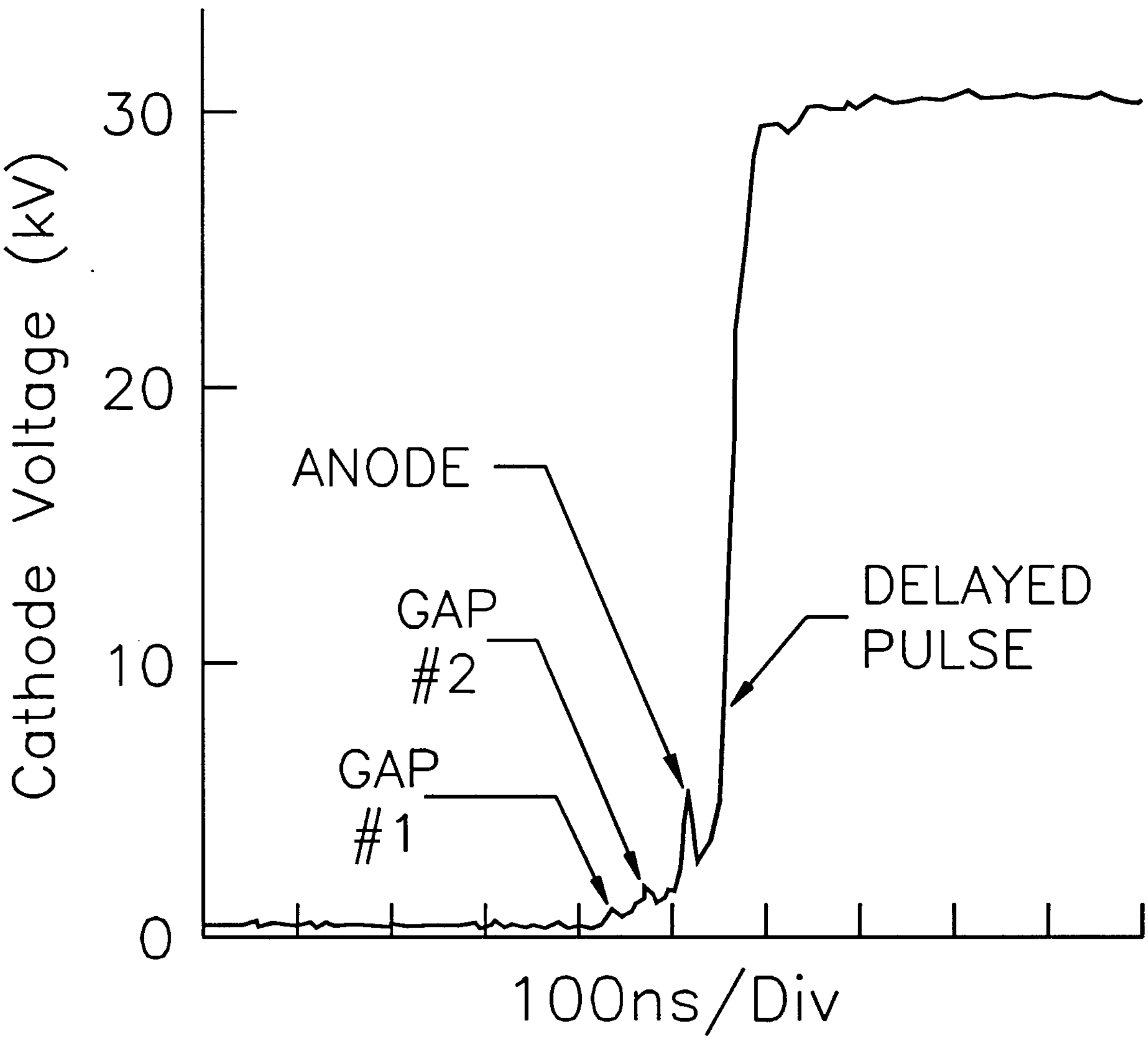

Fig. 6: CX1171 Cathode Pulse with 72 cm^2 CMD5005 Ferrite on Anode.

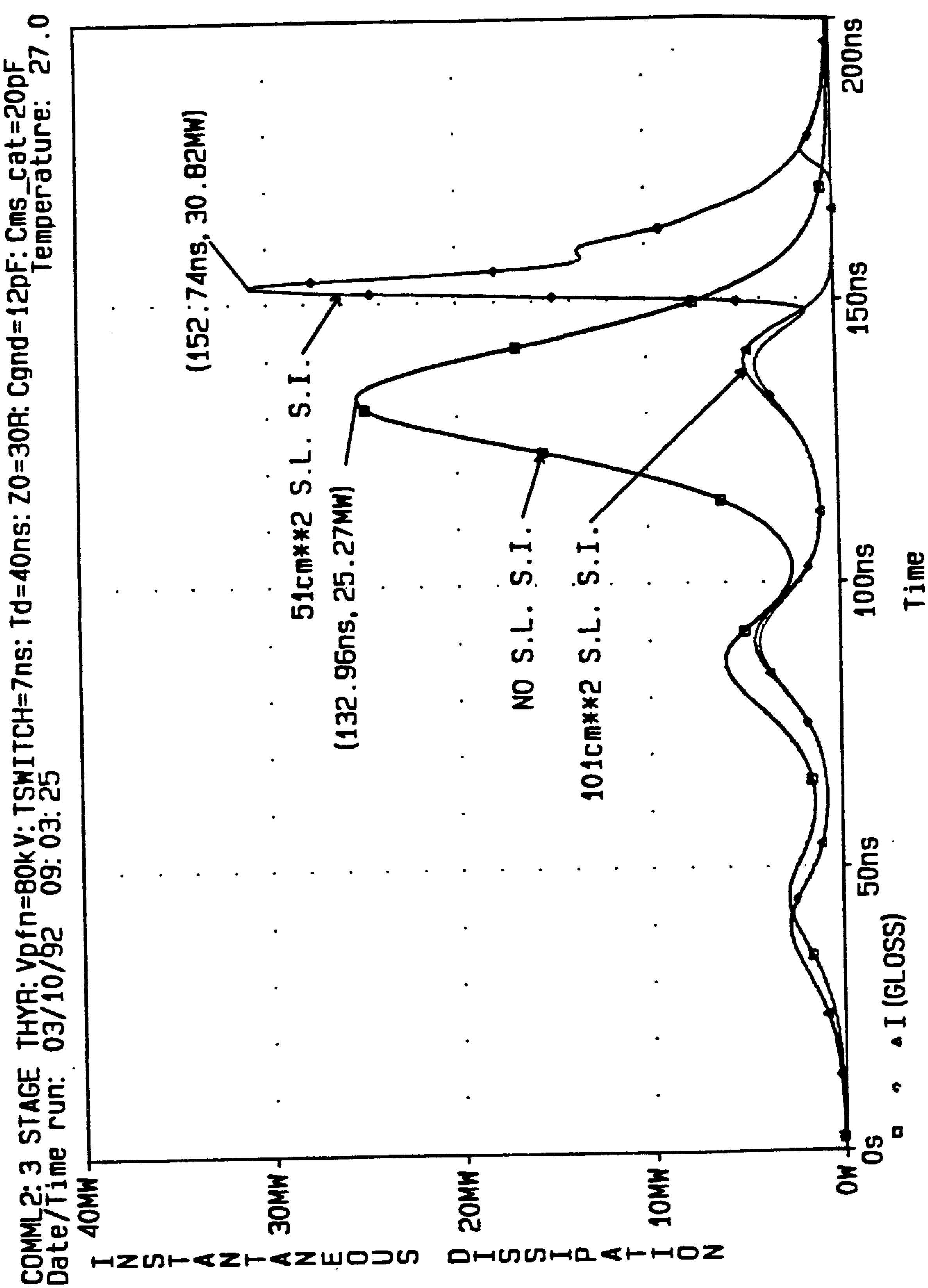

Fig 7: Instantaneous power dissipation in thyratron, calculated from $((V_a - V_k) \times I_k)$, for magnetic CSA's of 0 cm^2, 51 cm^2 and 101 cm^2 connected on anode. [PFN pre-charge=80 kV; 'TSWITCH'=7 ns; Z_0 = 30 Ω; parasitic capacitance from grading ring to ground=12 pF; 20 pF stray capacitance from cathode to ground; gap turn-on delay=40 ns; no saturating inductor].

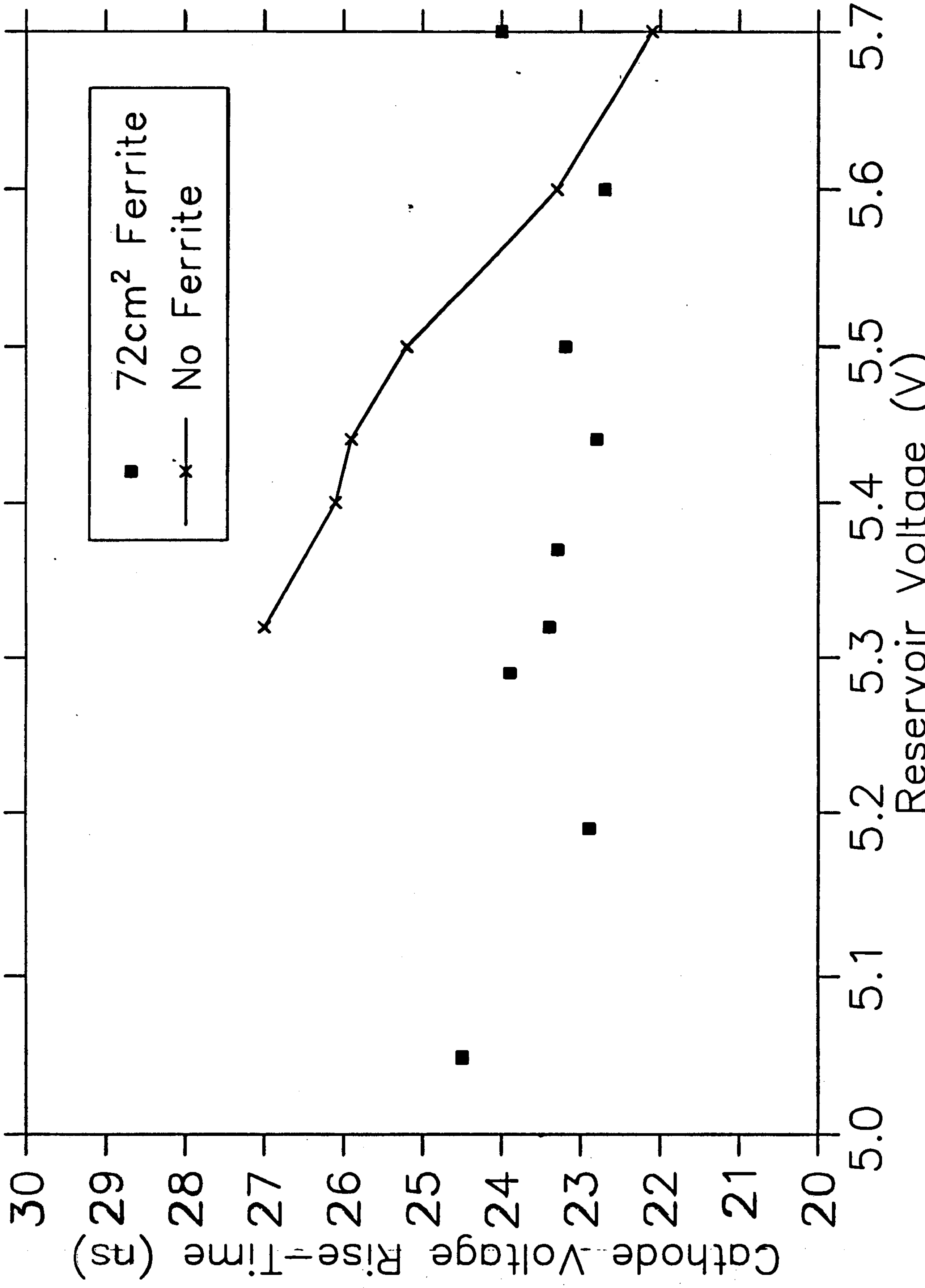

Fig. 8: Cathode Voltage Rise Time as a Function of Reservoir Voltage and Presence of Ferrite on Anode.

THYRATRON RELIABILITY and LIFETIME

MODULATOR-KLYSTRON WORKSHOP @SLAC
FOR FUTURE LINEAR COLLIDERS
STANFORD UNIVERSITY, CA
OCTOBER 9-11, 1995
MODULATOR SWITCH SESSION

H.C. GRUNWALD
SR. ENGINEERING MANAGER
TRITON ELECTRON TECHNOLOGY
EASTON, PA 18044-0100
10/10/95

THYRATRON LIFE LIMITING FACTORS

NON-CATASTROPHIC WEAR OUT MODES
- GAS CLEAN-UP
- CATHODE DEPLETION

GAS CLEAN-UP MECHANISMS
- LACK OF INTERNAL COMPONENT CLEANLINESS
  - CHEM CLEANING, H2 FIRING, PROCESSING
- CATHODE COATING EVAPORATION
- METAL VAPOR
  - INVERSE CONDUCTION (MOLYBDENUM)
  - LOW EMISSION CATHODE/SPARKING (NICKEL)

CATHODE DEPLETION MECHANISMS
- EXCESSIVE TEMPERATURE
  - HEATER POWER
  - i^2_{RMS} (R) LOSSES
  - MARGINAL TUBE DESIGN FOR THERMAL MANAGEMENT
  - ION BACK BOMBARDMENT
- INCOMPLETE CATHODE AREA UTILIZATION
  - GEOMETRY/ASPECT RATIO
  - INSUFFICIENT AUXILIARY ELECTRODE PRE-IONIZATION
- EMISSION MECHANISM/CONSTRUCTION
  - CONVENTIONAL, OXIDE COATED, SURFACE SPRAY CATHODE
  - CONVENTIONAL DISPENSER TYPE
  - UNIQUE DISPENSER TYPE

MAJOR ISSUE: CATHODE

Triton
ELECTRON TECHNOLOGY DIVISION

The cathode is the most critical component in all electron tubes.

Super power and extremely rapid rate of rise switching application have here-to-fore been unachievable for thyratrons due to the constraints imposed by large aspect ratio (tall), relatively low emission density cathodes of classical, surface-coated construction.

Microwave tubes (klystron and TWT) and UK thyratrons have used simple geometry, dispenser cathodes with considerable success. Hydrogen gas, back ion bombardment has restricted its LIFETIME/application - until now.

As a direct result of recent ITT & TRITON ETD IR&D project work, two patents were issued in 1991 which define geometries conducive to operation in a hydrogen gas environment and describe a theoretically derived method for the design of practical cathodes.

The novel construction employs a planar (low profile) geometry with well defined grooves parallel to ion flow with emission current density capability an order of magnitude greater than benchmark conventional designs. The low profile geometry reduces device height (inductance) with a consequent reduction in electron transit time resulting in rapid current rise performance.

UNIQUE DISPENSER CATHODE DESIGN

- 7.62 CM (3.0") DIAMETER
- 0.68 KG (1.5 LB)
- 82% DENSITY POROUS TUNGSTEN
- CIRCULAR 1.27 CM (0.5") HIGH CONCENTRIC VANES
- 25 MM (0.1") VANE SPACING (5:1 ASPECT RATIO)
- 285 CM^2 TOTAL EMITTING AREA
- 4 BAO: 1CAO: 1 AL_2O_3 IMPREGNANT
- MOLYBDENUM - RHENIUM SUPPORT CYLINDER
- 500 WATT TUNGSTEN, POTATO MASHER HEATER

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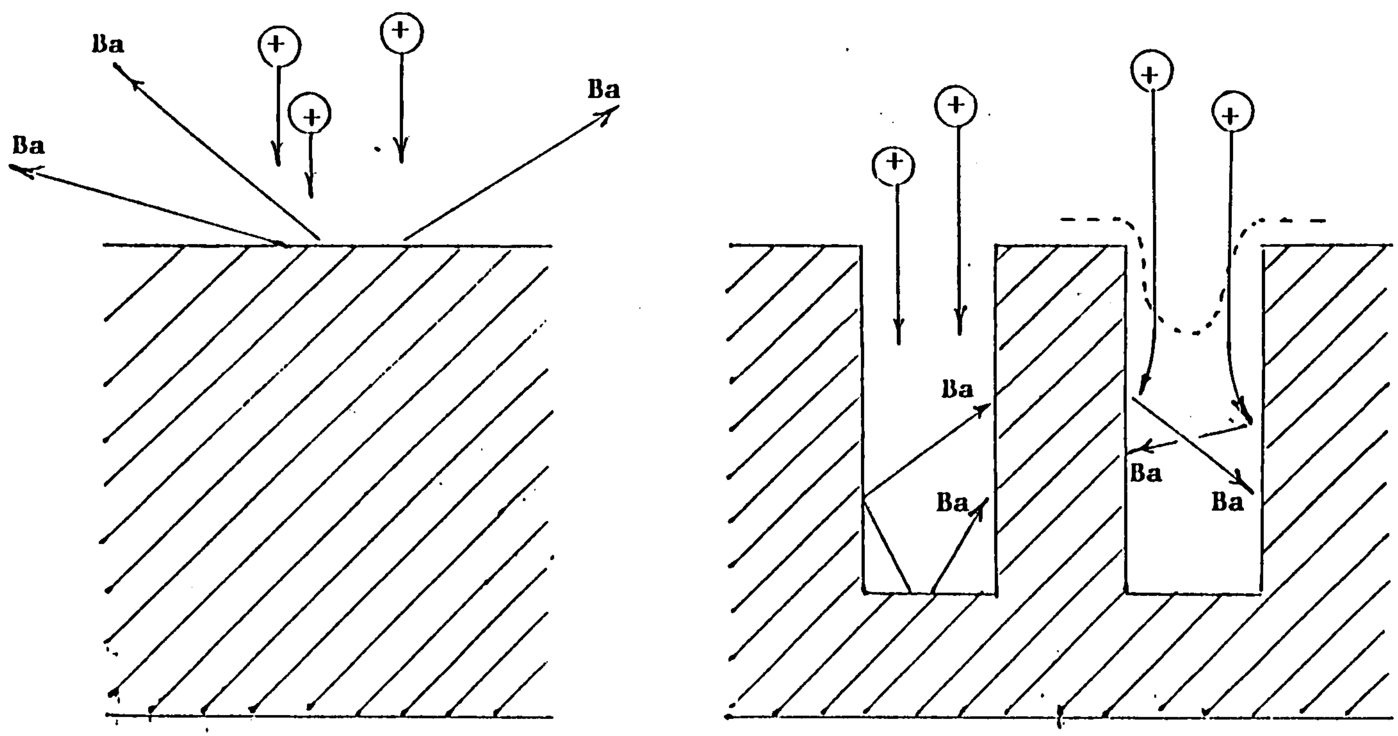
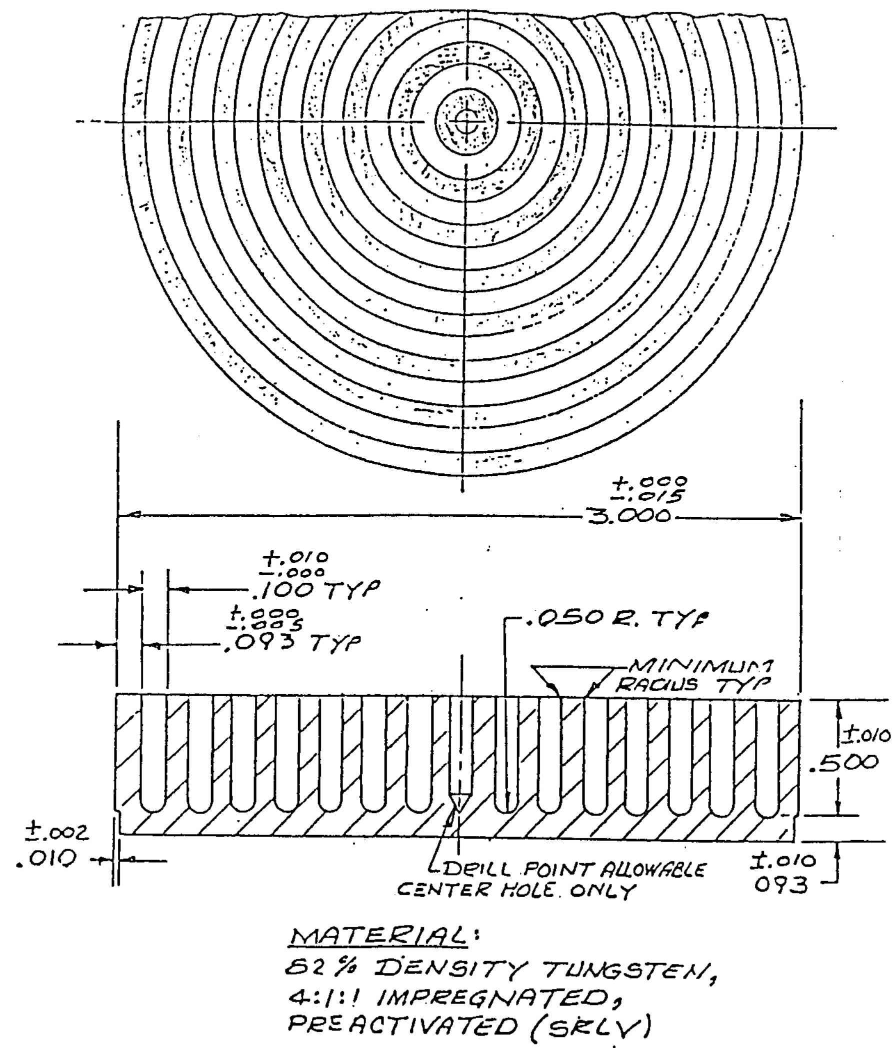
NOVEL
DISPENSER
CATHODE
DESIGN
ELECTRON TECHNOLOGY
cm
inches
Triton
ELECTRON TECHNOLOGY DIVISION



GROOVED DISPENSER CATHODE
GEOMETRY



PROTOTYPE GROOVED DISPENSER CATHODE

United States Patent [19]

Grunwald

[11] Patent Number: 5,063,324

[45] Date of Patent: Nov. 5, 1991

[54] DISPENSER CATHODE WITH EMITTING SURFACE PARALLEL TO ION FLOW

[75] Inventor: Henry C. Grunwald, Bethlehem, Pa.

[73] Assignee: ITT Corporation, New York, N.Y.

[21] Appl. No.: 502,078

[22] Filed: Mar. 29, 1990

[51] Int. Cl.⁵ H01J 1/28; H01J 61/09

[52] U.S. Cl. .... 313/346 DC; 313/630; 313/632

[58] Field of Search .... 313/346 DC, 609, 632, 313/631, 630

[56] References Cited

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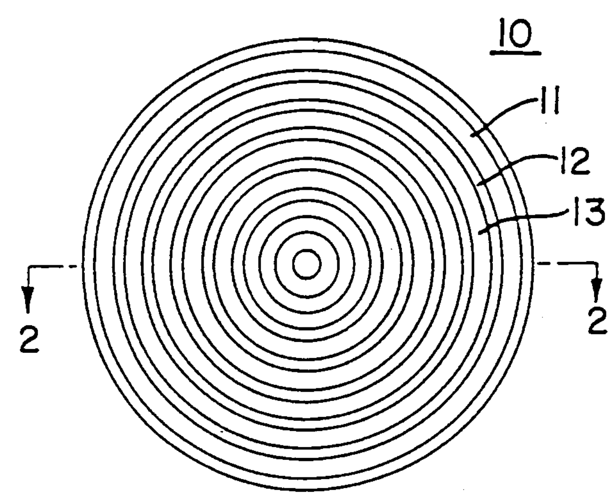
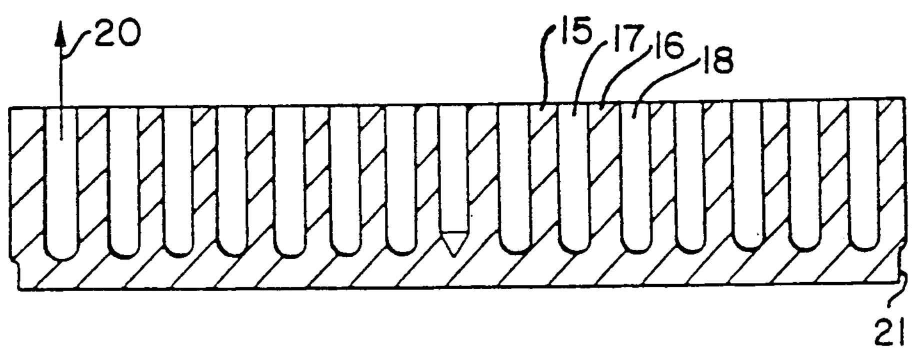
Primary Examiner—Palmer C. DeMeo
Attorney, Agent, or Firm—Arthur L. Plevy

[57] ABSTRACT

A dispenser cathode for a gas filled tube is fabricated from a porous metal material impregnated with an electron emitting material and has on an emitting surface at least one geometric aperture of a given depth and width and having steep vertical walls which serve to compensate for the deleterious effects of ion back bombardment.

20 Claims, 3 Drawing Sheets





DISPENSER CATHODE WITH EMITTING SURFACE PARALLEL TO ION FLOW

BACKGROUND OF THE INVENTION

This invention relates to dispenser cathodes for use in diffuse gas discharge tubes and more particularly to a dispenser cathode which employs an emitting surface parallel to ion flow.

Dispenser cathodes have been employed for a number of years and generally use a tungsten-base material. The modern dispenser cathode consists of a strongly bonded, continuous metallic phase of a refractory metal or metals such as tungsten. The tungsten cathodes are interspersed uniformly with an emitting material. The porous metal matrix acts as reservoir from which the emitting material can diffuse to the surface to maintain an active layer and consequently provide a low work function surface for the thermionic emission of electrons. This definition excludes oxide coated cathodes, pure metal emitters and thoriated tungsten. Certain dispenser cathodes employ a porous tungsten structure and are impregnated with a molten mixture of barium oxide and other compounds which enhance the emission and lower the work function. The density of the tungsten structure can be varied from 75% to 85% of theoretical by volume.

As indicated, modern dispenser cathodes are well known and for a review and examples of such dispenser cathodes reference is made to an article entitled MODERN DISPENSER CATHODES by J. L. Cronin, published in I.E.E.E. Proceedings, Volume 128, Part 1, No. 1, February 1981, pages 19-32. This article explains the various types of dispenser cathodes which are employed in the prior art as well as the various materials utilized in such cathodes. Thus as one can ascertain, the dispenser cathode has been in existence for quite some time and essentially has been employed in gas discharge tubes such as high power thyratrons and so on. There have been many problems associated with dispenser cathodes as evidenced by examples given in the above noted reference. A major problem associated with such cathodes is caused by ion back bombardment of the dispenser cathode which occurs during tube operation. The bombardment of the cathode structure by ions will deplete the surfaces of the cathode of emitting material. This of course results in low emission until a new active layer migrates up from the bulk. Thus in normal tube operations, ion bombardment of the cathode which is a consequence of the charge transfer in the discharge will deplete the cathode of emitting material and hence substantially reduce the operating capability and life of the cathode and therefore the tube.

It is an object of the present invention to provide a cathode emitting surface which substantially eliminates the detrimental effects of ion back bombardment.

SUMMARY OF THE INVENTION

A dispenser cathode for use in a gas filled electron tube, said cathode having an electron emitting surface with said cathode fabricated from a porous refractory metal interspersed with an electron emitting material, with said cathode when in operation subjected to ion back bombardment which can deplete said electron emitting material from said surface, the improvement therewith comprising at least one groove located on said emitting surface and characterized in having steep vertical walls separated one from the other by a given distance with said groove being a specified depth with respect to said distance to enable said cathode to emit electrons from said steep vertical walls operating to cause bombarding ions which impinge upon the same to cause evaporated emitting material and radiated thermal energy to deposit on the opposite wall, and, to cause secondary electron emission.

BRIEF DESCRIPTION OF THE FIGURES

FIG. 1 is a top plan view of a circular vane dispenser cathode according to this invention.

FIG. 2 is a cross sectional view taken through line 2—2 of FIG. 1.

FIG. 3 is a partial top plan view of a straight vane dispenser cathode assembly according to this invention.

FIG. 4 is a cross sectional view taken through line 4—4 of FIG. 3.

FIG. 5 is a perspective plan view of a dispenser cathode assembly employing serpentine surface configurations to provide vertical vanes.

FIG. 6 is a perspective plan view of a dispenser cathode assembly employing partial straight line configurations to form vane assemblies.

FIG. 7 is a partial cross section view of a thyratron employing a dispenser cathode according to this invention.

DETAILED DESCRIPTION OF THE FIGURES

Referring to FIG. 1 there is shown a top plan view of a dispenser cathode according to this invention. As seen the dispenser cathode basically is circular in the top plan view and essentially is of a disk-like configuration as further shown in the cross sectional view of FIG. 2. The cathode includes a relatively large emitting area and for example the diameter of such a cathode can be 3 inches or greater. The cathode is fabricated from a 82% density porous tungsten block structure which is impregnated with a mole ratio of $4BaO:1CaO:1Al_2O_3$. These blocks can be machined to provide a concentric ring geometric configuration. Thus as shown in FIG. 1 the concentric rings or grooves such as **11**, **12** and **13** provide a series of upstanding vane structures as shown more readily in the cross sectional view of FIG. 2. Each vane structure such as **15** and **16** is fabricated at a specified height with a specified spacing based on a aspect ratio of approximately 5:1. Thus for example, a typical vane height employed was approximately 0.5 inches with a vane spacing of 0.1 inches based on this aspect ratio of 5:1. The width of the vane or concentric flange was also about 0.1 inches (0.093 inches). This ratio is important to provide a prerequisite for a secondary electron emission factor greater than unity and conservation of thermal energy and coating between the vane side surfaces. As can be seen between each vane there is essentially a void or a well as **17** and **18**. These wells are deep enough to allow anode penetration. In this manner the well can not be too deep or there will be no emission from the lower section of the cathode wells. The vertical walls which exist between the vanes enable enhanced emission surfaces but operate to prevent the loss of emission material by ion bombardment. As one can see, the vanes are oriented parallel to the direction of ion flow. Hence the vanes are essentially parallel to the direction of ion flow as denoted by arrow **20** as shown on FIG. 2.

The cathode of FIG. **1** has a diameter of 3 inches. The height of each vane to the circular bottom recess being so on as long as they have opposed emitting surfaces for secondary emission, emitting material conservation and thermal efficiency. Thus within known duty cycle, peak current and desired current rise time one can select the cathode parameters regarding the width of the vanes the depth of the vanes, as well as the separation of the vanes.

Referring to FIG. 7 there is shown a typical cross sectional view of a thyratron utilizing a dispenser cathode 70 according to this invention. As seen the dispenser cathode 70 is located within the thyratron. Essentially the outer shell of the thyratron comprises a plurality of metal and ceramic cylinders which formulate the entire tube structure. Such thyratrons are fairly well known. The cathode rests on a support cylinder 71 which support cylinder is typically brazed to the dispenser cathode on the slightly indented bottom surface of the dispenser cathode, as for example, shown in FIG. 2 by reference numeral 21 and FIG. 4 by reference numeral 35. As seen the bottom of each of the cathodes has a slightly recessed flange onto which the cathode support cylinder is secured by brazing. Typically the cathode support cylinder is 50% molybdneum and 50% rhenium, brazed to the cathode using 60% molybdenum and 40% ruthenium. Located within the cathode support cylinder may be the cathode heater. The remainder of the tube consists of a grid section 72 and anode section 73 with the internal cavity of the thyratron being filled with an appropriate gas 74. The structure shown in FIG. 7 is typical of existing thyratrons essentially consisting of cylinders which have the configuration as shown. The cathode 70 consist of a massive 10.5 centimeters (4.0 inch) diameter, 560 cm^2 emitting area fabricated from 82% density porous tungsten block structure which is impregnated with a mole ratio of $4BaO:1CaO:1Al_2O_3$. The tungsten blocks fabricating the cathode were machined to provide concentric ring geometric configurations as for example depicted in FIG. 1 and 2. The vane height was defined as 1.27 centimeters (0.5 inch) with a vane spacing at 25.4 millimeters (0.1 inch) based on aspect ratio of 5:1. This aspect ratio being a prerequisite for secondary electron emission factor greater than unity between the vane side surfaces. The cathode is heated by means of a 750 watt potato masher tungsten heater located within the cathode heat choke which is the support cylinder, as for example, cylinder 71. The cathode is typically heated to 1050° C. As indicated the cathode material is porous barium impregnated tungsten materials which are utilized based on their favorable concurrent properties of low work function (2.2–2.6 ev) and, high melting point (greater than 3680° K.). Physical configuration of the cathode is a planar low profile vane structure of concentric rings or parallel rectangular sections on a common thermally isolated base plate. The cathode can be a brazed assembly or structures machined from single blocks. Thus as one can ascertain from FIG. 7, the emitting surface of the cathode which is the surface that faces the anode is characterized by having a plurality of vanes which are essentially formed by means of concentric circular grooves or straight linear slots on the surface of the cathode which faces the anode. All the cathodes have a closed bottom as indicated in both FIGS. 2 and 4, and the vanes emanate and extend from the closed bottom.

I claim:

1. A dispenser cathode for use in a gas filled tube as an electron emitting surface with said cathode fabricated from a porous refractory metal interspersed with an electron emitting material, with said cathode when in operation subjected to ion back bombardment which undesirably can deplete said electron emitting material from said surface, the improvement herewith comprising:

at least one aperture located on said emitting surface and characterized in having steep vertical walls separated one from the other by a given distance such that said steep vertical walls of said at least one aperture extend to a specified depth not to exceed the thickness of said cathode with respect to said given distance whereby said at least one aperture does not pass through said cathode to enable said cathode to emit electrons when heated with said steep vertical walls operating to cause bombarding ions which impinge upon said wall to cause emitting material to deposit on the opposite wall.

2. The dispenser cathode according to claim 1, wherein said at least one aperture is a groove.

3. The dispenser cathode according to claim 1 wherein there are a plurality of apertures on said emitting surface.

4. The dispenser cathode according to claim 1 wherein said specified depth is about five times said given distance.

5. The dispenser cathode according to claim 1, wherein said refractory metal is tungsten with said electron emitting material being barium aluminate.

6. A dispenser cathode for use in a gas filled electron tube, said cathode having an electron emitting surface with said cathode fabricated from a porous refractory metal interspersed with an electron emitting material, with said cathode when in operation subjected to ion back bombardment which undesirably can deplete said electron emitting material from said surface, the improvement therewith comprising:

at least one groove located on said emitting surface and characterized in having steep vertical walls separated one from the other by a given distance with said at least one groove being a specified depth with respect to said distance to enable said cathode to emit electrons when heated with said steep vertical walls operating to cause bombarding ions which impinge upon said wall to cause emitting material to deposit on the opposite wall.

7. The dispenser cathode according to claim 6 wherein said specified depth is about five times said given distance.

8. The dispenser cathode according to claim 6 wherein said refractory metal is tungsten with said electron emitting material being barium aluminate.

9. The dispenser cathode according to claim 6 including a plurality of grooves located on said emitting surface and spaced one from the other by said given distance.

10. The dispenser cathode according to claim 9 wherein said plurality of grooves are a plurality of concentric circular grooves located on said surface and spaced one from the other by said given distance.

11. The distance cathode according to claim 9, wherein said grooves are a plurality of linear grooves spaced one from the other by said given distance.

12. The dispenser cathode according to claim 6 wherein said at least one groove is a serpentine groove.

13. The dispenser cathode according to claim 6 wherein the ratio of said depth of said at least one

groove to said width of said at least one groove is about five to one.

14. The dispenser cathode according to claim 6 further including means for heating the same to a temperature to cause electron emission.

15. The dispenser cathode according to claim 4 wherein said temperature is 1050° C.

16. The dispenser cathode according to claim 6 wherein said metal is 82% density porous tungsten impregnated with a mole ratio of $4BaO{:}1CaO{:}1Al_2O_3$ employed as said electron emitting material.

17. The dispenser cathode according to claim 16 wherein said at least one groove machined into said surface.

18. The dispenser cathode according to claim 6 wherein said cathode is a disk-like structure having a top circular emitting surface of a given diameter and a thickness substantially less than said diameter.

19. The dispenser cathode according to claim 6 further including a support member coupled to the side of said cathode for supporting the same in said gas filled electron tube.

20. The dispenser cathode according to claim 6 wherein said gas filled electron tube is a thyratron filled with hydrogen gas.

* * * * *

GROOVED DISPENSER CATHODE DESIGN PROCEDURE

STEP 1) DETERMINE Javg FROM DUTY CYCLE CURVE — $\frac{amp}{cm^2}$

2) TUBE DROP

$$Vd = 100 + .833\,(J_{avg}) \qquad \text{volts}$$

3) AVERAGE PLASMA SHEATH WIDTH

$$Ls = \left[\frac{24 \times 10^{-2}\,(Vd)^2}{5.9 \times 10^{9}\,(J_{avg})}\right]^{1/3} \qquad \text{cm}$$

4) CONDUCTIVITY

$$S = \frac{Ls}{.833} \qquad \frac{1}{\Omega cm}$$

5) DEFINE

$$J_o = .85(J_{avg})$$

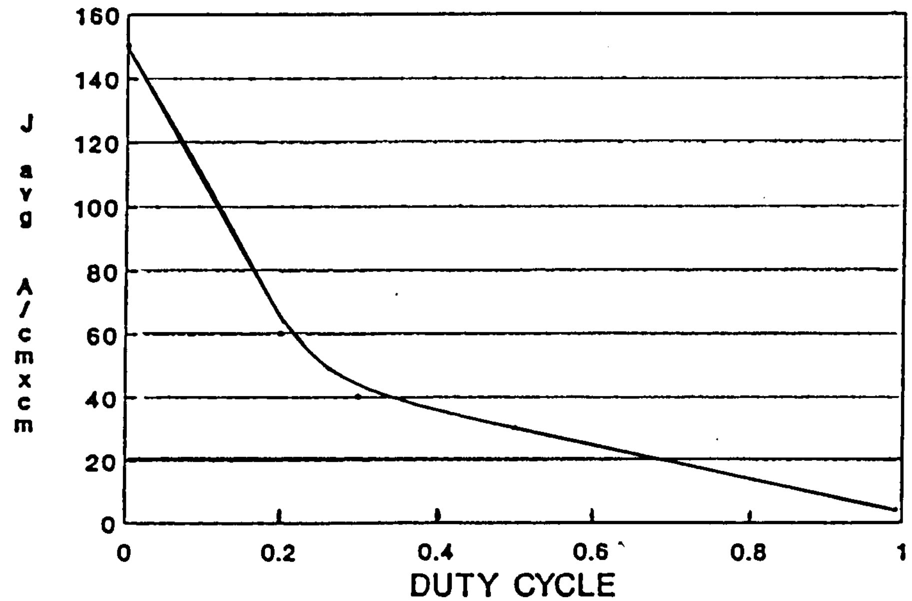
6) GROOVE DEPTH

$$D = \frac{2(J_{avg} - J_o}{S(2.5 \times 10^{3})} \qquad \text{cm}$$

7) CATHODE DIMENSIONS

$$ID = \frac{[Ip/J_{avg}(\pi)D - 40Ls]}{2} \qquad \text{cm}$$

$$OD = ID + 40Ls \qquad \text{cm}$$

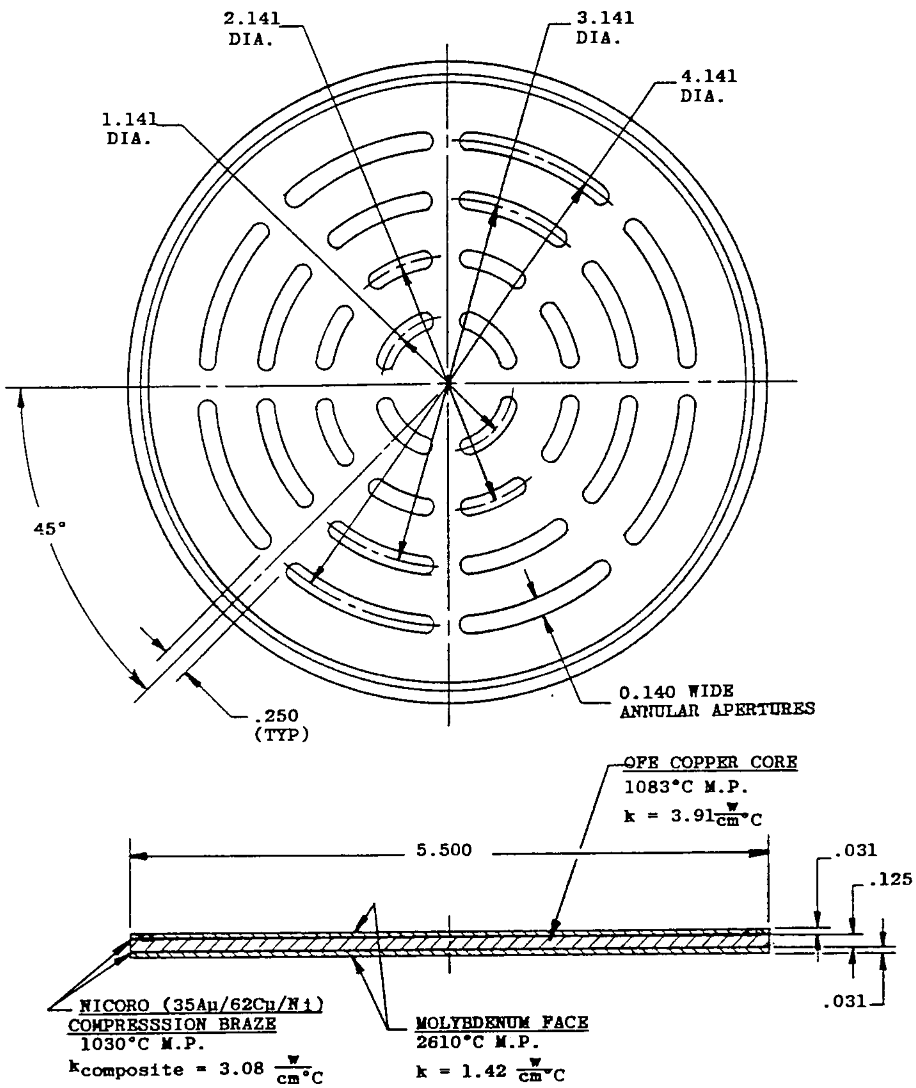


Average Current Density Versus Duty Cycle

DEMONSTRATED CATHODE PERFORMANCE

TEST VEHICLE		F-266	F-241
PARAMETER			
ANODE VOLTAGE	(e_{py})	40 KV	47 KV
PEAK CURRENT	(i_b)	4000 a	6000 a
PULSEWIDTH	(t_p)	4 usec base, 1/2 sine	5.5 usec ESW
REPETITION RATE	(pps)	5,000	30-120 (VARIED)
DUTY (T.S. LIMIT)	-	30 seconds "on"	CONTINUOUS
AVERAGE CURRENT	(I_B)	50.9 ADC, burst	4.0 ADC
ANODE DISSIPATION	(P_B)	800×10^9 v·a.pps	35×10^9 v·a.pps
AVERAGE POWER	(P_o)	1.02 MEGAWATTS	96 KILOWATTS
COOLING	-	OIL IMMERSED	FORCED AIR
LIFE	-	NOT TESTED	40,000 HRS. TO DATE
TEST SITE		PPL, FT. MONMOUTH, NJ	SLAC, STANFORD, CA

Triton



COMPOSITE GRID PARTITION FOR SUPER POWER THYRATRONS

THYRATRON
SUBASSEMBLIES

"CONTINUOUS OPERATION OF A 250 KW THYRATRON"*

Henry C. Grunwald
ITT Electron Technology Division
Easton, PA
Joseph McGowan
Electronics Technology & Devices Laboratory
Ft. Monmouth, NJ
John E. Creedon**

Abstract

ITT ETD has designed, fabricated and delivered three (3) high power thyratrons, Type F259, in which the use of a dispenser cathode is a major design improvement. By substituting the dispenser cathode in lieu of a conventional oxide coated structure, ITT is attempting to develop a device of extremely high average current capatibility (500 amperes is the Phase III objective). Present state of the art is eight (8) amperes. Two (2) of the F259's have been tested by ETDL using it's high power modulator facilities. Both of these tubes have demonstrated the feasibility of operating above the Phase I objective of 18 ampheres. Continuous operation for several hours at an average current of 20 amperes and at a repetition rate of 1000 hertz has been achieved. A third tube was delivered to Lawrence Livermore Laboratory where it is currently being evaluated in the Free Electron Laser modulator. Testing is continuing to establish the ultimate peak current capability and barium depletion characteristics on life.

Introduction

Multi-megawatt average power thyratron performance is a key technology issue for successful Strategic Defense Initiative (SDI) advanced systems operation. The initial phase of a multi-year development program has been directed toward the establishment of an understanding of the physical limitations and capabilities of super power thyratrons. Additionally, near-term fabrication of prototype devices was initiated. Work included the extension of known technology to theoretical maximums by scaling techniques and novel approaches utilizing vast departures from classical design methods. Development models were manufactured, electrically conditioned at the ITT ETD Easton facility and delivered to ETDL, Pulse Power Laboratory, Ft. Monmouth, NJ, LANL, Los Alamos, NM and the Experimental Test Accelerator, LLNL, Livermore, CA for operational and system conformance testing. The major program milestone achieved, in the first phase of this task, was the successful design, construction and test of a dispenser cathode thyratron with continuous operation capability of in excess of 20 amperes average, at pulse repetition rates to 1000 hertz.

Objective specifications and demonstrated performance levels for Phase I of the project are shown in Table 1:

Table 1

Phase I Thyratron Objectives and Performance Achieved

Parameters	Objective	Performance Demonstrated
Peak Anode Voltage (epy)	25,000	50,000 volts
Peak Anode Current (ib)	12,500	16,000 amperes
Pulse Width (tp)	5	5-10 microsec.
Pulse Repetition Rate (prr)	10-100	100-1000 hertz
Average Current (Ib)	18	21 amperes dc

Technical Approach

Due to the short period of performance allowed for Phase I, simultaneous evaluation of key objectives, namely cathode, grid and envelope structure design, was performed on common prototype thyratrons. These prototypes were shipped to the Pulse Power Laboratory, Ft. Monmouth, NJ for test and evaluation, after preliminary test at the ITT ETD Easton, PA, facility. Evaluation objectives were dictated by the circuit constants of the Ft. Monmouth Pulse Power Test facility and were directed toward potential SDIO system applications. Tests were designed and performed to extract the maximum data, without destroying the device under test. Long-term testing, to further characterize the tubes and to verify life capability, is continuing and is currently in process at ETDL, Ft. Monmouth, NJ and LLNL, Livermore, CA. The major milestone achievement to date is operation at an average current of 20 amperes for in excess of 36 million pulses at pulse repetition rates of up to one (1) kilohertz for extended periods (exceeding five (5) hours) without fault, prefire or inverse clipping. The tubes are still completely operational and further evaluation is continuing at increasingly elevated power levels. The maximum operating capability of the ITT ETD prototype F259 thyratron has not yet been established, notwithstanding the Phase I objectives have been demonstrated.

Tube Construction Features

Construction of the developmental F259 thyratron included the following features:

- o Porous tungsten, dispenser cathode
- o Non-symmetrical, two (2) gap gradient grid structure
- o External metal cylinder control grid structure
- o Refractory metal and copper laminated grid partition;brazed construction
- o Shunt-path molecular hydrogen replenishment

A cross-sectional view of the prototype device incorporating all of the foregoing construction features is shown in Figure 1. A photograph of the external structure of the F259 is shown in Figure 2.

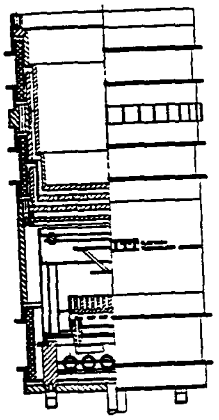


FIGURE 1
F259 CROSS-SECTION

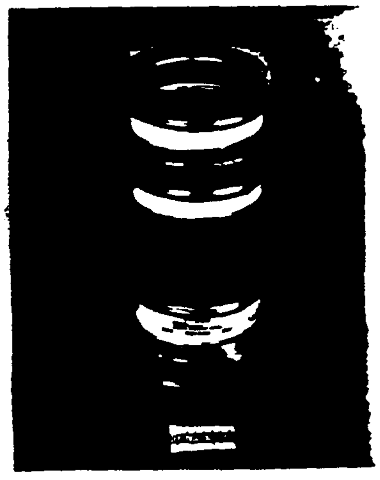


FIGURE 2
F259 EXTERNAL CONSTRUCTION

Cathode Design

The cathode consists of a massive 0.682 kg. 7.62 cm diameter, 82% density porous tungsten block structure, impregnated with a mole ratio of 4BaO:1CaO:1 Al_2O_3. The blocks were machined into two alternate geometric configurations:

1) circular concentric vanes of 285 cm^2 and

2) straight vanes of 270 cm^2 total emitting surface area.

Vane height was defined as 1.27 cm and vane spacing at 2.54 mm, based upon an aspect ratio of 5:1, a prerequisite for a secondary electron emission factor greater than unity between the vane side surfaces. The cathode is heated to 1050°C operating temperature by a 500 watt "potato - masher" tungsten heater, located within the cathode heat choke (molybdenum rhenium) cylinder. No distinct advantage between the two (2) alternate vane configurations has been determined to date. A photograph of this cathode/reservoir construction is shown in Figure 3.

FIGURE 3
F259 CATHODE/RESERVOIR SUB-ASSEMBLIES

Non-Symmetrical Gradient Grid Design

Classically, care is taken to insure equal interelectrode capacitance for the gaps of gradient grid tubes. In the nested cup configuration, this approach "buries" the control grid (a highly dissipative electrode) deep within the tube, thermally insulating it from the external cooling media at the ceramic envelope walls. The F259 discards the above approach and provides maximum thermal conductivity from grid apertures to external sink by locating the control grid on an external copper cylinder of large 486 cm^2 heat transfer surface area. A comparison of the control grid external heat transfer surfaces of the benchmark, conventional F241 design and the developmental F259 device is illustrated in Figure 4. The F259 electrode and body ceramic subassemblies are shown in the photograph of Figure 5.

Anular apertures of 3.5 mm width were utilized in both grid and baffle plates, yielding an effective opening area of 21 cm^2 in the control grid and 18.0 cm^2 in the gradient grid and control grid baffle. This equates to long pulse, peak current capability of 29 ka and 25 ka respectively, using the empirically determined 1.4 ka/cm^2 maximum aperture current density value.

Aperture locations and overlap were calculated to preclude line of sight anode field penetration. Designs were verified by computer plot of equipotential voltage lines within the tube structure. The data was obtained from the solution of the LaPlace Equation in the ITT ETD Electron Trajectory Program (based upon the Herrmannsfeldt SLAC gun code) for the given geometry.

A typical equipotential field plot used in voltage field penetration analysis is shown in Figure 7.

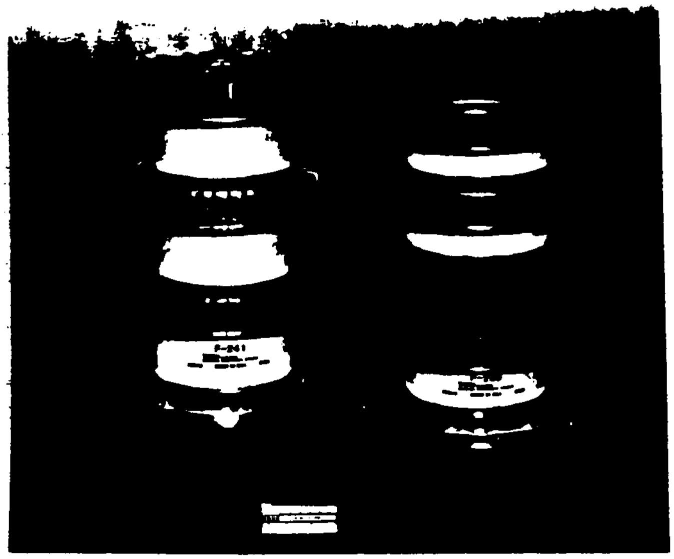


FIGURE 4
F259 VS F241 GRID STRUCTURE COMPARISON

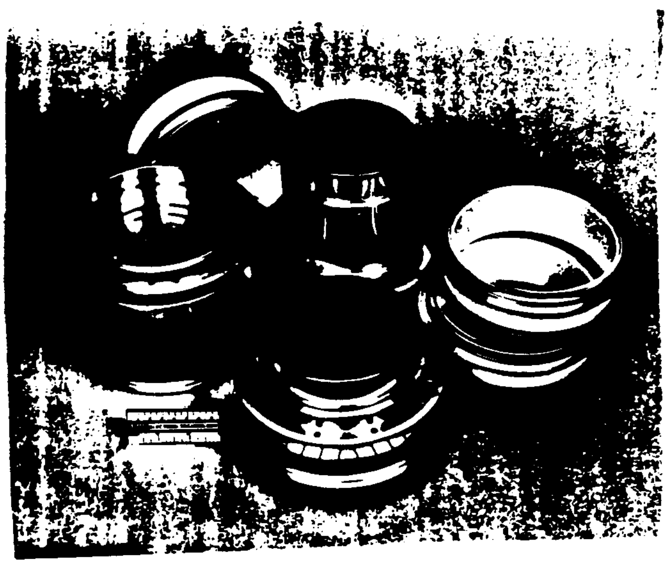


FIGURE 5
F259 ELECTRODE ASSEMBLIES

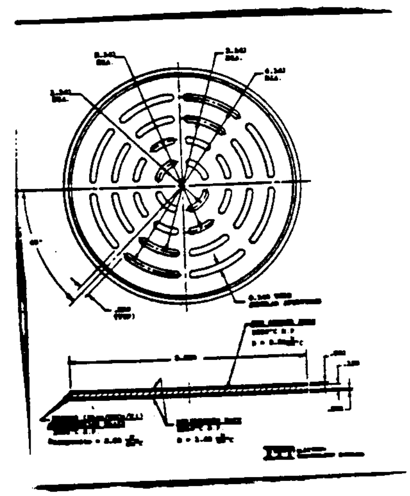


FIGURE 6
MOLYBDENUM/COPPER LAMINATE GRID

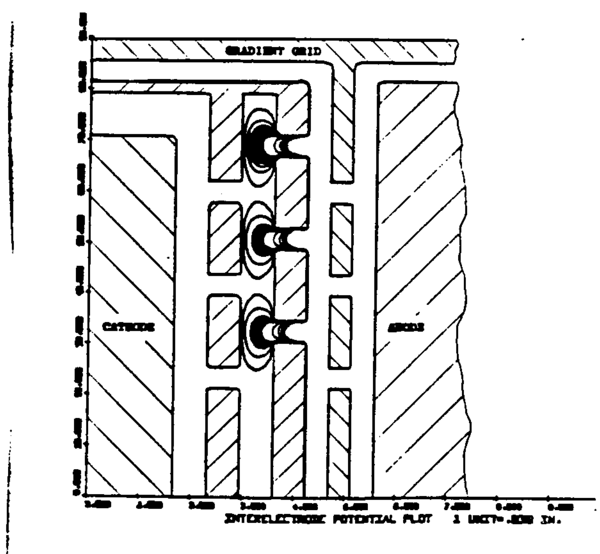


FIGURE 7
EQUIPOTENTIAL FIELD LINE PLOT

Grid Material and Aperture Design

Thermal conductivity of grid members plays a major role in super power thyratron operation. Surface thermal integrity, or freedom from localized heating and subsequent metal vapor arcs, may be achieved by the utilization of among others, three (3) construction techniques:

1) Molybdenum Partitions
2) Tungsten Carbide, Flame Spray Coated Copper
3) Molybdenum-Copper-Molybdenum Laminate

Of the three (3), the composite grid partition shown in Figure 6 has proven the most reliable, to date. The high surface melting temperature of molybdenum (2610°C) is complemented by the high thermal conductivity (3.91 watt/cm °C) of the copper core.

Gas Cooling By Molecular Hydrogen Circulation

A shunt gas path was included in the construction by machining 5 mm holes in the electrode rings, in parallel to the main discharge path. The shunt gas path benefits were twofold and dramatic:

1) Replenishment of molecular neutral gas to enhance internal heat transfer. (NOTE: Principal cooling of internal tube components is accomplished by thermal conduction through the gas.)

2) Provision for a source of electrons to replace those "pumped" from the gap regions, thereby tending to equilibrate gas density throughout the entire tube.

The aggregate hole was calculated to equal the anular cross-sectional area of electrode O.D. to ceramic cylinder I.D. space, thus providing a constant path cross-section for neutral gas flow around the main discharge path.

Reservoir and Gas Fill

Four (4) large titanium hydride reservoirs were utlized to maintain a 500 micron pressure of hydrogen gas within the thyratron. Temperature/pressure equilibrium was accomplished with 40 watts maximum, of reservoir heater power. Particular attention was directed to thermally decoupling the reservour from the cathode. Potential parasitic heating of the reservoir at the required super power rms cathode currents, due to the associated cathode ohmic losses, could destabilize the optimum reservoir basepoint if thermal shielding were not carefully considered.

Thyratron Test Data

Electrical conditioning and preliminary test, at the ITT Electron Technology, Easton, PA facility, was performed in a 600 KW, 30 KV DC, line-type modulator, fitted with a 4.0 ohm, 7.5 microsecond Pulse Forming Network (PFN), with matched resistive load. No inverse clipper circuitry was utilized. Tubes were operated continuously in air with forced cooling at up to peak forward voltages of 54 kv and at average currents up to 7 amperes prior to shipment to the Ft. Monmouth Pulse Power Test Facility.

The initial Ft. Monmouth Test Facility consisted of a 3.3 megawatt, 22 kv dc power supply and a 10 microsecond PFN having a 3.5 ohm impedance. An air-cooled Ohmweave load was used that gave a small positive mismatch. No inverse clipper circuitry was utilized. The tube under test (TUT) was immersed in non-circulating transformer oil.

ITT ETD type F241 thyratron, shown in Figure 4, was selected for initial technology benchmark device capability testing. Reliable operation was recorded at:

epy = 26 kv, ib = 6,500 a, PRF = 184 pps, Ib = 12 Adc.

Internal thermal device limitations became evident after fifteen (15) minutes of operation at:

epy = 32 kv, ib = 8,000 a, PRF = 184 pps, Ib = 14.8 Adc.

On the basis of the benchmark evaluation, it was concluded that the all copper grid structure of the F-241 was capable of 12.5 Adc, continuous operation, oil immersed.

The ITT ETD type F259 prototype thyratron shown in the photograph of Figure 2 and in outline in Figure 1 was then installed and evaluated with the 3.5 ohm network. The device was operated for greater than 3.6×10^7 pulses (to date) at various repetition rates (400, 500, 940, 1000 pps) at anode voltages of 18 to 30 kv for continuous operating periods to five (5) hours at 20 to 21 Adc, without fault (high voltage overload), prefire or clipping. Tube performance was steady and showed no sign of degrading. Thyratron thermal management design was verified by the stabilization of anode operating temperature at 100°F after 60 minutes of 20 Adc operation. It should be noted that although the 20 Adc average current level and the 1,000 pps pulse repetition rate EXCEEDED the project objective goal levels, they represent the maximum current LEVEL OF TESTING---not ultimate device capability. Continued testing and final characterization of the Phase I design will be incorporated into the goals and objectives of the follow-on phase of this research program.

*A portion of the support for this work was provided by the Department of Energy, Los Alamos National Laboratory, NM and partially funded by ETDL and ITT ETD.

**Mr. Creedon is a consultant with SRI, International.

Acknowledgements

The authors wish to acknowledge the significant contribution to device mechanical design by Charles L. Shackelford, ITT ETD.

Modulator Switch Session Summary
D. Ficklin

The presentations and discussions that followed covered these topics:

1. Anode ferrite - no data currently available as to the useful lifetime extension of thyratron shots from 10^8 to 10^9.
2. Is Lifetime reliability directly related to the number of gaps?
3. Cathode temperature is directly related to the lifetime - further discussion on this subject to include some form of filament auto power reduction.
4. Pre-trigger thyratron instead of dc priming of the thyratron. EEV claims much improved lifetimes. There is yet no substantiated evidence directly comparing modes of operation. SLAC has experience, no analysis has yet been done.
5. Positive mismatch - the myth revisited. Much discussion about the utilization of positive mismatch versus efficiency.
6. Primary thyratron failure modes - (Turnquist)
    - Envelope material failure
    - Envelope depletion
    - Cathode depletion

Question about anode destruction due to ion bombardment

7. Reverse currents, and fast turn on - a question was raised about the damages caused by reverse currents in the thyratron. General consensus was that fast reverse diodes would minimize inverse voltage on the thyratron. Concern was voiced about speed of diode conduction in limiting the peak value of inverse voltage.
8. Plasma quenching, recovery within the thyratron - use a delay of the network recharge cycle to allow for a cooling of the thyratron plasma. Note, this ties in with the usage of smart switching power supplies or command charge circuits.
9. At this point, there was a statement by H. Menown describing his international experience with various modulator systems and the forms of mismatch that were used. This was to reinforce the minimizing or elimination of the positive mismatch now used at SLAC.

Conclusions:

1. Get rid of the positive mismatch.
2. Utilize a reverse diode
3. Usage of dual triggering for lifetime improvements.
4. Use a form of automatic power reduction for the thyratron filament.
5. Full optimization will be required to integrate the thyratron into the modulator to maximize the thyratron lifetime.

Further Observations and Questions:

1. Utilization of magnetics to improve thyratron lifetimes
2. Question about choice of 100 kV, 5 kA versus 50 kV, 10 kA thyratrons and related multi-gap reliability
3. Cost of manpower used for thyratron ranging program versus automatic system and associated equipment. Note here that Fermilab uses 25 kHz for both filament and reservoir power in their floating cathode systems.
4. Question about the anode delay and related jitter and how will that affect the system operation. What will be the specified allowable jitter?
5. Can the thyratrons be produced with current technology for a 50 k hour lifetime?

Pseudo-Spark Switch Development

at CERN

for the LHC Beam Dumping System

L. Ducimetiere, P. Faure, U. Jansson, H. Riege,
M. Schlaug, G.H. Schröder, E.B. Vossenberg

LHC PARAMETERS

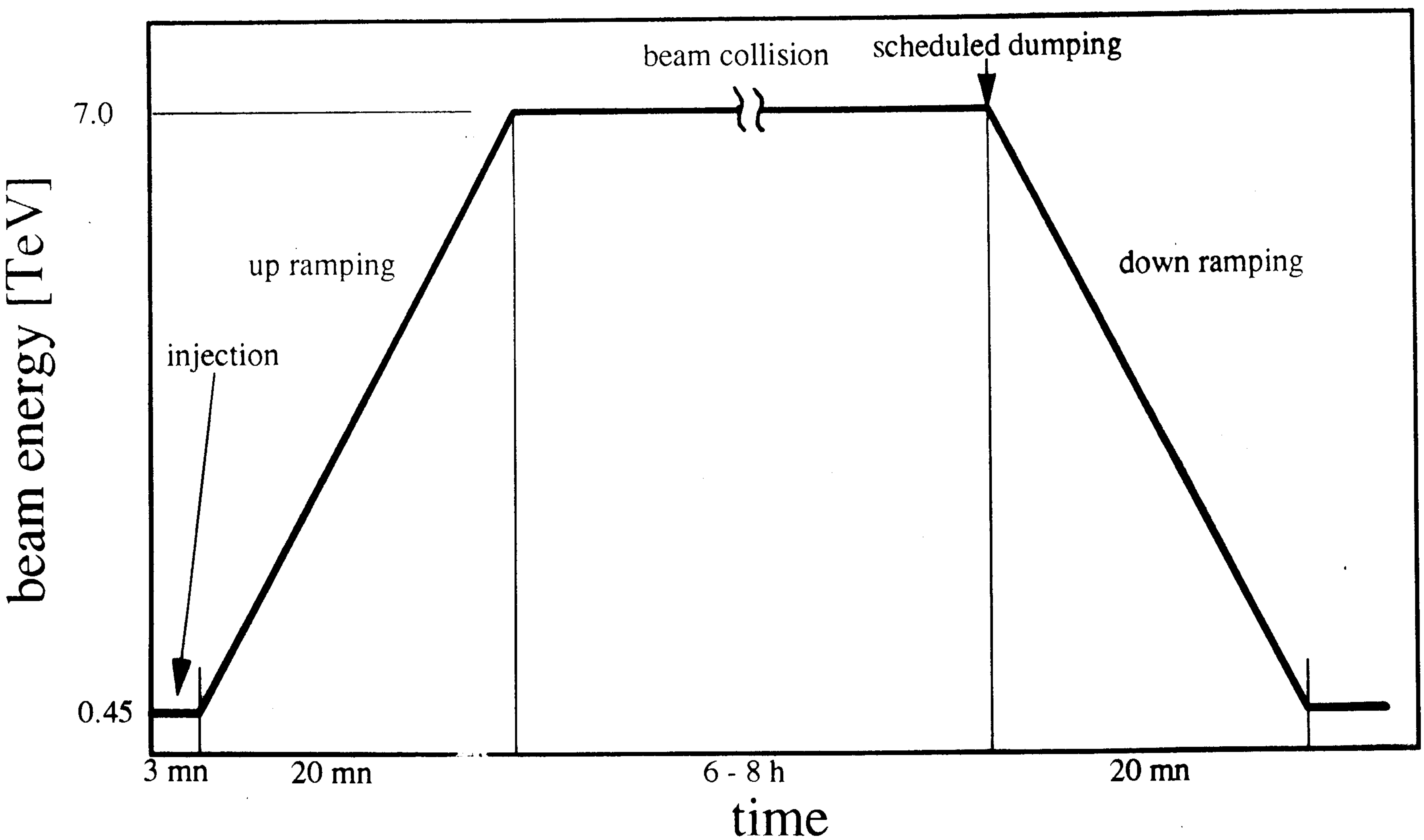
RING PARAMETERS

Circumference	m	26659
Revolution period	μs	88.924
Number of collision regions		2 (protons)

DESIGN PARAMETERS

		Proton collider
Beam energy	TeV	7.0
Dipole magnetic field	T	8.65
Luminosity	$cm^{-2}s^{-1}$	10^{34}
Number of bunches		2835
Bunch spacing	m | ns	7.5 | 25
Particles per bunch		10^{11}
Particles per beam		$2.8 \cdot 10^{14}$
Stored beam energy	MJ	332

LHC operation cycle



LHC beam dumping system

Main parameters

- **Type of system :**

  Fast kicker system extracting each beam within one revolution from the collider orbit and directing it onto an external graphite absorber

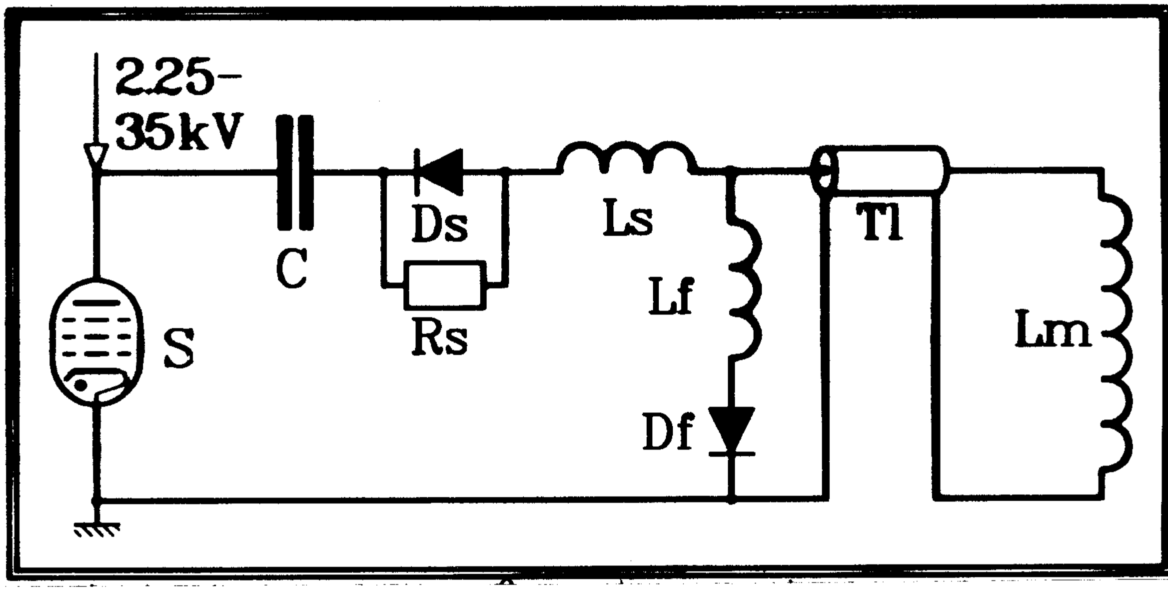
- **Magnetic field characteristics :**

- Rise time	3	μs
- Flat top duration	86	μs
- Fall time	1800	μs
- Peak magnetic field	0.8	T

- **Magnet parameters :**

- Tape wound steel cores		
- Tape thickness	50	μm
- Magnet length	1	m
- Number of magnets	2x12	

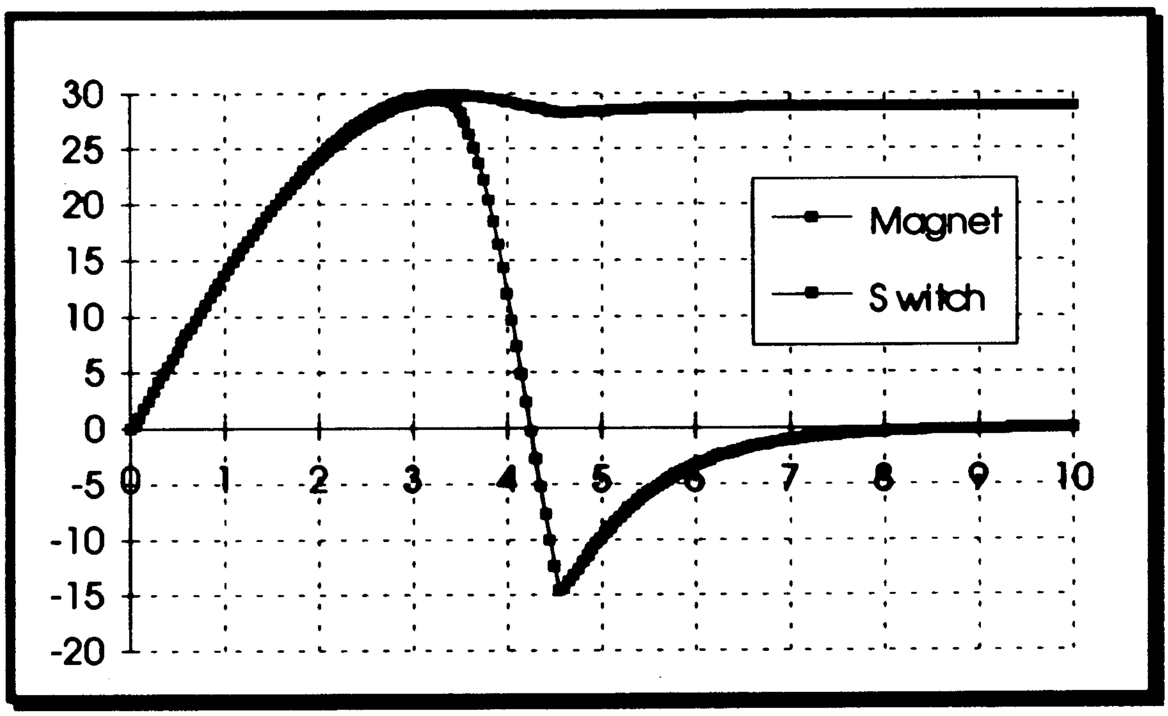
LHC BEAM DUMP GENERATOR



C = 2μF   R = 0.7Ω   Ls, Lf = 150nH

Lm = 2.1μH   T1 = coaxial, 250nH   S = CX-1575C

Basic circuit diagram

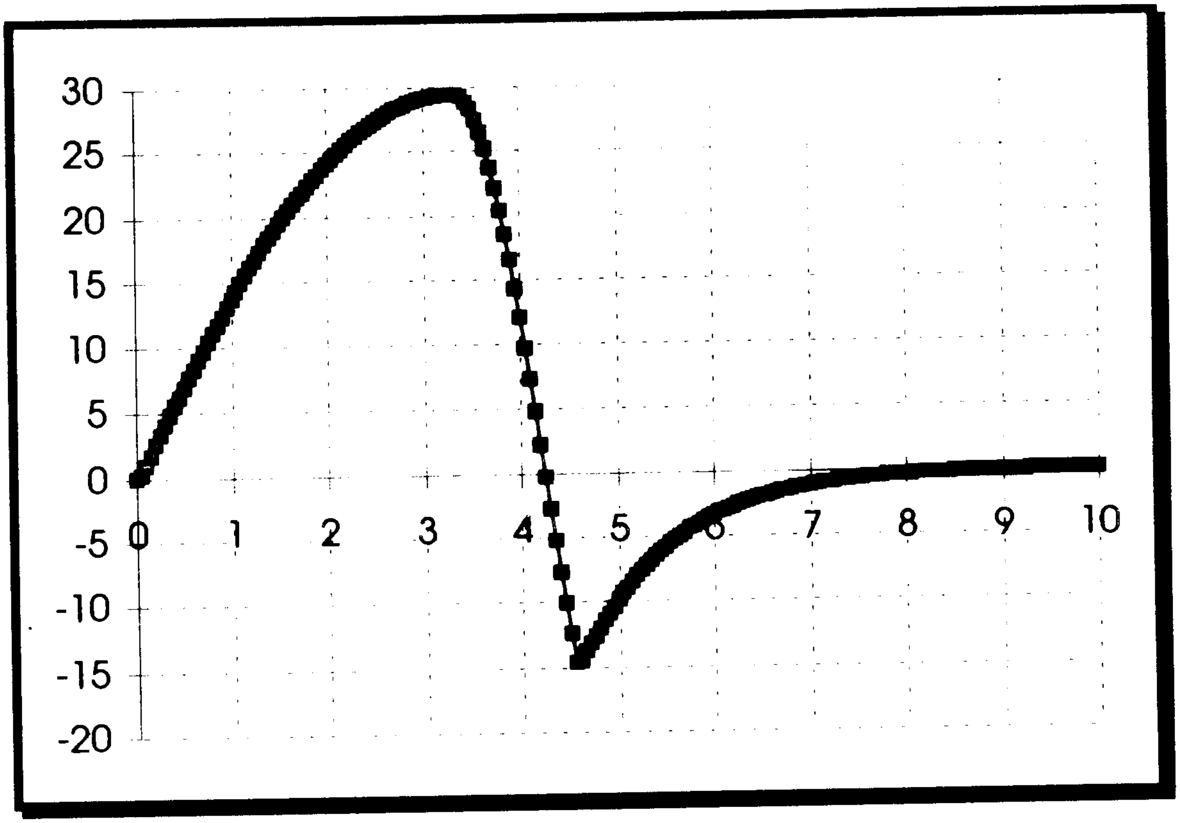


(Hor. scale 1 μs/div., Vert. scale 5 kA/div.)

Switch and magnet current

T01.doc

LHC BEAM DUMP GENERATOR



(Hor. scale 1 μs/div., Vert. scale 5 kA/div.)

Switch current

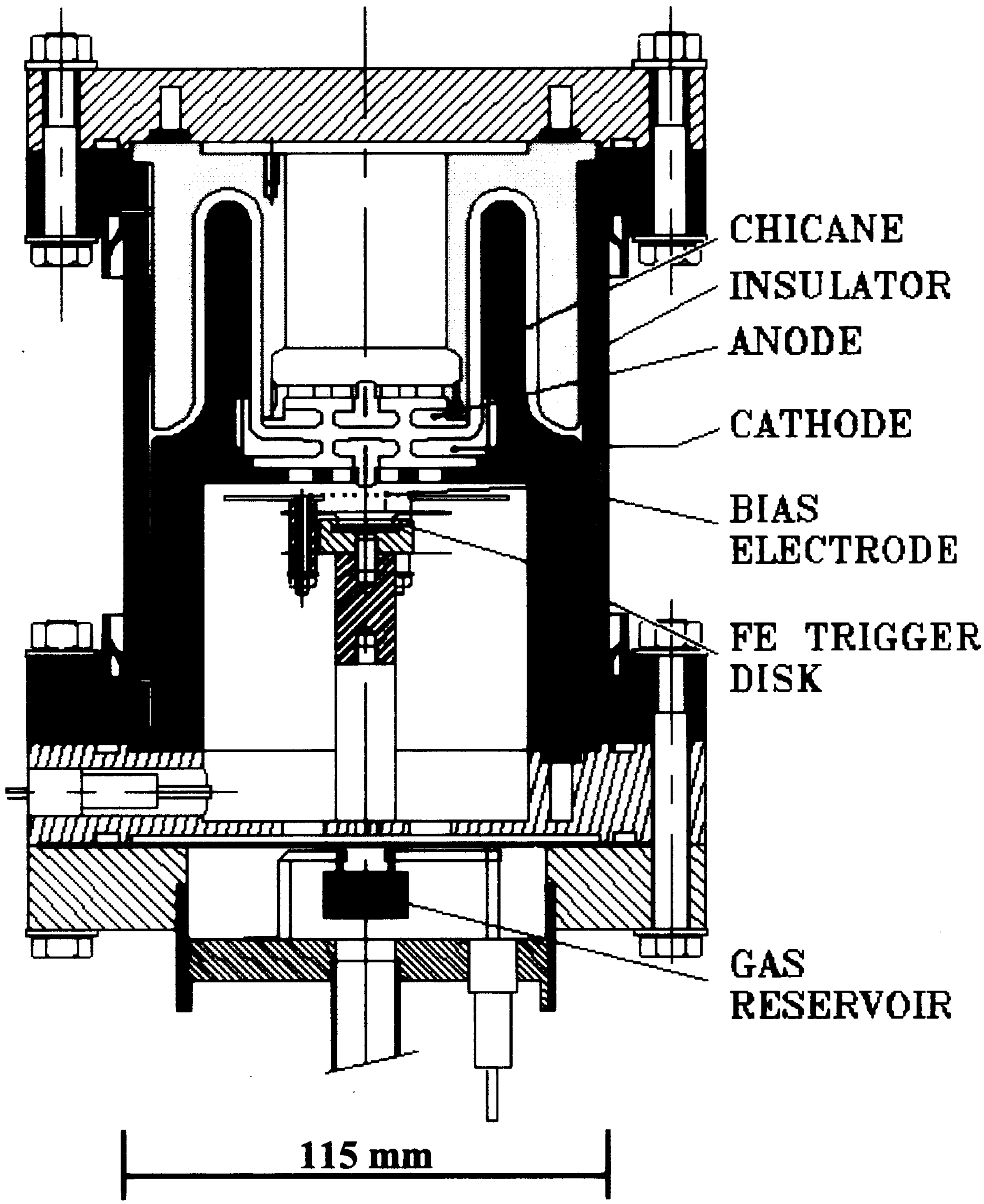
Voltage range	2.25 - 35	kV
Current amplitude pos./neg.	+30/ -15	kA
Current rise/falltime	3.5/1	μs
Current rate of rise/fall	15/45	kA/μs
Pulse duration	8	μs
Charge transfer pos./neg.	89/20	mC
Repetition time min. @ 2.25 kV	10	s
typ. @ 35 kV	6	h
Total lifetime	100000	pulses
Prefire rate	$<<10^{-4}$	

Switch requirements

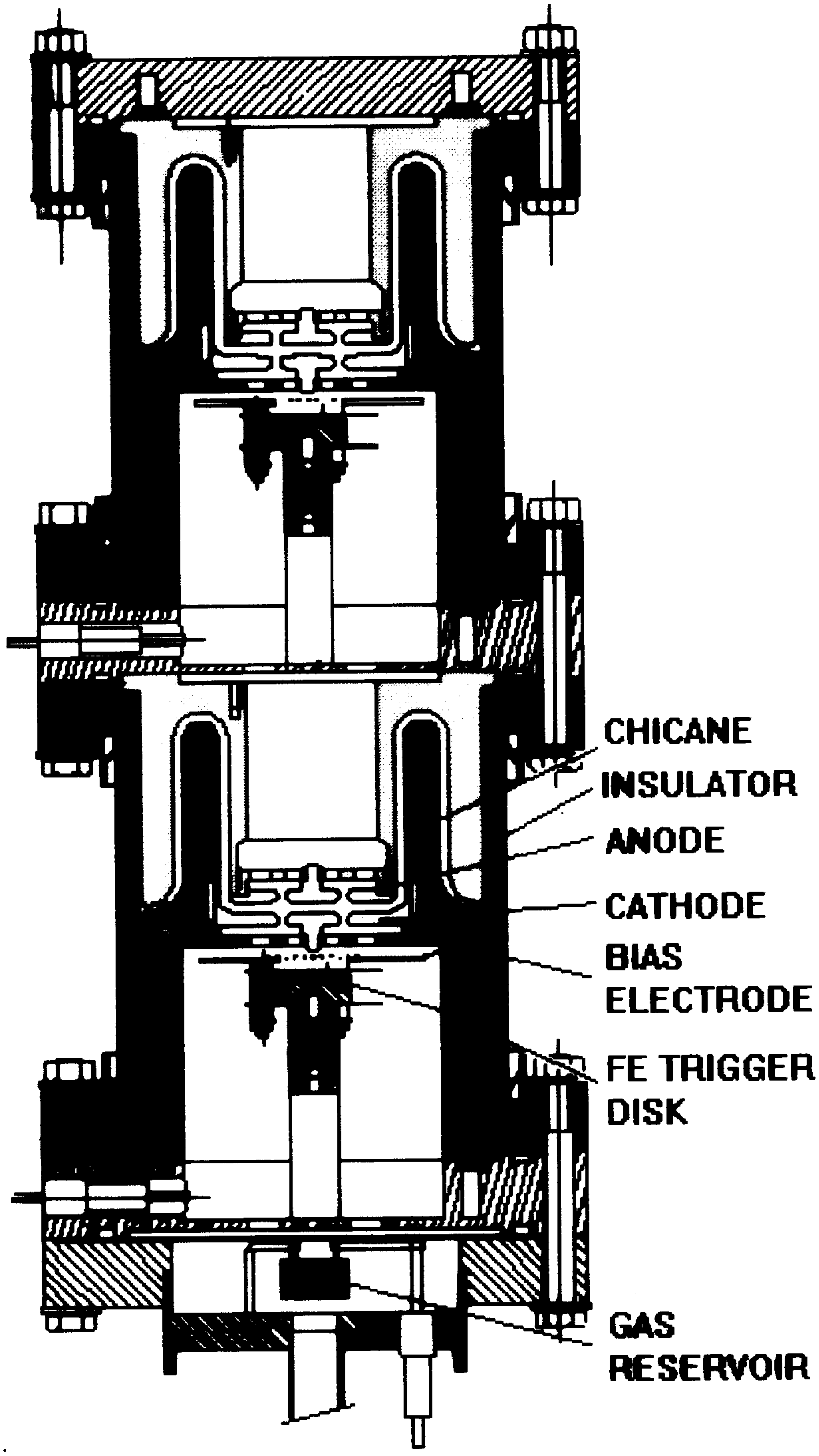
SWITCH TYPES

- **Thyratrons**
- **Modified GTO's (FHCT's)**
- **Pseudo Spark Switches**

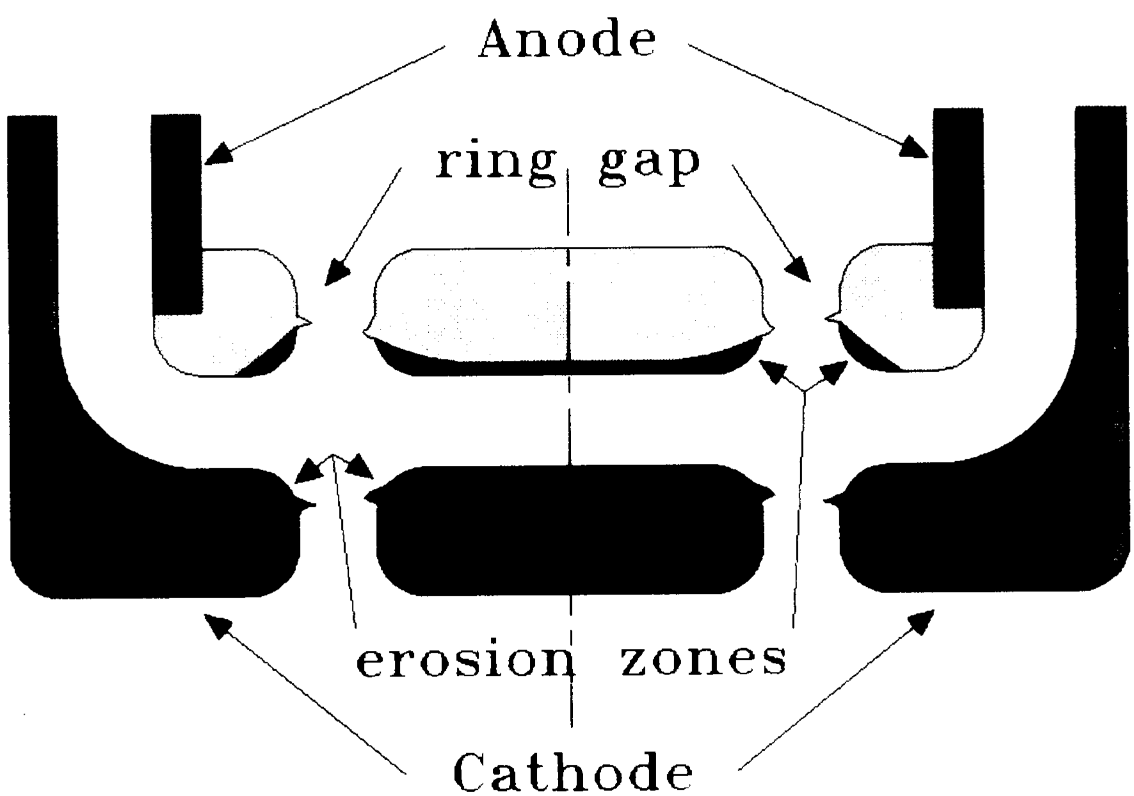
PSS6 (schematic)



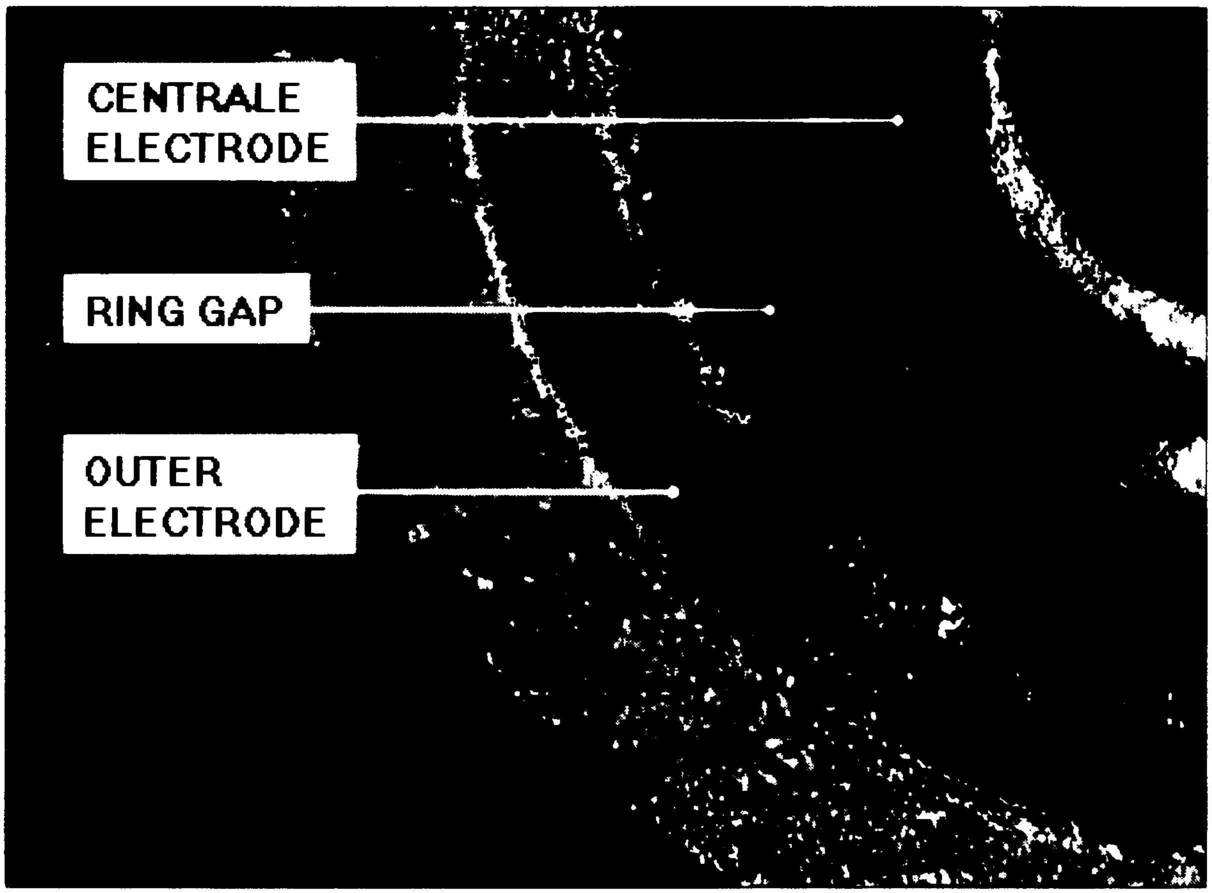
PSS7 (schematic)



SCHEMATIC SECTION THROUGH ELECTRODES



EROSION PATTERN WITH NEEDLES



- **Current quenching and steps in forward voltage drop are significant problems for our application**

- **Both of them seem to be typical problems of a pseudospark discharge**

⇒ We need a better understanding of these physical phenomenons for being able to cure them

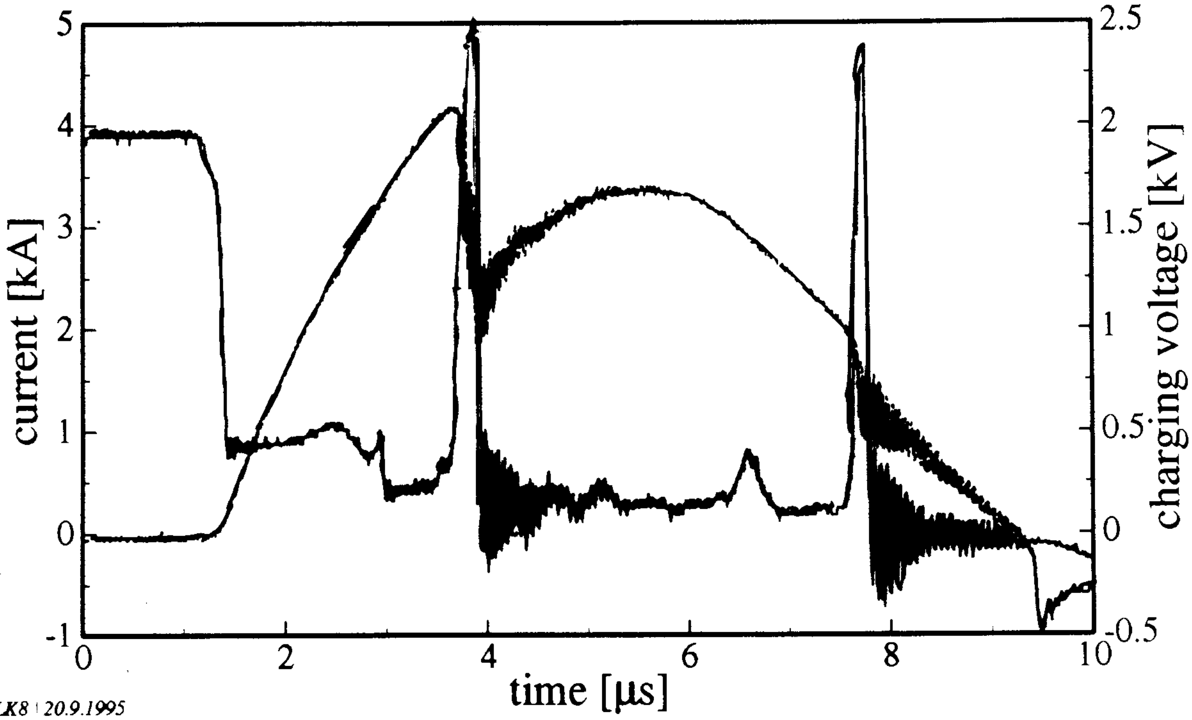
Quenching:

- depends strongly on cleanliness conditions and gas composition,
- depends strongly on gas pressure,
- appears only within certain current and voltage ranges,
- depends on the transfered charge,
- depends clearly on the electrode geometry,
- can lead to very periodic "Quenching bursts",
- cannot be influenced by the triggering,
- does not appear after the ignition of "hot spots",
- appears favoured in a homogenious stage of the discharges,
- causes an explosion of the discharge plasma,
- is followed by a transition to a lower impedance,
- starts "side-on-seen" with a reduction in the discharge luminosity,
- ends "side-on-seen" with an increase in luminosity and spreading out of the discharge,
- causes often the ignition of "hot spots".

Forward voltage drop steps:

- depend strongly on cleanliness conditions and gas composition,
- start only at a certain current and voltage level,
- are shifted with increasing charging voltage / discharge current to earlier time instants,
- are from a certain voltage range onwards no longer distinguishable from the main voltage breakdown,
- have within a certain parameter range a large time jitter,
- are coupled to a transition to a lower impedance,
- depend not or only slightly on gas pressure,
- depend not or only sligthly on the electrode hole geometry,
- cannot be influenced by the triggering,
- are not directly connected to quenching,
- cause "end-on-seen" a darkening of the outer edge of the central electrode,
- cause in certain parameter ranges the ignition of "hot spots",
- are not a consequence of the ignition of "hot spots",
- don't appear after the ignition of "hot spots".

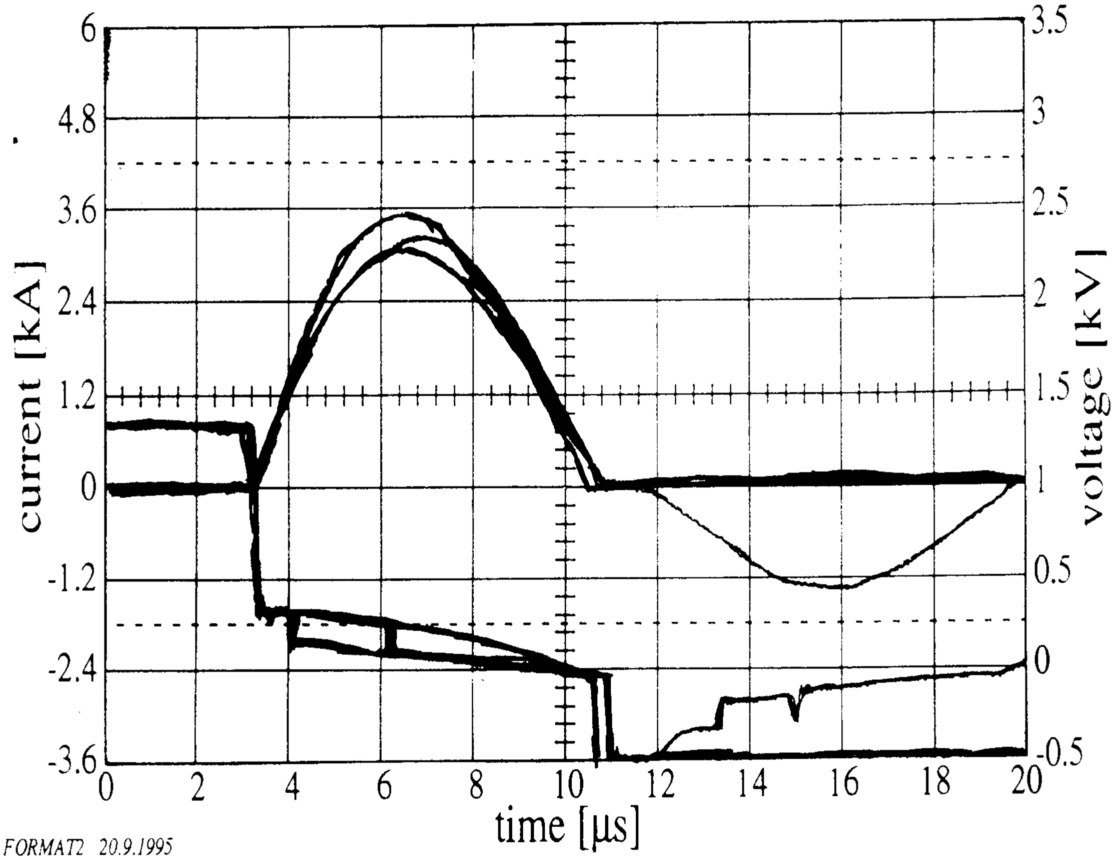
Appears as a sudden **and very fast interruption** of the main current in **the course** of **the discharge.**



TALK8 | 20.9.1995

Typical current and anode voltage shapes of a discharge with quenching

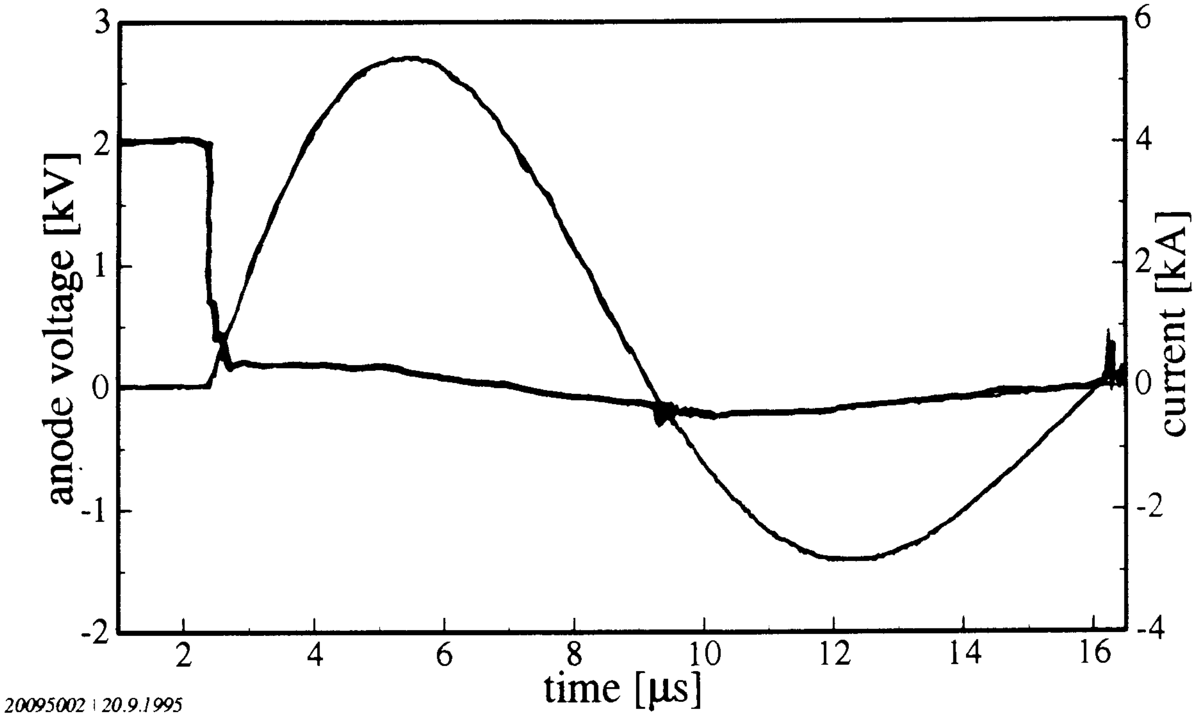
Appears as a sudden and fast transition from a higher into a lower impedance of the discharge gap.



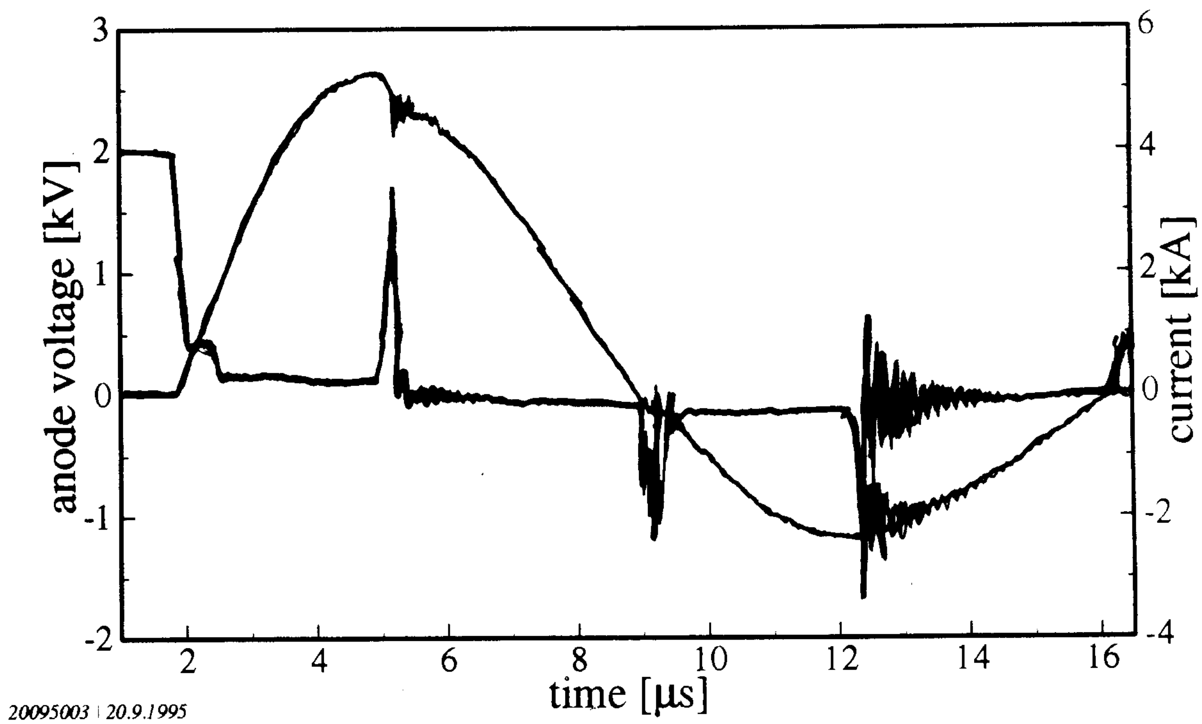
Typical current and anode voltage shapes of a discharge with a clearly visible forward voltage drop step

CURRENT & VOLTAGE PULSE SHAPES AT A CHARGING VOLTAGE OF 2 kV & A PRESSURE OF 15 Pa DURING THE FIRST 100(a) & AFTER ~750 DISCHARGES (b)

(a) during first 100 discharges:

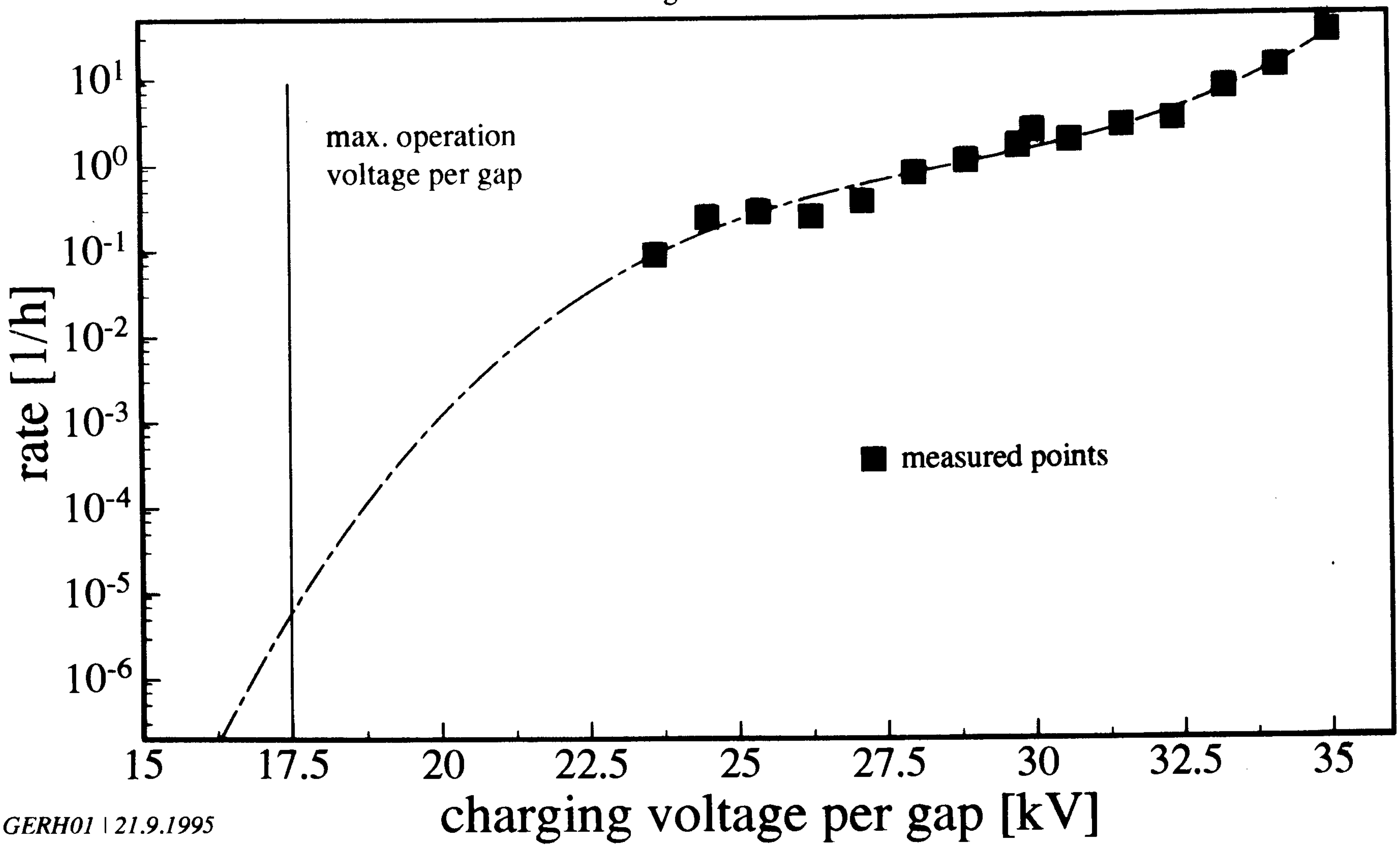


(b) after 750 discharges:



Prefire rate of PSS 10 (2 gaps)

(U_{getter} = 5.1 V)



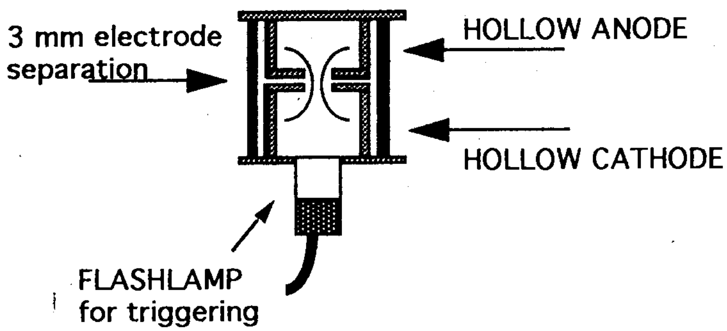
GERH01 | 21.9.1995

- **Current quenching can be shifted out of the working range by choosing a suitable ring gap geometry (e.g. central electrode diameter: 16 mm) and using pressure tracking. Another possibility which we intend to investigate could be the addition of a small percentage of heavy nobel gases.**

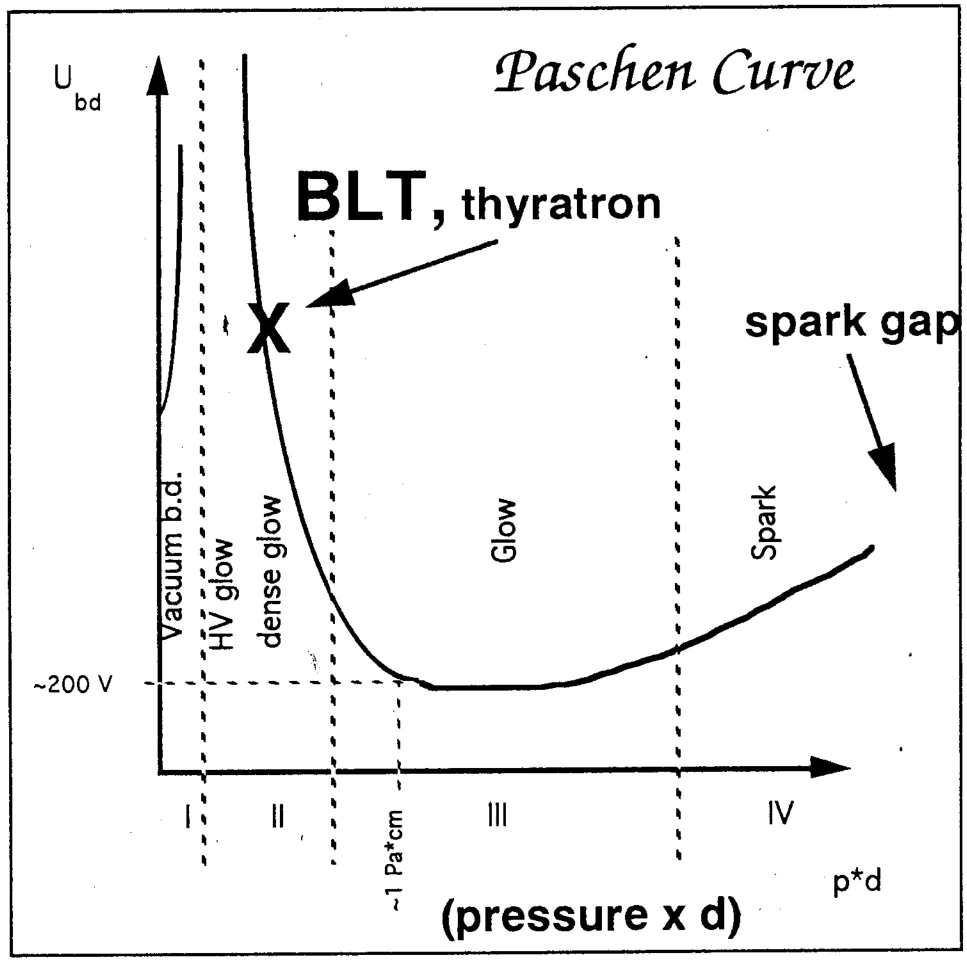
- **Steps in forward voltage drop seem to be significantly influencable only by the gas composition.**

⇒ ***We are going to carry out experiments with different gas compositions.***

Pseudospark, Back Lighted Thyratron Overview



- Pressure typically 0.1-0.5 torr
- Hydrogen, helium, nitrogen...
- 10's of kV, blocking voltage
- ≈2-100 kA peak current
- High voltage hold-off achieved by left-hand side of Paschen curve operation
- Typical electrode separation ≈ 3mm



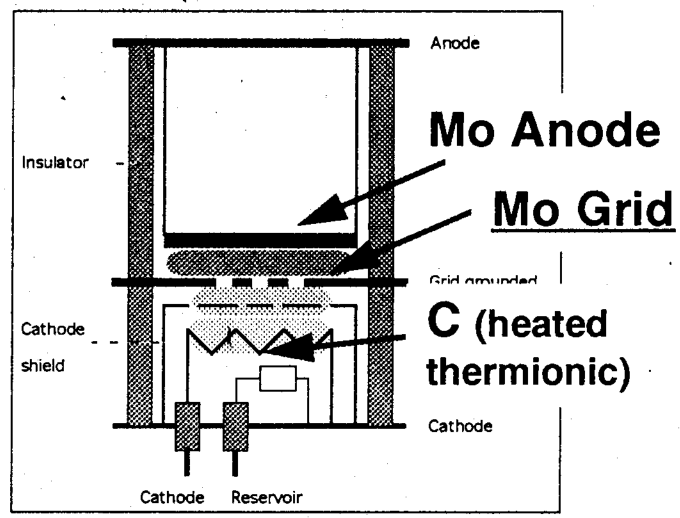
High voltage hold-off mechanism

Thyratron, Pseudospark Comparison

<u>Hydrogen thyratron</u>

Anode-<u>grid</u> separation
3 mm for high hold-off

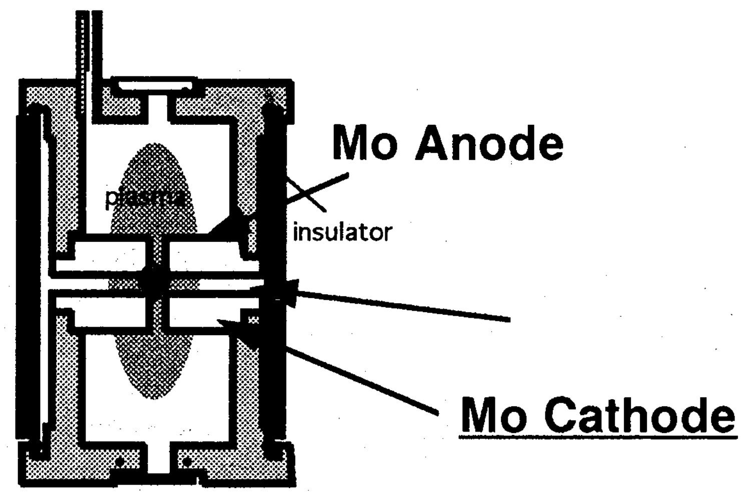
0.5 torr



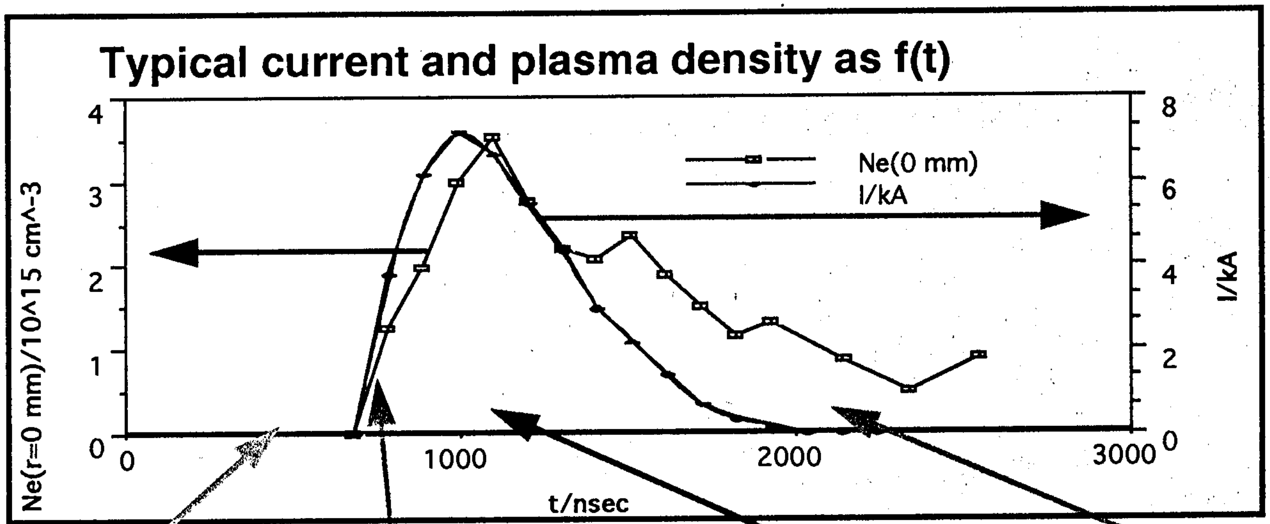
<u>Pseudospark</u>

Anode-<u>cathode</u> separation
3 mm for high hold-off

0.1-0.5 torr

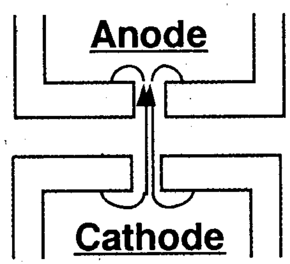


Sequence of Phases

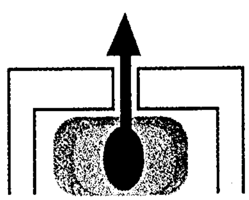


Predischarge Phase → **Hollow Cathode Phase** → **Super-emissive Phase** → **Recovery Phase**

Predischarge Phase
- Long path breakdown
- Electrons from back of cathode

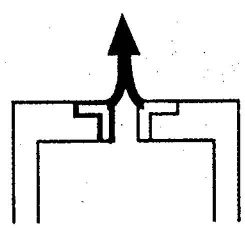


Hollow Cathode Phase
- Emission from hollow cathode plasma
- Current < ≈1kA



Applications
- electron beam
- ion beam
- microwave

Super-emissive Phase
- Emission from cathode surface
- Current 1 to ≈ 100 kA



Applications
- high power switching
- electron beam
- passive plasma lens

Recovery Phase

Martin Gundersen 10/5/95 3
BLT's and Pseudosparks

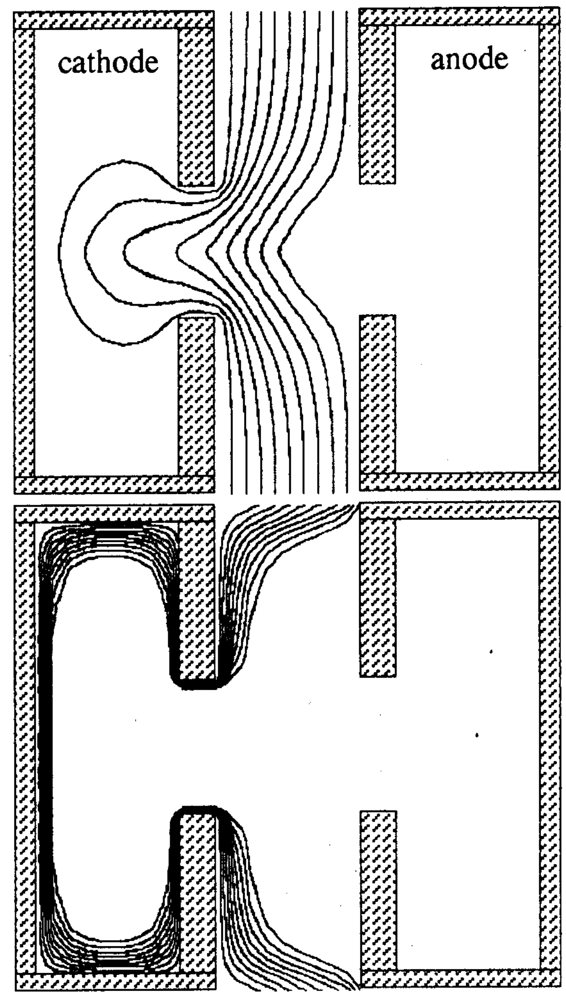
The hollow cathode phase plays an important role leading to super-emission

- A uniform plasma is produced during the transient hollow cathode phase
- This plasma effectively shorts most of the cathode-anode gap without forming spatially inhomogeneous arcs, and brings ≈anode voltage close (≈100μm) to the cathode (A virtual anode is formed close to the cathode).
- The voltage applied over a short distance results in a high field at the cathode surface (≈10^5-10^6V/cm)
- Because the plasma is uniform, the field is uniformly applied to a macroscopic area (≈cm^2)
- The field is amplified mainly by surface defects rather than non-homogeneous plasma characteristics (as with a typical arc)

Model for Super-Emission

A. Anders, S. Anders, V. Puchkarev

- **Emission from a large number of cathode spots**
- **A virtual plasma anode in close proximity to the cathode leads to a high electric field. An extremely high electric field is therefore provided over a large area (≈ 1 cm^2). For instance, at a voltage of 10 kV the sheath is of order 100 Debye length, $E_c \approx 10^7$ V/cm ($\beta \approx 10$).**
- **This field ignites many nonstationary, vacuum-arc-like cathode spots**
- **This can explain the observed current density, macroscopically homogenous current distribution, and time constants, *and erosion***



"Model for explosive electron emission in a pseudospark "superdense glow", A. Anders, S. Anders and M. A. Gundersen, Phys. Rev. Lett. **71** (3), 364 (1993).
"Fast Processes on cathode surface resulting from pseudospark dischage", V. Puchkarev, IEEE Trans. Plasma Sci. **21**, 725 (1993).
Discussions at Bad Honnef, fall 1992, and High power electronics Conf., Russia, July 1992.

Remarkably fast transition from hollow cathode emission to super-emission

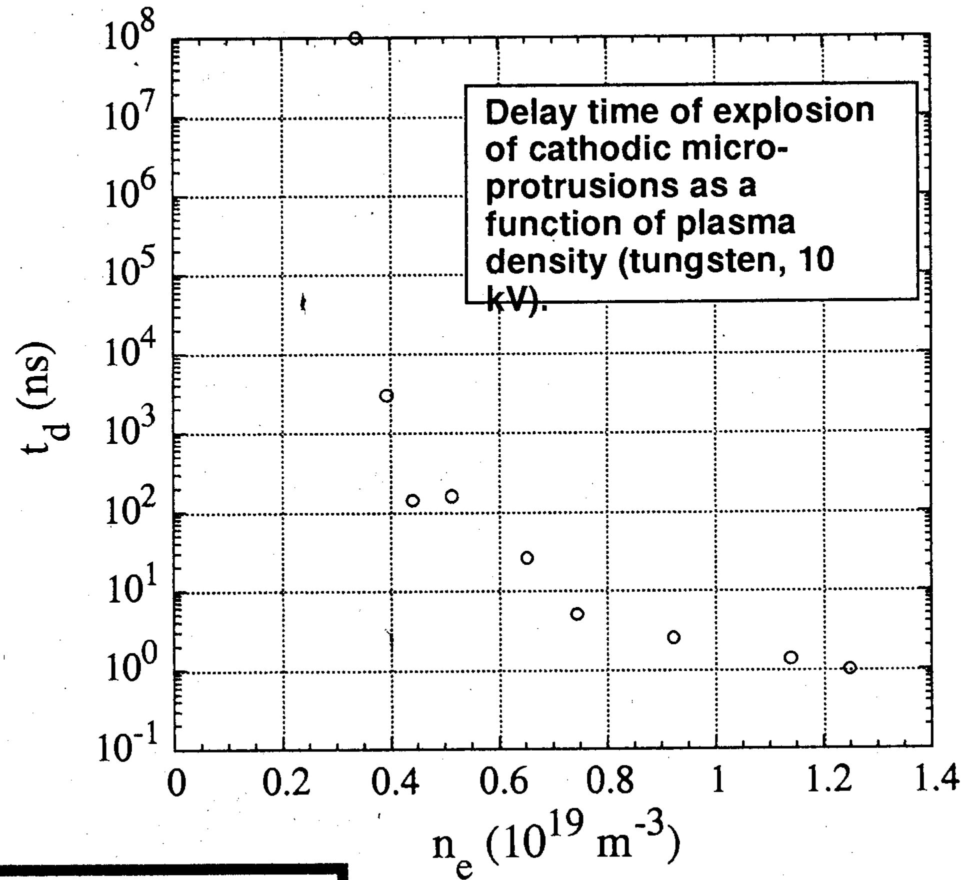
Transition from "non-explosion" to "explosive processes" occurs nearly instantaneously, when n_e satisfies the following criterion:

317

$$n_e \geq n_e^{cr} = \frac{2\varepsilon_0}{eU_c}\left(\frac{E_c^{cr}}{\beta}\right)^2$$

for Tungsten, this is:

$$E_{CS}^{cr} \approx 1 \times 10^8 \ \mathrm{V/cm}$$
$$n_e^{cr} \approx 5 \times 10^{13} \ \mathrm{cm}^{-3}$$



The Delay changes from *SECONDS TO NANOSECONDS* when plasma density changes by ≈ 2

Pseudospark High Power Switches

- Presently a 'niche' between thyratrons and spark gaps
  - "Conveniently" higher current than thyratrons, but shorter life
  - Longer life than spark gaps, voltage more variable, but lower ultimate current limit
  - Aachen approach improves peak current
- Life limiting issues related to electrode erosion
- Triggering stability over life is an issue
  - The emission process is fundamentally different than thyratrons. It is very pressure dependent, and difficult to control over long life
- There are many different types of thyratrons. It makes sense to develop more types of pseudosparks

ALTERNATIVE SWITCHES, PSEUDO-SPARK SWITCH SUMMARY

V. Nesterov

The present state of Pseudo-Spark Switch (PSS) Development for CERN's Large Hadron Collider was presented by G. Vossenberg. Schematic cross sections of two prototypes PSS6 and PSS7, the second composed of two PSS6 gaps in series, were shown, and design criteria, materials and construction, test results reviewed. Attention was given to an electrode erosion pattern, needle formations as well as to quenching behavior and forward voltage drop steps. It was verified that

1) Quenching :

depends strongly on cleanliness conditions and gas composition,
depends strongly on gas pressure,
appears only within certain current and voltage ranges.
depends on the transferred charge,
depends clearly on the electrode geometry,
can lead to very periodic "Quenching bursts",
cannot be influenced by triggering,
does not appear after ignition of "hot spots",
appears favored in homogeneous stage of the discharges,
causes an explosion of the discharge plasma,
is followed by a transition to a lower impedance,
starts "side-on-seen" with a reduction in the discharge luminosity,
ends "side-on-seen" with an increase in luminosity and spreading out of discharge,
causes often the ignition of "hot spots".

1)Forward Voltage Drop Steps:

depend strongly on cleanliness conditions and gas composition,
start only at a certain current and voltage level,
are shifted with increasing voltage/discharge current to earlier time instants,
are from a certain voltage range onwards no longer distinguishable from the main voltage breakdown,
have within a certain parameter range a large time jitter,
are coupled to a transition to a lower impedance,
depend not or only slightly on gas pressure,
cannot be influenced by triggering,
are not directly connected to quenching,
cause "end-of-seen" a darkening of the outer edge of the central electrode,
cause in certain parameter ranges the ignition of "hot spots",
are not a consequence of the ignition of "hot spots",
don't appear after the ignition of "hot spots".

Conclusion:

Current quenching and steps in forward voltage drop are significant problems for CERN application,
Both of them seem to be typical problems of pseudo-spark discharge,
Better understanding of these physical phenomenon is needed.

Gunderson offers a succinct conclusion on page ___ which eliminates (at this time) the pseudo-spark as a modulator switch for the requirements of this workshop.
These remarks are repeated below:

Pseudo-sparks operate at higher current than thyratrons but for shorter lifetimes.
Pseudo-spark triggering stability over life is an issue.
More pseudo-spark development is needed.

SOLID STATE SWITCH ALTERNATIVES FOR KLYSTRON MODULATORS

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1 Specifications for Switch for Klystron-Modulator

The Next Linear Collider at SLAC will require some 3000 Klystron-Modulators: the following specifications apply for the switch for the Klystron-Modulators[1]:

Blocking voltage	= 75 kV
Current	= 3 kA
Flat-top pulse width	= 1.2 μs
Pulse rise & fall times	= 300 ns
Repetition frequency	= 180 pulses per second

Therefore:

average di/dt to current peak = 10 kA/μs;
average current 1 A.

For the Klystron-modulator application under consideration a closing switch is required. Reliability is a major issue, and therefore the switch should be conservatively rated (e.g., for voltage, current, di/dt, power dissipation). A semiconductor switch would have to be constructed from one or more stacks of individual semiconductors: hence snubber circuits and dc grading circuits will be required.

If a thyratron switch is used for the modulator, it is desirable that it has a life of at least 30,000 hours at 180 pulses per second[1]. This paper briefly reviews the available semiconductors (see Figures 1 & 2) so as to identify a possible alternative switch, with a life of significantly more than 30,000 hours, for the klystron-modulators.

2 Summary of Abbreviations

MOSFET:	Metal Oxide Semiconductor Field Effect Transistor
SIT:	Static Induction Transistor
BJT:	Bipolar Junction Transistor

IGBT:	Insulated Gate Base Transistor
MCT:	MOS-Controlled Thyristor
GTO:	Gate Turn-Off thyristor
HDGTO:	Hard-Drive Gate Turn-Off thyristor
PC Switches:	Photo-conductive Switches

3 MOSFETs & SITs

MOSFETs & SITs are unipolar devices – conduction is mainly due to the flow of one type of carrier: due to the absence of minority carrier stored charge, these devices exhibit fast switching speeds (~50 ns), and low gate drive power requirement[2]. On-state resistance exhibits a positive temperature coefficient, therefore these devices are suitable for paralleling.

3.1 MOSFET

Figure 3 shows a summary of the ratings of MOSFETs available from Advanced Power Technology (APT). These MOSFET ratings lie in the range from 1000 V, 11 A continuous (44 A pulsed), to 100 V, 75 A continuous (300 A pulsed).

SAL & TRIUMF have positive experience of connecting MOSFETs in series to produce a continuous train of pulses[3, 4, 5, 6, 7]. Figure 4 shows two stacks of 14 series MOSFETs: the two stacks are operated in push-pull to produce a continuous train of 10^6 pulses per second, of 10 kV magnitude, with rise and fall times of approximately 40 ns[6, 7].

LLNL have tested a MOSFET matrix, with 8 parallel stacks, in single-shot mode, with pulses of approximately 500 ns duration, at 5 kV and 3 kA[8]. In burst mode (two 5-pulse bursts of 200 ns pulses) the MOSFET matrix has been tested at 5.3 kV and 1.1 kA[8]: the di/dt obtained to current peak was approximately 12 kA/μs.

With a high voltage MOSFET (1 kV) rated at 44 A pulsed (e.g., APT1001) the MOSFET matrix would require at *least* 80 series APT1001 MOSFETs per stack and 70 parallel stacks. Allowing for redundancy, and non-ideal voltage and current sharing, the matrix would probably consist of 100 series APT1001s per stack $\times$ 80 parallel stacks $\rightarrow$ 8,000 MOSFETs per klystron-modulator. At US$10 per MOSFET $\rightarrow$ US$80,000 per klystron-modulator.

NOTE: individual MOSFETs would not be paralleled in the matrix, else if one MOSFET failed to short-circuit it would short out the whole row of MOSFETs.

Conclusion — it is theoretically possible to build a switch for a Klystron-Modulator using MOSFETs. However MOSFETs would probably be unsuitable because of cost and complexity (number of MOSFET's required), and the physical size of such a switch.

3.2 SIT

"The GaAs SIT exhibits fast switching speeds, characteristic of power MOSFETs, and low conduction losses characteristic of silicon IGBTs. It is therefore a potential replacement for these devices in the 150–500 volts, 1–10 ampere regime. ...... Discrete SITs could be series-coupled to fabricate optically-triggered modules, and to achieve a wide range of voltage ratings, up to 5 kV"[2].

Conclusion — SITs are presently unsuitable because of their voltage and current ratings.

4 BJT

Devices are available in ratings up to 1000 V and 80 A (e.g. ESM 4020 from GEC Plessey).
Rise-time is typically greater than approximately 1 μs for power devices.
DC current gain is typically 5 to 10.

Conclusion — BJTs are unsuitable because of their rise-time.

5 IGBT

IGBTs have lower on-state resistance and higher blocking voltage capability than MOSFETs, but exhibit slower switching speeds than MOSFETs[2].

Figure 5 shows a summary of the rating of IGBTs from several manufacturers. Many power IGBTs with significant Collector-Emitter voltage ratings have rise-times in the 800 ns range. Advanced Power Technology have a series of IGBTs with maximum rise-times in the order 150 ns (70 ns typical). The highest Collector-Emitter voltage in the APT range is 1 kV: the APT65GL100BN has a rated collector current of 65 A continuous, 130 A pulsed.

With a high voltage IGBT (1 kV) rated at 130 A pulsed, an IGBT matrix would require at *least* 80 series IGBTs per stack and 25 parallel stacks. Allowing for redundancy, and non-ideal voltage and current sharing, the matrix would probably consist of 100 series APT65GL100BN per stack $\times$ 30 parallel stacks $\rightarrow$ 3,000 IGBTs per klystron-modulator. At US$40 per IGBT $\rightarrow$ US$120,000 per klystron-modulator.

NOTE: Individual IGBTs would not be paralleled in the matrix: else if one IGBT failed to short-circuit it would short out the whole row of IGBTs.

Conclusion — it is theoretically possible to build a switch for a Klystron-Modulator using IGBTs. However IGBTs are probably unsuitable because of cost and complexity (number of IGBTs required), and the physical size of the switch.

6 MCT

Figure 6 shows a summary of the rating of several fast switching and asymmetric thyristors.

Standard thyristors have a limited di/dt capability (e.g. 200 A/μs immediately following turn-on). Spreading rate is approximately 0.1 mm/μs, therefore a large gate-cathode periphery is required to ensure uniform dissipation during turn-on[9]: this is at the expense of conduction losses.

Thyristors with a 100mm diameter junction are available at blocking voltages up to 6.5 kV[9]. ABB have developed an 11 kV symmetrical thyristor, which consists of 4 (3 kV) thyristor chips stacked in a common housing[10]. This thyristor has been tested to currents of 50 kA with a di/dt of 600 A/μs (50 kA waveform is a quarter sine-wave with a time to peak of $\sim$200 μs)[10].

Conclusion — standard thyristors are not suitable because of their limited di/dt capability.

7 GTO

7.1 Standard GTO

Figure 7 shows a summary of the rating of several standard GTOs.

A standard GTO thyristor is optimised for its turn-off characteristics by heavy metal doping, diffused anode-shorts and irradiation[11]. A standard GTO has a maximum di/dt capability of $\sim$600 A/μs during turn-on[11].

Conclusion — standard GTOs are not suitable because of limited di/dt capability.

7.2 Modified GTO ($\rightarrow$ thyristor)

With light doping and unshorted anode the device can be used as a CLOSING switch with excellent turn-on characteristics[11]. Westcode have worked with CERN SL Division to develop a modified GTO (WG200045E6G), which is a symmetrical 4.5 kV device (66 mm diameter junction). The modified GTO has been tested to 70 kA, with a di/dt of 20 kA/μs [off-state blocking voltage=1.6 kV][11]. The gate-drive was 150 V, 240 A peak (200 A/μs), 100 A minimum [i.e., hard-drive]. The modified GTO has a gate-cathode periphery of approximately 7 m. Figure 8 shows a current pulse of over 60 kA whish was switched using the Westcode WG200045E6G modified GTO: the current peak occurs approximately 10 μs after turn-on.

A 250 kA pulser has been designed at TRIUMF for an experiment at BNL: the pulser design utilized the Westcode WG200045E6G modified GTO[12]. The 250 kA pulser consisted of 5 parallel modules, with up to 6 series GTOs per module.

ABB have developed a High Current Thyristor (HCT) with 6 m of gate-cathode periphery (a modified GTO), compared with 30 cm for a conventional thyristor of the same diameter[11, 9]. The thyristor is an asymmetrical device (thin wafer for high current operation), and therefore it is necessary to protect the thyristor against reverse voltage, e.g. with diodes. The thyristor has been tested up to 100 kA with a di/dt of 15 kA/μs[9]: the gate drive was 80 A peak, with a di/dt >50 A/μs.

A switch composed of HCTs with a 30 kV blocking voltage capability for the switch, a peak current of up to 10 kA (maximum di/dt ~8 kA/μs), an operating frequency of up to 200 Hz, and an integrated trigger and cooling unit would cost approximately US$30,000[13].

ABB believe that the switch specifications could be met using modified GTOs: however the short rise-time would demand a very substantial gate-drive[14]. In order to achieve a suitable gate drive it may be necessary to consider a new semiconductor device: ABB will shortly be announcing a 4.5 kV blocking voltage (asymmetrical) hard-drive GTO (HDGTO). A 6 kV version of the HDGTO is expected to be available in early 1996[14]. The 6 kV HDGTO has a budgetary price of US$2,500 in large quantities[14]. The HDGTO includes a gate-drive board. The HDGTO will have a gate-flange (NOT lead) brought outside; a metallized PCB will contact the flange. This arrangement will permit gate current to flow into the device gate from around the full 360° device periphery[14], thus allowing a very hard-drive for the gate. Twenty-three of 6 kV HDGTOs, applied at 3.8 kV DC, per Klystron-Modulator (including 3 redundant HDGTOs) would cost US$57,500 for HDGTOs per Klystron-Modulator. In addition diodes may be necessary to protect the HDGTO from inverse voltage.

Assuming a cost of US$1400 per modified GTO (small quantity price for Westcode WG200045E6G GTOs: ABB have also indicated a price of US$1300 for a 4.5 kV [*Asymmetrical*] HCT), and 28 GTOs per stack → US$39,200 for GTOs per Klystron-Modulator.

Conclusion — a modified GTO is potentially suitable for use in an alternative switch for a Klystron-Modulator.

8 PC Switches

Photoconductive switches have achieved the following duties[15]:

at 100 kV & 5 kA (120 ns wide pulses):	life of 1-2 pulses
at 1 kA (120 ns wide pulses):	life of 4 pulses
at 1 kA (1 ns wide pulses):	life of several thousand pulses

Conclusion — PC Switches are unsuitable because of their limited life with pulse duration greater than ~100ns.

9 Conclusion re suitable semiconductors

The HCT from ABB (a modified GTO), and modified GTO from Westcode are potentially suitable candidates for replacing thyratrons in Klystron-Modulators. These devices appear to have adequate di/dt and peak current capability. As a result of the voltage rating of the Westcode modified GTO and ABB HCT, several tens of devices would be required to be connected in series to achieve the required blocking voltage. Connecting thyristors in series is a standard procedure in many industries, for example a thyristor valve for use in a High Voltage Direct Current (HVDC) link can have over 100 thyristors connected in series: these HVDC schemes are designed for a life of 25 years[16]. To achieve such high reliability, 'redundant' thyristors are included in the thyristor stack; any devices that fail are replaced during an annual maintenance period.

The modified GTOs would probably cost in the range of US$40,000 to US$58,000 per Klystron-Modulator.

10 Reliability

In order to ensure high reliability it is important to match the specific characteristics of the semiconductor device with its application[17]. The highest rate of failure of semiconductors occurs immediately after manufacture, but the process of aging and debugging gradually lowers this rate: failure rate diminishes with time[17].

In order to ensure high reliability "diodes and thyristors should be operated at 50 to 80% of their maximum voltage rating, and junction temperatures should not exceed 70 to 80% of maximum rating"[17].

In order to estimate reliability of a semiconductor switch, as a replacement for a thyratron, use Table 5-1 of reference [17]. Assume a junction temperature of 100°C, and a stress ratio of

0.5 (stress ratio is based on maximum current and dissipation and rated current and dissipation): from Table 5-1 of reference [17] the Thyristor Basic Failure Rate = 0.022 Failures/10^6 hours. Other factors, such as environmental factors, effect the failure rate. However, for the purposes of this example, round the above Basic Failure Rate to 0.1 Failures/10^6 hours. A failure rate of 0.1 Failures/10^6 hours is consistent with the 100 FIT (failures in time) suggested by ABB[14]. Where 1 FIT = 1 failure in 10^9 operating hours.

To achieve a switching blocking voltage of 75 kV, and assuming a modified GTO with a blocking voltage of 4.5 kV: apply the modified GTO at say 67% of its rated blocking voltage → 3 kV[1]. Therefore 25 modified GTOs are required per Klystron-Modulator. Allow 10% redundancy → 28 modified GTO switches per Klystron-Modulator.

Using a Basic Failure Rate of 0.1 Failures/10^6 hours × 28 modified GTOs per Klystron-Modulator → 2.8 GTO Failures/10^6 hours/Klystron-Modulator, i.e., 1 GTO failure/350,000 hours/Klystron-Modulator. With 3 redundant modified GTOs per Klystron-Modulator, there can be 3 GTO failures per Klystron-Modulator before the Klystron-Modulator needs to be shutdown → 3 GTO failure/1,000,000 hours/Klystron-Modulator. This failure rate is significantly better than that of a thyratron.

NOTE: the estimated failure rate for the semiconductor switch neglects other components, such as diodes (required if it is necessary to protect the switching devices from reverse voltage), and gate drive circuitry.

The stack of modified GTOs could be modular so that individual GTO modules can be easily replaced. Diagnostics at each module would indicate if a device has failed to short-circuit (the usual mode of failure).

11 Other Issues

The following issues will also require consideration:

- An adequate gate-drive, required to achieve the specified di/dt and repetition rate, may cause excessive gate-dissipation, and thus flashover between the gate and cathode region[14].
- Referred impedance of klystron, as seen on the primary side of the transformer[18]: how does the referred impedance influence the design of the semiconductor switch?;
- Duty cycle of the PFN voltage: the duty-cycle may effect the blocking voltage at which the semiconductors can be applied;

[1] Failure of devices applied at over 3 kV/device are attributable to avalanche turn-on caused by photons[14]

- dV/dt of the reapplied PFN voltage: an excessive dV/dt can cause ungated turn-on of, and damage to, the semiconductor switch[19];
- Good matching of characteristics, e.g. turn-on delay time, of the semiconductors (also holding of spares from the original batches);
- Snubber circuit time-constants;
- Non-coherent turn-on of the semiconductor devices: adequate snubber circuits will be required to prevent overvoltage on one or more semiconductor devices[11, 19];
- Fault conditions: maximum voltage, current, di/dt and dV/dt which the semiconductor switch may be subject too.
- Adequate diagnostics are required so that a failed semiconductor can be readily replaced.
- Overall system efficiency must be high[20]: how does the efficiency of the semiconductor switch compare with a thyratron?.

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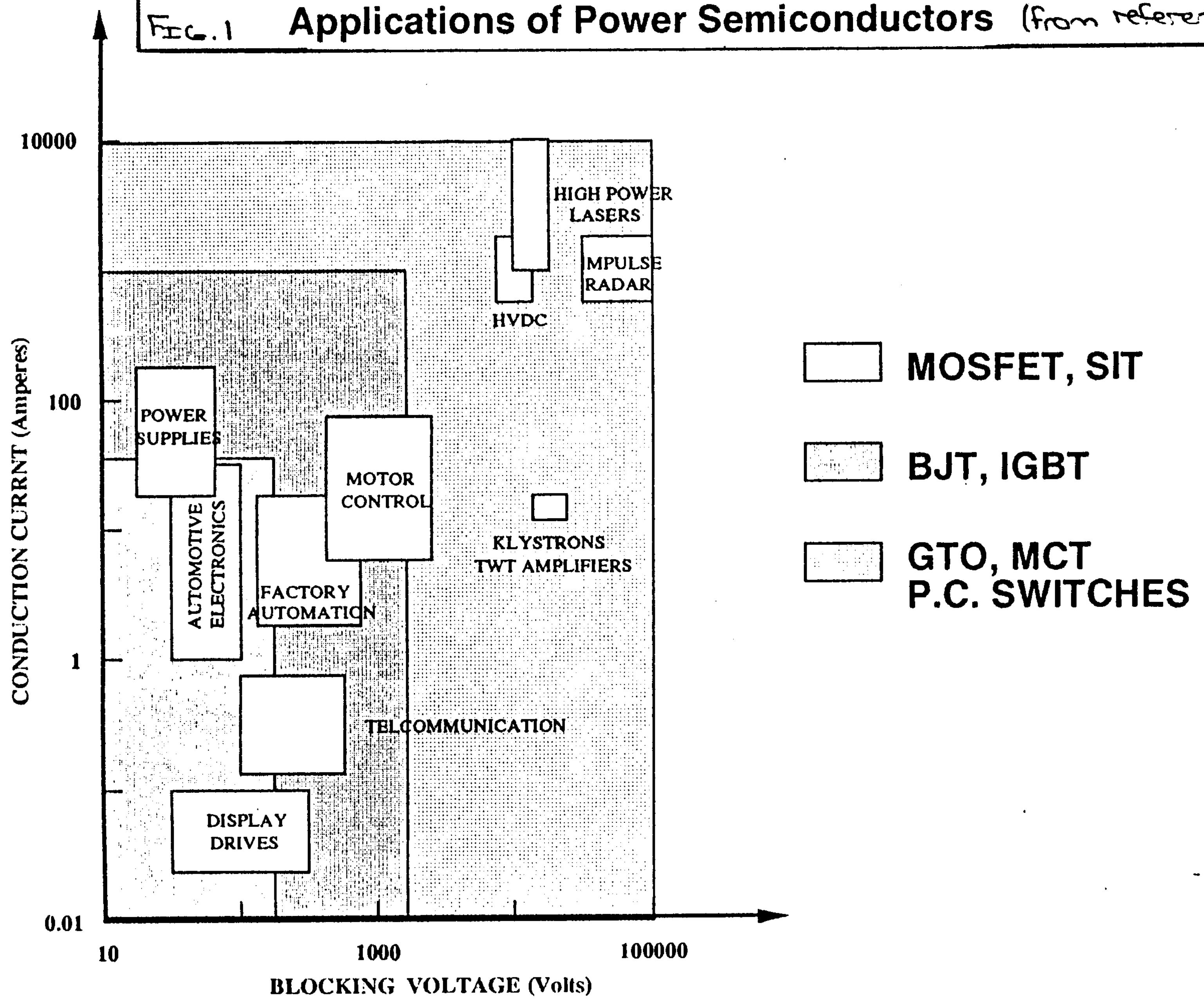
FIG. 1 **Applications of Power Semiconductors** (from reference [2])



Powerex, Inc., 200 Hillis Street, Youngwood, Pennsylvania 15697-1800 (412) 925-7272
Powerex, Europe, S.A. 428 Avenue G. Durand, BP107, 72003 Le Mans, France (43) 41.14.14

Figure 2: Application for Power Devices (from Powerex databook "IGBT MODULE: Applications and Technical Data Book (March 1993))

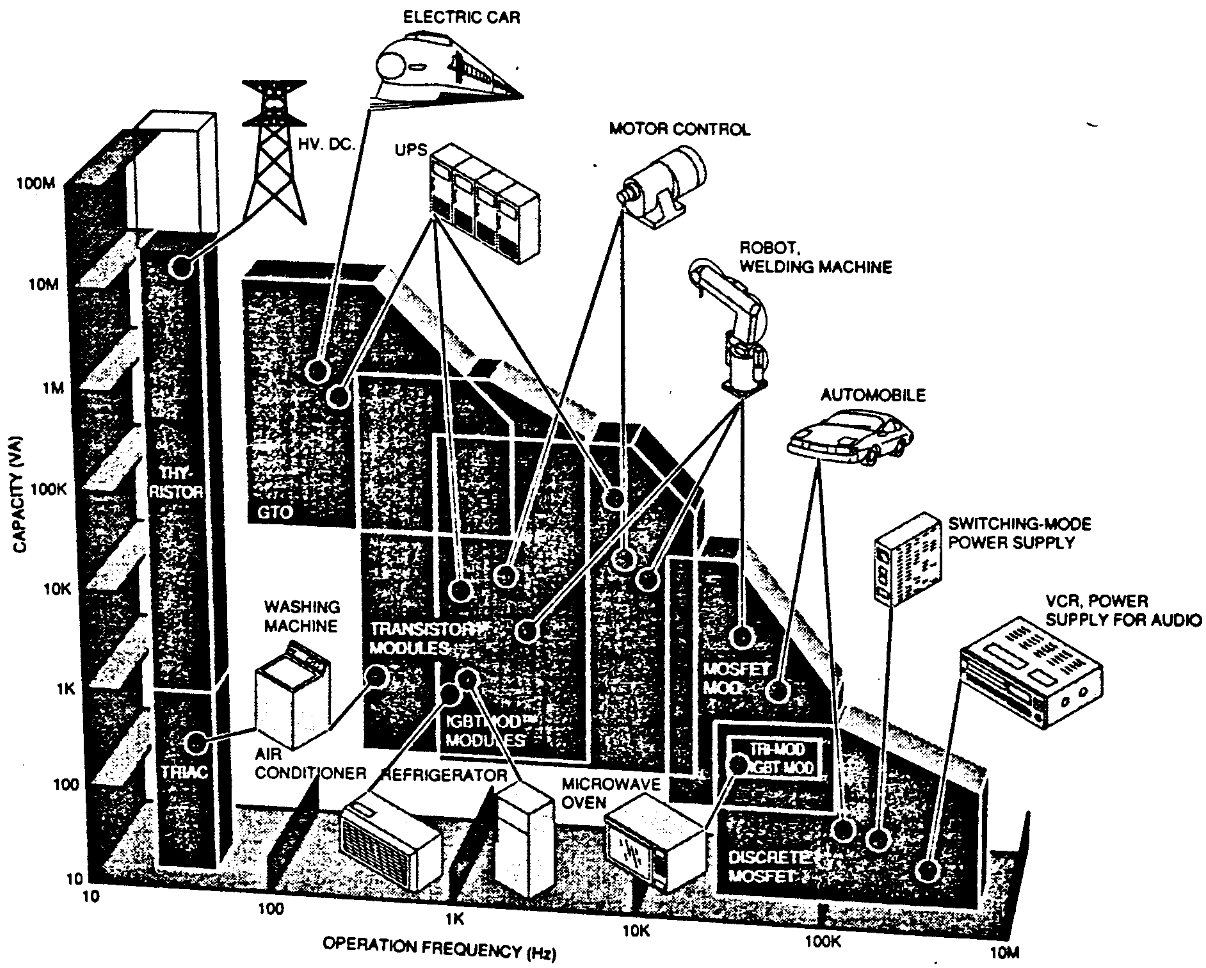
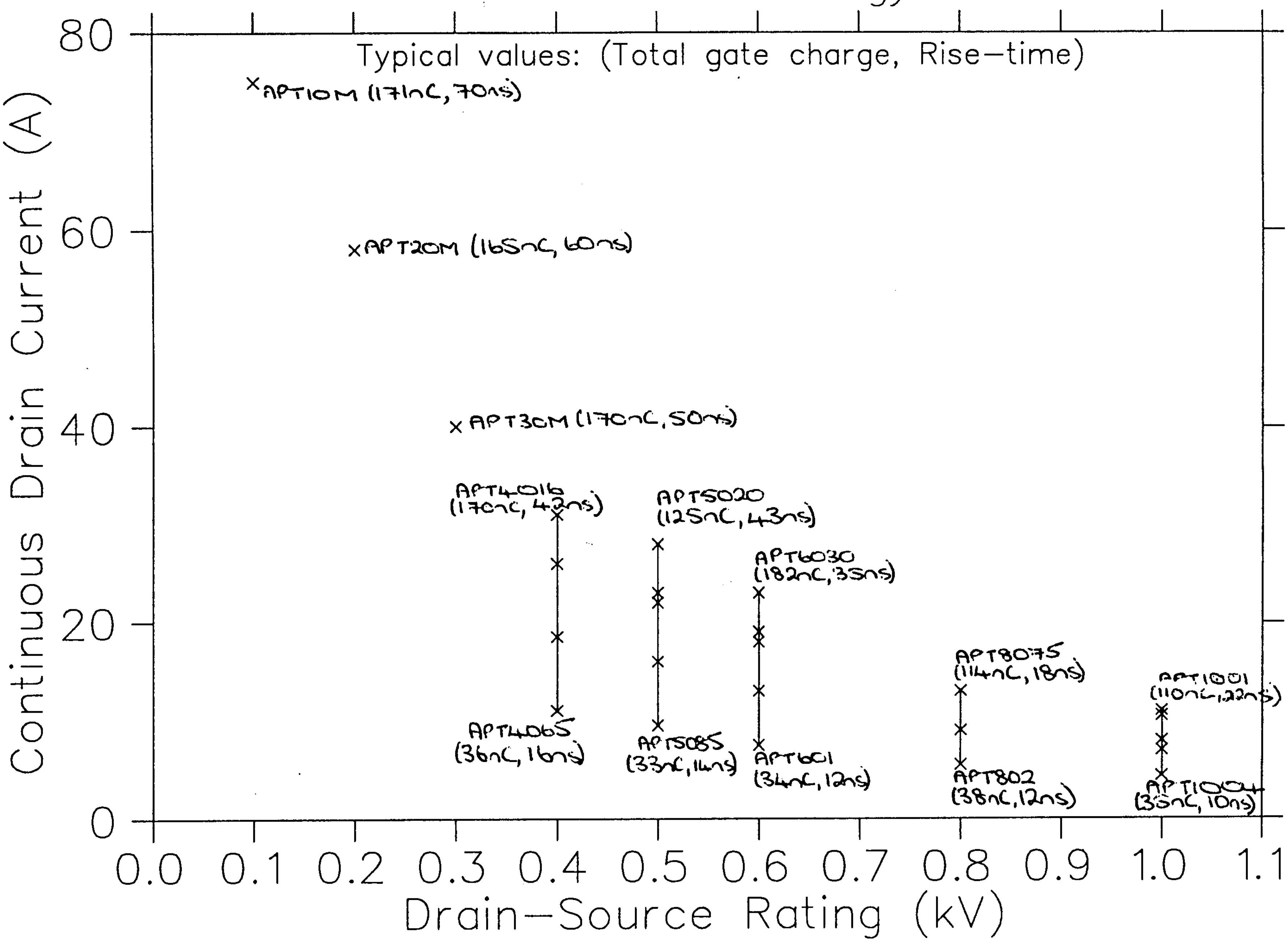


FIG 3: Advanced Power Technology MOSFETs



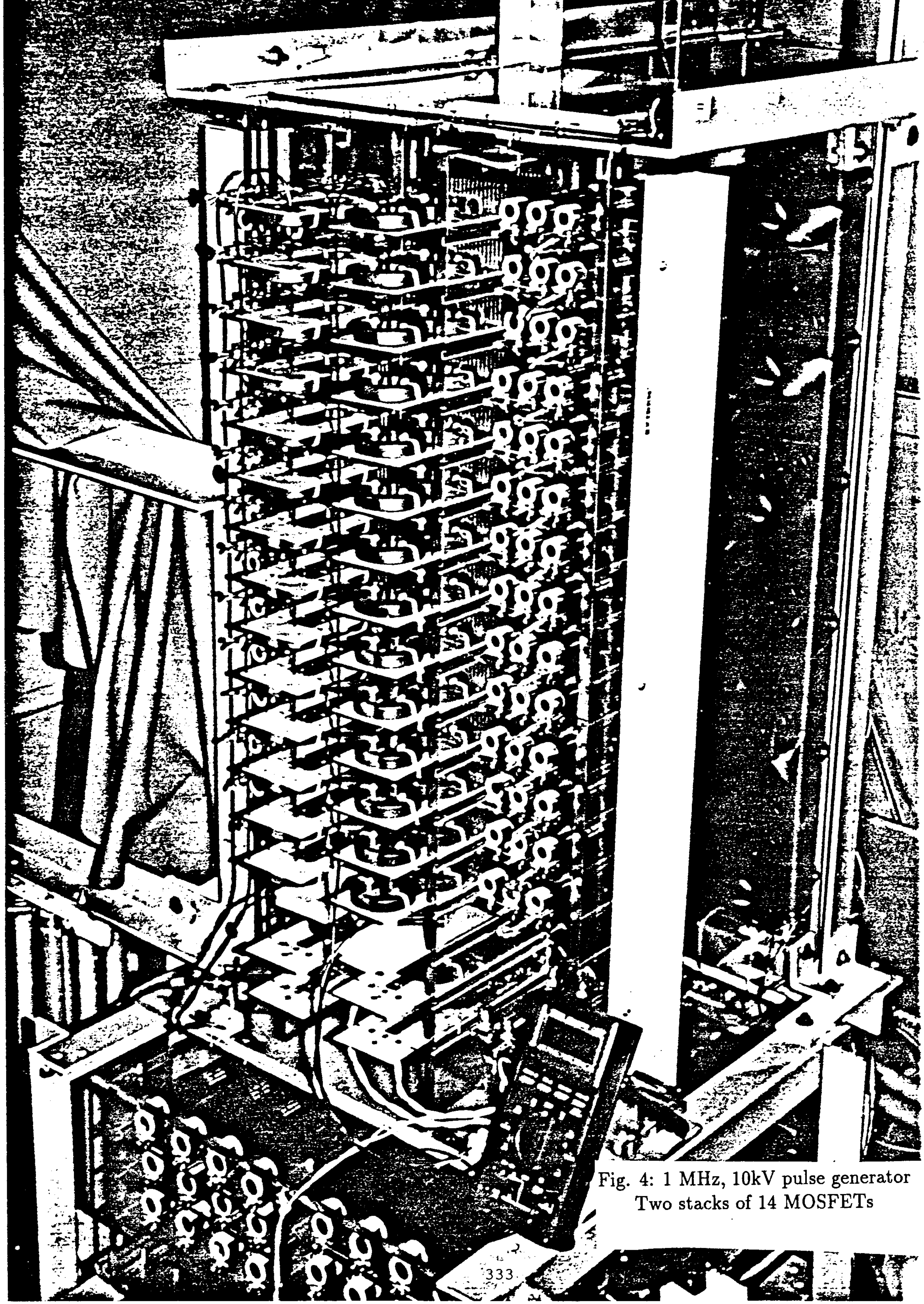


Fig. 4: 1 MHz, 10kV pulse generator
Two stacks of 14 MOSFETs

Figure 5: Selection of Insulated Gate Bipolar Transistors

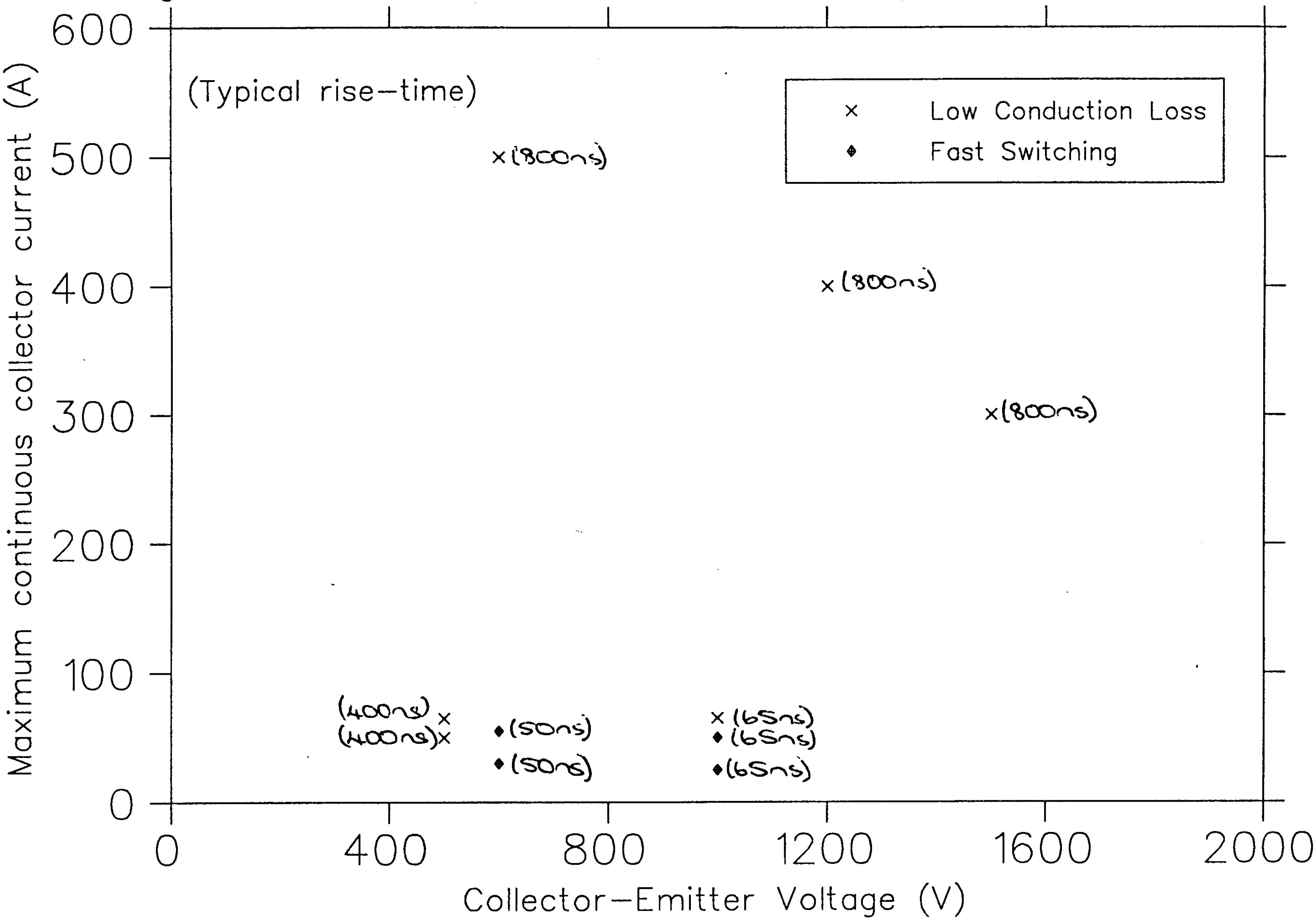


FIG 6: Fast Switching & Asymmetric Thyristors

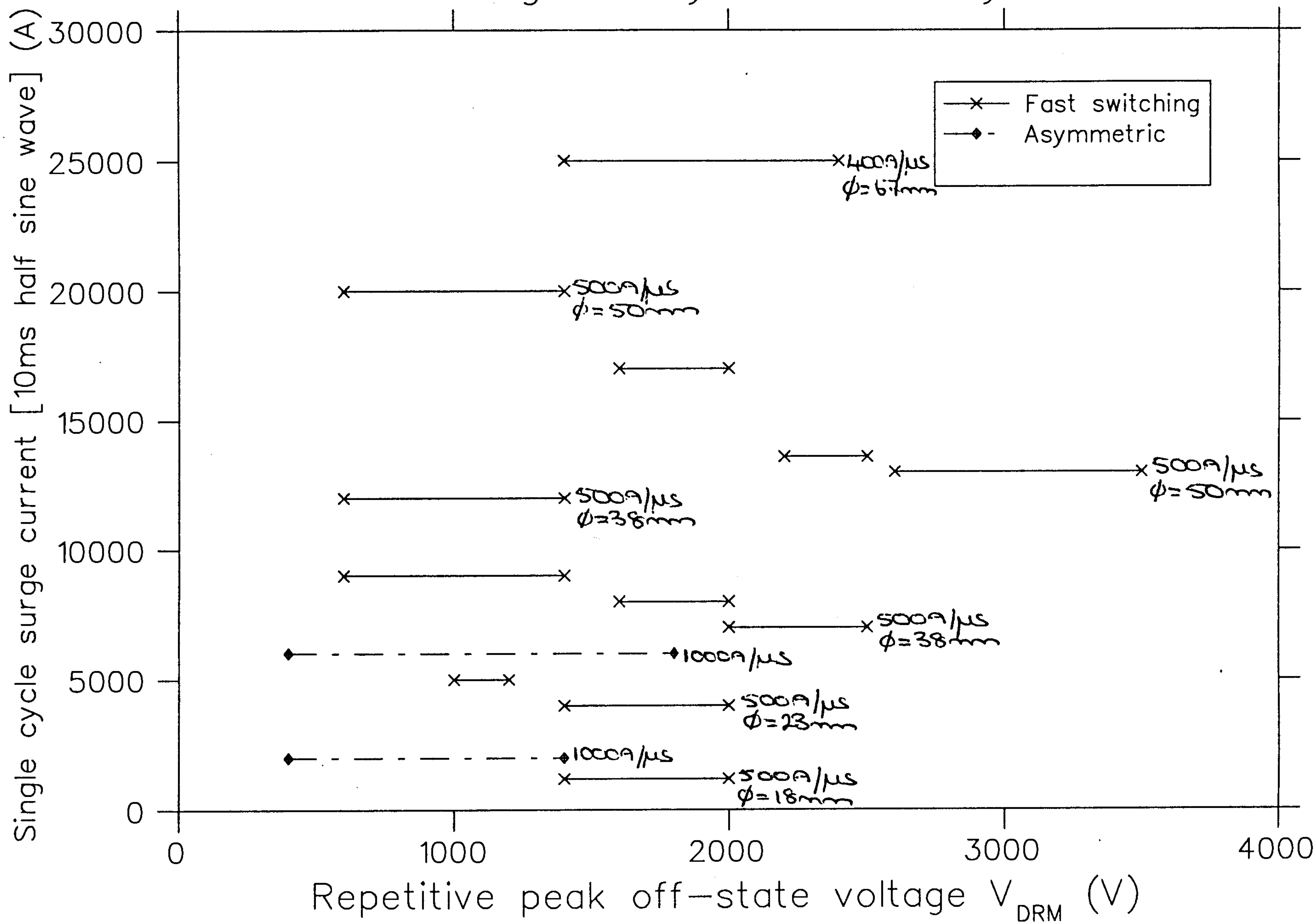
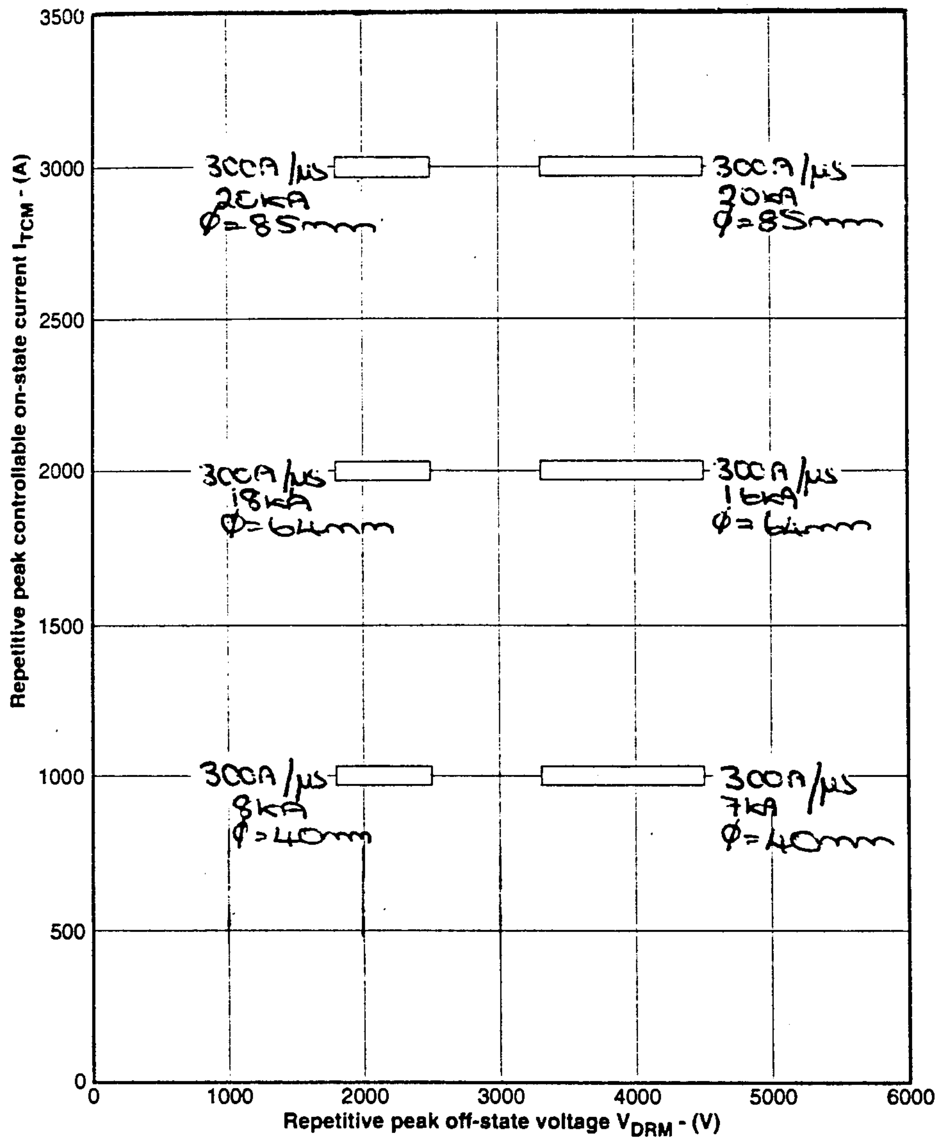


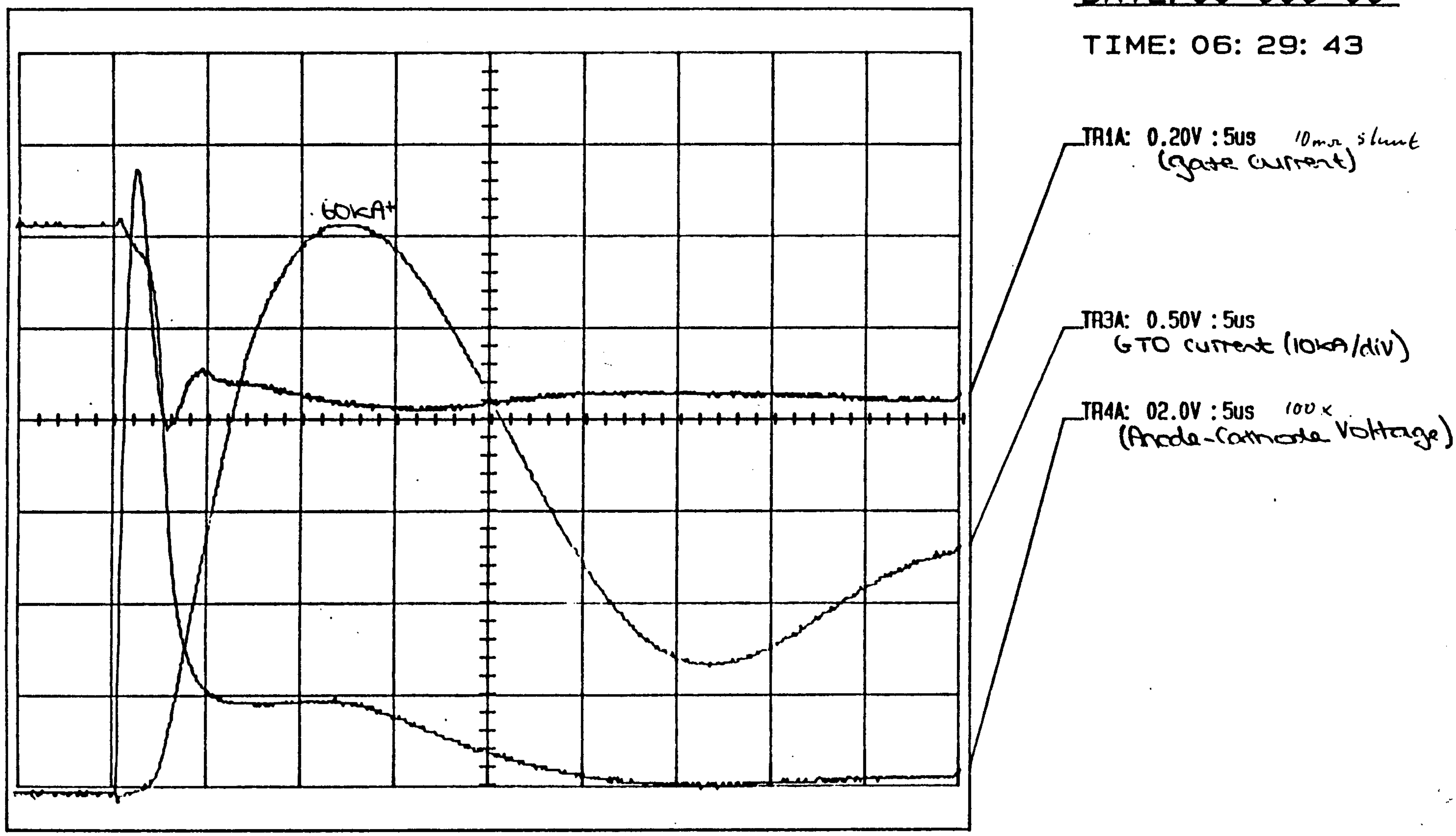
FIG 7: Standard Gate Turn-Off Thyristors



di/dt at I_{TCM}

Single cycle surge current (10ms half sine wave)

FIGURE 8: Measured Waveforms for Westcode WG20004SE6G modified GTO

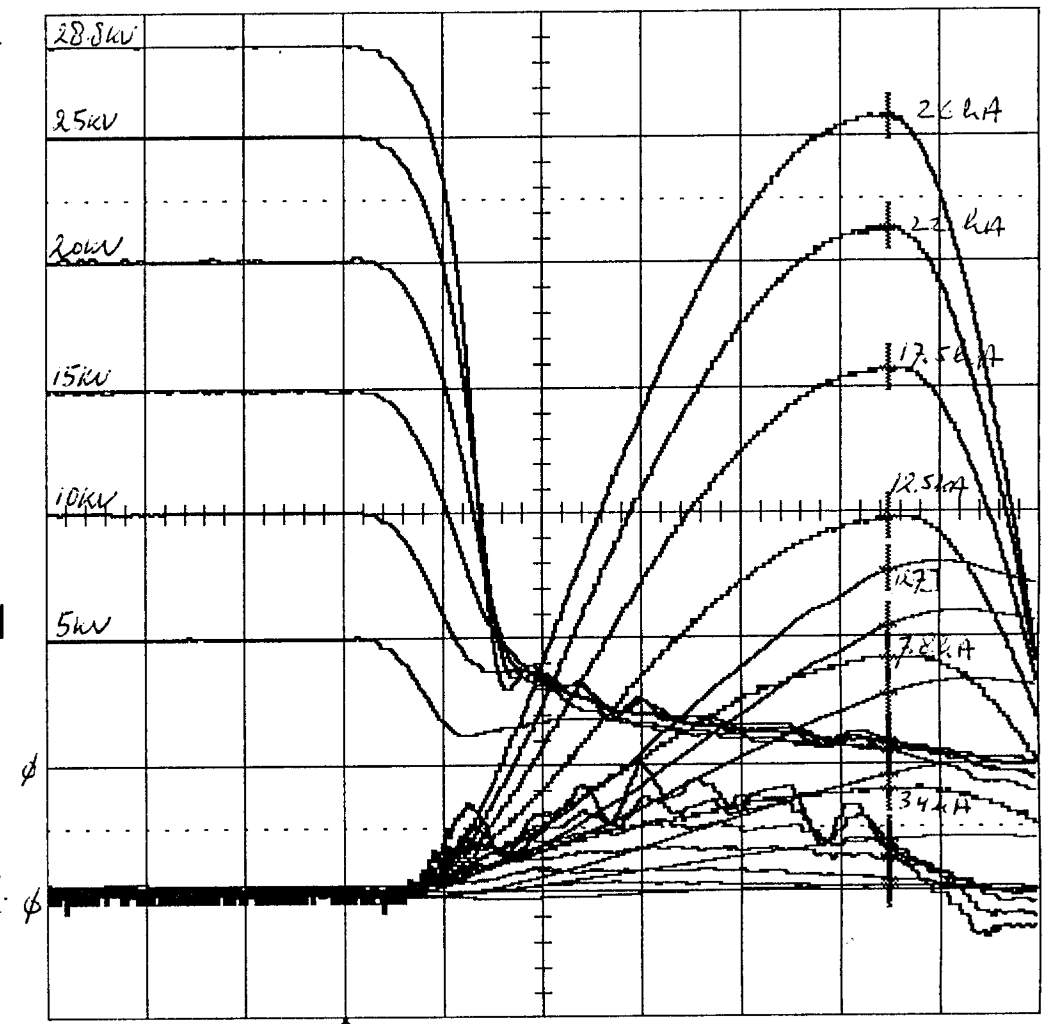


kV	kA	Z	J
28.8	25.94	1.11	127
25.0	22.25	1.12	102
20.0	17.50	1.14	075
15.0	12.49	1.20	043
10.0	07.74	1.29	017
05.0	03.39	1.47	0.01
0	0	0	0

LHC BEAM DUMP GTO-SWITCH.

10X WG20045 (4.5kV) in Series

CERN, E.V.



1 µs / div.

ALTERNATIVE SWITCHES, SOLID STATE SWITCH SUMMARY

Mike Barnes

Assuming the following specifications:

75 kV blocking voltage

di/dt = 10 kA/μs avg.

3 kA current

300 ns rise and fall times

Modified GTO's are the most promising semiconductor for the above duty.

Westcode and ABB both have modified GTO's that are closing switches capable of

≈20 kA/μs → ≈70 kA/μs.

But the Westcode GTO is the only available symmetrical GTO (modified) that I am aware of.

Cost of modified GTO's for a series stack with 75 kV blocking voltage:

≈US$40,000 to US$58,000 for GTO's,

i.e. 5 → 8 times the cost of comparable thyratron.

Potential reliability of a stack of 28 modified GTO's (assuming GTO's are conservatively applied) and with 3 redundant GTO's per stack

MTBF => 3 failures/10^6 hours/klystron-modulator

i.e. 25 → 30 times a comparable thyratron (currently available).

Requires significant R&D,

e.g. could GTO gate-cathode region be modified/tailored for above duty.

Future improvements to semiconductor switches may make semiconductor switch even more promising and reduce cost.

10 stack GTO switch (28.8 kV, 25.9 kA → 127 J/pulse.

∴ 1 GTO ≈ 13 J/pulse (switching and conduction losses)

Scale GTO loss/pulse $\propto I^2$

∴ for a klystron-modulator switch for NLC (if I ≈ 3 kA)

GTO loss/pulse ≈ $13\ J \times (3{,}000/25{,}900)^2 \approx 0.2$ J/pulse

∴ loss per GTO at 180 pps => 36 J/sec

NOTE: above estimate underestimates switching losses and overestimates conduction losses.

<u>or</u> at 3 kA ≈> 12 J/10 GTO's

=> 12 J/GTO/pulse

at 180 pps => <u>220 J/s</u>

Thermal resistance of junction to case (double sided cooling)

= 0.017 °C/W (Westcode WG200045E6G)

∴ $T = 220 \times 0.017 \approx$ <u>4 °C</u>.

When comared to a thyratron the GTO switch would not require:

heater supply

reservoir supply

gradient grid voltage

Hence adjustment of reservoir voltage is eliminated and overall modulator efficiency is higher.

Other significant factors in favor of the GTO as compared to a the thyratron:

GTO switch does not produce x-rays.

GTO does not require a warm-up period.

GTO does not require high voltage conditioning.

Easy diagnostics for GTO switch.

GTO has a smooth turn-on: low noise level.

EEV THYRATRONS FOR NLC KLYSTRON MODULATORS

R. Sheldrake, C. R. Weatherup and C. A. Pirrie

Proposed Thyratron Conditions

The high power X-band klystrons for the Next Linear Collider (NLC) are specified to operate at 500 kV, 500 A. In order to drive such klystrons the power modulator switch conditions are currently proposed as 72 kV anode voltage, 7 kA pulse current, 1.5 μs pulse width at 120 p.p.s., which is 2 A average. Current rise time needs to be <100 ns. In view of the large number of modulators (>3000), a lifetime in excess of 50,000 hours is specified for the thyratron switch.

Closest Relevant Experience

Some kicker magnet switch parameters are the closest to the proposed NLC modulator conditions and there is extensive operating experience over 20 years with thyratron type CX1171 (Fig. 1) at CERN(1), Fermilab(2), KEK and GSI Darmstadt which shows that this tube design can operate reliably at 80 kV, 3 kA, 2 μs, 1 p.p.s. for periods in excess of ten years. CX1171 thyratrons are now also employed in a variation of this circuit(3) which now offers a rise time of 25 ns (10 – 90%) to 6 kA (dI/dt of 190 kA/μs).

Thyratron average current in these kicker applications is low (⩽100 mA). However, typical modulators, such as the standard SLAC type, require switch tubes operating at several amps average current, but only up to 50 kV and with a low dI/dt (typically <20 kA/μs). These high average current modulator conditions have been addressed by EEV with enhanced barium aluminate cathode technology rather than the traditional oxide cathode technology of the CX1171.

The barium aluminate cathode CX1836A type thyratrons (Fig. 2) are now demonstrating lives of over 15,000 hours at up to 50 kV, 6 kA, 6 μs pulses at 120 p.p.s. (>4 A average) at SLAC(6), CERN(7) and Argonne(8). Experience at Argonne is particularly relevant since the final modulator design there employed the fast switching design techniques developed for kicker magnet driving in order to increase current rise time and thereby extend the flat top pulse length. The adoption of coaxial screened interconnections has had the added benefit of reducing radiated noise and associated control problems.

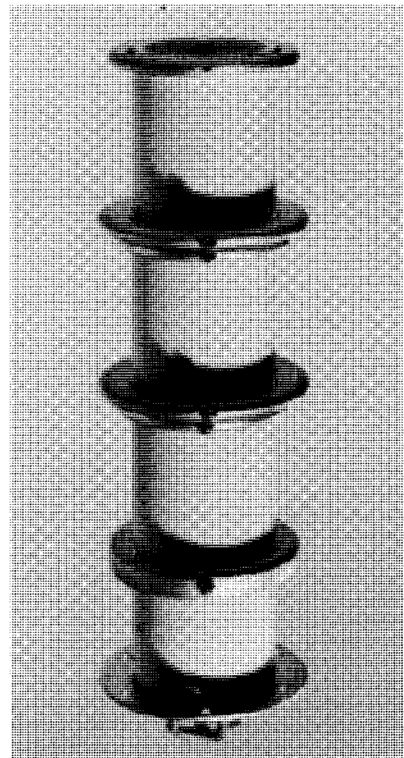


Fig. 1 CX1171

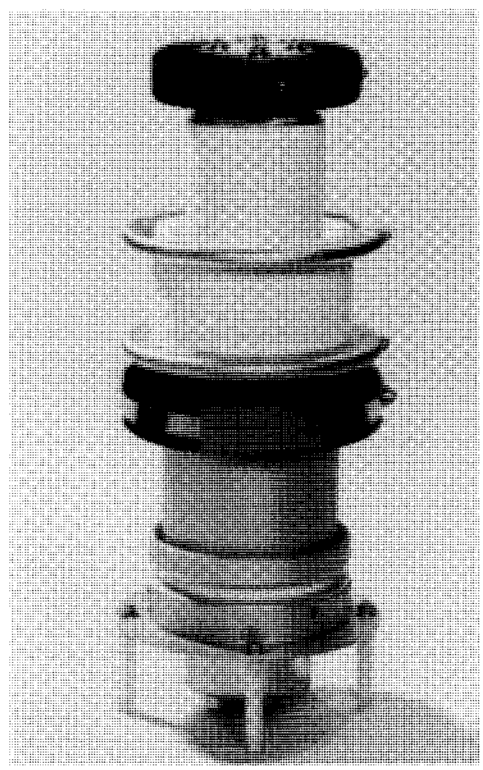


Fig. 2 CX1836A

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Subsidiary of the General Electric Company, p.l.c. of England.

Proposed Thyratron Switch

The CX1171 will require several enhancements to ensure reliable performance at the higher average power of the NLC modulator. Principally this will involve the use of enhanced barium aluminate cathode technology which has already established good performance at much higher average powers in radars and linacs as described above. In fact, this development has already taken place to address the conditions required for the kickers proposed for the TRIUMF KAON factory. The conditions are similar to those for the CX1171 kickers (see above), except operation was to be at 50 Hz, not 1 Hz. Work has also been done to enhance the thyratron switching speed by the use of saturating anode inductors at TRIUMF[5] and also at CERN[4].

The CX2171 thyratron (Fig. 3) incorporates the first phase of cathode enhancement and has already demonstrated successful and reliable operation at conditions near those required. Lack of test equipment has prevented this tube operating simultaneously at the high voltage, fast switching speed and high average current required. However, the CX2171 operates reliably at 4 A average current at 70 kV, 9 kA (low dI/dt), 6 μs at 74 Hz and at 85 kV, 6 kA, 2 μs at 5 p.p.s. with dI/dt $\approx$100 kA/μs. There is a high degree of confidence therefore that the CX2171 will operate reliably under NLC conditions.

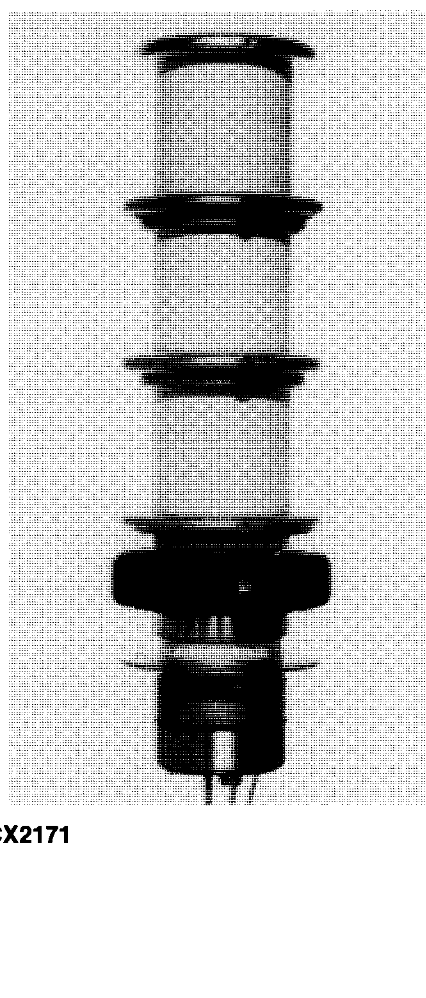

Fig. 3 CX2171

The relationship between cathode size, average current and cathode life is fairly well understood. The CX2171 has a projected life, under the proposed NLC modulator conditions, approaching 25,000 hours. To reach 50,000 hours a larger cathode tube would be required. This tube would be similar to the current production CX2193 thyratron (Fig. 4).

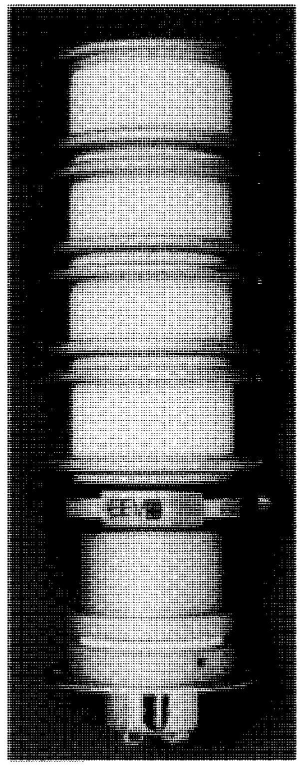

Fig. 4 CX2193

One important point which has a direct bearing on the tube life is thyratron triggering. It is common practice to use a d.c. priming discharge to a trigger grid near the cathode (G1) with a negative d.c. bias on a second grid (G2). Conduction is initiated by applying a fast pulse to G2. Although this is a convenient method and adequate for many applications, the use of a d.c. plasma with a current of only a few hundred milliamps does not give sufficient pre-ionisation of the cathode-grid space and therefore subjects the cathode to greater stress than necessary.

It is possible to overcome this to some extent by splitting a single grid pulse between grids, and a significant improvement in switch lifetime has been achieved by this method[6][7]. However, the greatest benefits can be obtained by using separate grid pulses on G1 and G2 with the G2 pulse delayed by 0.5 to 1 μs. The G1 pulse needs to reach several tens of amps at the peak for a tube like the CX2171. For larger cathode tubes such as the CX2193 this current should be increased to about 100 A. In view of the relatively slow pulse requirements, the G1 pulse can be easily generated by a thyristor or FET based generator. The fast G2 trigger pulse can also be generated by a properly designed FET or IGBT switch based generator.

Other Modulator Issues

As indicated above, the CX2171 can easily achieve current pulse rise times in the region of 30 ns. However, it is the common experience that the pulse rise time at the klystron or kicker magnet is $\geqslant 100-150$ ns because of the inductance associated with the pulse transformer or kicker magnet designs. For the NLC, the challenge, therefore, is to match the rise time capability of the pulse transformer to that of the thyratron in its low inductance housing.

The highest thyratron switching speeds are achieved at the highest gas pressures (highest reservoir voltage). In the case of the CERN fast kicker system, the gas pressure can be maximised since the PFL is command charged. Not only does this decrease the high voltage holding time, but it also removes any difficulties with switch recovery before recharge. Best switch performance is thus readily achieved. The NLC will also benefit from these advantages if the proposed commanded inverter supplies are used to charge the PFL.

Conclusion

EEV's existing thyratron switching technology is already capable of meeting the NLC conditions with a high degree of reliability. Lifetime targets will be achieved by choosing an appropriate sized cathode. The most important next step is for a modulator to carry out real life tests; candidate thyratrons are available for evaluation now.

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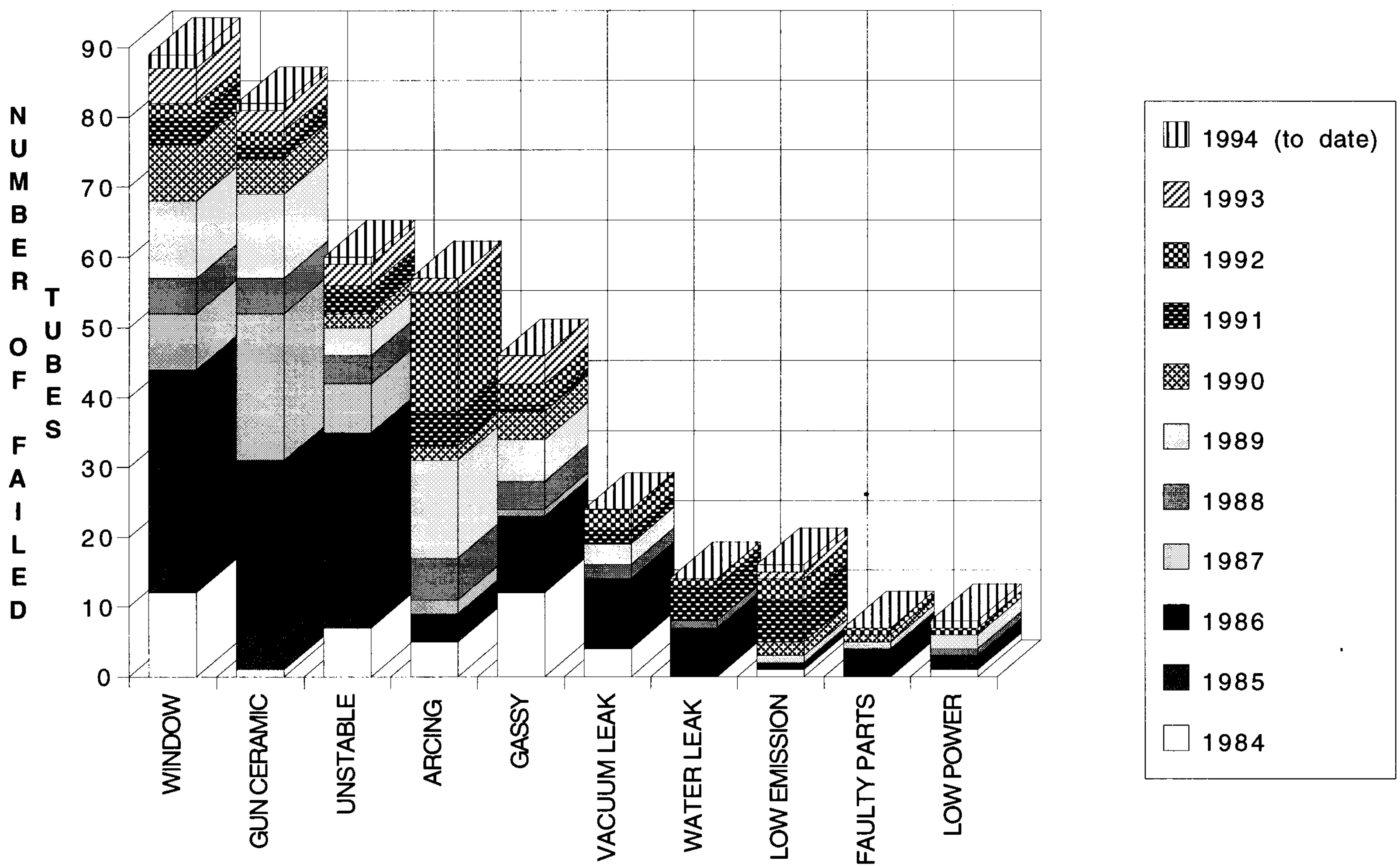
SLAC KLYSTRON RELIABILITY

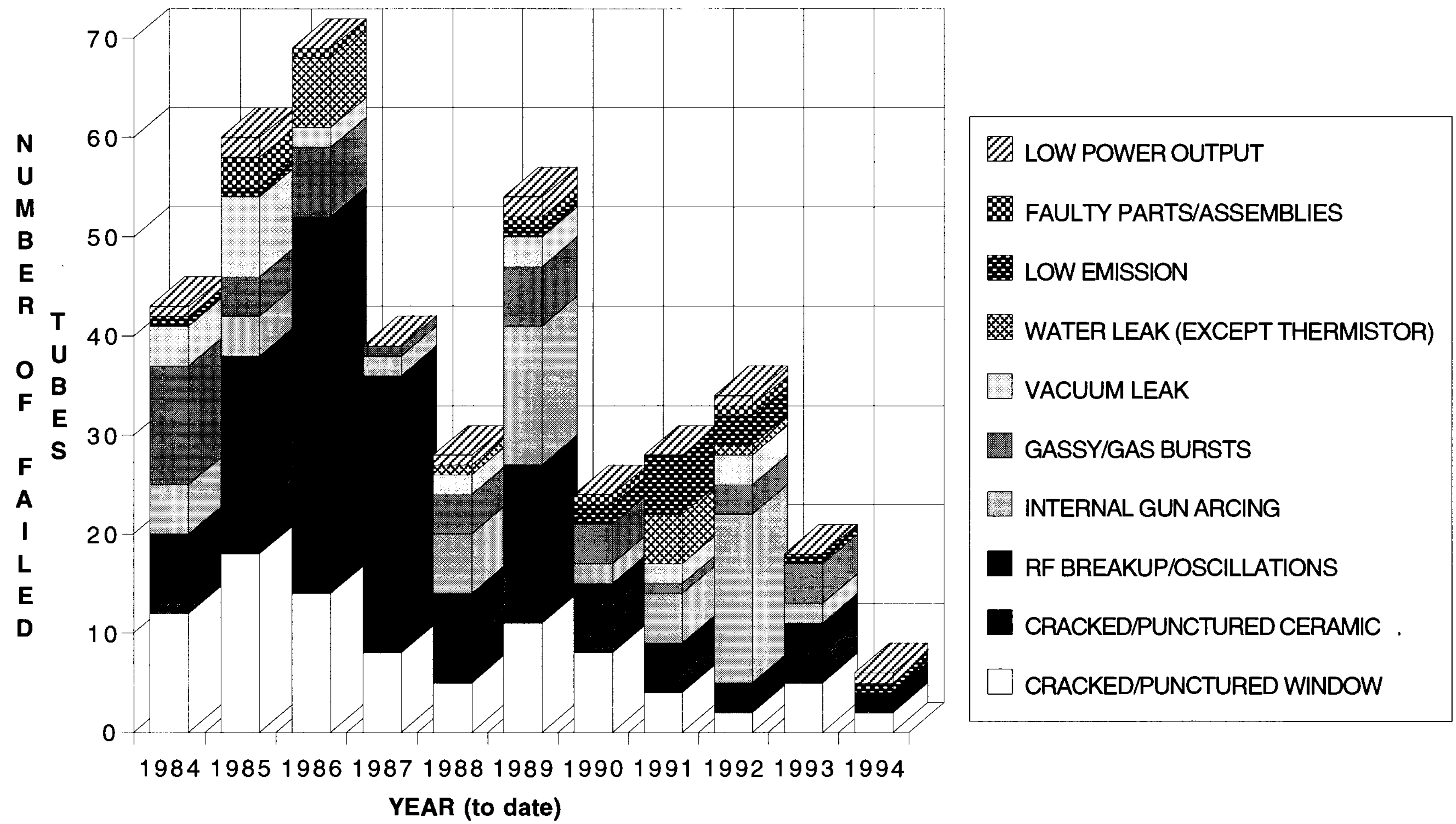
G. CARYOTAKIS

TEN MOST COMMON CAUSES OF 5045 KLYSTRON FAILURES (1984-1994)



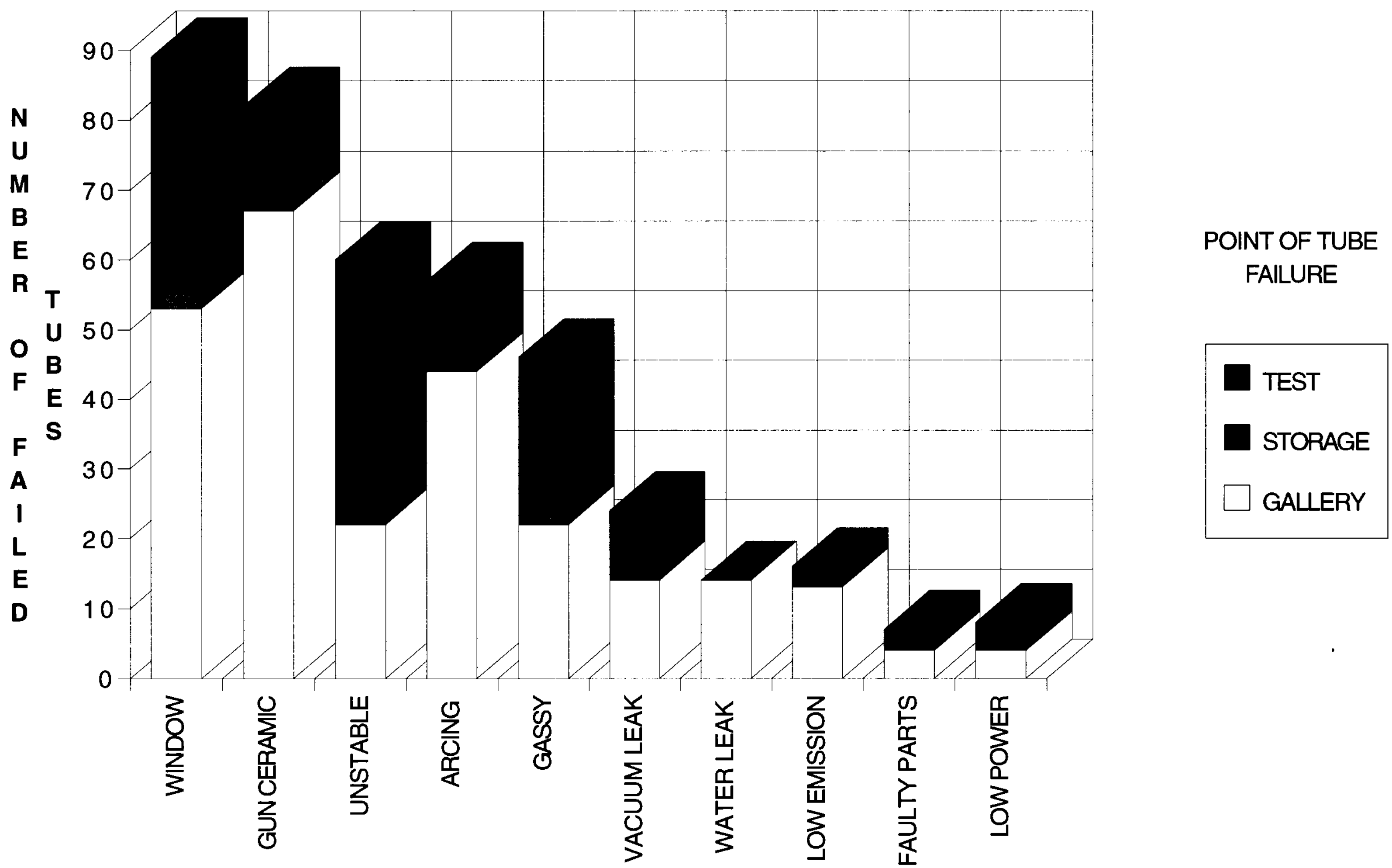
FAILURE CHART (BY YEAR) MPD 4/25/94

TEN MOST COMMON CAUSES OF 5045 KLYSTRON FAILURES (1984-1994)



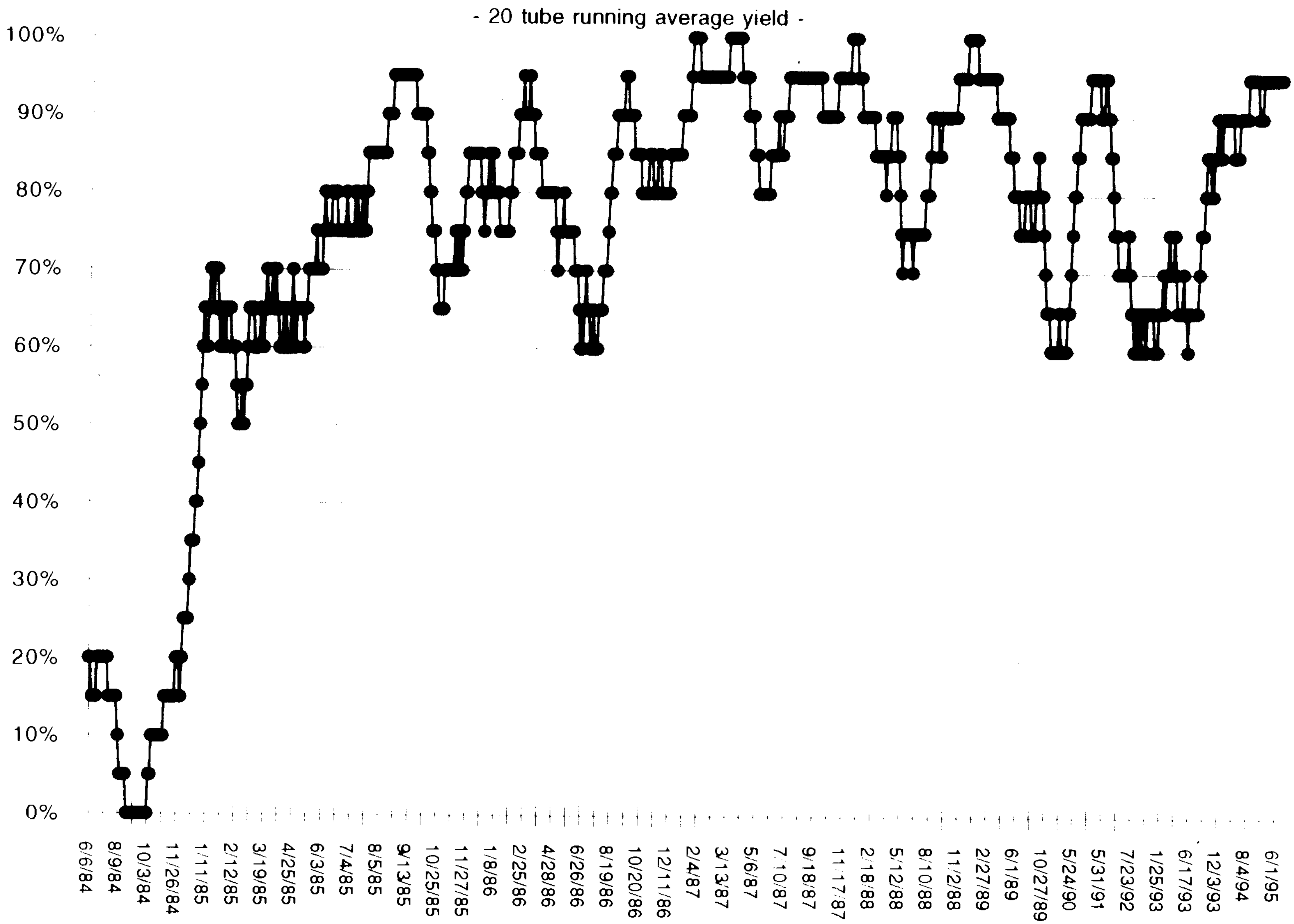
FAILURE CHART (BY FC) MPD 4/25/94

TEN MOST COMMON CAUSES OF 5045 KLYSTRON FAILURES (1984-1994)



FAILURE CHART (G+S+T) MPD 4/25/94

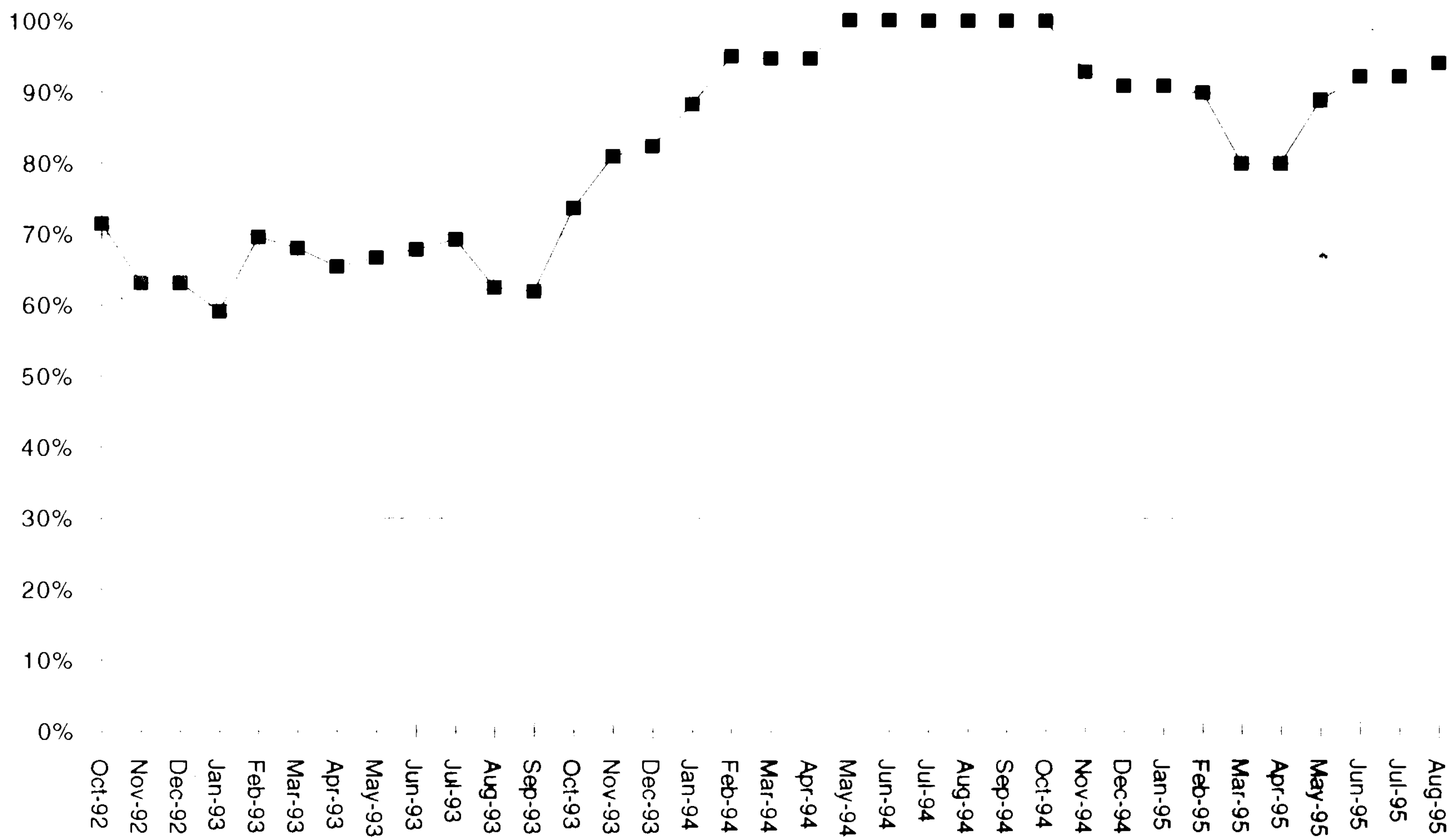
5045 KLYSTRON TUBE YIELD



10/6/95 CHC ?0 5045 kly Yld.AUG-95

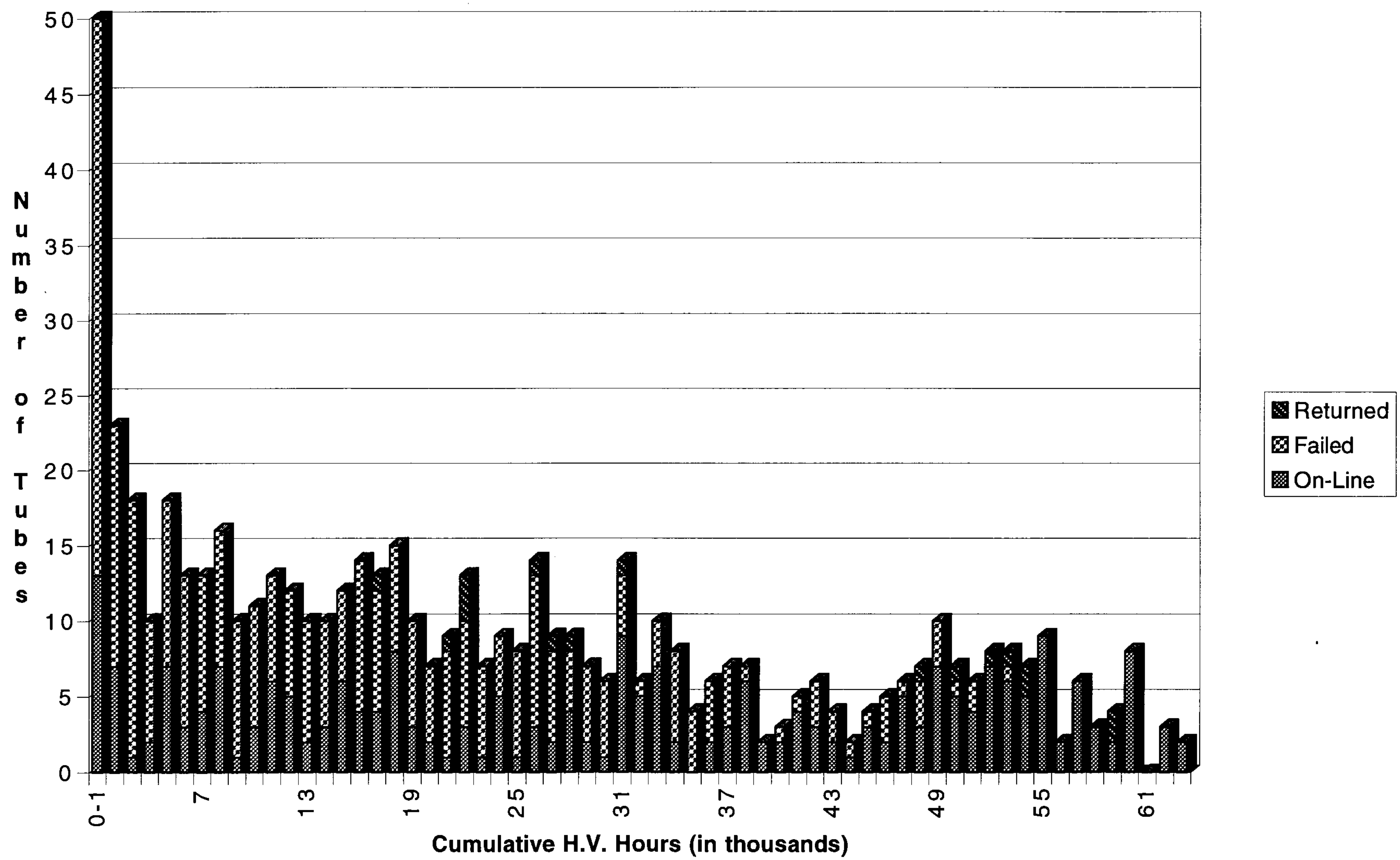
5045 Klystron Production

6 Month rolling average yield



MPD 10/5/95

Graph Showing Cumulative H.V. Hours of On-Line, Failed and Returned 5045 Klystrons



MPD 3/13/96

SLAC-PUB-6543
June 1994
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A HISTORY OF THYRATRON LIFETIMES AT THE STANFORD LINEAR ACCELERATOR CENTER*

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Abstract

The Stanford Linear Accelerator Center (SLAC) has been in almost continuous operation since the middle 1960s, providing a remarkable opportunity to amass thyratron data. This paper reviews the history of this thyratron usage, focusing primarily on data collected during the last ten years of accelerator operation.

There have been two distinct operating conditions during the history of operation at SLAC. Prior to 1985, the fundamental thyratron operating points were 46 kV anode voltage (Epy), 4.2 kA peak current, 3.8 μs equivalent square pulse (esp), with a maximum repetition rate of 360 pulses per second (pps). The accelerator was upgraded during 1985, and the thyratron operating points are now 46 kV Epy, 6.3 kA, 5.4 μs esp, with a maximum repetition rate of 120 pps.

The SLAC high-energy physics research program requires that each of the available modulator klystron units provide a stable microwave energy source. Within these constraints, this paper explores historical thyratron lifetimes at SLAC, reviewing the available data to determine how long these thyratrons can be expected to operate before failure currently or recently used in the 243 accelerator modulators.

INTRODUCTION

The Stanford Linear Accelerator Center functioned for many years as originally designed. In early 1985, there was a major upgrade to accommodate the newly developed 50 Megawatt pulsed S-Band Klystron. This rework of all linear accelerator (linac) modulators altered the thyratron operating condition to an Epy of 46kV at 5,600 amps into a 1:14 pulse transformer to drive the new klystrons.

Prior to and during the conversion of the linac modulators, concern was expressed about the existing ITT F143 and Wagner CH1191 thyratrons being capable of operating at the higher required power. Therefore, 48 of the 243 modulators used in six sections of the accelerator were modified to use two thyratrons each. After additional testing, the existing Wagner CH1191s and the ITT F143/CH1191 rebuilds were found to be fully capable of operating the new modulator configuration, so all of the dual thyratron modulators were eventually reconfigured back to single thyratron operation.

During the period of the linac upgrade, it was found that the new 5405 klystron could operate at 350kV, with 60 megawatts of power out. This required modification of all 1:14 pulse transformers to 1:15, increasing the peak primary current through the thyratron from 5,600 to 6,100 amps. With this change, we could continue to use the diminishing thyratron inventory while actively engaged in a search for new thyratrons that would operate the new 5045 klystrons.

Initial checkout of the modulator systems was accomplished at 10 pps. Most of the accelerator commissioning work done through 1990 was accomplished at 60 pps or less. During part of the conversion process, the accelerator continued to operate particle beam experiments with the pulse rate limited to 10, 30 or even 60 pps. No experience was available to establish or reliably project thyratron lifetimes. Even limited operation at 120 pulses per second for a month did not establish any benchmarks. The prediction of the rate of consumption of thyratrons in the linac modulators was therefore based on conjecture. Modulator reliability in the Stanford Linear Collider (SLC) configuration is discussed by A. R. Donaldson et al., "SLAC Modulator Operation and Reliabiltiy in the SLC Era" in the1992 20th Power Modulator Symposium, IEEE Confrence Record CH3180-7/92/0000-0152.

The linac commenced operation at 120 pulses per second in July 1990. In July, 11 thyratrons were changed in the linac modulators, followed by 18 in August, 4 in September, 19 in October and 10 in November, when the run was completed. During this run cycle, the initial symptoms of premature thyratron failure due to internal problems with Grid 1 appeared. During the three years of SLC operation at 10, 30 or 60 pps, the average replacement rate was 4.5 tubes per month. From 1988 through 1991, running at 60 pps, the replacement rate increased to 7.5 tubes per month. Running at 120 pulses per second, the replacement rate is 14 tubes per month. These rates include thyratron changes for any reasons.

An extensive testing program was established in March 1991 to verify the status of all thyratrons removed from operation in the linac. Of all thyratrons undergoing failure verification testing, 10% are recertified for operation in the linac modulators. This program provides hard data that is shared with the vendor to improve the reliability of their product.

The nature of the operational cycle at SLAC includes periods of time when the power is turned off for installation work, repairs, and upgrades. During the initial start up following an extended maintenance period, thyratron replacements run above average. The actual number of changes varies, without correlation to time turned off, or prior operating conditions. During a recent holiday down time, the thyratron filament, reservoir, and dc keep-alive circuits were left on in an attempt to reduce replacements. This decreased the number of replacements, but required operating 243 power supplies at 121 kilowatts. At three weeks, cost of power is cheaper; at five weeks, power costs are greater than savings.

Of the 440 thyratron replacements in the linac that occured during the three years since September of 1991, the earlier internal problem with the Grid 1 failure was a significant cause. Originally appearing in the F241s, this type of failure mode also appeared in other models, and will be discussed as part of the data presented for each thyratron model. The large number of changes has significantly altered lifetime profiles.

We look at current lifetime profiles and age profiles, grouped by specific thyratron model. This data is dynamic. Here, it is presented in a static format. All mention of hours refers to the thyratron high-voltage running time recorded by electromechanical meters on the front of each modulator. The age and lifetime profiles are extracted from the thyratron data base and may be viewed on computer. These graphs are based on run-time meter readings taken approximately at the end of each month. Data current as of May 31, 1994, was used to generate the hours history plots shown for the thyratrons models presented. Filament run-time data is also recorded, but is not included in this discussion.

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Litton Model 4888

The thyratron high voltage run time hours for Litton's model 4888 thyratrons are in the range of one to six thousand hours, from a sample statistically small compared to other vendors. Design work, and prototyping produced the first tube in June 1993, with production deliveries started August of 1993. Litton is still in the post development stage of production, correcting of minor problems, improving and optimization testing procedures.

The first thyratron was installed into the linac in June 1993. Today there are 16 in use. During a maximum 8750 hours of high-voltage running time, the earlier problem with Grid 1 failure has been seen in only one thyratron to date. Due to the very short period of time available to collect meaningful lifetime data, it is too soon to project an accurate lifetime.

OmniWave Model 1002

Production or rebuilding of the Wagner carcasses started in late 1984 with the first deliveries beginning in January 1985, and ceased nearly 6 1/2 years later after approximately 250 tubes had been rebuilt. The Thyratron Age Profile graph (Figure 1) plots quantity versus age for the 10% of the total model 1002 thyratrons which are still in active service. Most of the 15 thyratrons centered in the bell of the distribution curve at 20,000 hours were produced late in the production. The two oldest thyratrons have close to 50,000 hours.

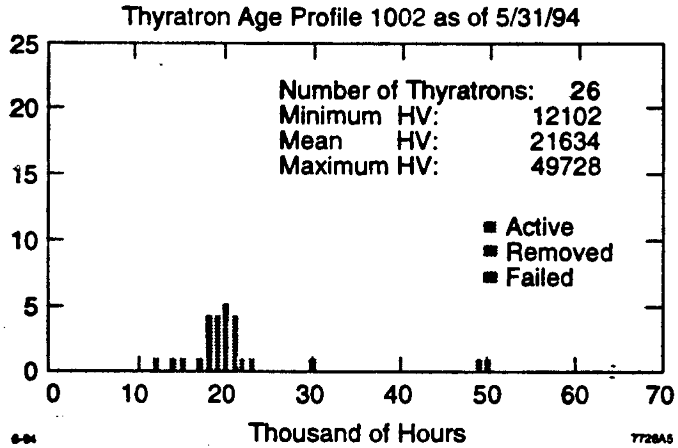


Figure 1. The quantity of tubes versus the high-voltage running-time hours. One thyratron failed at 30,000 hours since the readings.

Examination of the Thyratron Lifetime Profile in Figure 2 shows that almost half of the 145 thyratrons failed with 5,000 hours or less. One significant failure mode for this model was the rapid rise in required reservoir voltage. A second failure mode is the tripping off of the modulator power supply on a high voltage over current fault. This is likely to be a result of vaporized metal being deposited on the ceramics in the vicinity of the electrode gaps. Seven of the OmniWave model 1002 failures have been due to Grid 1 problems. Fourteen thyratrons have failed since passing the 20,000 hour mark. Figure 1 shows that OmniWave did have the ability to produce a rebuilt thyratron with the capability of 20,000 plus hours of operation.

English Electric Valve Ltd. Model CX1836A

Fifty-four model CX1836As were delivered, starting in October 1992, through May 1993 to fill a serious need for spare thyratrons. The design of the CX1836A enabled the tube to be an identical replacement.

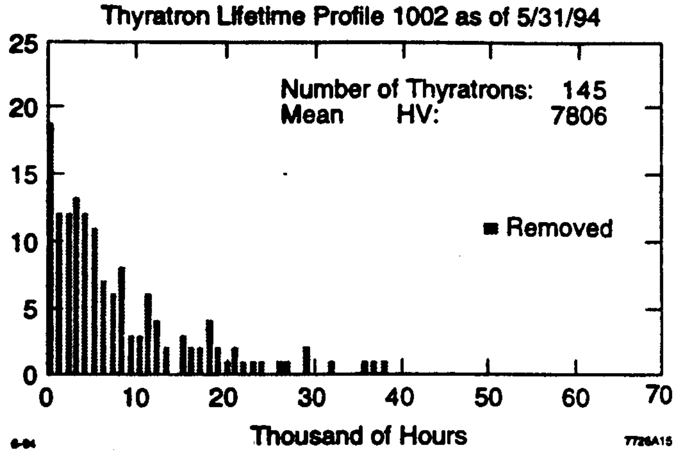


Figure 2. The quantity of tubes verus the high-voltage running time hours at the time of removal from the linac modualtor. There were 19 failures with less than 500 hours of high-voltage running time.

Fifteen of the CX1836As currently active in the linac. A problem manifested as external arcing from Grid 1 to ground reduced the number of CX1836A thyratrons active in the linac. A fix was found by working closely with English Electric Valve, and all of the removed CX1836As have been modified and recertified for use. The CX1836A is the only thyratron model that has not suffered from the Grid 1 problems prevalent with all other models used in the linac modulators.

English Electric Valve Ltd. Model CX2410

The CX2410 is the result of a SLAC request for a six-nch diameter thyratron with an oxide cathode. Deliveries started July 1992 and ran through July 1993. Outgrowth of this particular design is the CX2412, which supports and brings Grid 1 through the ceramic in the same fashion as Grid 2. The CX2412 is currently operational in a linac modulator with 4,500 hours of high-voltage run time. There are three tubes in active service, and a fourth tube that was removed from service after 3,200 hours and verified as failed due to Grid 1 problems.

ITT Model F143

Deliveries of just over 220 ITT rebuilt Wagner carcasses started in March 1974, and proceeded through October 1981. There are three remaining active thyratrons, with a fourth that was removed at 55,000 hours. Retesting has yet to be done.

Going back seven years to June 1987, Figure 3 displays the Thyratron Age Profile graph for the half of the linac modulators that were utilizing the F143 thyratron.

The decrease in the population of F143s with less than 2,000 hours is due to depletion of the F143 spares. In June 1987, 28 of the active thyratrons had exceeded the 20,000 hour point, and 25 thyratrons had been removed with 20,000 hours or more. There is an apparent randomness in high-voltage hours for the thyratrons removed from the gallery. Here again, with enough time, is proof that a thyratron can be manufactured or rebuilt that has the capability of providing over 20,000 hours of high voltage run time.

Figure 4 is a presentation of theThyratron Lifetime Profile of total high-voltage hours for all of the F143 thyratrons that have been removed from use in the linac modulators. The bar on the left edge in the range of 0 to 500 hours indicates there were nine thyratrons that failed

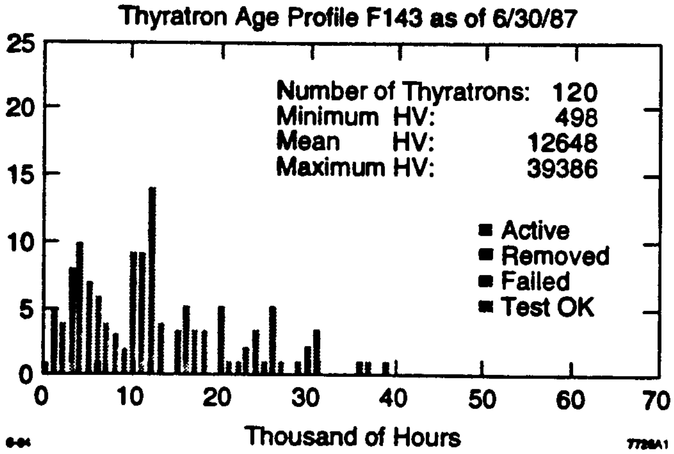


Figure 3. The quantity of tubes versus the high-voltage running-time. Five thyratrons failed during the month, three others were removed and recertified for operation and later used. This represented the largest quantity of the model F143s used in the linac modulators.

prior to 500 hours. This small quantity is a direct result of the acceptance testing program, although not all of the infant mortality failures were caught. SLAC rejected 28 F143s—some were reprocessed by ITT and returned, others were simply replaced. There is a peak in the number of failures at 26,000 to 27,000 hours. Here is effective proof that 20,000 hour thyratrons can be produced in quantity. The predominate failure mode for the F143 has been unstable operation or due to high-voltage power supply over current faults. Only seven F143s have been documented with the Grid 1 internal failure problem.

ITT Model F241

First delivery of ITT's model F241 started in July 1985 and continues today. Over 400 model F241s have been received and tested and of those, over 340 have been utilized in the linac modulators.

Figure 5 shows the Thyratron Age Profile for 58 active F241s in service at the beginning of June 1994, with two removals at six and nine thousand hours. The low quantity of thyratrons recently installed is due to there being a selection of five different models to choose from. Two thyratrons with 33,000 high-voltage hours are still in operation. One of these is on loan to SLAC for lifetime testing of a dispenser cathode.

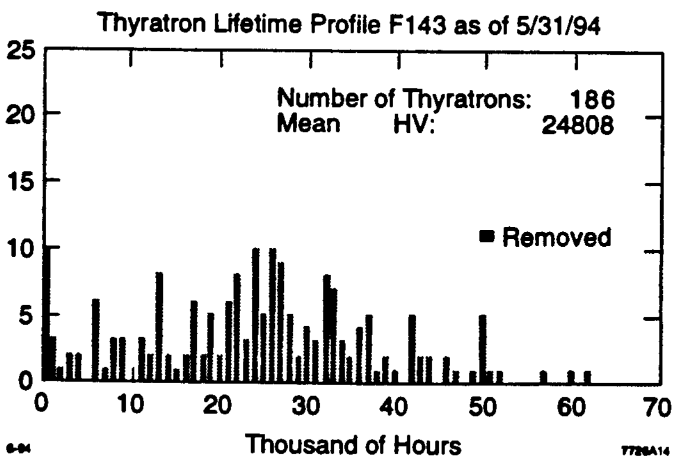


Figure 4. The quantity of tubes versus the high-voltage running-time hours at the time of removal from the linac modualtor. Only 10 failed with less than 500 hours of high-voltage running time.

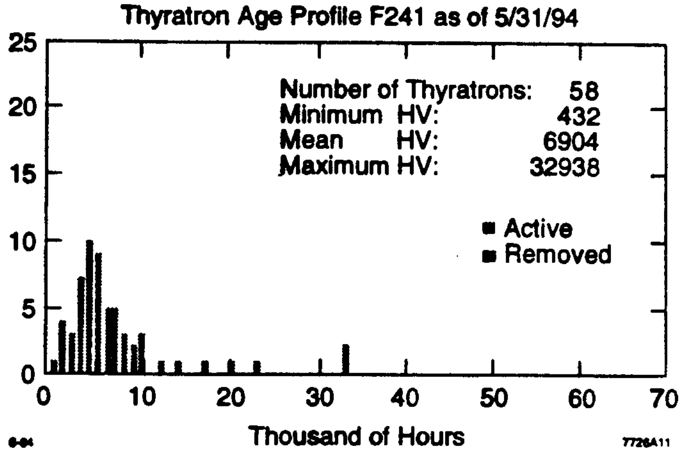


Figure 5. The quantity of tubes versus the high-voltage running-time hours. Two were removed, one with 5,000 hour and the second with 9,000 hours. Failure verification has yet to be done.

During the last three years, SLAC experienced significant losses in the F241 population, primarily due to the internal failure in Grid 1. The Grid 1 failure mode was first effectively documented by the F241 failures. Figure 6 displays the Thyratron Lifetime Profile. A large failure rate at six to seven thousand hours is predominately due to the Grid 1 problem. Diagnosis showed that there were two separate types of failures. In the first, part of Grid 1 developed a short to the cathode ground. The second type of failure was nonconduction from the cathode to Grid 1. This was only found upon attempted operation of the thyratron. Thyratron autopsies revealed serious erosion of the top of the cathode structure and disintegration of the Grid 1 element. Engineering discussions with ITT resulted in a change in design, and the F241 thyratron continues to be a stable workhorse for operational requirements of the linac.

ITT Model F310

When it became evident that the recent utilization of the failed Wagner carcasses was not a viable process, a switch was made to rebuilding the failed model F241

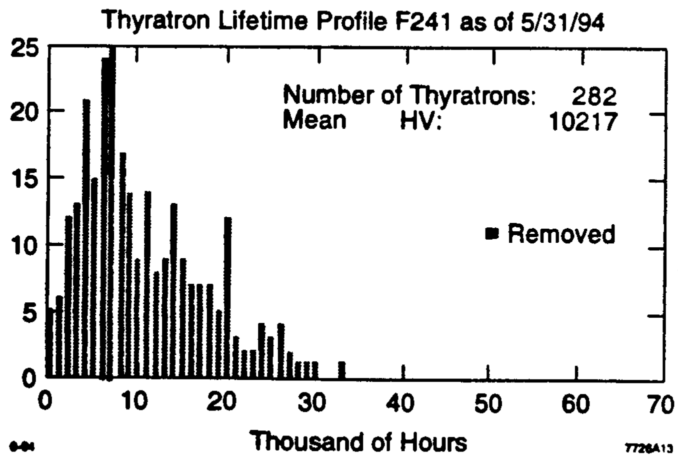


Figure 6. The quantity of tubes versus the high-voltage running-time hours at the time of removal from the linac modualtor. Five failed with less than 500 hours of high voltage runing time. The large peak at 6,000 to 7,000 hours can directly be attributed to the failures associated with the Grid 1 problem.

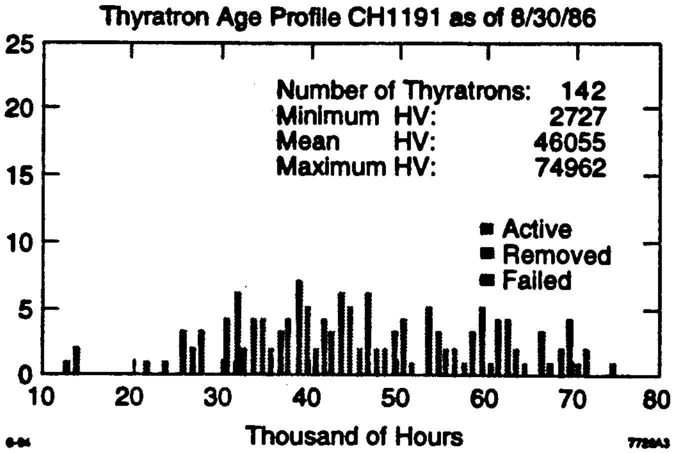


Figure 7. The quantity of tubes versus the high-voltage running-time hours.

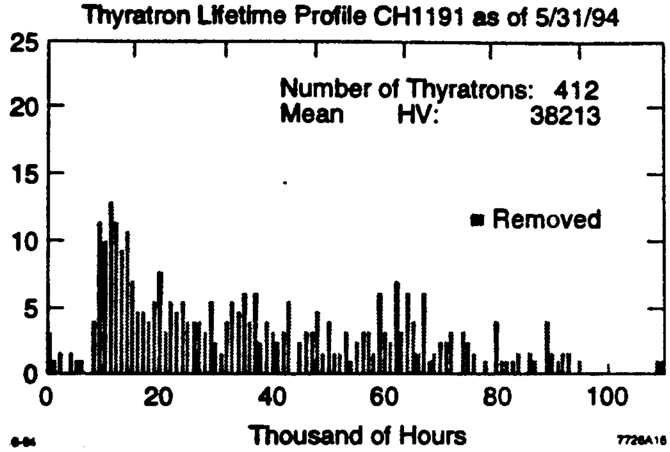


Figure 8. The quantity of tubes versus the high-voltage running-time hours at the time of removal from the linac modulator.

thyratrons. Operationally and physically, the F310s are identical to the F241. Deliveries of the rebuilt tube, now called F310, started in August 1992. Over 140 F310s have been in service in the linac modulators to date. Model F310s also suffer from losses caused by the Grid 1 problems. Experience indicates rebuilding the F310s from the F241 carcasses is viable and cost effective.

Wagner Model CH1191

Production delivery started in September 1964, starting a long run that delivered approximately 1600 thyratrons and rebuilt an additional 125. Not all of the CH1191 thyratron data exists in the computer files—approximately 35% is currently available from the last part of the production. The conversion of the linac to SLC type operation during the summer of 1985 came ten years after the last thyratron delivery from Wagner. Meanwhile, 20 thyratrons are still in service in the linac, with hours ranging from a minimum of 75,000 hours to top of 120,000 hours. This grouping provides exciting data for product lifetime. The remaining 20 thyratrons currently in service are considered to be at the high end of the distribution curve. These veterans create a tough benchmark for comparison. In this group, Wagner serial number 7RE 513, received February 1, 1974, was installed in Sector 27 Modulator 8 on February 25, 1974. This thyratron has been in continuous service since that date and has 119,225 hours as of May 31, 1994. This is the very top end of thyratron lifetimes recorded at SLAC. The last rebuilt CH1191 was installed in a linac modulator in 1982.

Looking back in time to August 1986, Figure 7 shows the Thyratron Age Profile at that point in time when there were 142 of the CH1191s in active service. Evidence was beginning to mount that the CH1191s had the ability to operate for long periods of time. Even later, in January 1989, when the oldest of the OmniWave model 1002 thyratrons reached the 20,000 hour mark, there were still 70 CH1191s active in the linac modulators, with lifetimes ranging from a minimum of 30,000 hours to a high of 84,000 hours.

The Thyratron Lifetime Profile (Figure 8) shows only 35% of the CH1191 thyratrons used at SLAC. Much of the very old data, pre-1985, only exists in paper log form and has yet to be entered into the computer. This means that below 30,000 hours, the actual population is much larger than shown. Reviews of the log book indicate lifetimes much shorter than 20,000 hours, with one old failure report from the late 1970s stating, "Longest One Yet" for a CH1191 that lasted more than 20,000 hours.

Summary

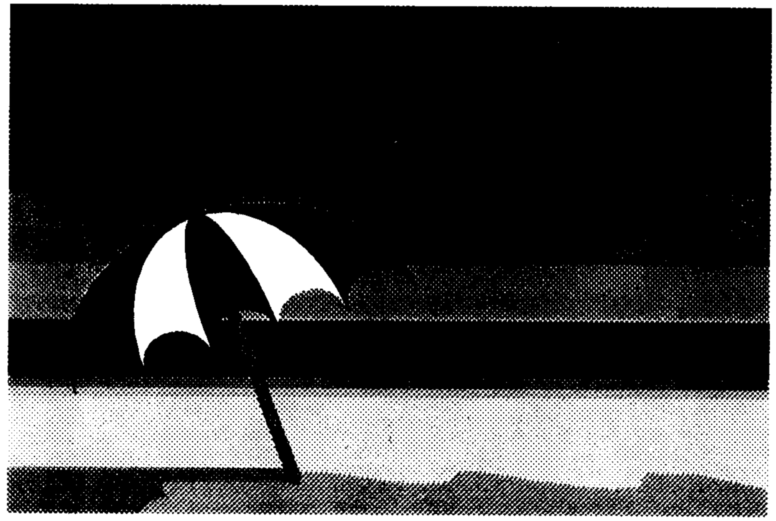
While the longevity and history of the various thyratron models varies widely, all of the current models have been modified, revised, or created within the last two years. Much of this data is difficult to apply or project for use with the revised models now in use. With the changes that have been made, all of the lifetime history clocks have been effectively reset.

Many other interesting tidbits of information have been unearthed in the research for this paper. Based on models F143, F241, and the F310, ITT has provided a total of over 8.7 million tube hours operation. The ITT thyratrons, even with the rediscovery of the Grid 1 problem, have been a reliable work horse in the linac modulators. OmniWave, including the tubes that were accepted and used, has provided over 1.7 million tube hours of high-voltage operation for the linac. Wagner, with the 35% of CH1191 thyratron data available, has provided over 17.5 million tube hours of operation. And the linac is sill running!

Acknowledgments

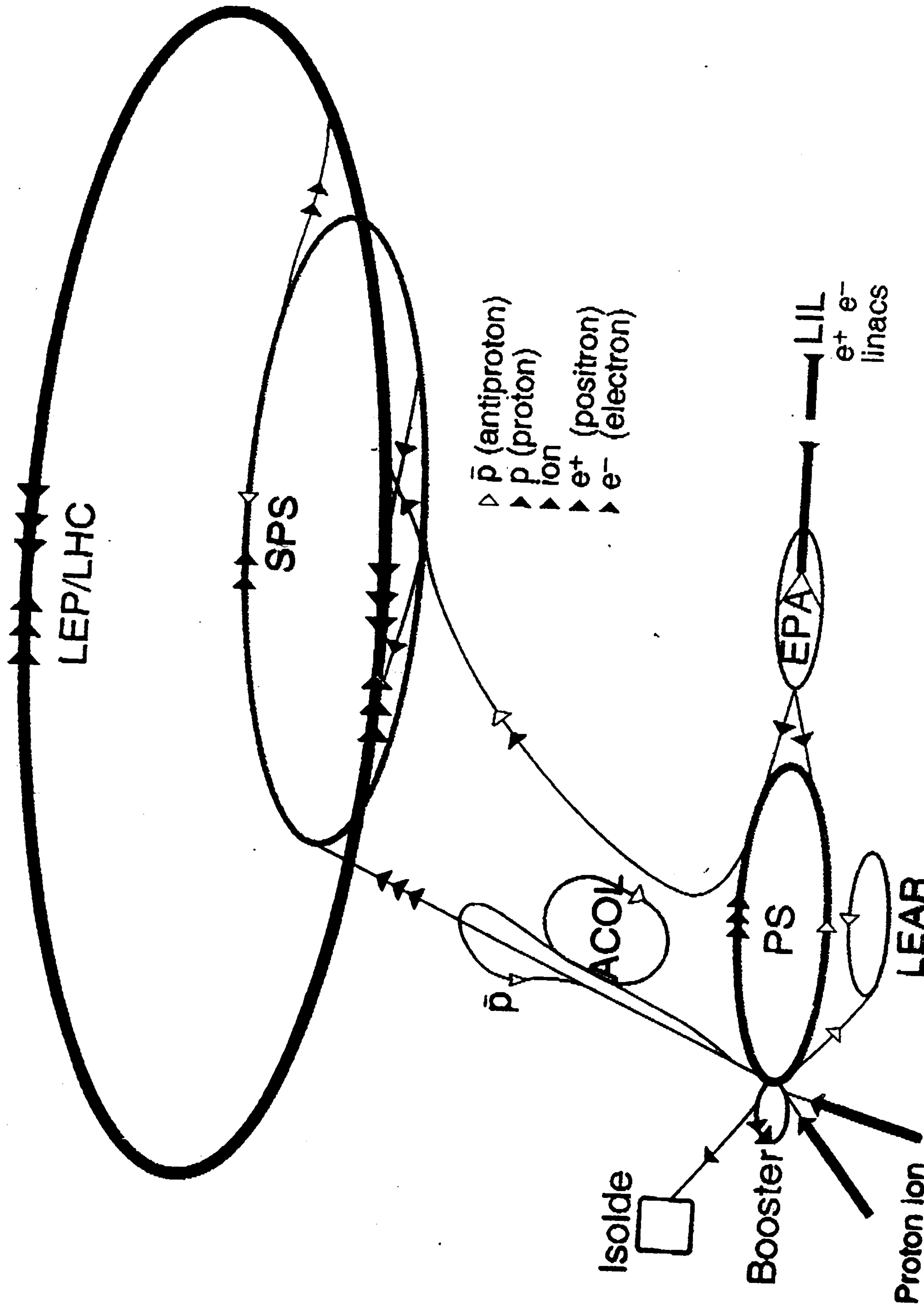
The author is indebted to R. Hanselman, N. Tarvid and R. Ecken for their direct support in continuing the existing information system and providing foundation for further development. Thanks is given to C. Olsen, B. Bradford, and others who kept past records. The staff of the Accelerator Maintenance West group, who perform timely diagnosis, make the replacements of the thyratrons, and document the changes, deserve credit for all of their efforts. The author greatly acknowledges the test technicians charged with the task of performing all of the acceptance tests, and the retesting of all the thyratrons. The author thanks R. Koontz for his support, as well as George Caryotakis, Department Head, Klystron and Microwave Department, for his interest in this project.

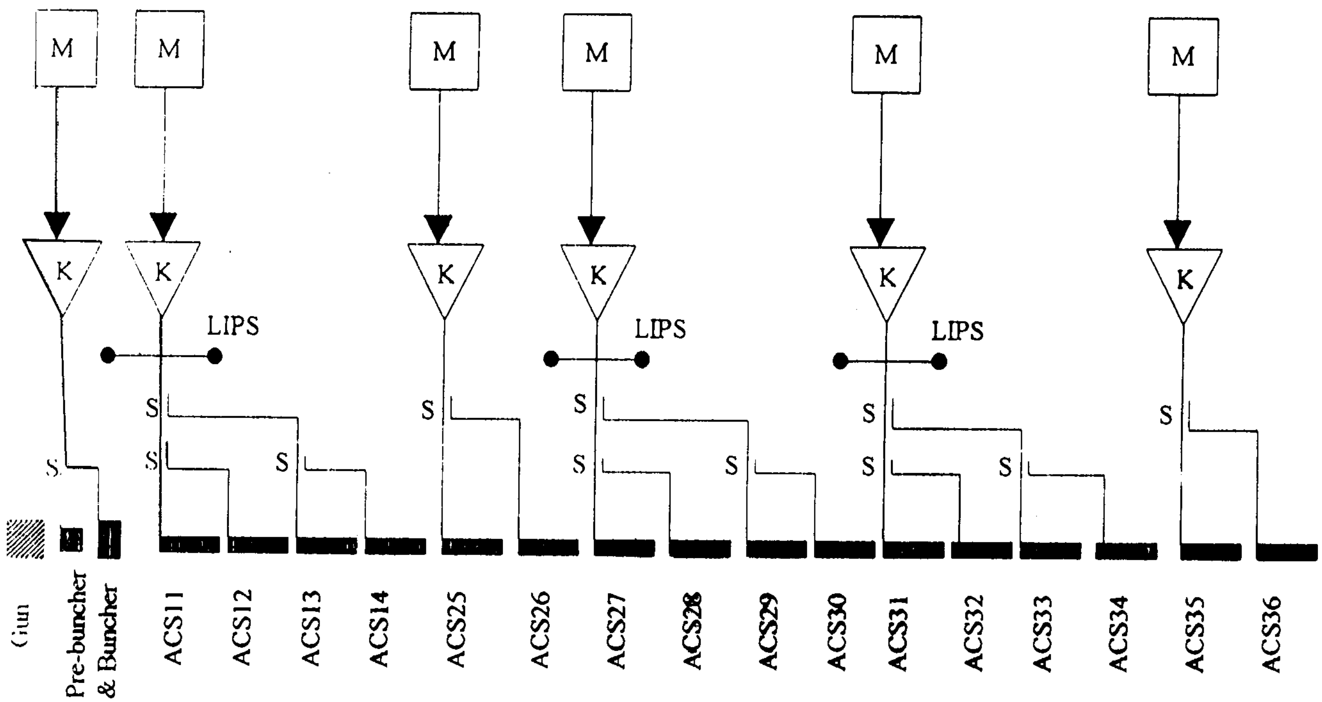
Review of LIL klystron-modulator reliability



- Recording and analysis of interlock fault data
- Management of klystrons and thyratrons
- Testing and conditioning of spare parts
- Reliability centered maintenance analysis
- Acoustic noise improvements

CERN PS Division
P. PEARCE


LEP/LHC
SPS
▷ p̄ (antiproton)
▲ p (proton)
▲ ion
▲ e⁺ (positron)
▲ e⁻ (electron)
LIL
e⁺ e⁻
linacs
EPA
PS
LEAR
ACOL
p̄
Isolde
Booster
Proton Ion
linacs



M = High Voltage Modulator

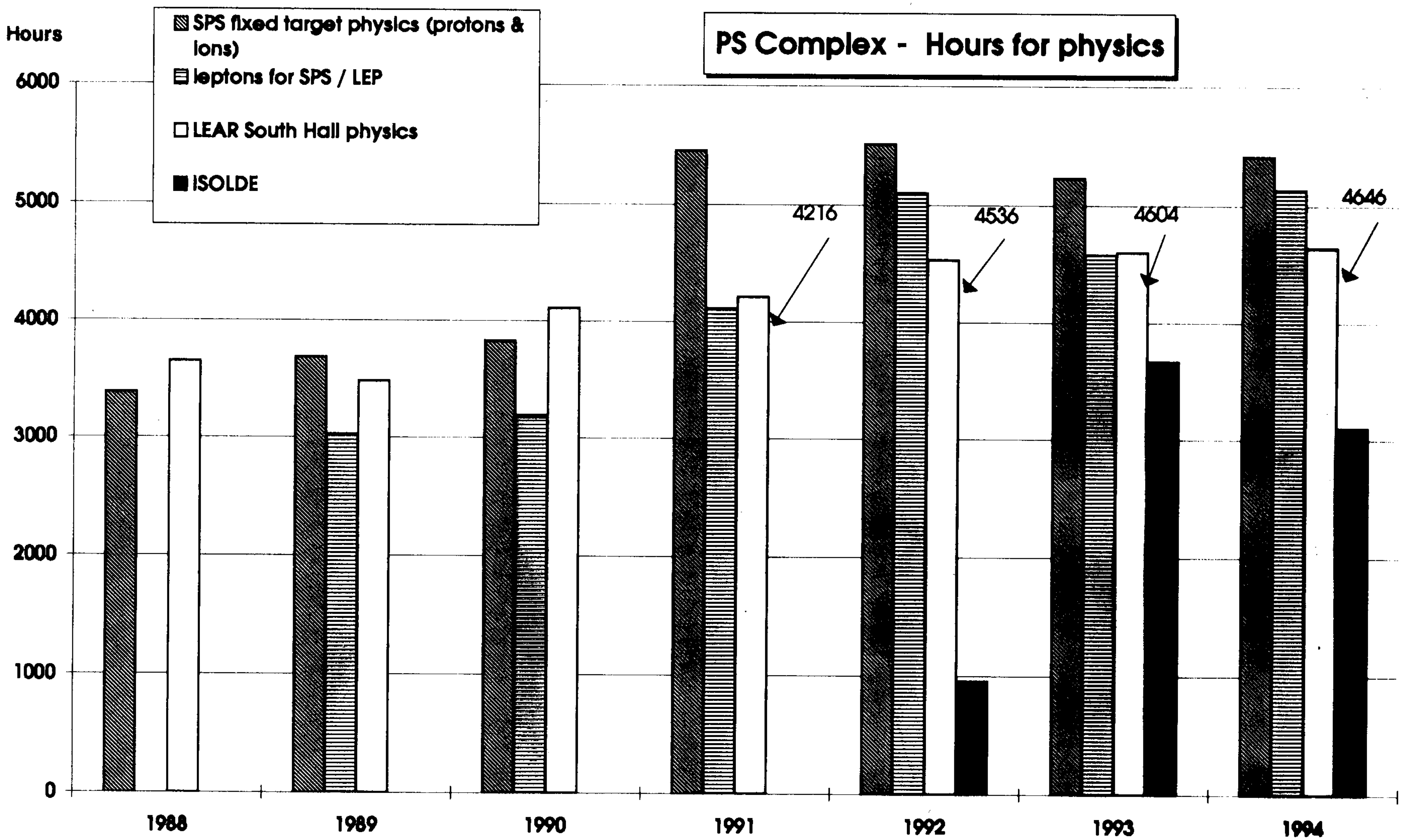
K = Klystron

LIPS = Pulse Compressor

S =Power Splitter

ACS = Accelerating Sections

Schematic diagram of the LPI accelerator



PS Complex - Hours for physics
Hours
6000
5000
4000
3000
2000
1000
0
SPS fixed target physics (protons & ions)
leptons for SPS / LEP
LEAR South Hall physics
ISOLDE
4216
4536
4604
4646
1988
1989
1990
1991
1992
1993
1994

Fig.2

Evolution of the fault time per machine (equipment and external faults)

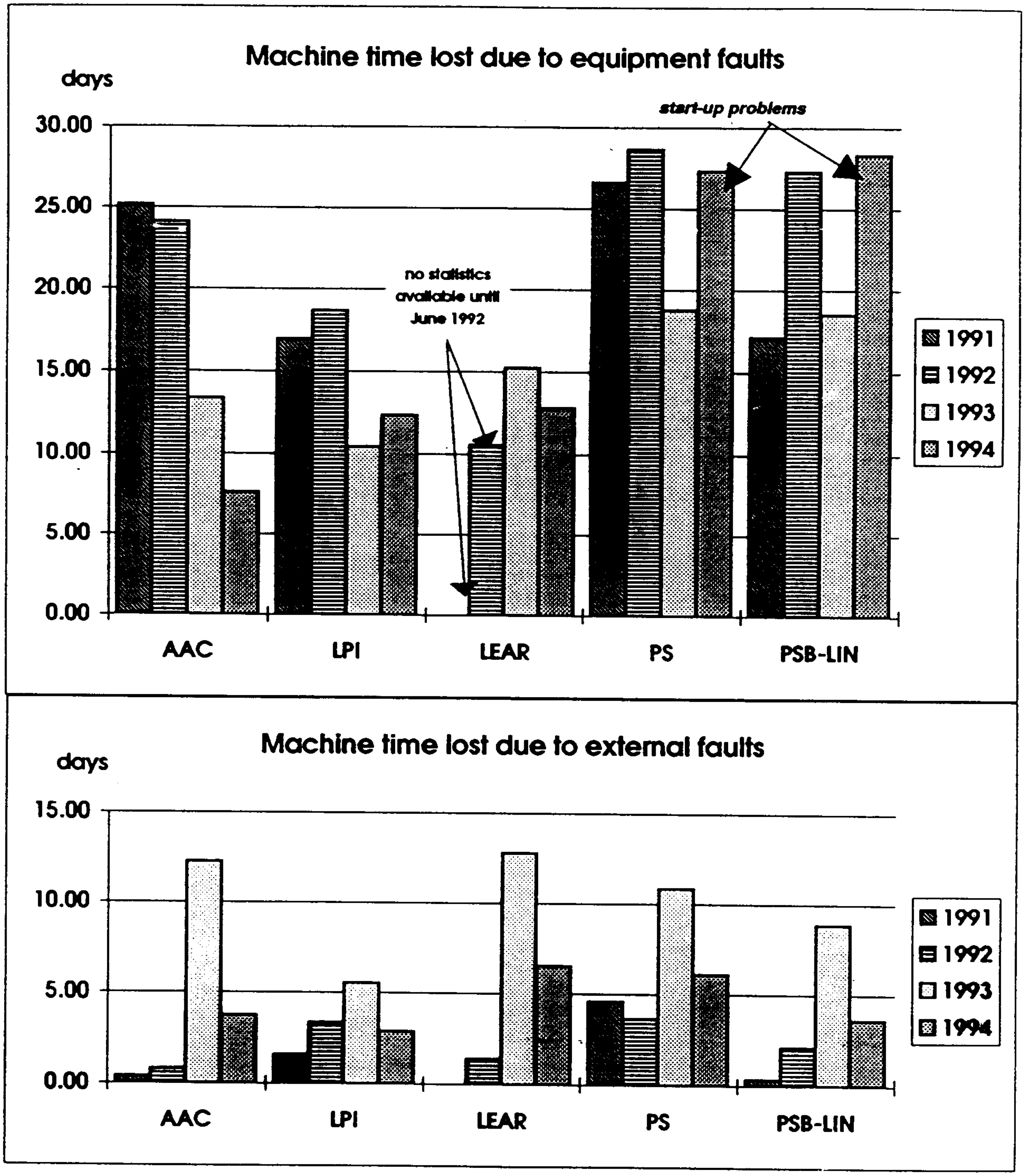
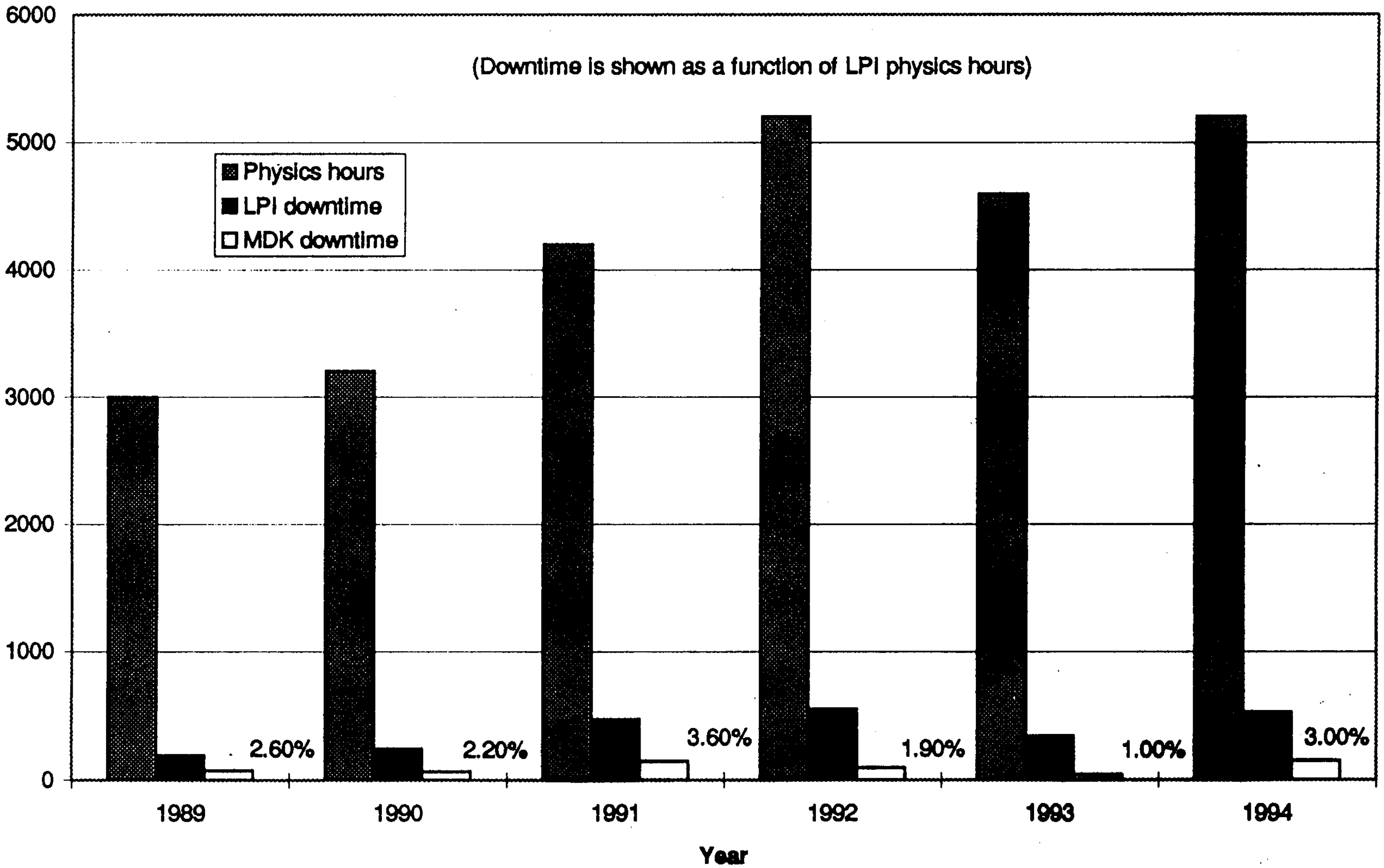
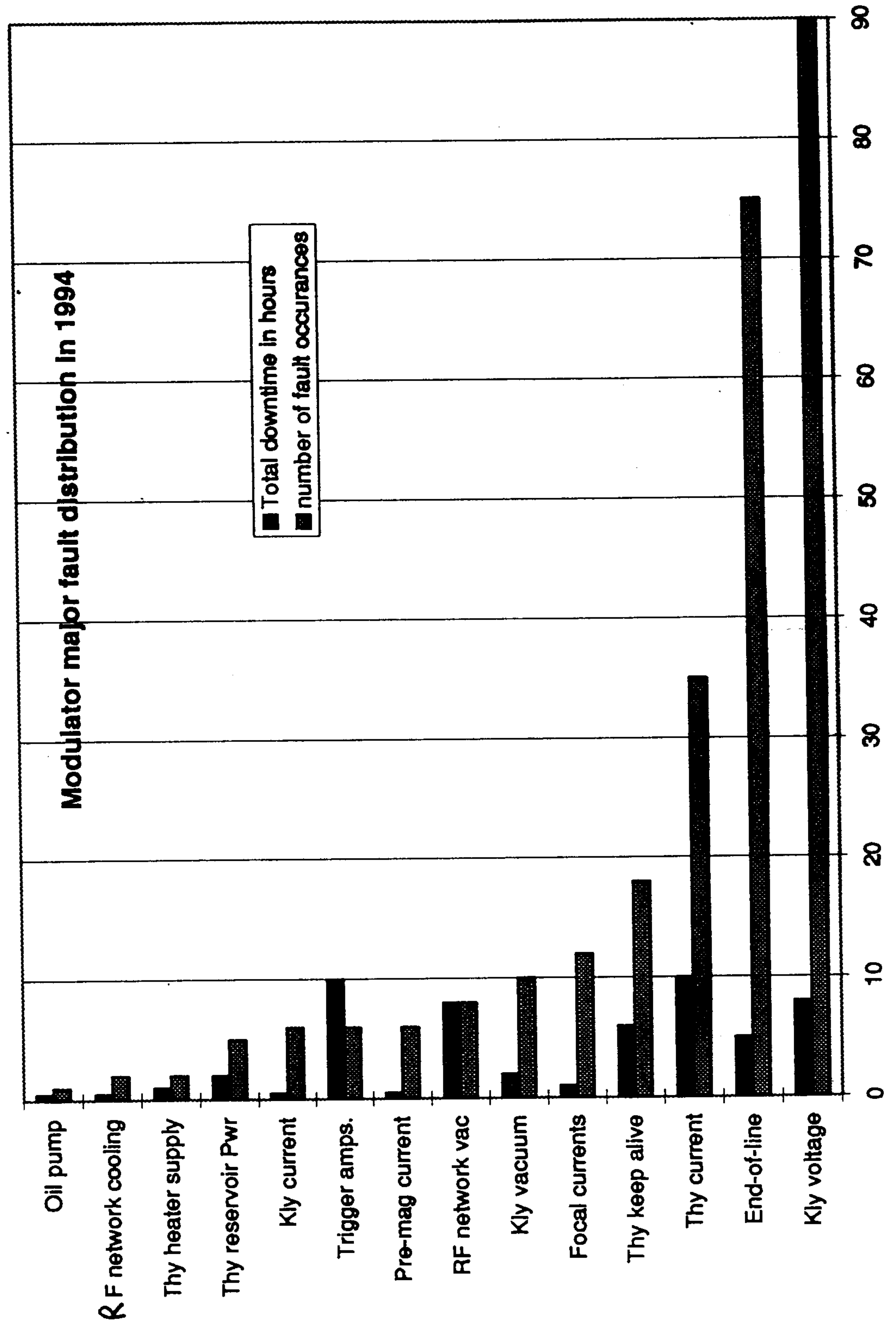


Fig. 15

PS Complex - LPI physics and downtime hours

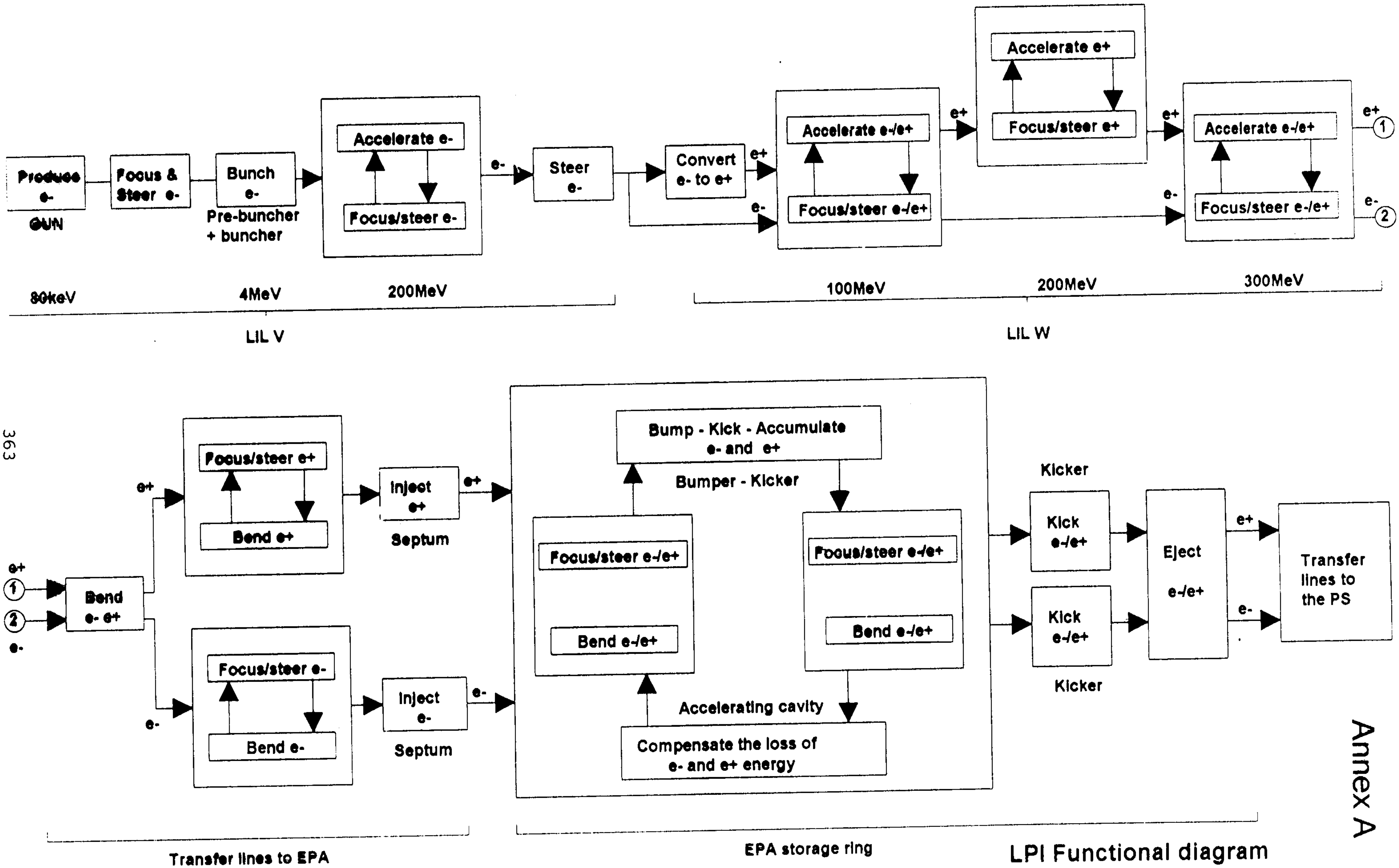


360


Modulator major fault distribution in 1994
Total downtime in hours
number of fault occurances
Oil pump
RF network cooling
Thy heater supply
Thy reservoir Pwr
Kly current
Trigger amps.
Pre-mag current
RF network vac
Kly vacuum
Focal currents
Thy keep alive
Thy current
End-of-line
Kly voltage
0
10
20
30
40
50
60
70
80
90

Reliability evaluation

- The Functional analysis was made with specific sub-systems of the LIL accelerator. This enabled a functional diagram of the LIL mach to be made and a preliminary reliability analysis of some significan items.
- The FMECA analysis ensures that potential equipment problems ha been considered and addressed. The cornerstone of this analysis is t FMECA form that is filled in for each sub-assembly, its component and for each possible failure mode. A criticality rating is given for each failure mode.
- The RAM data was obtained from a group of 12 questions which ha to be answered for each sub-assembly under investigation.
- The Assembly Criticality Evaluation is based on the above criticali rating and the RAM data factors to give an overall reliability assessment of that particular sub-assembly.



LPI Functional diagram

F1 - Produce e-

Equipment concerned	
- Electrons Gun: Cathode, Grille, Anode And supporting it: - Electronic control / computer interface (CAMAC) - Ionic pumps - Pulse amplifier tubes - High Voltage source	
Support means	**Monitor / Control means**
- Power Supply - Timing	- Electronic control / computer interface (CAMAC)
Operational constraints	
- Pulses of 15 nsec. - 20 minutes for starting: OFF, Cathode heating, High Voltage supply, Pulse amplification.	
Maintenance	
- Yearly replacement of defective parts. - Pulse amplification tubes replacement. - Dust filters replacement (once per year).	<u>Scheduled Maintenance time:</u> ~ 160 manhours/year
Failures	
- Analogic electronic devices are susceptible to failure (most have been replaced by digital devices). *(see Comments)*	<u>% of total LPI failures:</u> 2,11 % (1991) 0,95 % (1992)
Further information	
- In theory there exists a complete back-up Gun. In reality, a critical sub-system between the Cathode and the Anode of the back-up Gun has been removed, due to an earlier failure. It has been replaced and will be tested in the near future. - Electronic control devices placed in modules (easily replaced). - Gun responsibles are thinking about preparing a second back-up Gun.	

Remarks
- No more expected failures due to the fact that most of the pieces/units of the Gun have been replaced during the last few years because of recurrent failures. - The necessity of a second back-up Gun should be studied (perhaps it will not be needed). - A replacement part for the back-up gun has taken over a year to be produced by industry due mainly to a lack of clear specifications/information for the part. Clearly, if the gun had failed during this period this would have had a significant impact on Leptons production, as no redundant system was available.

F2 - Bunch e-
F3 - Accelerate e-/e+

Equipment concerned	
- Pre-Buncher + Buncher - Accelerating Sections And supporting them: - Klystrons (KLY) - Klystron Modulators (MDK): DQ'ing, High Voltage Power Supply (HV/PSU), Pulse Forming Network (PFN), Switch Thyratron (SW), Converter (TY) - Control: Computering Interface, Protection (Static and Dynamic) - Booster Klystron - Boxes A, B, and C - LIPS	
Support means	**Monitor / Control means**
- Power Supply - Thermal Control: Water refrigeration system, Air ventilation sytem - Timing	- Computer interface (CAMAC) - Protection: Static, Dynamic
Operational constraints	
- 30 minutes for starting: OFF, Heater ON, Standby, Pulse. - High Voltage pulses (100Hz) in MDK and KLY: vibrations. - During e- operation mode the MDK27 pulse is delayed and it does not accelerate the electrons.	
Maintenance	
- Daily inspection and operation at control. - Yearly dismount and mount of each klystron modulator. - Testing of spare parts. - Filters cleaning or replacement. - Booster Klystron tubes replacement. - Security verifications. - Repair of replaced units. - LIPS test and verification.	<u>Scheduled Maintenance time:</u> MDK/KLY: ~ 3640 manhours/year Other equipment: ~ 490 manhours/year
Failures	
- Many kind of failures mainly from MDK/KLY.	<u>% of total LPI failures:</u> MDK/KLY (HF): 35,58 % (1991) 18,87 % (1992) Others (3Ghz): 11,21 % (1991) 2,68 % (1992)
Further information	
- Expensive equipment and replacement parts. - Complex and sensitive equipment. - There is one extra MDK/KLY used for tests. - The protection system is going to be adapted to utilise microprocessors.	

FMECA TABLE

FMECA Failure Modes, Effects and Criticality Analysis	SYSTEM: LPI	MACHINE: LIL	SUBSYSTEM: Klystron Modulator (MDK)
	ASSEMBLY: End-Of-Line Circuit Assembly Function: Protect Pulse Forming Network and Thyratron		Ref.: 8.

Ref.	Item	Function	Ref.	Failure Modes	Failure Effects	Failure Detection Method	Criticality	Observations
8.3.	Resistors	Allow correct voltage distribution across Diodes during pulse	A	Overheating of Resistors	=> insulating oil heats up	- None except inspection	Low	
8.4.	Printed Circuit Card	Support Diodes / Capacitors / Resistors	A	Printed track breaks	=> Interlock No. 234 stops Modulator at Heater Mode => Machine (LIL) operation stopped or changed	- Interlock No. 234: Thyratron Current	Medium	
8.5.	Oil	Cool and insulate End-Of-Line Circuit components	A	Poor quality insulating Oil	=> End Of Line Current Interlock (No. 235) signals generated by Measuring Transformer => Interlock No. 235 stops Modulator at Heater Mode => erratic Thyratron Current Interlock (No. 234) signals => Interlock No. 234 stops Modulator at Heater Mode => Machine (LIL) operation stopped or changed	- Interlock No. 235: End Of Line Current - Interlock No. 234: Thyratron Current	Medium	
8.6.	Housing	Hold End-Of-Line Circuit components in sealed container	A	Housing breaks	=> oil flows out causing possible internal arcing => Interlocks No. 234 and/or 235 stop Modulator at Heater Mode => Machine (LIL) operation stopped or changed	- Interlock No. 234: Thyratron Current - Interlock No. 235: End Of Line Current	Medium	
8.7.	Measuring Transformer	Measure end-of-line fault current	A	No signal	=> no end of line protection signal	By oscilloscope	Medium	

F8 - Kick e-/e+

Equipment concerned	
- Injection kickers - Ejection kickers And supporting them: - High Voltage devices - Electronic control - Oil refrigeration system	
Support means	**Monitor / Control means**
- Power Supply - Thermal Control - Timing	- Monitoring of power sources - Protection: Interlocks (temperature)
Operational constraints	
- 15 minutes for starting (pre-heating). - High Voltage pulses.	
Maintenance	
- Inspection of switches. - Yearly and intermediate equipment review and inspection. - Periodical visual inspections.	Scheduled Maintenance time: ~ 360 manhours/year
Failures	
- High Voltage related equipment are susceptible to failure (particularly the thyratrons). - Electronic devices are susceptible to failure. - The equipment are susceptible to failures during starting periods.	% of total LPI failures: 2,90 % (1991) 9,47 % (1992)
Further information	
- Oil tubes were replaced because of leaks. - Each ejection kicker can be used as back-up of the other one in case of emergency. For implementing this, only operation parameters changes are required. - There is only one EPA kickers maintenance responsible, and he is the only one that knows in detail the EPA kicker functioning. - EPA kickers maintenance responsible has not enough time to implement all the scheduled maintenance tasks. - Obtaining spare parts from industrial suppliers is often very difficult as technical specifications related to parts procured by CERN are often not maintained by the industrial supplier after delivery of the original part.	

F11 - Inject e-/e+
F12 - Eject e-/e+

Equipment concerned	
- Injection septa (magnetic) - Ejection septa (magnetic) And supporting them: - Power sources - Connectors - Water refrigeration system - Parameters management devices - Protection system	
Support means	**Monitor / Control means**
- Power Supply - Thermal Control - Water refrigeration system - Timing	- Protection: Interlocks (vacuum control, water flow control)
Operational constraints	
- Ejection septa are pulsed.	
Maintenance	
- Water refrigeration system inspection and control. - Periodical inspections. - Verification of connections. - Yearly replacement of defective parts.	Scheduled Maintenance time: ~ 200 manhours/year
Failures	
- Failing of connections is a potential source of fire. - Interlocks are susceptible to failure.	% of total LPI failures: 0,83 % (1992)
Further information	
- There is an electrostatic septum installed in EPA but it is no longer used. - There is a specific water refrigeration system for septa. - The LPI septa maintenance responsibles have not enough time to implement all the scheduled maintenance tasks. - Many of the maintenance tasks required are periodic inspection activities.	

Remarks
- An analysis should be made to classify the scheduled maintenance tasks for optimal use of available maintenance time.

RAM Data Table

RAM DATA	I. Number of Spares Stocked at CERN		
System: LPI	Machine: LIL	Subsystem: MDK	

1. High Voltage Filter	1 assembly	6. Trigger Amplifier	1 assembly (a new model is being tested)
1.1. Capacitors	1 set	6.1. Low Voltage Power Unit	
1.2. Resistors	1 set	6.2. High Volt. Power Unit	- Small Thyratron: 6 items
1.3. Inductors	1 set	6.3. Small Thyratron	
1.4. Connections	1 set	6.4. Small Pulse Transform.	
1.5. Nylon Wires	1 roll	6.5. Keep Alive Power Unit	
		6.6. Protection Circuit	
2. Pulse Forming Network	1 assembly operating in Test Modulator		
2.1. Capacitors	10 items	7. Premagnet. Power Unit	1 item
2.2. Inductors	0 (made in CERN as needed)		
2.3. Tuning Slugs	0 (made in CERN as needed)	8. End-Of-Line Circuit	1 assembly
2.4. Non-Linear Resistors	1 set	8.1. Diodes	
2.5. Ross Relay Circuit	1 item	8.2. Capacitors	
		8.3. Resistors	
3. Thyratron Assembly	3 assemblies	8.4. Printed Circuit Cards	
3.1. Thyratron	- Thyratron: 10 items	8.5. Oil	
3.2. Gradient Grid Circuit		8.6. Housing	
3.3. Keep-Alive Circuit		8.7. Measuring Transformer	
3.4. Heater Transformer			
3.5. Reservoir Transformer		9. Front-End Snubber Ass.	1 assembly
3.6. Cooling Fan(s)		9.1. Capacitors	
3.7. Connectors		9.2. Resistors	
		9.3. Fan	
4. Triaxial Assembly	1 assembly	9.4. Connections	
4.1. Triaxial Cable	20 meters of Triaxial cable		
4.2. High Voltage Plug	2 sets	10. Thy./Kly. C/V. Measur.	1 assembly
4.3. High Voltage Socket	2 sets		
		11. Interlock Assembly	1 assembly
5. Klystron Assembly	1 assembly	11.1. Interlocks	
5.1. Pulse Transformer	2 items	11.2. State Lines	
5.2. Filter Inductors	1 set	11.3. Measurement Crate	1 item
5.3. Filter Capacitors	2 sets	11.4. Pulse Surveyor Crate	1 item
5.4. Heater Transformer	1 set		
5.5. Cur. Meas. Transform.	4 sets	12. Control Interface	1 assembly except Digital Transceiver
5.6. Voltage Divider	2 sets	12.1. Digital Transceiver	
5.7. Focal Coils	1 item of each type	12.2. State Coordinator	- Digital Transceiver: 0 (from CERN stores)
5.8. Klystron	> 4 items of each type	12.3. Act. Sequencer Heater	
5.9. Waveguide W. Connect.	1 item	12.4. Act. Sequencer Standby	
5.10. SF_6	1 item	12.5. Act. Sequencer Pulse	
5.11. Power Connections	0 (made in CERN as needed)		
5.12. Ion Pumps	(integral with Klystron)	13. SF_6 Gas Distributor	1 assembly
5.13. Water Cooling	0 (fixed installation)		
5.14. Power S. for Ion Pumps	2 items	14. RF Output Coupler	1 item

RAM DATA	F. TIME NECESSARY FOR REPLACING		
	SYSTEM: LPI	MACHINE: LIL	SUBSYSTEM: MDK

1. High Voltage Filter	2 hours	6. Trigger Amplifier	0,5 hours
1.1. Capacitors	0,5 hours	6.1. Low Voltage Power Unit	1 day
1.2. Resistors	4 hours	6.2. High Volt. Power Unit	1 day
1.3. Inductors	4 hours	6.3. Small Thyratron	0,5 hours
1.4. Connections	4 hours	6.4. Small Pulse Transform.	1 day
1.5. Nylon Wires	4 hours	6.5. Keep Alive Power Unit	1 day
		6.6. Protection Circuit	1 day
2. Pulse Forming Network	1 day		
2.1. Capacitors	2 hours	7. Premagnet. Power Unit	10 minutes
2.2. Inductors	2 hours		
2.3. Tuning Slugs	2 hours	8. End-Of-Line Circuit	1 hour
2.4. Non-Linear Resistors	2 hours	8.1. Diodes	2 days
2.5. Ross Relay Circuit	2 hours	8.2. Capacitors	2 days
		8.3. Resistors	2 days
3. Thyratron Assembly	0,5 hours	8.4. Printed Circuit Cards	2 days
3.1. Thyratron	0,5 hours	8.5. Oil	2 hours
3.2. Gradient Grid Circuit	0,5 hours	8.6. Housing	2 days
3.3. Keep-Alive Circuit	0,5 hours	8.7. Measuring Transformer	1 hour
3.4. Heater Transformer	2 hours		
3.5. Reservoir Transformer	2 hours	9. Front-End Snubber Ass.	1 hour
3.6. Cooling Fan(s)	0,5 hours	9.1. Capacitors	1 hour
3.7. Connectors	2 hours	9.2. Resistors	1 hour
		9.3. Fan	1 hour
4. Triaxial Assembly	2 hours	9.4. Connections	1 hour
4.1. Triaxial Cable	2 days		
4.2. High Voltage Plug	2 hours	10. Thy./Kly. C/V. Measur.	0,5 hours
4.3. High Voltage Socket	2 days		
		11. Interlock Assembly	1 hour
5. Klystron Assembly	2 hours (except Klystron tube)	11.1. Interlocks	10 minutes (plug in)
5.1. Pulse Transformer	2 days	11.2. State Lines	10 minutes
5.2. Filter Inductors	2 days	11.3. Measurement Crate	1 hour
5.3. Filter Capacitors	2 days	11.4. Pulse Surveyor Crate	1 hour
5.4. Heater Transformer	2 days		
5.5. Cur. Meas. Transform.	2 days	12. Control Interface	0,5 hours
5.6. Voltage Divider	2 days	12.1. Digital Transceiver	10 minutes
5.7. Focal Coils	2 days	12.2 State Coordinator	10 minutes
5.8. Klystron	2 days	12.3. Act. Sequencer Heater	10 minutes
5.9. Waveguide W. Connect.	1 hour	12.4. Act. Sequencer Standby	10 minutes
5.10. SF_6	4 hours	12.5. Act. Sequencer Pulse	10 minutes
5.11. Power Connections	4 hours		
5.12. Ion Pumps	(integral with Klystron)	13. SF_6 Gas Distributor	2 hours
5.13. Water Cooling	1 day		
5.14. Power S. for Ion Pumps	1 hour	14. RF Output Coupler	2 hours

ASSEMBLY CRITICALITY EVALUATION TABLE

Assembly Criticality Evaluation	SYSTEM: LPI	MACHINE: LIL	SUBSYSTEM: Klystron Modulator (MDK)
	ASSEMBLY: Thyratron Assembly		Ref.: 3.

		Summary Data	Crit. Factors
A.	Reliability (number of failures during 1992)	~ 150 failures Mainly due to: . Thyratron . Keep Alive Circuit	High
B.	Availability (hours of unavail. during 1992)	~ 4 hours Mainly due to: . Thyratron	Medium
C.	Redundancies	None	High
D.	Scheduled Maintenance	Yearly *except for* - Thyratron: Reservoir adjustment of ITT tubes: . up to 1000 hours, no adjust . 1000 to 5000 hours, every 500 hours . >5000 hours, every 200	Medium/Low
E.	Scheduled replacing periodicity	At failure *except for* - Thyratron: Between 8000 to 15000 hours - Cooling Fan(s): 15000 hours	High/Low
F.	Time necessary for replacing	*Assembly:* 0,5 hours *Items:* from 0,5 to 2 hours	Low Low/Medium
G.	Economic cost per assembly / item	*Assembly:* 22500 SFR *Items:* from 50 to 2000 SFR per item *except for* - Thyratron: 16500 SFR	High Low/High
H.	Manufacturers	*Assembly:* CERN *Items:* CERN and external	Medium Medium/High
I.	Number of spares stocked at CERN	*Assembly:* 3 assemblies (Thyratron: 10 items)	Low
J.	Time necessary for having new spares	*Assembly:* 3 months (with EEV Thyratron) 7 months (with ITT Thyratron) *Items:* 1 month *except for* - Thyratron: 2 months (EEV) 6 months (ITT)	Medium Low/Medium
K.	Time necessary for repairing	*Assembly:* 8 hours *Items:* 2 hours or scrap/replace	Low Low/High
L.	Repairing means	*Assembly:* CERN *Items:* CERN or scrap/replace	Medium Medium/High

Comments and Recommendations

The large number of failures are mainly due to Thyratron and Keep Alive Circuit. It is important to note that only the failures of the Thyratron result in unavailability. Usually these failures are minor failures that do not require replacement of the Thyratrons (which are usually replaced during yearly shutdowns). The aging of the Thyratron is gradual and therefore its replacement can be foreseen.

The complete assembly can be replaced in 30 minutes (some items need 2 hours). Therefore, if one item of the Thyratron Assembly fails the overall assembly shall be replaced and the failed item repaired later.

3 spare Thyratron Assemblies (excluding Thyratron) appears too much. It means, that 4 failures (with replacement) in 1 month would have to occur before having a shortage of spares. The optimized number should be obtained with a better knowledge of the reliability of the items. It appears that 1 spare Thyratron Assembly and 1 or 2 more spare Keep-Alive Circuits would be enough.

For the Thyratron itself, 10 spares appears too much. And in regards to the fact that each Thyratron costs 16500 SFR the number of spares should be further optimized.

It is to be noted that the Thyratron delivery time is different for the ITT (6 months) and for the EEV (2 months) Thyratron. And, the shorter the delivery time is the less stocked spares are needed for maintaining the same level of reliability.
One study about the optimization of the Thyratron spares can be seen below in chapter 3.5.1.3.

Assessed Criticality of the Assembly:	High

Note: For further data information see RAM Data Tables.

MESURAGE DU NIVEAU SONORE

RAPPORT E/95-08/TEC

Date : 25 Avril 1995

Lieu : Bat 2001 (galerie Klystrons)

Point de mesure :
- Klystron 13
- Point P13

Caractère du bruit :
continu (LEQ = niveau instantané)

Temps d'exposition :

Indice N

Niveau acoustique continu équivalent :

Croquis du lieu :

Voir plan des mesures page 2.

Remarques :

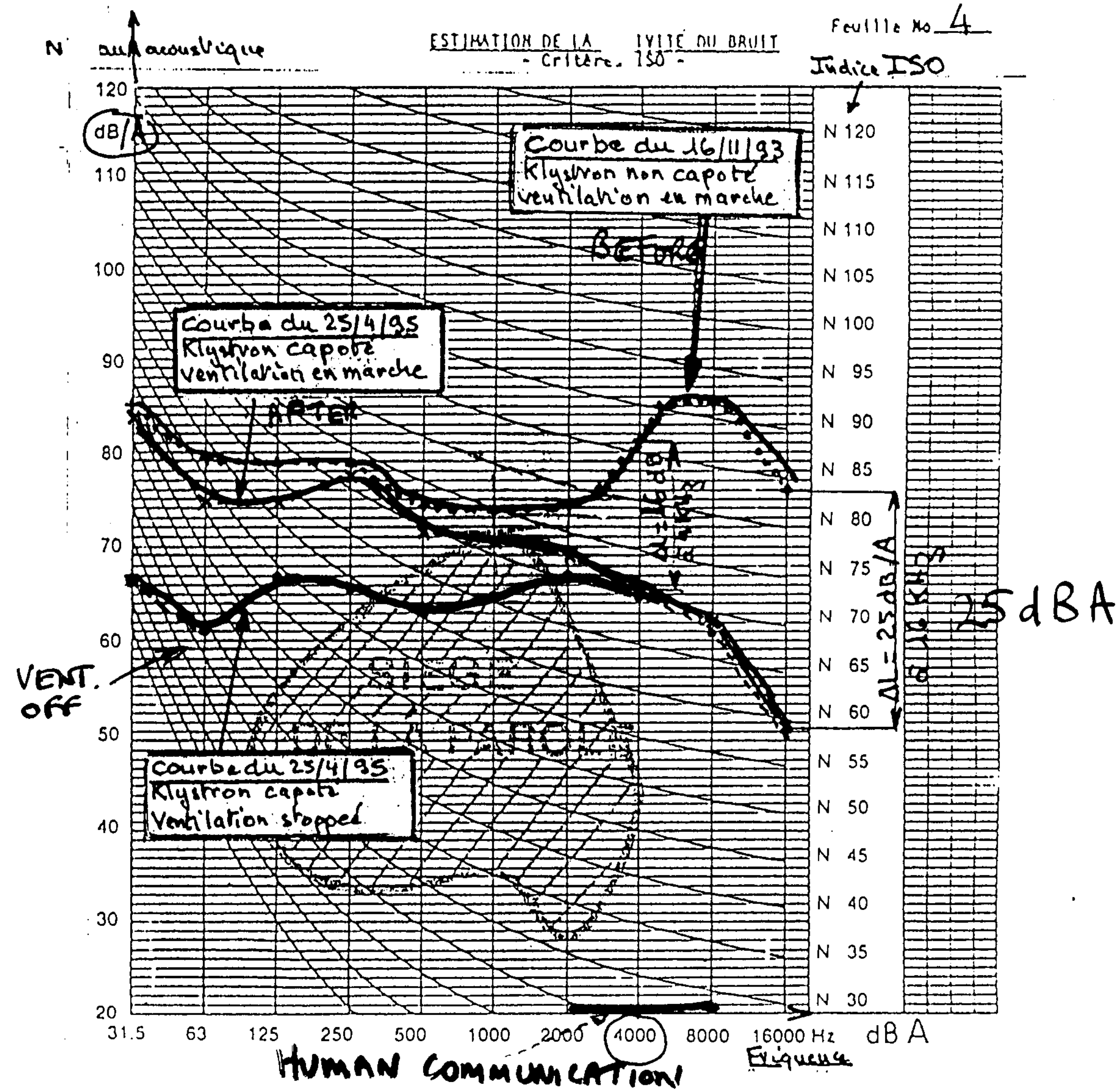
Indice ISO 16.11.93 = N 92

Indice ISO 25.4.95 = N 72,5

Indice ISO 25.4.95 sans ventilation = N 70

CERN P. Beynel 25.04.95 TIS.ES

Feuille No 4



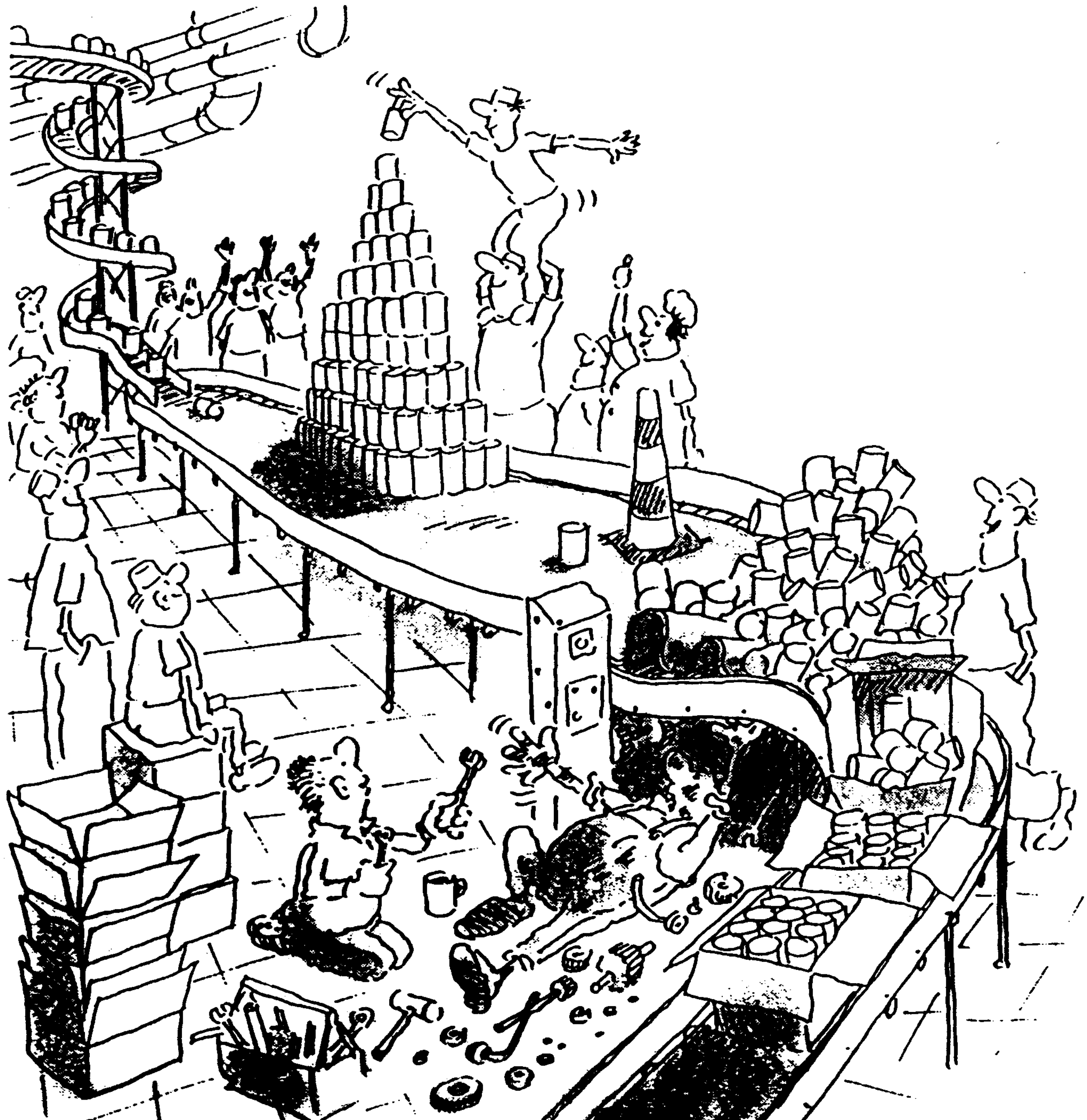
Point P13 : Niveaux acoustiques équivalents / LEQ en dB/A

Mesure du 16.11.93 : 86,6 dB/A (avec ventilation) → N_{ISO} 92

Mesures du 25/4/95 : 77.5 dB/A (avec ventilation) → N_{iso} 72.5

74.0 dB/A (sans ventilation) → N_{iso} 70

Down – time! How much can you afford?



A Review of LIL Klystron-Modulator System Reliability

P. Pearce, G. McMonagle and G. Rentier

CERN, PS Division, Geneva, Switzerland.

1. Introduction

The LIL machine was commissioned in 1988 and came on-line permanently as the source of electrons and positrons for LEP physics at the end of 1989. As is shown below in Figure 1 the PS complex with LIL as the LEP pre-injector was accounted for in physics hours, and also for downtime from the start of 1989. The annual amount of physics time has built up to about 5000 hours and is contained within 3 major runs during the year, with an average production run lasting about 1500 hours. The klystron-modulators usually accumulate about an extra 800 hours on top of this due to testing, setting up and machine development periods. However the reliability of the klystron-modulator system is judged by its availability for LEP physics, and so downtime in this note refers to that which occurs during a production period.

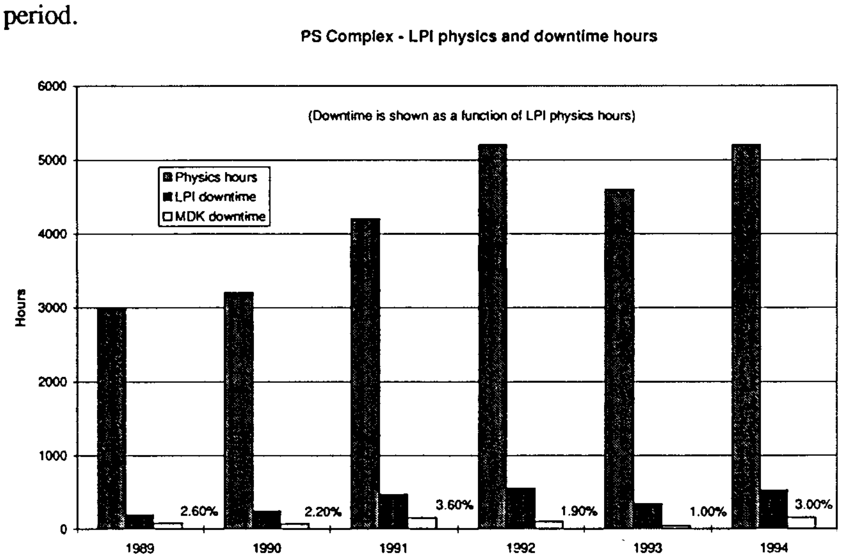


Figure 1

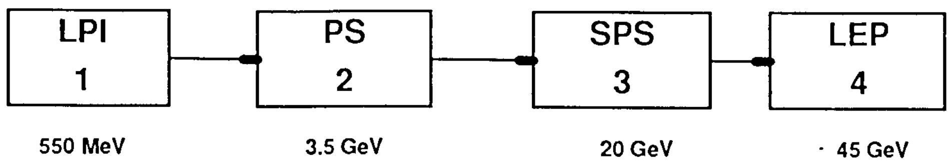
The total physics hours for LEP during the first two runs of 1995 are 3370 hours. The amount of recorded fault time for the klystron-modulators is 27 hours, or 0.8% downtime which is closer to the levels of 1992/3 than 1994. Since the last klystron-modulator workshop, held in CERN in 1991, a careful and continuous review of the system has been made concerning Reliability, Availability and Maintainability (RAM). The recommendations derived from that workshop have in most cases been put into practice, with a noticable improvement in the three RAM areas. The general points which have been covered are:

a) Recording and analysis of fault data.
b) Management of klystrons and thyratrons.
c) Testing and conditioning of spare parts.

A high reliability of the LIL and its klystron-modulators is necessary since the LPI complex forms part of a series production chain comprising the LPI, PS, SPS and LEP as in Figure 2. The reliability of this series chain is given by the product rule of reliability, and the greater the number of series elements in the production chain (that have a reliability figure less than unity) the lower the overall reliability. This is expressed below, where the reliability of a system comprising of n sub-systems is the product of the individual sub-system reliabilities. That is:

$$R_s = \prod_{i=1}^{n} R_i$$

Paper presented at the 2nd Klystron-Modulator workshop at SLAC for Future Linear Colliders 9th to 11th October 1995.



ACCELERATOR PRODUCTION CHAIN

Figure 2

The overall reliability of the lepton production process, viewed from the downtime and the individual reliability of each of the accelerators, in the way described, is at present about 93%.

2. Modulator fault data

The bigger the system, and probably the greater the number of faults that can occur, can lead to a difficulty in keeping track of individual problems. The LIL-CTF klystron-modulator system has only nine modulators, and so is a small system compared to SLAC. At the present time all of the six on-line modulators are required for the production process. From the remaining three modulators, two are used for Linear Collider test facility studies and one is used for RF processing and testing of spare equipment and klystrons.

Depending on the quality and quantity of the information presented to the operating and maintenance teams under fault conditions,the amount of downtime will be decreased if it is directly usable. The protection interlock system of the modulator equipment has essentially a series chain of interlock contacts coming from a variety of sensors, and which operate at different levels within the scheme. This means that a certain amount of cascading of fault indication and interlocks will occur when a problem is detected at a higher level. Previously all of this fault data was presented simultaneously to the operator, who had to judge from experience, what parameter was at the origin of the fault, with the remaining usually being created as a consequence of the protection chain. Having a large number of faults whose downtime was less than 10 minutes duration gave rise to large amounts of information that had to be understood.

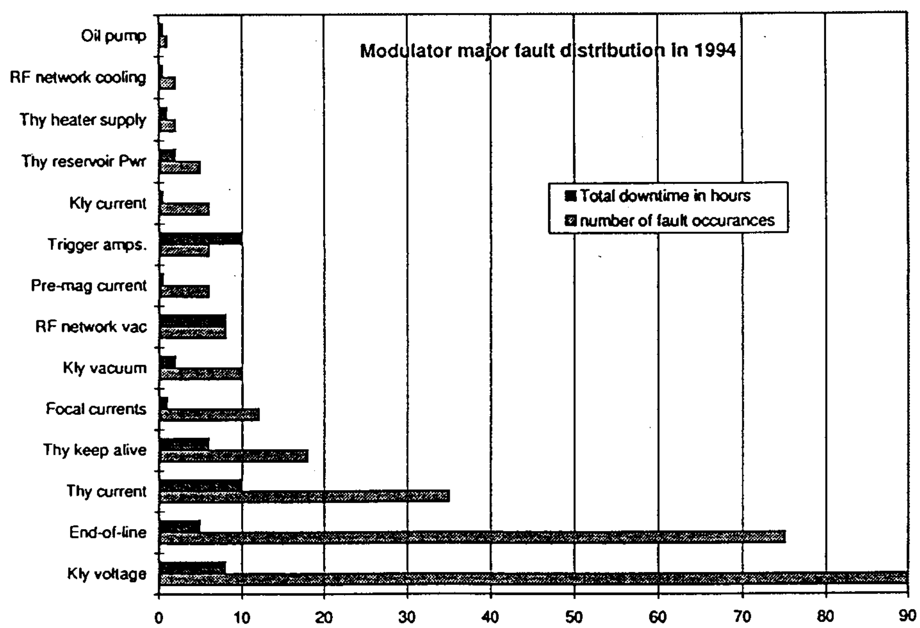


Figure 3.

In Figure 3 the Pareto type graph shows fault interlocks with the number of times a particular one has occurred as well as the total time incurred. The effect of a large number of non fatal short duration faults, increases very considerably the total downtime. The new interlock system with the ability to capture and store locally in real time these faults as they occur, in the order they are detected and then tag this with the date and time has improved very considerably the information available. This has permitted the maintenance team to quickly locate and rectify the source fault, and has provided data that enabled equipment problems to be analysed and solutions to be found. Using this approach the quantity of short duration faults has decreased and overal system reliablity maintained at a high level.

Other CERN papers at this workshop show how the locally stored data is transmitted to the central control system and then subsequently is stored on the Oracle data base. This then allows further analysis and tracking of fault trends across the system in an effort to trace and eliminate the effects of hard to find intermittent faults. One of the side effects of this work has been a complete re-appraisal of the methods of setting up the electronics that form part of the real time protection equipment and the frequency of checking their performance.

3. Klystrons and thyratrons.

Klystrons and thyratrons are the essential elements of the pulsed modulators in the LIL system and their performance directly affects the production process reliability. Although there are only six modulators involved in the pre-injector, there is no overall equipment redundancy. In certain modulator failure situations an increase in their RF output power can allow the process to continue, providing changes are made to RF timing or these klystron voltages are increased. For the majority of modulator faults however there is no beam until the equipment is restored to an operational state. At present the average lifetime of these components in operation is about:

Klystrons	22,000 hours
Thyratrons	12,000 hours

A few klystrons have performed very well having pulsed for about 35,000 hours, but the majority have to be replaced at between 18,000 and 22,000 hours. In the present system we have a mix of Thomson TH2094 and TH2100C klystrons together with Philips-Valvo YK1600 klystrons. These are rated for operation at 35MW peak RF output power, with a 4.5µs pulse width. The system runs at a 100Hz repetition rate.

The thyratrons being used are also a mix of makes and types. Originally the system was commisioned with ITT thyratrons, KU275C. There are now ITT and EEV thyratrons running in the modulators, the latter being the CX1836A and CX1536A models. The dc keep-alive circuit on grid 1 for the CX1836A tubes has been replaced with a single trigger pulse and zero bias to improve performance and lifetime. Since thyratron triggering was also a problem due to short lifetimes of the small trigger tube (thyratron) in the trigger amplifier unit, this is being improved with the use of solid state trigger units. The range of lifetimes seen with both makes of thyratron has been between 5000 hours and 27,000 hours (one ITT), although a few thyratrons have failed very early in life.

The majority of modulator faults occurring were generally found to be linked to mal-functioning of thyraton switches or with the klystron assemblies. These are usually detected as a current or voltage fault in the system. A particular problem linked to thyratron behaviour, seen with tubes that have their reservoir voltages ranged, is current switch-off during the pulse when gas pressure gets low and adjustment is not made soon enough. The inverse fault voltage created is applied to the klystron cathode causing internal breakdowns that increases the klystron vacuum pressure, so that it trips on the vacuum pressure interlock. The use of a tail clipper circuit that will avoid large inverse voltages appearing is being tested. The EEV thyratrons now being used have internal gas pressure stabilisation using a barrettor that has reduced this switch-off problem considerably, and the periodic ranging of reservoir voltage seems no longer necessary (at least up to the 11,000 hours of present experience).

The klystron reliability from Thomson and Philips-Valvo is good with only a few small faults, mostly related to integral ion pumps that cause vacuum trips due to internal sparking, or variability of cathode lifetimes for some early klystrons. At the end of their useful life, when a klystron can no longer deliver nominal RF power reliably, they are either put into a single socket running at lower power (4MW), or are returned to the manufacturer for reconditioning. Electrical faults in the klystron tank have been the source of several problems. The oil quality inside these tanks was being affected by the internal cooling system that caused warm air to condensate on cold pipes, and water droplets fell through the oil onto high voltage components causing intermittent voltage faults. This has been eliminated by sealing the tanks and providing overflow vases for the hot oil expansion. With the above changes to the klystron and thyratron assemblies the present fault rate of the modulators is at about 0.1% per week which corresponds to about 10 minutes downtime/week for the system.

4. Reliability evaluation.

During 1992 a reliability centered maintenance evaluation was made of the modulator system to determine the overall maintenance requirements. This was directed towards maintaining the reliability inherently designed into the equipment by analyzing those factors that affect reliability and availability and to optimize the maintenance programme. The method used had four distinct phases:

a) **Collection of information to carry out the analysis.**
A technical description with boundary, hierachy, function and redundancy levels of the modulator system defined with respect to the LPI accelerator. Operational requirements such as performance and maintenance aspects. Reliability data and dominant failure modes and their detection methods.

b) **Identification of all modulator equipment.**
The establishement of a comprehensive equipment and sub-system register. This enables the identification of maintenance significant equipment, and safety consequences for the system.

c) **Specification of maintenance tasks.**
Some equipment have technical characteristics that require special maintenance procedures. Design changes may render this type of equipment less failure prone, instead of continuing with the special maintenance.

d) **A review of the adopted maintenance tasks and procedures.**
This phase was done after sufficient experience and data had been acquired from the changes made in the first three phases above.

Some of this data is shown in Figure 4 below.

RAM Data	E. Scheduled Replacing Periodicity		
	System: LPI	Machine: LIL	Subsystem: MDK

Item	Periodicity
1. High Voltage Filter	During yearly inspection depending on component values and their state or at failure - Nylon Wires: Yearly replacement
1.1. Capacitors	
1.2. Resistors	
1.3. Inductors	
1.4. Connections	
1.5. Nylon Wires	
2. Pulse Forming Network	During yearly inspection or at failure
2.1. Capacitors	
2.2. Inductors	
2.3. Tuning Slugs	
2.4. Non-Linear Resistors	
2.5. Ross Relay Circuit	
3. Thyratron Assembly	At failure - Thyratron: Between 8000 to 15000 hours depending on individual tubes performance - Cooling Fan(s): 15000 hours
3.1. Thyratron	
3.2. Gradient Grid Circuit	
3.3. Keep-Alive Circuit	
3.4. Heater Transformer	
3.5. Reservoir Transformer	
3.6. Cooling Fan(s)	
3.7. Connectors	
4. Triaxial Assembly	During yearly inspection or at failure
4.1. Triaxial Cable	
4.2. High Voltage Plug	
4.3. High Voltage Socket	
5. Klystron Assembly	During yearly maintenance/inspection or at failure - Klystron: about 18000 hours - Waveguide Window Connections: yearly - SF_6: after each breakdown - Ion Pumps: (integral with Klystron)
5.1. Pulse Transformer	
5.2. Filter Inductors	
5.3. Filter Capacitors	
5.4. Heater Transformer	
5.5. Cur. Meas. Transform.	
5.6. Voltage Divider	
5.7. Focal Coils	
5.8. Klystron	
5.9. Waveguide W. Connect.	
5.10. SF_6	
5.11. Power Connections	
5.12. Ion Pumps	
5.13. Water Cooling	
5.14. Power S. for Ion Pumps	

Item	Periodicity
6. Trigger Amplifier	At failure
6.1. Low Voltage Power Unit	
6.2. High Volt. Power Unit	
6.3. Small Thyratron	
6.4. Small Pulse Transform.	
6.5. Keep Alive Power Unit	
6.6. Protection Circuit	
7. Premagnet. Power Unit	At failure
8. End-Of-Line Circuit	During yearly maintenance or at failure
8.1. Diodes	
8.2. Capacitors	
8.3. Resistors	
8.4. Printed Circuit Cards	
8.5. Oil	
8.6. Housing	
8.7. Measuring Transformer	
9. Front-End Snubber Ass.	At failure - Fan: Yearly, or during intermediate shutdown inspections if defective
9.1. Capacitors	
9.2. Resistors	
9.3. Fan	
9.4. Connections	
10. Thy./Kly. C/V. Measur.	At failure
11. Interlock Assembly	At failure
11.1. Interlocks	
11.2. State Lines	
11.3. Measurement Crate	
11.4. Pulse Surveyor Crate	
12. Control Interface	At failure
12.1. Digital Transceiver	
12.2. State Coordinator	
12.3. Act. Sequencer Heater	
12.4. Act. Sequencer Standby	
12.5. Act. Sequencer Pulse	
13. SF_6 Gas Distributor	At failure
14. RF Output Coupler	At failure

RAM Data	F. Time Necessary for Replacing		
	System: LPI	Machine: LIL	Subsystem: MDK

Item	Time
1. High Voltage Filter	2 hours
1.1. Capacitors	0,5 hours
1.2. Resistors	4 hours
1.3. Inductors	4 hours
1.4. Connections	4 hours
1.5. Nylon Wires	4 hours
2. Pulse Forming Network	1 day
2.1. Capacitors	2 hours
2.2. Inductors	2 hours
2.3. Tuning Slugs	2 hours
2.4. Non-Linear Resistors	2 hours
2.5. Ross Relay Circuit	2 hours
3. Thyratron Assembly	0,5 hours
3.1. Thyratron	0,5 hours
3.2. Gradient Grid Circuit	0,5 hours
3.3. Keep-Alive Circuit	0,5 hours
3.4. Heater Transformer	2 hours
3.5. Reservoir Transformer	2 hours
3.6. Cooling Fan(s)	0,5 hours
3.7. Connectors	2 hours
4. Triaxial Assembly	2 hours
4.1. Triaxial Cable	2 days
4.2. High Voltage Plug	2 hours
4.3. High Voltage Socket	2 days
5. Klystron Assembly	2 hours (except Klystron tube)
5.1. Pulse Transformer	2 days
5.2. Filter Inductors	2 days
5.3. Filter Capacitors	2 days
5.4. Heater Transformer	2 days
5.5. Cur. Meas. Transform.	2 days
5.6. Voltage Divider	2 days
5.7. Focal Coils	2 days
5.8. Klystron	2 days
5.9. Waveguide W. Connect.	1 hour
5.10. SF_6	4 hours
5.11. Power Connections	4 hours
5.12. Ion Pumps	(integral with Klystron)
5.13. Water Cooling	1 day
5.14. Power S. for Ion Pumps	1 hour

Item	Time
6. Trigger Amplifier	0,5 hours
6.1. Low Voltage Power Unit	1 day
6.2. High Volt. Power Unit	1 day
6.3. Small Thyratron	0,5 hours
6.4. Small Pulse Transform.	1 day
6.5. Keep Alive Power Unit	1 day
6.6. Protection Circuit	1 day
7. Premagnet. Power Unit	10 minutes
8. End-Of-Line Circuit	1 hour
8.1. Diodes	2 days
8.2. Capacitors	2 days
8.3. Resistors	2 days
8.4. Printed Circuit Cards	2 days
8.5. Oil	2 hours
8.6. Housing	2 days
8.7. Measuring Transformer	1 hour
9. Front-End Snubber Ass.	1 hour
9.1. Capacitors	1 hour
9.2. Resistors	1 hour
9.3. Fan	1 hour
9.4. Connections	1 hour
10. Thy./Kly. C/V. Measur.	0,5 hours
11. Interlock Assembly	1 hour
11.1. Interlocks	10 minutes (plug in)
11.2. State Lines	10 minutes
11.3. Measurement Crate	1 hour
11.4. Pulse Surveyor Crate	1 hour
12. Control Interface	0,5 hours
12.1. Digital Transceiver	10 minutes
12.2. State Coordinator	10 minutes
12.3. Act. Sequencer Heater	10 minutes
12.4. Act. Sequencer Standby	10 minutes
12.5. Act. Sequencer Pulse	10 minutes
13. SF_6 Gas Distributor	2 hours
14. RF Output Coupler	2 hours

Figure 4

As some equipment requires more maintenance than others to achieve the same level of reliability a distinction was made within the modulator system by breaking down the equipment into three categories:

- i. Functional significant equipment, that has a direct impact on reliability, availability or safety.
- ii. Maintenance cost significant equipment, included in a maintenance programme. Failure will result in high costs and significant downtime.
- iii. Non-significant equipment, that are left in service for cost effectiveness reasons until they fail, when they are immediately replaced.

The major modulator components including thyratrons, klystron tank assemblies and high voltage charging units are maintenance cost significant since they are expensive to maintain and require more repair time if they fail in service. Tested spare parts are very necessary for high system availability and a test modulator was installed in 1993 for testing and calibration of these components.

FMECA Failure Modes, Effects and Criticality Analysis				SYSTEM: LPI	MACHINE: LIL	SUBSYSTEM: Klystron Modulator (MDK)	
ASSEMBLY:	Triaxial Assembly					Ref.: 4.	
Function:	Transmit high voltage pulse to Klystron tank						
Ref.	**Item**	**Function**	**Ref.**	**Failure Modes**	**Failure Effects**	**Failure Detection Method**	**Criticality**	**Observations**
4.1.	Triaxial Cable	Transmit high voltage pulse to Klystron tank	A	Loss of pulse transmission due to: . open circuit Cable	⇒ no high voltage pulse at Klystron ⇒ Modulator does not function ⇒ high voltage breakdown in air or oil ⇒ Interlocks No. 234 and/or 235 stop Modulator at Heater Mode ⇒ Machine (LIL) operation stopped or changed	- Interlock No. 234: Thyratron Current - Interlock No. 235: End Of Line Current	Medium	
			B	Breakdown of assembly due to: . faulty insulation of cable	⇒ breakdowns cause high current surges in Thyratron ⇒ Interlocks No. 234 and/or 235 stop Modulator at Heater Mode ⇒ Machine (LIL) operation stopped or changed	- Interlock No. 234: Thyratron Current - Interlock No. 235: End Of Line Current	Medium	
4.2.	High Voltage Plug	Transmit high voltage pulse to Klystron tank	A	Loss of pulse transmission due to: . open circuit Cable	⇒ no high voltage pulse at Klystron ⇒ Modulator does not function ⇒ possible high voltage breakdown in air or oil ⇒ Interlocks No. 234 and/or 235 stop Modulator at Heater Mode ⇒ Machine (LIL) operation stopped or changed	- Interlock No. 234: Thyratron Current - Interlock No. 235: End Of Line Current	Medium	No automatic means of detecting whether the HV Plug is in the HV Socket. A microswitch interlock is being designed.
			B	Breakdown of assembly due to: . faulty insulation of Plug connection	⇒ breakdowns cause high current surges in Thyratron ⇒ Interlocks No. 234 and/or 235 stop Modulator at Heater Mode ⇒ Machine (LIL) operation stopped or changed	- Interlock No. 234: Thyratron Current - Interlock No. 235: End Of Line Current	Medium	
4.3.	High Voltage Socket	Transmit high voltage pulse to Klystron tank	A	Loss of pulse transmission properties due to: . open circuit Socket	⇒ no high voltage pulse at Klystron ⇒ Modulator does not function ⇒ possible high voltage breakdown in air or oil ⇒ Interlocks No. 234 and/or 235 stop Modulator at Heater Mode ⇒ Machine (LIL) operation stopped or changed	- Interlock No. 234: Thyratron Current - Interlock No. 235: End Of Line Current	Medium	No automatic means of detecting whether the HV Plug is in the HV Socket. A microswitch interlock is being designed.
			B	Breakdown of assembly due to: . faulty insulation of socket connection	⇒ breakdowns cause high current surges in Thyratron ⇒ Interlocks No. 234 and/or 235 stop Modulator at Heater Mode ⇒ Machine (LIL) operation stopped or changed	- Interlock No. 234: Thyratron Current - Interlock No. 235: End Of Line Current	Medium	

Figure 5.

In addition to the above a Failure Mode, Effect and Criticality Analysis (FMECA) was also made of possible failure events in the system. The FMECA is a causal evaluation derived from detailed equipment information where the end result of the many possible fault events is that the system ceases to function. Figure 5 shows the work sheet of the FMECA applied to the triaxial cable assembly

Assembly Criticality Evaluation		SYSTEM: LPI	MACHINE: LIL	SUBSYSTEM: Klystron Modulator (MDK)
ASSEMBLY:	Triaxial Assembly			Ref.: 4.

	Summary Data		Crit. Factors	Comments and Recommendations
A.	Reliability (number of failures during 1992)	0 failures	Low	From the data of 1992 statistics the reliability/availability of the assembly appears good.
B.	Availability (hours of unavail. during 1992)	0 hours	Low	The scheduled maintenance / replacing periodicity appears correct.
C.	Redundancies	None	High	
D.	Scheduled Maintenance	Yearly	Medium	The number of spares stocked at CERN appears also correct. However, one set of High Voltage Plug and one other of High Voltage Socket appears to be enough (in this case 3 failures in 2 months would have to occur before having a shortage of spares and this appears quite improbable).
E.	Scheduled replacing periodicity	During yearly inspection or at failure	Medium	
F.	Time necessary for replacing	*Assembly*: 2 hours *Items*: from 2 hours to 2 days	Medium Medium/High	
G.	Economic cost per assembly / item	*Assembly*: 1800 SFR *Items*: from 370 to 500 SFR per item	Low Low	
H.	Manufacturers	*Assembly*: CERN or external *Items*: external	Medium Medium/High	
I.	Number of spares stocked at CERN	*Assembly*: 1 assembly	Medium	
J.	Time necessary for having new spares	*Assembly*: 6 months *Items*: from 2 to 6 months	Medium Medium	
K.	Time necessary for repairing	*Assembly*: 2 days *Item*: scrap/replace	Low High	
L.	Repairing means	*Assembly*: CERN *Items*: scrap/replace	Medium High	

Figure 6.

Figure 6 is the combination of reliability data from Figure 4 and the FMECA data from Figure 5 as a criticality evaluation of the triaxial assembly component. The analysis objectives were to review equipment maintainability and maintenance tasks, and also the frequency and priority of applying them. This was also an opportunity to re-examine in detail the system for possible improvements or simplification. Since all modulators are identical in their construction and performance, an analysis of one enables a reliability evaluation of the total system to be obtained. From this review more appropriate test specifications and methods have been devised. The creation of a computer model for modulator fault analysis, as well as new hardware designs for the trigger amplifier and the control interface equipment have resulted from this reliability evaluation study.

5. General system improvements.

The LIL klystron gallery is a long 100 metre box structure where the hard concrete walls cause sound reverberation and emphasize the noise created by the large building ventilator fans and the klystron assemblies. Maximum noise levels were found at 92dBA, with an average of 85dBA, making working and concentration difficult over long time periods and can become a health and safety hazard in this type of environment. Detailed measurements were made around each modulator and along the gallery for acoustic data to design noise enclosures to be placed around the klystron assemblies. The measurements were made with and without the ventilation fans operating, since they make an extra contribution to noise levels below about 500 Hz. The measured noise at MDK13 position before and after the enclosures were installed is shown in Figure 7.

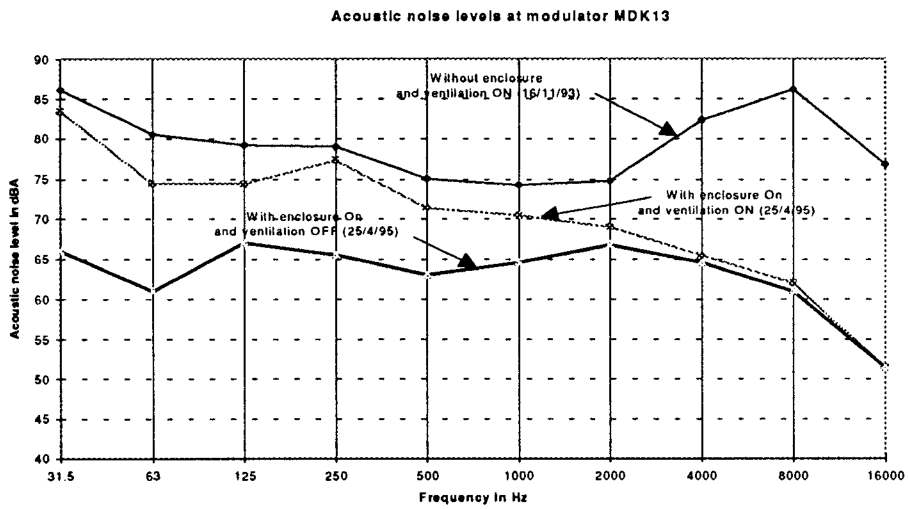


Figure 7.

Over the frequency range 2 to 6kHz, where the human ear can best percieve sound, the noise reduction obtained shows an improvement of between 15 and 20dBA. The enclosures also improve safety aspects, physically protecting all accidental contact with electrical power connections to a klystron tank. An additional benefit from the enclosures steel panels, with rockwool and synthetic fibre glass filler, is that they act as an electrical screen and provide a small 15 to 20% reduction in the pulsed electrical noise coming from the klystron assembly.

6. Summary.

A consistent effort was made to maintain and improve where possible the reliability of the modulator system. Analysis of the problems were made and selected action taken to improve performance by either designing out the problem or improving maintenance methods to overcome the effects.

7. References.

[1] P. Pearce, G. McMonagle, G.Rentier, Implementation of diagnostic hardware and software systems for CERN modulators. 2nd Klystron-Modulator workshop, SLAC, 1995

[2] G. Azzoni, D. Dagan, Operation statistics for PS Complex 1994. CERN-PS/OP/95-06

[3] M. Colin et al, 1994 SPS & LEP machine statistics. CERN SL/Note 95-15

[4] P. Pearce, Acoustic noise reduction enclosures for LIL modulators. CERN PS/LP 95-22

Reliability/Maintenance Issues of Klystrons and Thyratrons at KEK-PF-Linac

T. Shidara
KEK-PF-Linac

KEK 2.5 GeV Linac Mile-stone

(1978.4)	
1979.4	Construction started
1982.1	1st 2.5 GeV beam
1982.4	Operation
1985.10	Positron generator commissioning
1986.6	Positron generator operation for TRISTAN
1993.4	Linac upgrade for KEK-B started

Total operation hrs -- 58,000 hrs
25, 50 p.p.s.

Total no. of klystron sockets -- 48 + 3 + 4 + (7)

Parameters of the Injection Linac for KEKB

	PRESENT	KEKB
INJECTION BEAM		
energy [GeV]		
(e-)	2.5	8.0
(e+)	2.5	3.5
pulse length	< 2ns	single bunch
bunch width (σ_Z) [ps]	~5	~5
particle [x 10^9/pulse], (charge [nC/pulse])		
(e-)	2, (0.32)	8, (1.28)
(e+)	0.2, (0.032)	4, (0.64)
pulse repetition [pps]	25	50
emittance [x 10^{-8}m]		
(e-)	4	6.4
(e+)	80	88
energy width [%]		
(e-)	0.2	0.125
(e+)	0.22	0.25
MAIN ACCELERATOR		
unit length [m]	9.6	9.6
number		
(total)	46	57
(before e+ radiator)	3	26
(stand-by, energy tuning)	~ 3, +1	4, +2
energy gain [MeV/unit]		
(w SLED)	----	160
(w/o SLED)	62.5	90
input rf power [MW/unit]	20	40

Parameters of the high power klystrons

	Unit	Existing (PV3050)	PV3030A3	50MW
Beam voltage	kV	270	285(310)	315
Beam current	A	295	319(362)	370
Beam power	MW	80	91(112)	117
Beam pulse width	μs	3.5	5.5	5.5
Repetition rate	PPS	50	50	50
Peak rf output power	MW	33	40(50)	50
Avg. rf output power	kW	3.3	8.0	10
RF pulse width	μs	2	4	4
Efficiency	%	42	44	44
Perveance	$\mu A/V^{3/2}$	2.1	2.1	2.1
Overall length	mm	1317	1317	< 1400
Number of cavities		5	5	5
RF window		single	single	single

Comparison of the original and modified modulator specifications

	Original	Modified (SLED)	Modified (Recirculation)
Maximum peak power (MW)	84	117	153
Maximum average power (kW)	14.7	30	30
Transformer step-up ratio	1:12	1:13.5	1:15
Output pulse voltage (kV)	23.5	23.5	23.5
Output pulse current (A)	3600	5000	6530
PFN impedance (W)	6.0	4.7	3.6
PFN total capacitance (μF)	0.3	0.6	0.6
Pulse width (μs)	3.5	5.6	4.3
Rise time (μs)	0.7	0.8	0.8
Fall time (μs)	1.2	1.3	1.5
Pulse repetition rate (pps)	50	50	50
Maximum pulse height deviation from flatness (%)	0.3 (peak to peak)	0.3	0.3
Maximum pulse amplitude drift (%/hour)	0.3	0.3	0.3
Thyratron anode voltage (kV)	47	47	47

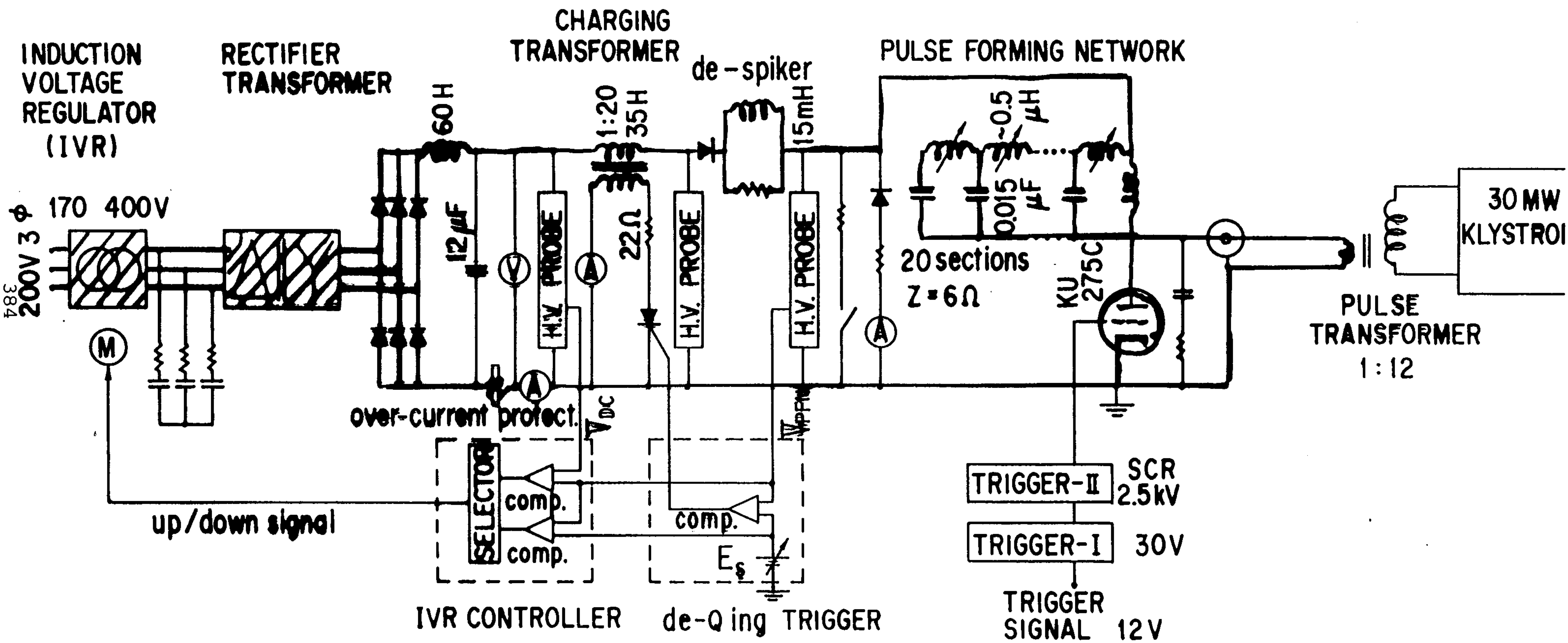

INDUCTION VOLTAGE REGULATOR (IVR)
RECTIFIER TRANSFORMER
CHARGING TRANSFORMER
de-spiker
PULSE FORMING NETWORK
200V 3 φ
170 400V
M
60H
12μF
V
H.V. PROBE
A
1:20
35H
22Ω
15mH
~0.5 μH
0.015 μF
20 sections
Z = 6Ω
KU 275C
30 MW KLYSTRON
PULSE TRANSFORMER
1:12
over-current protect.
V_{DC}
V_{PFN}
SELECTOR
comp.
comp.
comp.
E_s
up/down signal
IVR CONTROLLER
de-Q ing TRIGGER
TRIGGER-II
SCR 2.5kV
TRIGGER-I
30V
TRIGGER SIGNAL 12V

Table 1. Operation and failure time during this period

	date	operation time (hrs)	failure time (hrs)	rate (%)
FY 1992	Sep. 28–Nov. 11	1039	34.1	96.7
	Nov. 17–Dec. 21	800	9.8	98.8
	Feb. 8–Mar. 29	1153.5	6.4	99.5
FY 1993	Apr. 5–May 1	618	4.5	99.3
	May 6–June 2	636	5.0	99.2
	June 7–July 14	874	5.1	99.4
total		5120.5	64.9	98.7

Table 2. Averaged fault rate and averaged applied voltage to klystrons.

Period	Fault rate (/day·tube)	Applied voltage (kV)	Total operation (tube·days)
1985/8-1986/7	1.0	238	5,600
1986/8-1987/7	1.0	239	7,740
1987/8-1988/7	1.0	240	9,990
1988/8-1989/7	0.6	241	10,510
1989/8-1990/7	0.3	244	10,690
1990/8-1991/7	0.2	246	10,750
1991/8-1992/7	0.1	248	10,140
1992/8-1993/7	0.1	247	10,010

Table 3. Cumulative usage hours of the klystrons during the past years.

Period	Total	Unused	Failed		Living		MTBF
	No.of tubes	No.of tubes	No.of tubes	Mean age (hours)	No.of tubes	Av.op.time (hours)	(hours)
up to 1985/7	79	2	28	3,600	49	6,200	13,400
up to 1986/7	91	3	39	4,400	49	7,400	13,100
up to 1987/7	106	4	52	4,400	50	9,600	13,600
up to 1988/7	120	2	67	4,500	51	11,400	13,500
up to 1989/7	140	5	82	6,400	53	12,400	14,400
up to 1990/7	158	6	98	8,500	54	11,200	14,700
up to 1991/7	176	14	107	10,100	55	11,100	15,800
up to 1992/7	191	24	113	10,800	54	13,400	17,100
up to 1993/7	203	19	123	10,800	56	15,300	17,700

Table 4. Cumulative status of klystrons up to July 1993 corresponding to the year of production. Unused tubes are those which have never been used in the klystron gallery. STB(stand-by) tubes are those which have been used in the gallery and can be used there again.

Year of production	Cathode	Total No.of tubes	Unused No.of tubes	Living No.of tubes	Living (STB	Living Working e-	Living Working e+)	Living Av.op.time (hours)	Failed No.of tubes	Failed Causes (arcing	Failed Causes window	Failed Causes others)	Failed Mean age (hours)	Cumulative operation (tube-hours)	MTBF (hours)
1979	oxide	4	0	0	0	0	0	------	4	2	1	1	3,902	15,608	3,902
1980	oxide	20	0	1	1	0	0	3,657	19	13	5	1	9,050	175,606	9,242
1981	oxide	20	0	1	1	0	0	11,277	19	11	2	6	15,965	314,611	16,588
1982	oxide	9	0	1	1	0	0	2,120	8	5	2	1	10,054	82,549	10,317
1983	oxide	13	0	1	1	0	0	14,170	12	6	2	4	18,753	239,205	19,934
1984	oxide	13	1	0	0	0	0	------	12	10	0	2	9,950	119,401	9,950
1985	oxide	12	1	0	0	0	0	------	11	7	0	4	13,409	147,494	13,409
1986	oxide	15	0	1	1	0	0	11,568	14	13	0	1	3,524	60,910	4,351
1987	oxide	7	0	0	0	0	0	------	7	5	1	1	4,342	30,393	4,342
	total	113	2	5	5	0	0	8,558	106	72	13	21	10,783	1,185,777	11,187

Year of production	Cathode	Total No.of tubes	Unused No.of tubes	Living No.of tubes	Living (STB	Living Working e-	Living Working e+)	Living Av.op.time (hours)	Failed No.of tubes	Failed Causes (arcing	Failed Causes window	Failed Causes others)	Failed Mean age (hours)	Cumulative operation (tube-hours)	MTBF (hours)
1987	BI	7	0	5	0	5	0	27,857	2	0	1	1	16,748	172,782	86,391
1988	BI	20	1	15	3	9	3	20,393	4	0	3	1	12,814	357,153	89,288
1989	BI	18	1	11	0	10	1	19,194	6	0	5	1	10,525	274,284	45.7.14
1990	BI	18	6	9	1	7	1	12,568	3	0	2	1	8,902	139,817	4
1991	BI	15	8	5	0	4	1	4,106	2	0	2	0	2,843	26,216	1
1992	BI	12	6	6	0	5	1	3,652	0	0	0	0	-----	21,913	
	total	90	17	51	4	40	7	15,919	17	0	13	4	10,605	992,165	5
	total	203	19	56	9	40	7	15,262	123	72	26	25	10,758	2,177,942	1

Cumulative usage of the thyratron during the past fiscal years

Period	Total no.	Unused no.	Failed no.	Living no.		operation hrs
85/3	56	12	0	44	KU275C	6,800
86/3	56	4	0	52		9,700
87/3	61	7	2	52		13,700
88/3	74	17	5	52		18,200
89/3	74	15	7	52		23,700
90/3	83	20	10	53	F175	28,900
91/3	88	21	14	53		34,100
92/3	91	21	17	53		39,200
93/3	94	21	20	53		44,300
94/3	104 (10)	25	24	55 (10)	F241	49,600
95/3	126 (32)	37 (13)	27	62 (1)	L4888	54,800
96/3	144 (50)		27+?	64	CX2410	

Maintainability ← Fast trouble shooting; Monitoring
← Replacement ; Modularity
(easily repairable)

Maintenance free modulator is desirable

↓

Need enough margin

↓

cost! cost! cost! cost!!!

Klystron-Modulator System Performances For PLS 2-GeV Linac

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and W. Namkung

PAL, POSTECH, Pohang, S.Korea

(K&M Work Shop @SLAC, Oct. 1995)

Contents ;

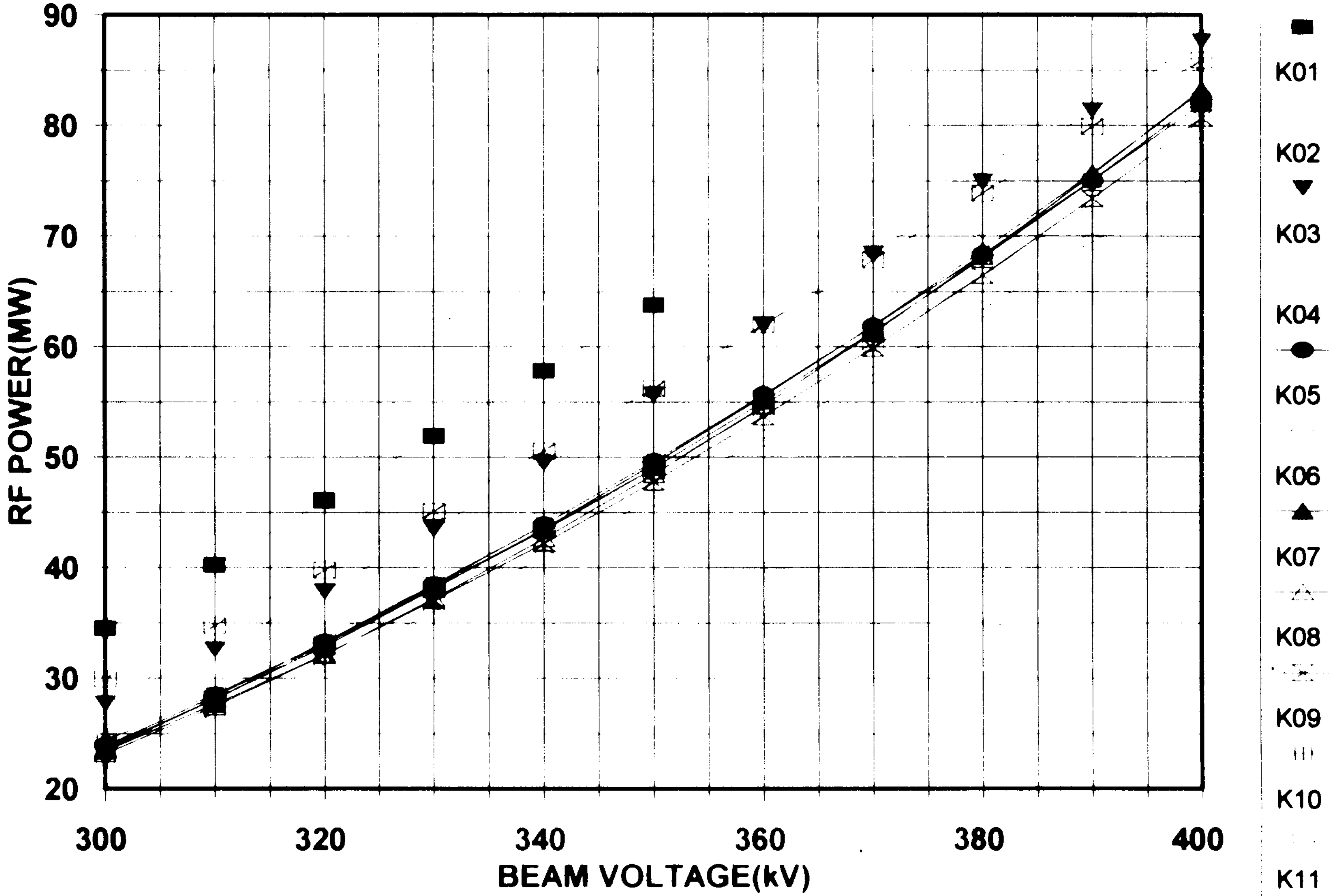
1. *PLS 2-GeV LiNAC Overview*
2. *Klystron-Modulator System*
3. *K&M System Performance*
4. *System Availability Statistics*
5. *Comments on System Troubles*
6. *System Upgrade Ideas*

Main Parameters of Klystron

Parameters	*E-3712*	*S-5045*
Operating Frequency (MHz)	2,856	2,856
Peak Power (MW)	80	67
Average Power (kW)	18	42
Pulse Length (μs)	4.0	3.5
Rep. Rate, *max* (pps)	60	180
Drive Power, *max* (W)	500	800
Beam Voltage, *max* (kV)	400	350
Beam Current, *max* (A)	500	415
Gain (dB)	52	53
Efficiency (%)	42	45
Micro-pervience	2	2
Manufacturer	*Toshiba*	*SLAC*

KLYSTRON RF POWER CHARACTERISTICS

(K01:SLAC 5045, K02~11:TOSHIBA E3712)



JUN 24 1994 TUBEDATA WB1 RFPOWER-Vb

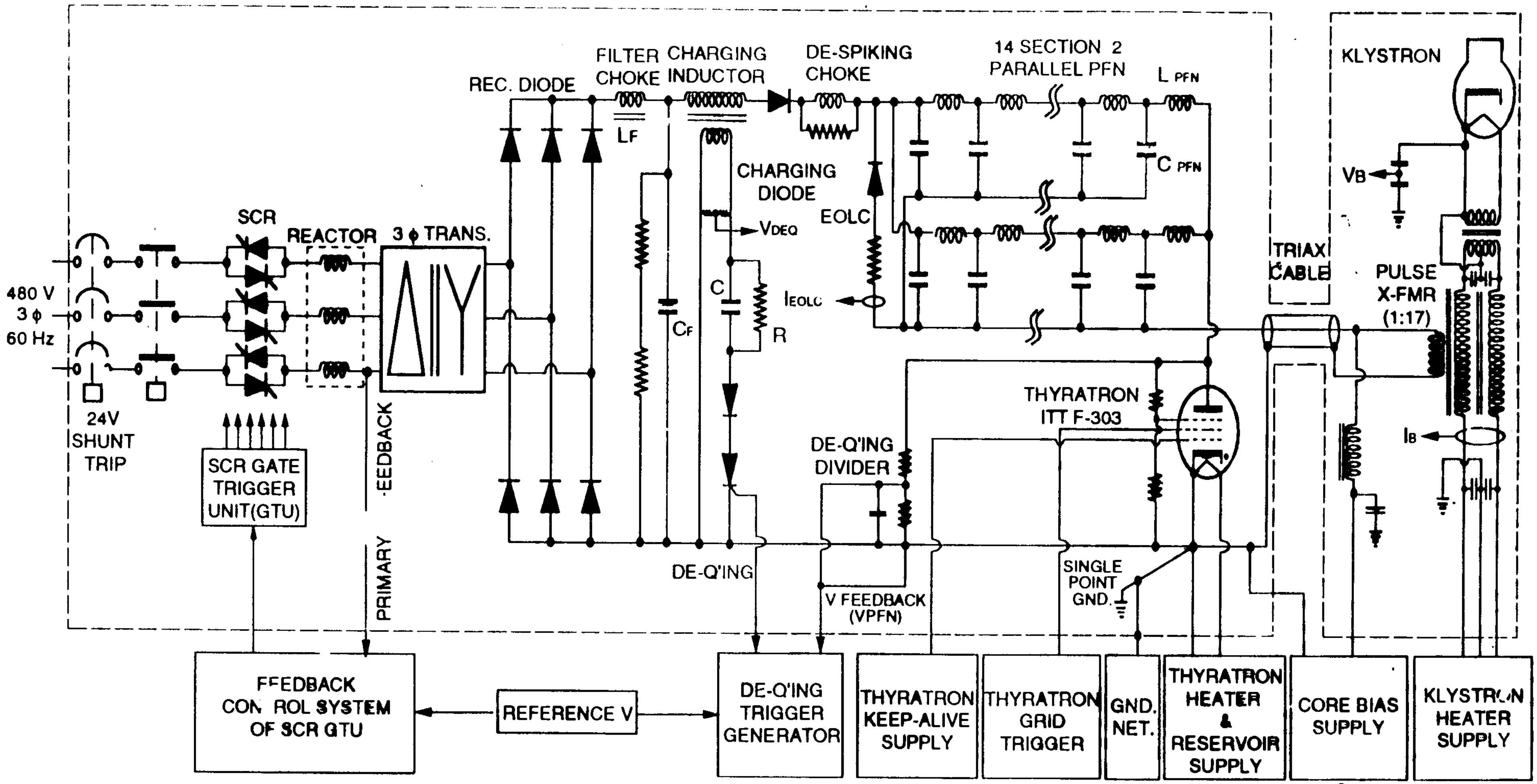
Main Parameters of Modulator

	PLS-150	PLS-200
• Peak Power (MW)	150	200
• Average Power (kW) @ 60 Hz	58.2	80
• Peak Beam Voltage (kV)	350	400
• Peak Beam Current (A)	420	500
• Max. Pulse Rep. Rate (Hz)	60	60
• Pulse Width (μs)		
– Flat top	3.5	4.4
– ESW	6.57	7.67
• Pulse Flatness (%)	± 0.5	± 0.5
• PFN Impedance (Ω)	3.73	2.74
• Pulse Risetime (μs)	0.8~1.0	0.8~1.0
• Pulse Falltime (μs)	1.5~2.0	1.5~2.0

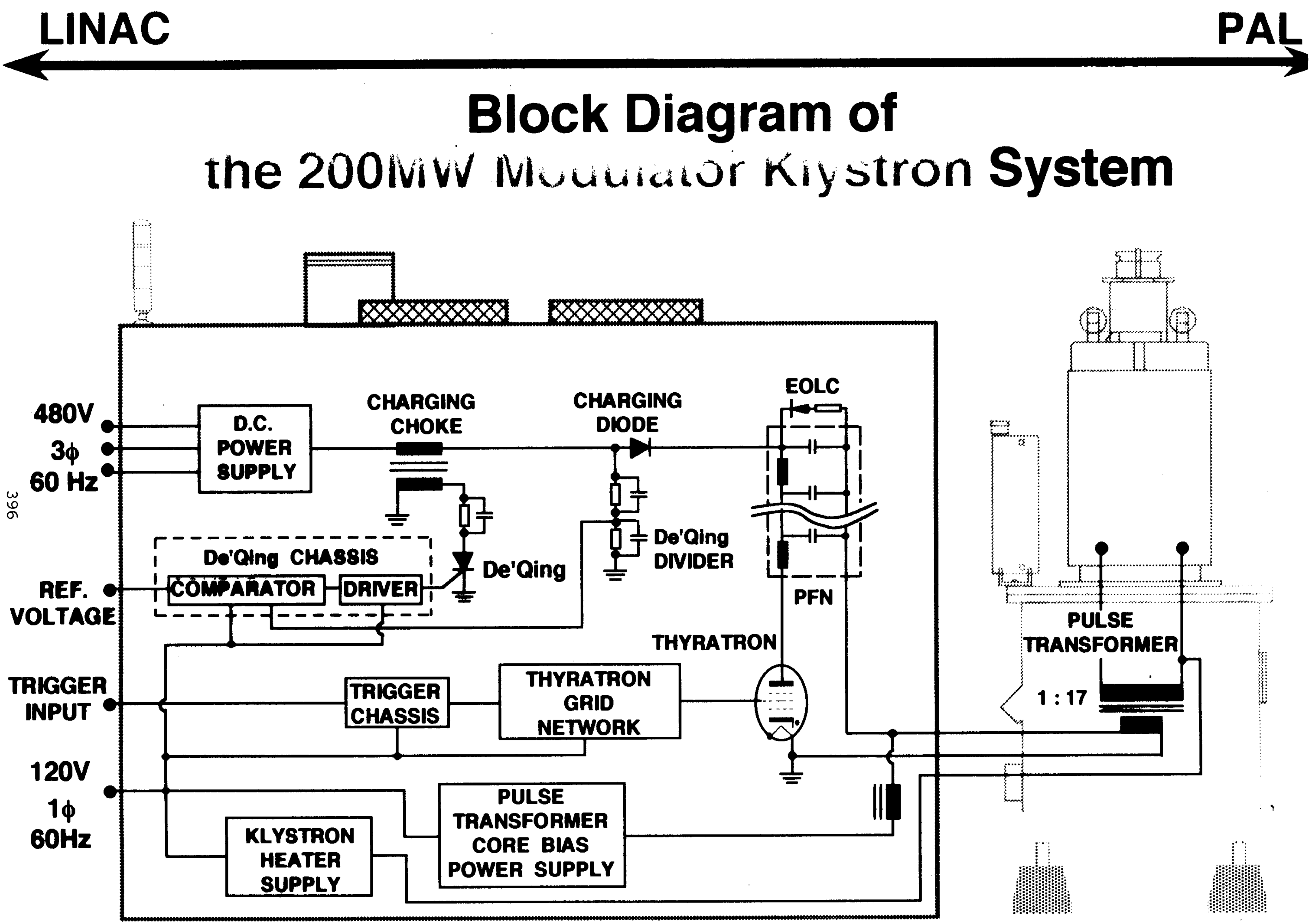
Table 1. Operation Parameter Summary for Klystron-Modulator

Peak beam power	**200-MW *max.* (400 kV @500A)**
Beam vol. pulse width	**ESW: 7.5 μsec, Flat-top: 4.4 μsec**
Pulse rep. rate	**120 pps *max.* (currently 30 pps)**
PFN impedance	**2.64Ω (5% positive mismatch)**
Voltage stabilization	**SCR, DC feedback & 5% De-Q'ing**
Pulse transformer	**1:17(turn ratio), L_{lk}:1.3μHy, C_{st}:69nF**
Thyratron switch	**Heating factor: 46.8×10^9, 8.5 kA peak anode current**
Klystron tube	**Drive power: ~300 W, efficiency: 40%, gain: ~53dB, peak power: 80 MW (currently running at 50 to 65MW)**

SD-951-000-01 DWG NO

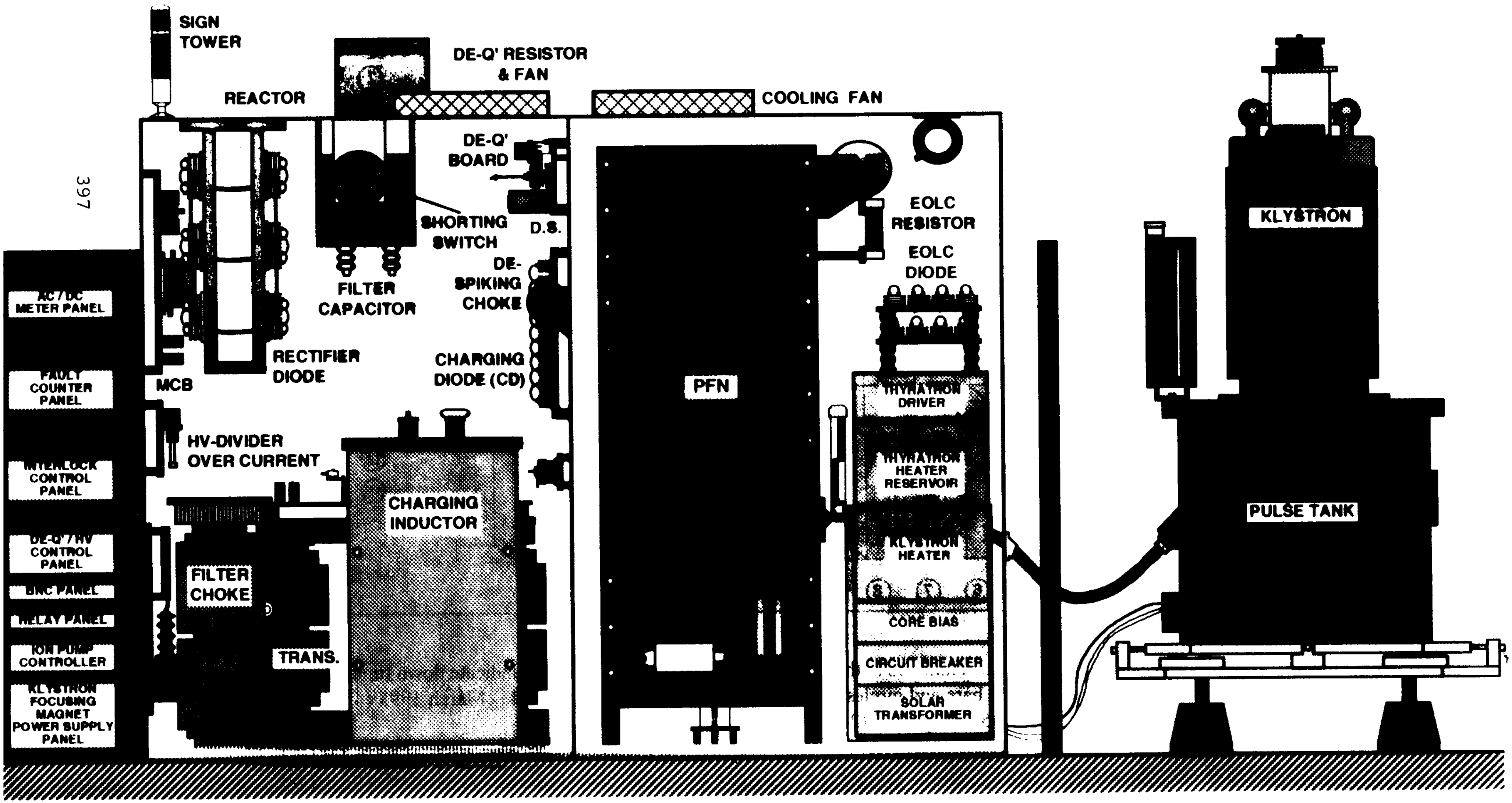


POHANG ACCELERATOR LABORATORY			
TITLE	SCHEMATIC DIAGRAM 200MW MODULATOR AND 80MW KLYSTRON		
SCALE		DWG NO	SD-951-000-01
UNIT	mm		



LINAC
PAL
Block Diagram of
the 200MW Modulator Klystron System
480V
3ϕ
60 Hz
D.C. POWER SUPPLY
CHARGING CHOKE
CHARGING DIODE
EOLC
PFN
De'Qing CHASSIS
COMPARATOR
DRIVER
De'Qing
De'Qing DIVIDER
REF. VOLTAGE
THYRATRON
TRIGGER INPUT
TRIGGER CHASSIS
THYRATRON GRID NETWORK
PULSE TRANSFORMER
1 : 17
120V
1ϕ
60Hz
PULSE TRANSFORMER CORE BIAS POWER SUPPLY
KLYSTRON HEATER SUPPLY

PLS-200MW MODULATOR & 80MW KLYSTRON FRONT VIEW



LINAC → PAL

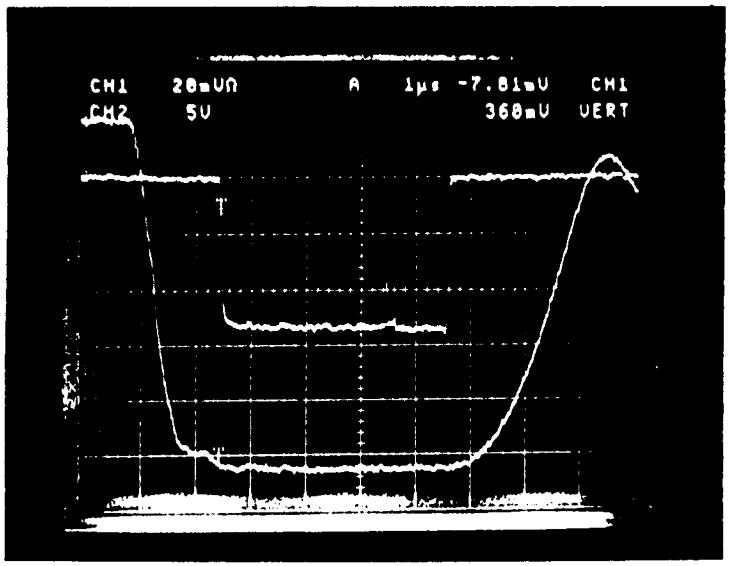
THYRATRON MAIN PARAMETERS COMPARISON

	ITT F-303	LITTON L-4888	EEV CX1836A
Heater Voltage (VAC)	6.0 ~ 6.6	5.9 ~ 6.7	6.0 ~ 6.6
Max. Heater Current (A)	80	90	90
Reservoir Voltage (VAC)	2.5 ~ 6.0	3.0 ~ 5.5	6.0 ~ 6.6
Reservoir Current (A)	20	40	7
Minimum Heating Time (minutes)	15	15	15
Max. Peak Anode V, forward (kV)	50(45.9)	50	50
Max. Peak Anode V, inverse (kV)	50	N/C	50
Min. DC Anode Supply V (kV)	2	10	5
Max. Peak Anode Current (kA)	15(8.5)	10	10
Max. Average Anode Current (ADC)	8(7.64)	8	10
Max. Heating Factor (pb = epy x ib x prr ,x10^9)	300(46.8)	400	N/C
Max. Anode Current Rate of Rise (kA/us)	50	16	10
Max. Anode Delay Time (us)	0.3	0.4	0.35
Max. Time Jitter (ns)	2	10	10

The values given in parenthesis are maximum operating range
with the 200 MW modulator

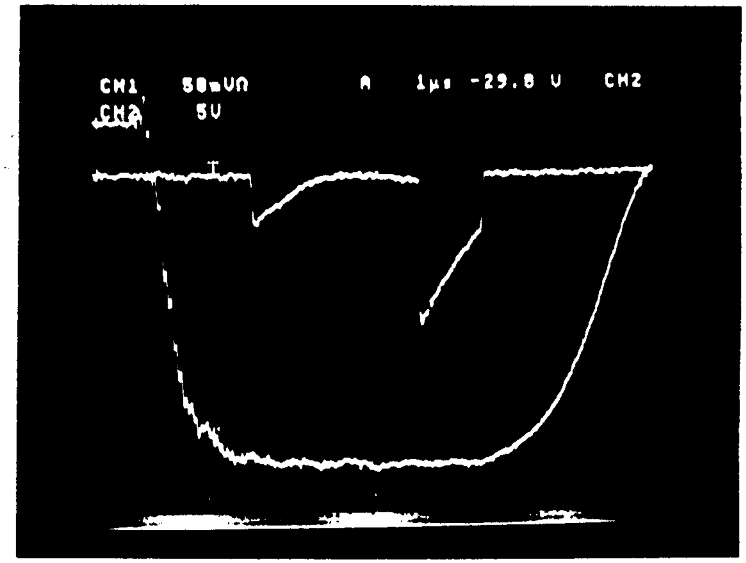
Klystron Beam Voltage & RF Output Power Waveforms

K-01 UNIT (SLAC-5045 Klystron)



1. RF source for the preinjector as well as main drive rf source.
2. Beam voltage = 340 kV, 30 pps
   RF output power = 57 MW
   RF pulse length = 4.1 μs

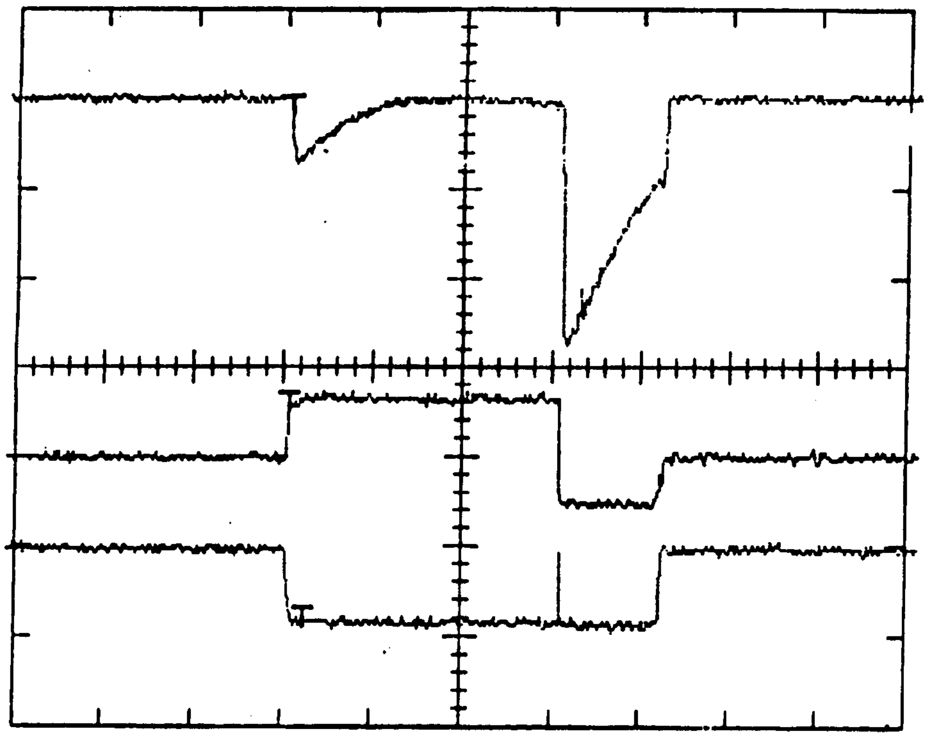
K-02 UNIT (E-3712 Klystron)



1. One of the regular module units
2. Beam voltage = 365 kV
   Tube RF output power = 60 MW
   PSK on @ 3 μs after drive turn on
   ED peak RF power = 336 MW

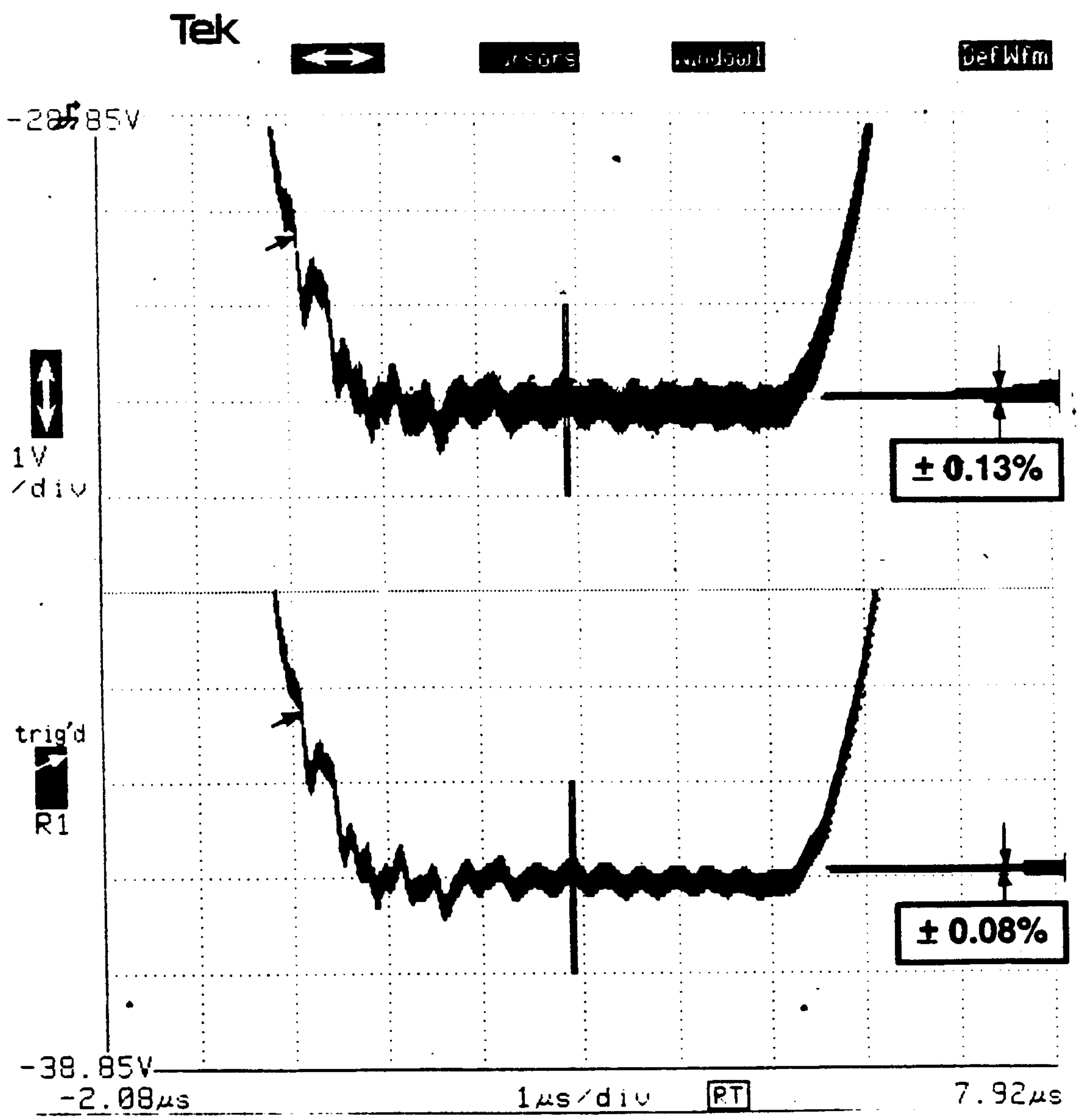
PLS/LINAC-K&M Gr./940622CMH

Klystron Beam Voltage and RF Output Power



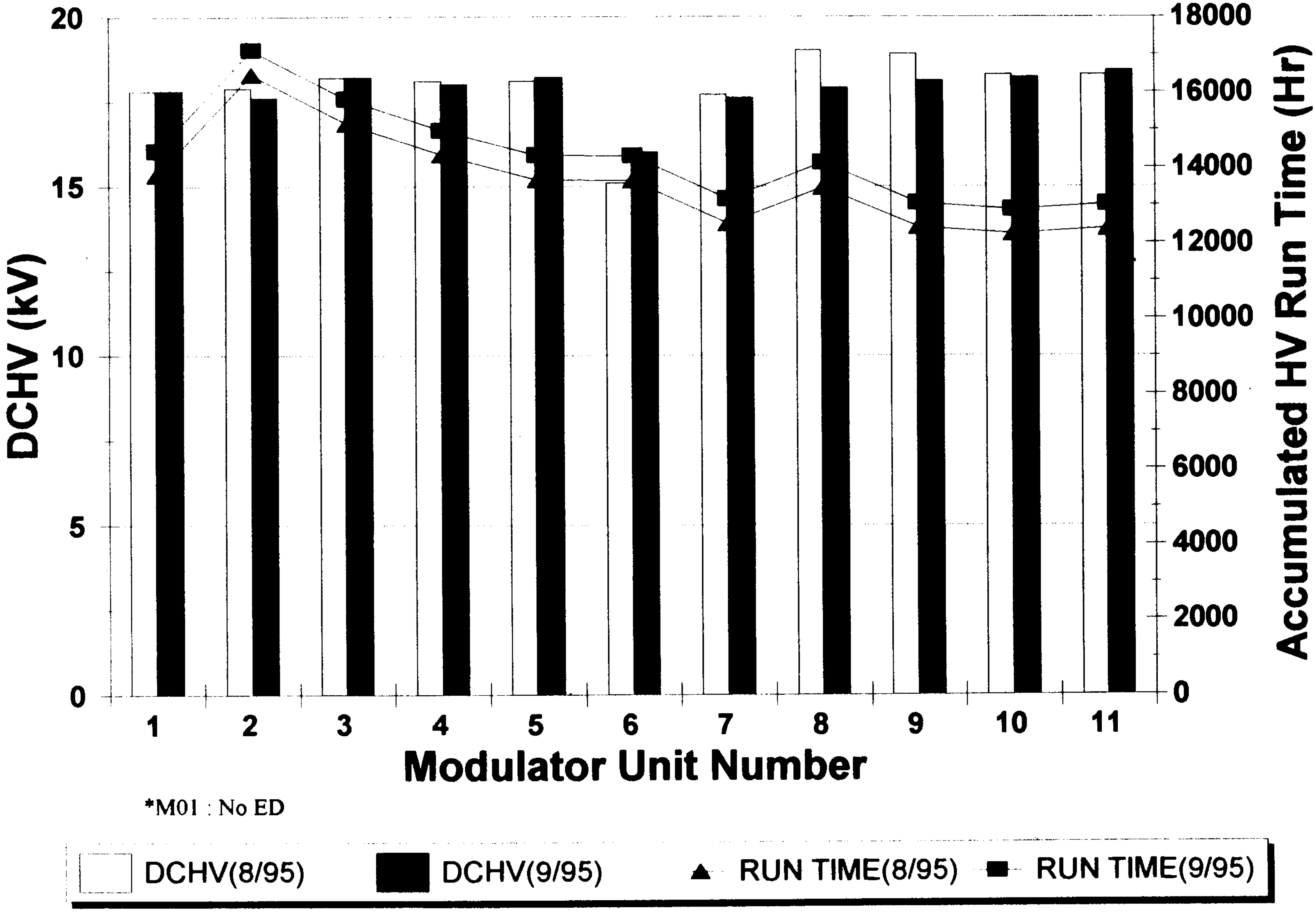
- *Typical RF Characteristics for tuned operation;*
  - *Top:SLED output (335 MW peak)*
  - *Middle: Phase of klystron output*
  - *Bottom: Klystron output (60 MW)*
- *1 μs/div (h) and relative unit (v)*

ACCUMULATED KLYSTRON BEAM VOLTAGE(399kV) WAVEFORMS WITH OUT DE-Q'ING(UPPER TRACE) & WITH DE-Q'ING(LOW ER TRACE)



Accumulated HV Run Time Statistics

(4.1microsec,10pps,ED Tuned; 9/22/95)



*M01 : No ED

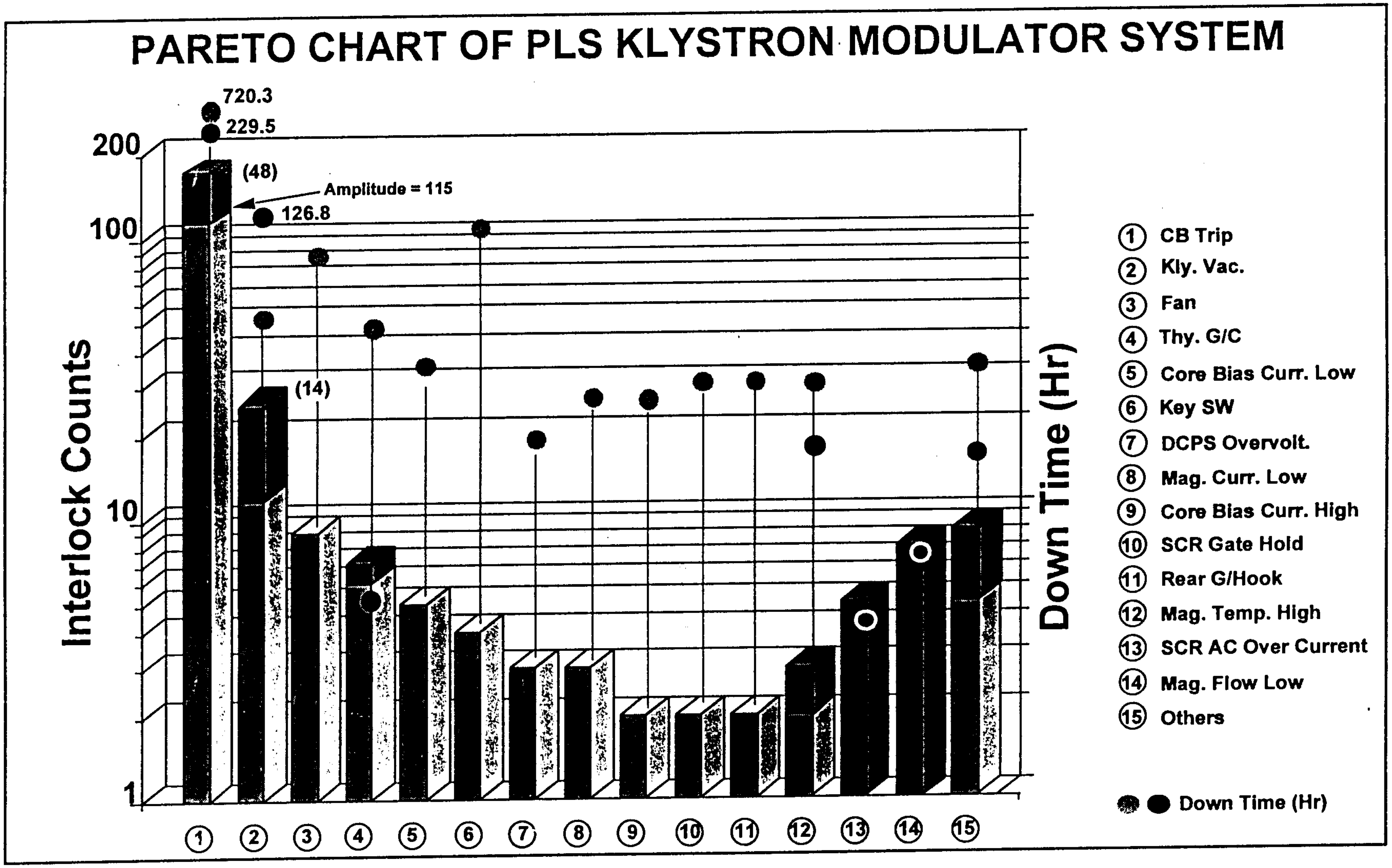


Fig. 3 Pareto chart of the system fault statistics. Numbers in the x-axis indicate type of faults, circles indicate down times, and the bars indicate accumulated interlock counts. Grey colored bars and circles are for the period of September 1994 ~ March 1995 (4752-Hr), and the black colored marks are for the period of April 1995 ~ July 1995 (2688-Hr).

RELIABILITY PARAMETER COMPARISON Between PLS & SLAC
(for Beam Operation Mode)

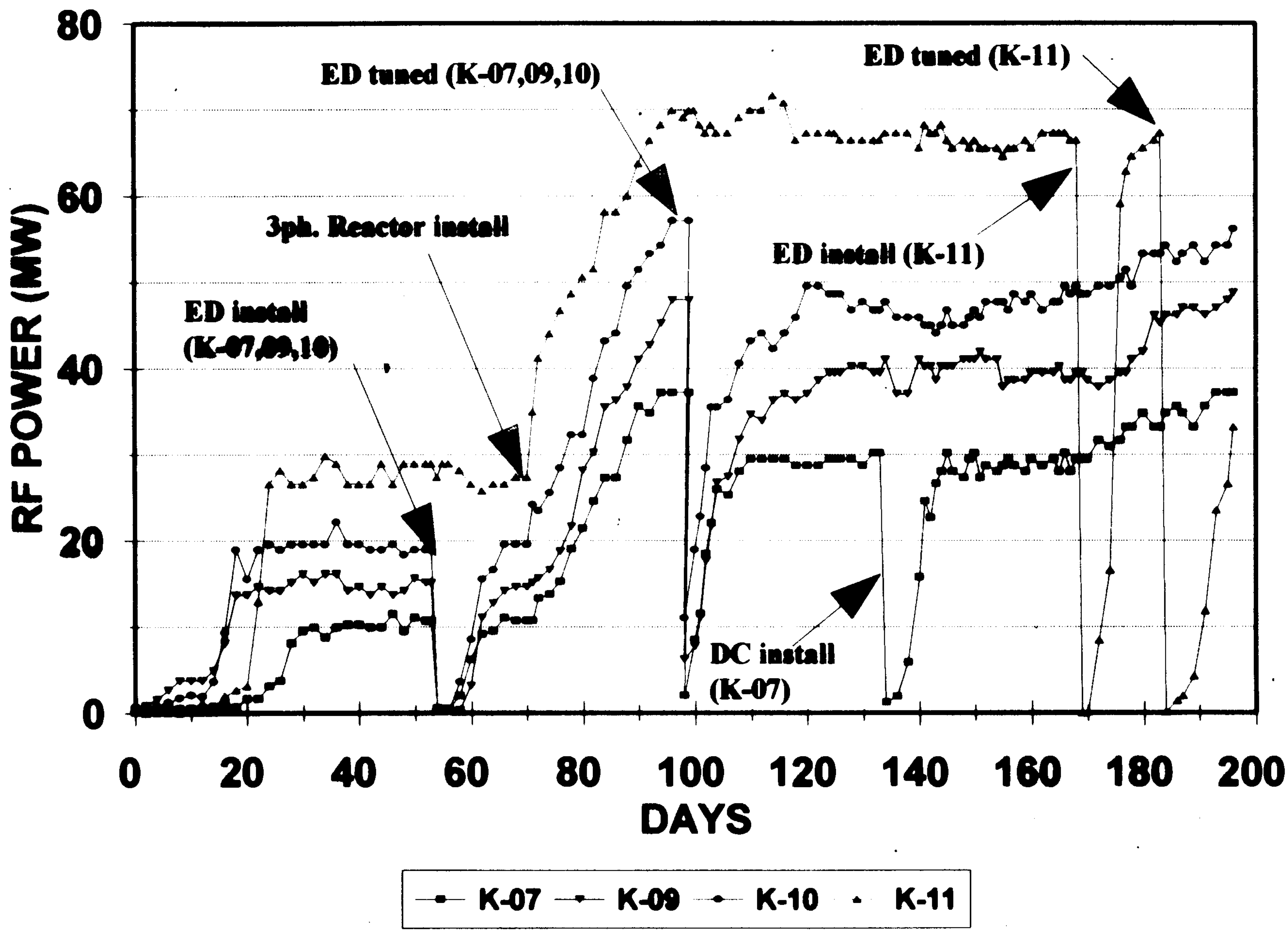
	PLS	SLAC
• Total Mod. Number	11	243
• Spare Modulators	0	14
• Operation Time (hr)*	4752(2688)	4000
• Total Failure Count	168(82)	997
• Total Down Time (hr)**	493(1150/403)	401
• MTBF (hr)	311(361)	975
• MTTR (hr/failure)**	2.6(6.8/4.9)	0.4
• Availability**	0.91(0.76/0.85)	0.90

* Operation Time for statistical analysis , **( ) : Standby RF Operation Mode without extended hour maintenance included.

MAJOR MODULATOR TROUBLES AND IMPROVEMENTS

MODULATOR INTERLOCKS	TROUBLES	IMPROVEMENTS
CB Trip DCPS Overvoltage SCR Gate Hold	Thyratron Related Troubles	Ranging or Command Charging
Klystron Vacuum	Klystron Related Troubles	Short Pulse Processing
Core Bias Current Low & High	Switching Noise Related Troubles	Noise Filtering

RF CONDITIONING MARCHING CURVES



Summary of Current Status

1. Klystron Modulator Systems ;

- Total < 1 + 10 > units under normal operation.
- System performance meets all design requirements.
- Over 140,000-Hrs of total H.V run time for 11 Klystrons.
- No serious technical problems or failures observed.

2. System's Reliability Analysis ;

- ~90% of system's availability for beam operation mode.
- Most of failures are due to the thyratron abnormality.

3. Others ;

- R&D for compact and efficient Klystron modulator
- R&D for system's reliability improvement underway.

KLYSTRON-MODULATOR SYSTEM PERFORMANCES FOR PLS 2-GeV LINAC*

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Pohang 790-784, Korea

0. ABSTRACT

The PLS 2-GeV linac employs 11 units of high-power pulsed klystrons (80-MW) as the main RF sources. The matching modulators of 200-MW (400-kV, 500-A) can provide a flat-top pulse width of 4.4 μs with a maximum pulse repetition rate of 120-Hz at the full power level. For a good stability of electron beams, the pulse-to-pulse flat-top voltage variation of a modulator requires less than 0.5%. In order to achieve this goal, we stabilized high-voltage charging power supplies within 1% by a phase controlled SCR voltage regulator (AC feedback). In addition, we employed DC feedback, which performed well within 0.5% variation of the PFN charging voltage. In this paper we analyzed the overall machine availability and the system fault statistics during the PLS (Pohang Light Source) commissioning operation. During this period the availability was ~90% for the case of 24-hr maintenance mode with 2-shift work, and the availability dropped down to ~75% for the case of day-time only (44-hr per week) maintenance mode. The most frequent type of static fault which require the attendance of a maintenance crew has been identified as main circuit breaker (CB) trip due to the abnormal behavior of thyratron switches. For the improvement of the system availability the SCR gate hold interlock and the slow start of the DC high voltage together with the automatic remote reset of the static faults using the control computer have been added during the '95 summer maintenance shutdown. PLS is now in the normal operation mode for the beamline user service (started from September 1, 1995). In this paper, we also presents the key features of the klystron-modulator system and the short term preliminary result of the availability analysis after the system modification, approximately 1-month period.

I. INTRODUCTION

PLS linac has been injecting 2-GeV electron beams to the Pohang Light Source (PLS) storage ring as a part of the ring commissioning operation since September, 1994[1]. The linac klystron-modulator (K&M) system has been in operation well before the ring commissioning, and the total accumulated high voltage run time of the oldest unit has reached beyond 15,000 hours as of Sep. 1995[2]. The K&M systems are normally operating in 70 to 80% of the rated peak-power level to avoid the multipactering phenomena occasionally occurring in a random fashion inside the waveguide networks and accelerating structures of the linac system. The sum of all high voltage run time for total 11 K&M systems installed in the PLS linac, is approximately 158,000 hours.

In this paper, we review overall system performance of the high-power K&M system. A special attention is paid on the analysis of all failures and troubles of the K&M system which affected the linac RF operations as well as beam injection operations for the period of September 1994 to July 1995. During this period, the machine has been in the operational mode for total 310 days. Summer shut-down and the scheduled maintenance shut-down time are excluded in the analysis.

II. K&M SYSTEM OVERVIEW AND PERFORMANCE

The key features of the K&M system design include the 3-phase SCR controlled AC-line power control, resonant charging of the PFN, resistive De-Q'ing, end-of-line clipper with thyrite disks, pulse transformer with 1:17 step-up turn ratio, and high power thyratron tube switching. The major operational parameters of the PLS-200-MW klystron-modulator system are listed in Table 1 and the system schematics are shown in Fig. 1. The details of the system design and performance characteristics are described elsewhere [2].

The shot-to-shot beam voltage stability is controlled by (1)the feedback of the DC high voltage from PFN to SCR primary input voltage control and (2)the resistive De-Q'ing. SCR DC feedback provides less than ±0.5% fluctuation, and additional De-Q'ing stabilizes the beam voltage better than ±0.1% fluctuation level. Fig. 2 shows the sample traces of the beam voltage accumulated more than an hour which exhibits less than ±0.1% fluctuation.

For the fault free stable operation of the system, the thyratron tube is one of the most important active components which require continuous maintenances and adjustments. The thyratron tubes which meet the PLS-200-MW system specifications are listed in Table 2 together with their specifications. ITT/F-303 and Litton/L-4888 are installed in our system, and the performance evaluations are underway. Recently EEV/CX-1836A has been installed also for the comparison. This effort is initiated to improve the system from the frequent occurring faults (see Fig. 3) caused by the irregular recovery action of the thyratrons, which strongly depends upon the reservoir control.

There are three types of system interlocks, namely dynamic, static, and personal protection interlocks. All the static fault activation is initiated by the relay logic circuit, and the dynamic faults which require a fast action response are activated using the electronic comparator circuit. When the system operation is interrupted by the static fault, it can be recovered either by the remote control computer or manual reset. However, we have been performing all manual resets till July 1995 for the purpose of the experience accumulation, such as to find the type of troubles and system bugs which can provide the idea of the system improvement. The statistical analysis of the machine availability presented in this paper is based on the operation method of the manual reset by the maintenance crew only, without using the remote computer control. On the other hand, in the case of dynamic faults, the system recovers automatically without the help of the control computer when the condition returns to a normal state.

Table 1. Operation parameter summary for klystron-modulator.

Peak beam power	200-MW max. (400 kV @500A)
Beam vol. pulse width	ESW 7.5μs, 4.4μs flat-top
Pulse rep. rate	120 pps *max.* (currently 30 pps)
PFN impedance	2.64Ω (5% positive mismatch)
Voltage stabilization	SCR, DC feedback & 5% De-Q'ing
Pulse transformer	1:17(turn ratio), L_{lk}:1.3μH,C_{st}:69nF
Thyratron switch	Heating factor: 46.8x10^9, 8.5 kA peak anode current
Klystron tube	Drive power:~300 W, efficiency:40%, gain:~53dB, peak power:80/65 MW (currently running at 50 to 65MW)

Table 2. Comparison of the thyratron tubes.

ITEM	ITT F-303	Litton L-4888	EEV CX-1836A
Heater (Vac/A) *max*	6.6 / 80	6.7 / 90	6.6 / 90
Reservoir (Vdc/A) *max*	6.0 / 20	5.5 / 40	6.6 / 7
Peak anode (kV/kA) *for*	50 / 15	50 / 10	50 / 10
Peak anode vol.(kV) *inv*	50	*n/c*	50
Avg. anode cur.(A) *max*	8	8	10
min DC anode vol.(kV)	2	10	5
Heating factor (x10^9) *max*	300	400	*n/c*
dI/dt (kA/μs) *max*	50	16	10
Anode delay (μs) *max*	0.3	0.4	0.35
Trigger jitter (ns) *max*	2	10	10

III. SYSTEM AVAILABILITY STATISTICS

Since the completion of the PLS 2-GeV linac installation in December 1993, all the K&M systems have been operating continuously except scheduled short-terms and long-term shut downs. Table 3 shows the total accumulated times of klystron's and thyratron's heater operation, and the high voltage run. Sum of the high voltage run time of each modulator has reached over 158,000 hours, and the experience accumulated so far provides the valuable information for the system's stable operation. Fig. 3 is the Pareto chart of the total system's static fault count data collected for the period of September 1994 to March 1995(grey colored) and April 1995 to July 1995 (dark colored). Net operation days during this period is 198 and 112, respectively. As mentioned in the previous section, the reset has been done by the maintenance crew only, and at the most of nights and weekends during the period no extra maintenance work has been performed except the ring injection operation time. Therefore the down time for the circuit breaker (①CB) trip which occurred the most frequently is unusually high among others. Other faults, such as fan(⑤) and key switch(⑥) are due mainly to faulty components, which no longer occur in any appreciable numbers after the replacement. Troubles related with tempreture and coolant flow are due to the faults in the cooling pump station.

Machine availability analysis has been performed based on the data using the techniques described in detail in reference [4]. The results are summarized and compared with the SLAC's in Table 4. The MTBF stands for the mean time between failures, and it is calculated by dividing the sum of the accumulated modulator run time with the total fault count (MTBF = N*TO/FC). The MTTR (mean time to repair, which is equal to the total down time divided by total fault counts, MTTR = TD/FC) is rather longer than the SLAC's due to the extensive inspection work of the entire system for the trouble shooting as well as crew training for the system maintenance. Especially, the lack of the experience on the thyratron operations and severe EMI environment have contributed a lot for the longer MTTR.

Approximately 76% of the machine availability (A = 1-MTTR*FC/TO) has been obtained with the maintenance work of 44-hr-per-week. However, during the beam operation mode when the maintenance crews are standby, approximately 91% of availability has been reached even without a standby K&M system. It indicates most of the system troubles are not so serious, and in many cases they are easily recoverable.

IV. COMMENTS ON SYSTEM TROUBLES

The most frequent system fault is the circuit breaker (CB) trip as shown in Pareto chart. This is due mainly to the problems in thyratron recovery actions which require elaborate reservoir ranging. Thyratron tubes of F-303 and L-4888 require ranging adjustment (see Table 2). According to our experience, they are changing in irregular patterns such that there exist no normal patterns or pre-symptoms which can be used for the preventive maintenance. Once it is out of normal operating point, there occur self-fire, firing miss, or slow recovery. The CX-1836A thyratron tubes require not so delicate ranging according to the manufacturer's specifications, and recently we have installed one unit for the comparison. Klystron tubes also showed an internal arcing causing the vacuum pressure trip in a random fashion (see ⓬ in Fig. 2). When this occurs in a row, we could recover to the normal operation after performing the short pulse processing (with approximately 1μs pulse width) for more than one day. However, this type of fault showed pronounced decrease as the run time accumulates.

Table 3. Accumulated run times (in hours) summary of the PLS 2-GeV Linac's K&M systems (total 11 sets); data collected on September 22, 1995.

Unit No.	HV run time	Kly. heater	Thyratron
MK-01	14,432	16,634	16,852
MK-02	17,107	924 (*1)	16,454
MK-03	15,807	16,568	18,667
MK-04	14,973	16,523	16,747
MK-05	14,312	15,908	16,422
MK-06	14,296	15,453	6,343 (*2)
MK-07	13,157	14,664	15,455
MK-08	14,123	15,473	15,397
MK-09	13,058	14,518	14,518
MK-10	12,890	14,333	1,547 (*3)
MK-11	13,033	14,447	8,114 (*2)

*1) Klystron replaced after heater run time of 18,883-hr due to the focusing solenoid trouble.
*2) Thyratrons replaced with L-4888 due to the failure of F-303 (after ~9500-hr life).
*3) Thyratrons replaced (F-241 to F-303) after ~8,000-hr run.

Table 4. Comparison of the K&M system fault analysis based on the data for the period of September 1994 ~ March 1995.

ITEM	*PLS**2	*SLAC*[4]
Number of modulators, *N*	11	243
Spare no. of modulators	0	14
Operation time (hr)*1, *TO*	4752	4000
Total failure counts, *FC*	168	997
Total down time (hr), *TD*	493 (1150)	401
MTBF (hr)	311	975
MTTR (hr/failure count)	2.6 (6.8)	0.4
System Availability, *A*	0.91 (0.71)	0.94*3

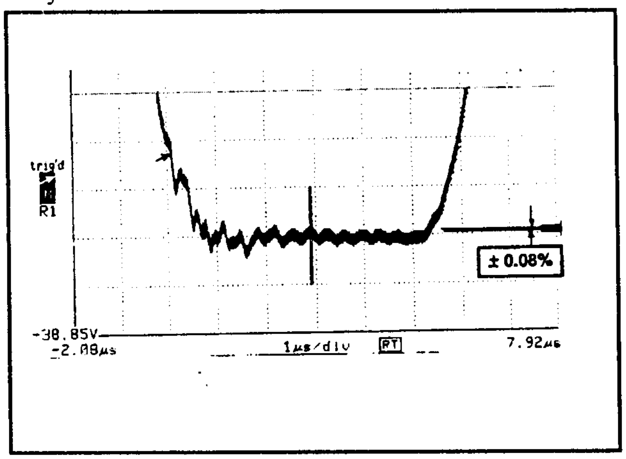
*1) Operation time for the statistical analysis.
*2) Numbers in ( ) indicates the standby RF operation mode without extended hour maintenance work (only 44 hr/week).
*3) Standby spare unit included

Other frequently occurred troubles are caused by the corona discharges. They occur when bad contacts exist in high voltage components, especially for the components which are connected by the spring type clamps. It has been found also that even a small corona discharge disturbs the ground potential, which are configured to have a single point ground connection inside the modulator, causing noise interferences in digital displays and/or SCR phase controls. Occasionally, this kind of EMI also affects LCD type displays of the nearby electronic equipment without affecting the performance, which became one of the normal check points for the system performance.

V. SUMMARY

It is approximately 1-year since the PLS 2-GeV Linac has started its operation. We have analyzed the klystron modulator system's performance record for the period. It is observed that the reliability of klystrons is well over our expectations compared with other components in the modulators. The life time of thyratron tubes appears to be reasonable except the occurrence of infant failures. However, the major improvement is necessary for the reservoir control which is the main source of system troubles. The machine availability statistics of the K&M system for the beam operation mode (typically 2 operators are on-duty) is calculated to be over 90%. It appears to us that there are still lots of rooms for the improvement toward the availability more than 95% with proper choices of the protection circuits and control logic. During the period of May 1995 to July 1995 we have modified our OCR (over current relay) interlock not to interrupt main CB but SCR gate (with static fault action) as an attempt to reduce major source of static fault. During the period no system damage has been occurred, and we now added remote reset control in the case of static fault. Just one month old statistics shows an excellent system's availability. Long term performance result will be reported as we accumulate enough data.

Fig.2 The flat-top ripple and the cumulative (>1-hr) stability measurement of the klystron beam voltage with DCHV feedback and De-Q'ing. Tektronix DSA-602 signal analyzer is used.



VI. REFERENCES

[1] W. Namkung, "PLS 2-GeV Linac," Proc. 1994 International Linac Conf., Tsukuba, Japan, Aug. 21-26, pp.14-18 (1994).

2] M. H. Cho et. al, "High Power Microwave System for PLS-2-GeV Linac," Proc. 1994 International Linac Conf., Tsukuba, Japan, Aug. 21-26, pp. 418-420 (1994), M. H. Cho et. al, "Design of 200-MW Pulse Modulator for PLS 2-GeV Electron Linac," Proc. 3rd European Particle Accelerator Conf., Berlin, Germany, Vol.2, pp. 1591-1593 (1992).

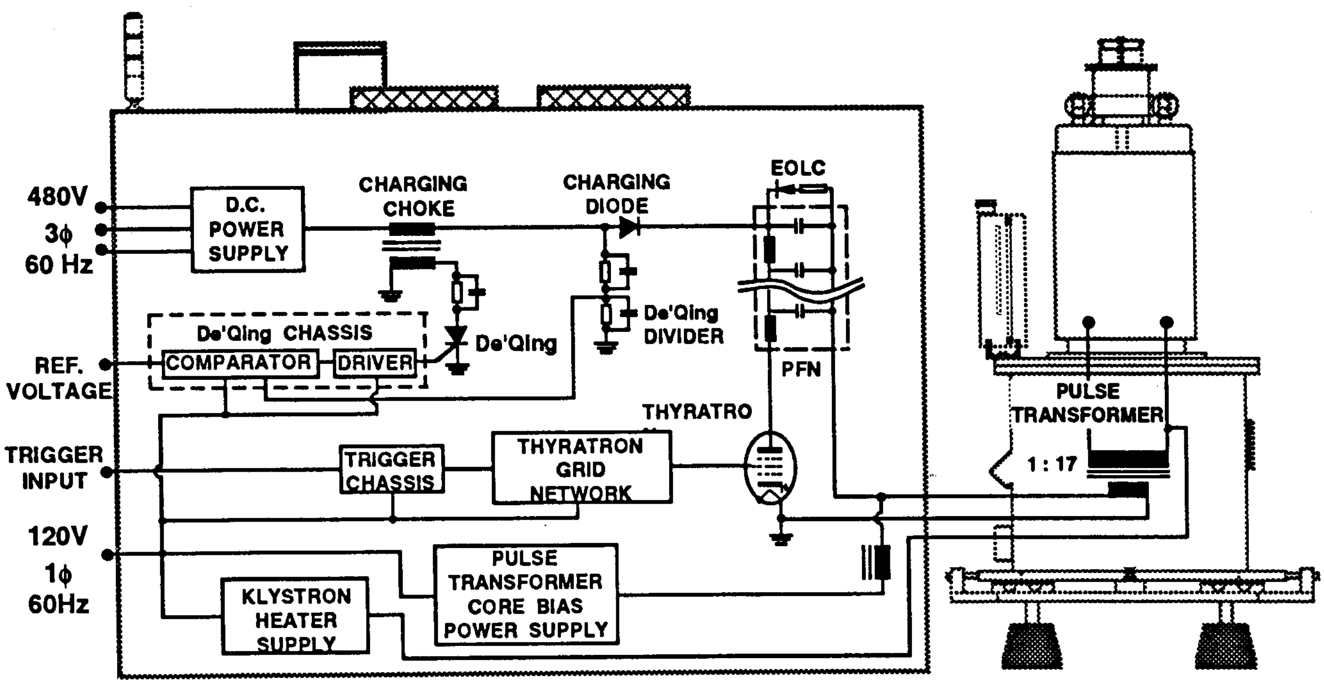
[3] I. S. Ko et. al, "Control of PLS 2-GeV Linac," Proc. 1994 International Linac Conf., Tsukuba, Japan, Aug. 21-26, pp. 825-827 (1994)

[4] A. R. Donaldson and J. R. Ashton, "SLAC Modulator Operation and Reliability in the SLAC Era," IEEE Conf. Proc. 20th Power Modulator Symposium, pp.152156 (1992).

VII. ACKNOWLEDGEMENT

The authors would like to express sincere thanks for all the K&M Group members, whose names are S.W. Park, S.D Jang, S.J. Park, Y.K. Son, K.T. Lee, and S.H. Kim, for their devoted work for the Klystron-Modulator system of the PLS 2-GeV Linac.

Fig. 1 Schematic drawing of the Klystron-Modulator system



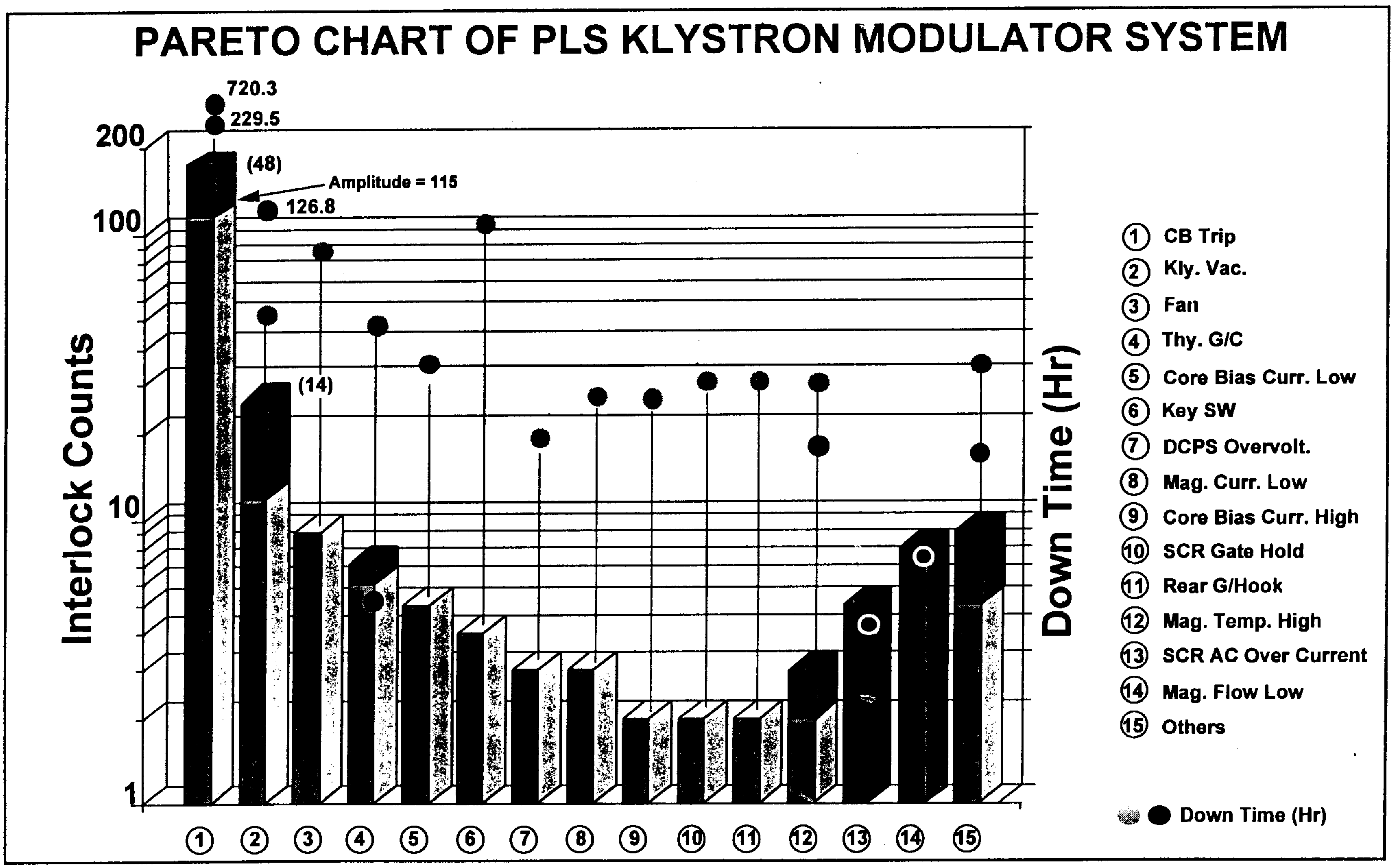
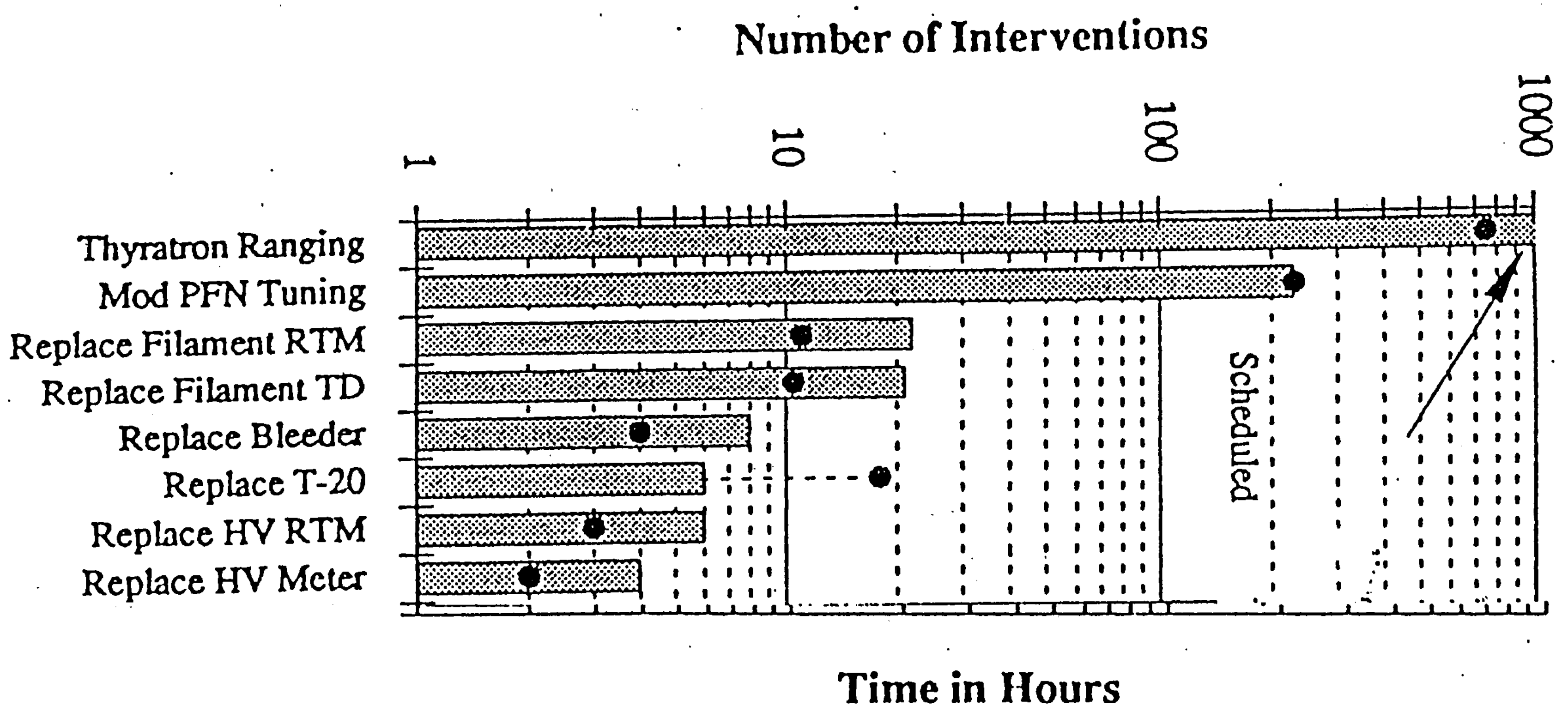
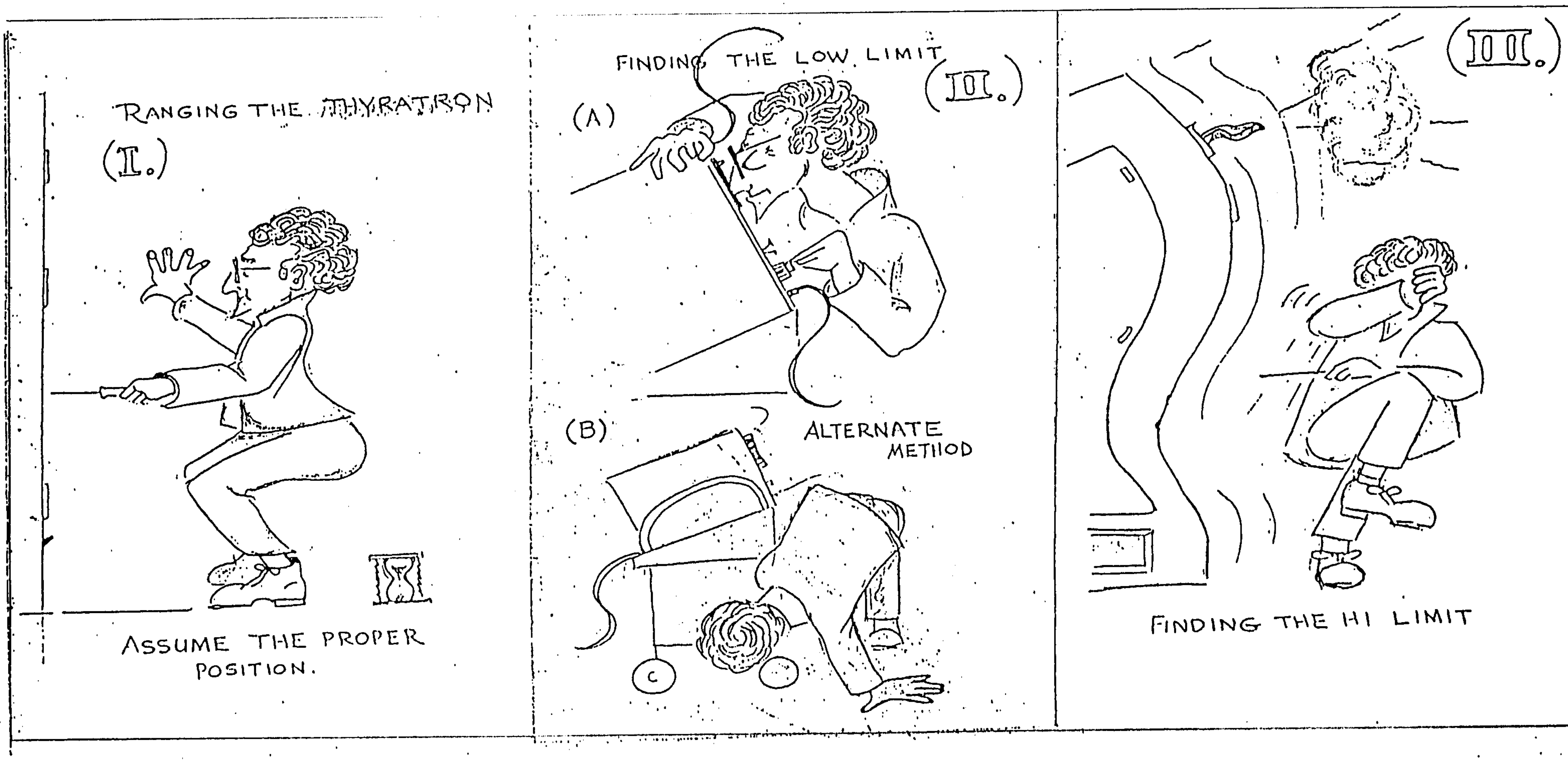


Fig. 3 Pareto chart of the system fault statistics. Numbers in the x-axis indicate type of faults, circles indicate down times, and the bars indicate accumulated interlock counts. Grey colored bars and circles are for the period of September 1994 ~ March 1995 (4752-Hr), and the black colored marks are for the period of April 1995 ~ July 1995 (2688-Hr).

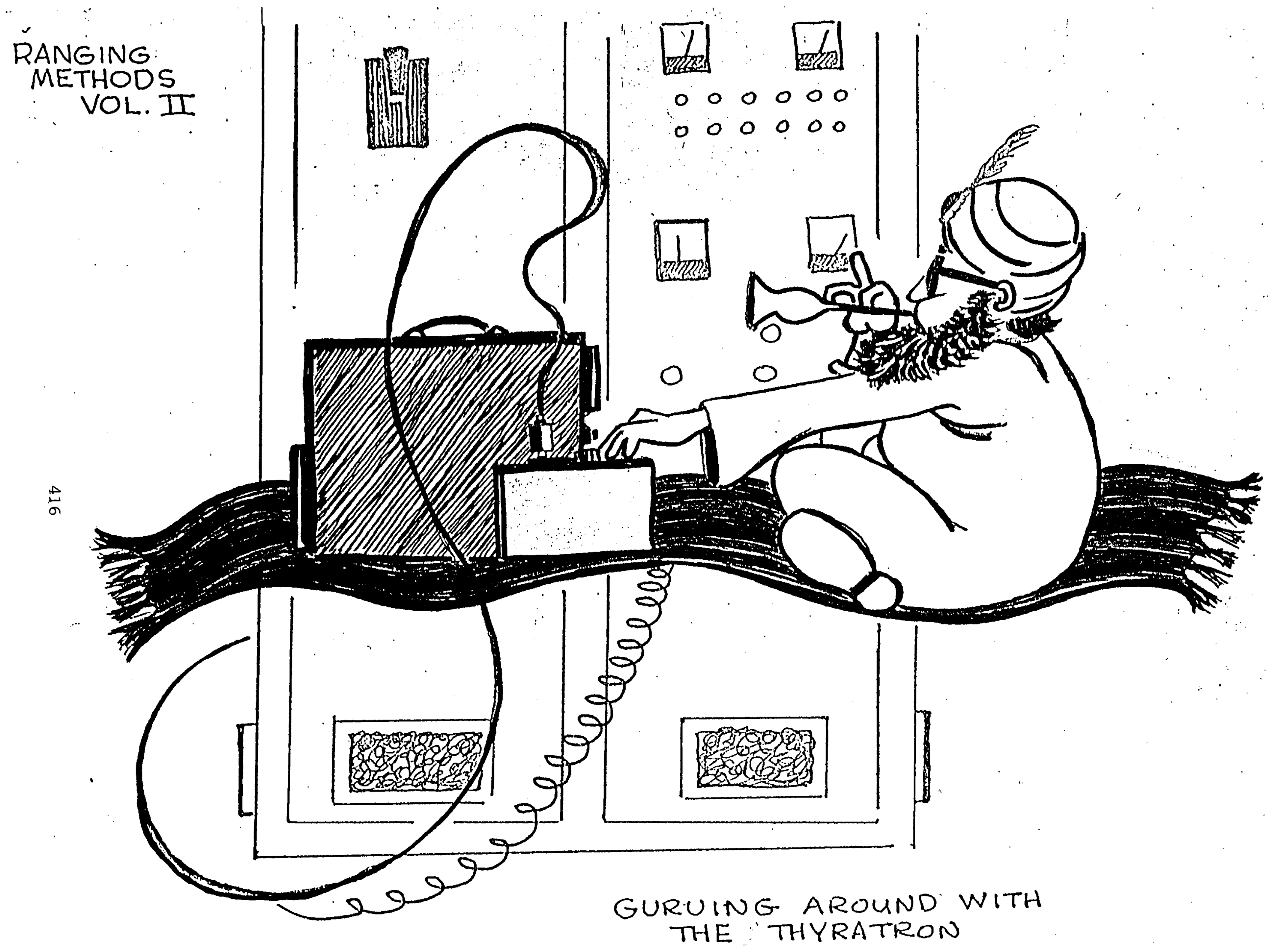
SLAC MODULATOR RELIABILITY

J. ASHTON


Number of Interventions
1
10
100
1000
Thyratron Ranging
Mod PFN Tuning
Replace Filament RTM
Replace Filament TD
Replace Bleeder
Replace T-20
Replace HV RTM
Replace HV Meter
Scheduled
Time in Hours



RANGING THE THYRATRON
(I.)
ASSUME THE PROPER POSITION.
FINDING THE LOW LIMIT
(II.)
(A)
(B)
ALTERNATE METHOD
C
(III.)
FINDING THE HI LIMIT


RANGING
METHODS
VOL. II
GURUING AROUND WITH
THE THYRATRON

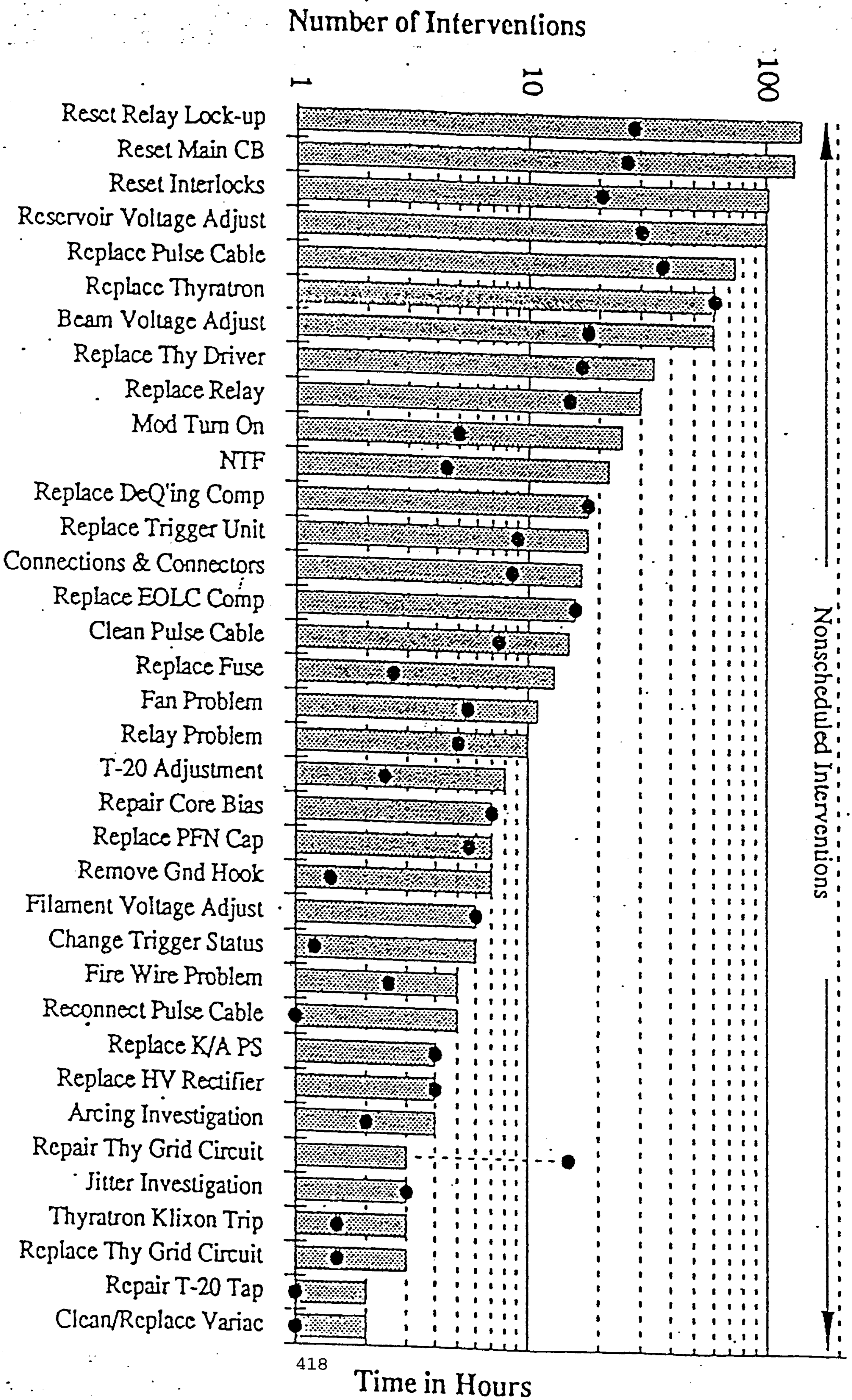
MODULATOR PM SIGN-OFF LIST

SECTOR ______ DONE BY _________ DATE ________

STATIONS

I. INSPECTION	1	2	3	4	5	6	7	8
A. GROUND HOOKS								
B. DOOR LATCHES & INTERLOCK SWITCHES								
C. LAMPS								
D. FANS								
E. PFN COILS & STRAPS								
F. MAIN CONTACTORS								
G. OIL LEAKS								
H. BNC FEED-THROUGHS								
I. BLEEDER RESISTORS								
J. SCR ASSY & RESISTOR STRAPS								
K. RFI FILTERS								
L. TRIGGER CHASSIS								
M. T20 & EOLC CONNECTIONS								
N. TRIAX & TANK SOCKET								
II. OPERATION								
A. K-28 SET								
B. SHUNT TRIP								
C. FAULT STEPPER								
D. K-14 (Min. 2 Sec Delay)								
E. TUNE PFN								
F. THYRATRON RESERVOIR SET								
G. HIGH VOLTAGE STABILITY								
H. NOTIFY MCC OF COMPLETION								

Page 1 of 1



Number of Interventions
1
10
100
Reset Relay Lock-up
Reset Main CB
Reset Interlocks
Reservoir Voltage Adjust
Replace Pulse Cable
Replace Thyratron
Beam Voltage Adjust
Replace Thy Driver
Replace Relay
Mod Turn On
NTF
Replace DeQ'ing Comp
Replace Trigger Unit
Connections & Connectors
Replace EOLC Comp
Clean Pulse Cable
Replace Fuse
Fan Problem
Relay Problem
T-20 Adjustment
Repair Core Bias
Replace PFN Cap
Remove Gnd Hook
Filament Voltage Adjust
Change Trigger Status
Fire Wire Problem
Reconnect Pulse Cable
Replace K/A PS
Replace HV Rectifier
Arcing Investigation
Repair Thy Grid Circuit
Jitter Investigation
Thyratron Klixon Trip
Replace Thy Grid Circuit
Repair T-20 Tap
Clean/Replace Variac
Nonscheduled Interventions
Time in Hours


TROUBLE
REPORT

TABLE I : Availability of SLC and Modulator Systems.

SLC Run Period	1991	1992	1993	94/5
PRR (Hz)	60	120	120	120
SLC Operating Hours	4008	5568	5736	6528
SLC Availability	0.6	0.818	0.828	0.794
244 System Mod "A"	0.884	0.829	0.849	0.863
15 Critical Mod "A"	0.990	0.994	0.992	0.991

TABLE II : System and Modulator Data for Four Runs.

	244 System	15 Critical	
SLC Operating Period	21,840	21,840	Hr
SLC/Modulator-hours	5.33 e6	3.27e5	
No. of Interventions	7537	437	
Total Repair Time	3167	203	Hr
System Failure Rate	0.345	0.020	P/hr
System MTTF	2.9	50.0	Hr
Modulator MTTF	707	750	Hr
Modulator MTTR	0.424	.464	Hr
System "Availability"	0.855	0.991	
System "A" w/ Spares	0.931	not applicable	

CONTINUING CONCERNS

Circuit Breaker Trips

Ancient Interlocks

Tweaking Thyratron Reservoir

Pulse Cable Mortality

Contactor Lifetime

SLAC-PUB-95-6909
May 1995

SLAC MODULATOR AVAILABILITY AND IMPACT ON SLC OPERATION*

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In 1991, the Stanford Linear Collider (SLC) operated, with diverse accelerator systems, at 60% availability. In the more auspicious 1992 and 1993 runs availability improved to over 80%. For the 94/95 run, the availability was also about 80%. Ignoring the eclectic-accelerator, this discussion will assess the dependence of the SLC on the reliability and hence, availability, of 244 klystron modulator systems that provide power to the machine's bunched-particle beams. Klystron modulator availability must be 99% for the accelerator to function at the 75% level. Fortunately, an excess of modulator/klystrons provides some redundancy and, therefore, allows some freedom from the requirement that all 244 systems perform simultaneously. There are, however, 15 specific exceptions. They populate strategic positions at the injector, damping rings, and positron production area of the accelerator complex. These, systems-without-spares, directly influence overall accelerator availability. Their calculated availability as an ensemble is 90%, but by chance they have operated at up to 99% [1]. Individually, a malfunction can bring an experimental program to a halt. The discussion includes a description of several improvements to increase future availability for the modulator system.

TABLE I: Klystron/modulator Deployment in the SLC.

LOCATION	QUANITY	E [GeV][1]
Injector Stations	5	0.2
Sector 1 Stations	5	1.15
N & S Damping Rings:		1.15
NRTL Compressor[2]	1	
SLTR Compressor[2]	1	
SRTL Compressor[2]	1	
Sectors 2 to 18 Stations	135	32.8
Sector 19 Stations	7	34.5
Positron Source:		
e^- To Target Station[2]	1	30.5-31.5
e^+ Accelerate Station[2]	1	0.2
Sector 20 Stations	7	36
Sectors 21 to 30 Stations	80	55
Energy to SLC Arcs		47
Energy to Detector		46
Total Station Count	244	

[1] Indicates the maximum possible energy (phase aligned) and does not include losses due to:
15 degree offset for BNS Damping
overhead for energy feedback
modulators down for maintenance
klystrons down for maintenance.

[2] Indicates stations which compress the beam but add no energy gain.

*Work supported by the Department of Energy contract DE-AC03-76SF00515

I. MODULATOR/KLYSTRON DEPLOYMENT

The linear accelerator presently uses 244 modulator/klystron stations (in 1991 only 243 stations were used). From Table I it is almost apparent that SLC has more modulators than needed for the required detector energy. This allows modulators to be repaired by substituting operational but off beam modulators to avoid long repair times. At any given time there may be as many as 14 modulators available as spares. However this is not a universal situation, and there are 15 critical modulators (indicated in bold type) which do not have substitutes, hence their critical designation.

Table II offers the specifications for the klystron–modulator station. The modulator operates at high voltage and high current, conditions that essentially stress electronic components.

TABLE II: Klystron and Modulator Characteristics.

Klystron Peak Power Out	67	MW
RF Pulse Width	3.5	μs
Klystron Beam Voltage	350	kV
Klystron Beam Current	414	A
Modulator Peak Power Out	150	MW
Repetition Rate	120	Hz (max)
Thyratron Anode Voltage	46.7	kV
Thyratron Anode Current	6225	A
Pulse Transformer Ratio	1:15	
Voltage Pulse Width	5.0	μs (ESW)
Pulse Flattop Ripple	±0.25	%
Nominal PFN Impedance	4	Ω
Total PFN Capacitance	0.70	μF

II. MODULATOR RELIABILITY

The SLC must operate at 120 Hz with a very high degree of reliability and on a continuous basis. Fortunately, we have a modest excess of modulator-klystron systems which allows some measure of redundancy, and hence some freedom from the constraint that all 244 modulator/klystrons operate simultaneously.

The modulator log books for 1991 through 1995 were poured into a database in order to analyze the reliability and hence availability of the modulators. The log books also recorded station problems associated with the modulator computer interface, klystron (which included rf, water, and vacuum problems), accelerator structure and waveguide problems allied with vacuum and water interlocks, klystron dc magnet circuit, and 600 Vac variable voltage substation operation. The database was designed to

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reveal specific modulator problems and the frequency of those problems. Prior to this analysis these revelations existed as only anecdotal recollections among the modulator cognoscenti, the data had not been quantified, accordingly it couldn't be used to provide evidence for improving the reliability of the modulators.

For five years of analysis, we take two approaches. First we compare hours of SLC operation and modulator problem counts to calculate and plot mean time to failure (MTTF) for the various modulator components as part of an entire system. Second, we take all of the reliability data, combine it, calculate availability, and offer the results in Table III with a run by run summary in Table IV.

The plots are divided into three types, the "reset & adjustment" intervention, the "repair then run" occurrence, and finally the component failure situation that requires removal and replacement of a component or sub-system. Consider Figure 1, it shows the "reset & adjustment" MTTF chart for the modulator system. The x-axis displays the category of reset or adjustment and the SLC operating year 1991, 92, 93, and 94/5. The MTTF in hours is on the y-axis. These hours indicate how often the reset or adjustments occur, or require a technician to travel to the Linac gallery. These MTTF's are not based on single modulators, but for the entire 244 station Linac. The modulators operated at 60 Hz for 1991 SLC run. The other three runs were at 120 Hz except for a few weeks of 60 Hz operation in 94/5.

For the "Reset Main CB" category, the MTTF axis indicates how often intervention was required to reset this main modulator circuit breaker over four distinct periods of SLC operation. This circuit breaker can trip for several reasons, but the typical case involves thyratron latch up because of high reservoir voltage or a malfunctioning thyratron. Normally the circuit breaker trips because the over current fault circuit fails to open the primary contactor for the hv power supply. The plot indicates that some improvement in this category has occurred over the years. The installation of a ferro-resonant voltage regulator in 1993 may be responsible for this slight increase in MTTF for the 94/5 run. Until the contactor or control scheme are improved or replaced we will continue to be plagued by these nuisance trips.

III. RELIABILITY AND AVAILABILITY

The five year database contains 7,537 nonscheduled interventions with 3,167 hours of allied repaired time for the 21,840 hour SLC/modulator operating period. This operating period can not be accurately measured as the front end (the first 13 modulators) must always come on weeks before the rest of the modulators down the linac.

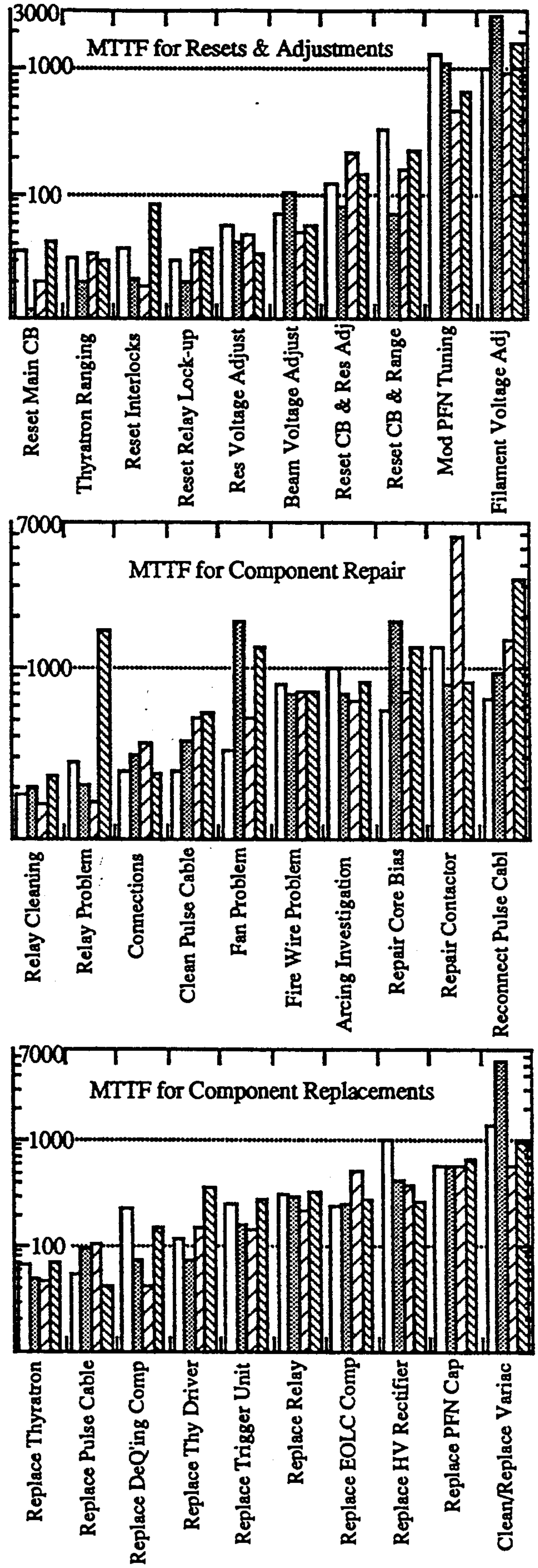


Figure 1. MTTF plots for the 244 modulator system.

The 21,840 hour figure was determined by approximate SLC operating periods for 1991 through 1995 which does not necessarily include front end turn on time or scheduled maintenance periods of less than 24 hours.

Total modulator–hours are then 244 (243 in 1991) modulators times 21,840 hours for 5.33 Mega modulator-hours of operation.

Assuming that a constant failure rate occurs for nonscheduled problems based on the operating hours and a typical Poisson distribution for electronic equipment failure,

Modulator System Failure Rate = 7537/21840 hr

Modulator System Failure Rate = 0.35 problems/hour,

or a problem occurs about once every three hours for the 244 units configured as a "system." This forces the modulator technicians to enter the linac gallery almost every three hours to correct a modulator problem. And these calculations don't include the external problems, e.g., vacuum and water interlocks for the klystron and accelerator waveguide, interface electronics or the 600 V ac utility power.

The modulator "mean time to failure" is then,

Modulator MTTF = 5.33 M hr. /7537

Modulator MTTF = 707 hours,

which when considering the age of modulators, thyratron fault rate, and relay control circuitry seems appropriate (the database error could be as high as ± 5%).

The calculation for the "mean time to repair" with our data gives,

Modulator MTTR = 3167 hr. /7537

Modulator MTTR = 0.424 hr. /problem

or the average modulator problem (a repair or intervention) requires about 25 minutes to correct.

The final calculation of interest to the accelerator operator and physicist is modulator availability, or when can it be depended on to work. The reliability experts give several definitions for availability, we will use the following as it has been applied to other accelerator systems.

Modulator System Availability = 1– (Failure Rate)(MTTR)

Modulator System Availability = 0.854

This would be the "availability" if there were no spares for the modulators, however as mentioned earlier there are up to 14 spares available and they can be activated within 12 minutes to replace a faulty unit. Using the 12 minute or 0.2 hour repair/replacement as the MTTR, then increases the "availability" to 0.931, a respectable increase that verifies the advantages of redundancy and available spares.

SLC operation is compromised when we run out of modulator spares, or when one of the 15 critical modulators fails. The database contained 437 nonscheduled interventions for the 15 critical modulators with a total time for repair of 203 hours. We apply the above calculations for the critical modulators and then compare the data with the entire ensemble of 244 modulators in Table III.

TABLE III: System and Modulator Data for Four Runs.

	244 System	15 Critical	
SLC Operating Period	21,840	21,840	Hr
SLC/Modulator-hours	5.33 e6	3.27e5	
No. of Interventions	7537	437	
Total Repair Time	3167	203	Hr
System Failure Rate	0.345	0.020	P/hr
System MTTF	2.9	50.0	Hr
Modulator MTTF	707	750	Hr
Modulator MTTR	0.424	.464	Hr
System "Availability"	0.855	0.991	
System "A" w/ Spares	0.931	not applicable	

The critical modulator value of 0.990 indicates that their availability was better than either of the above two calculations for Modulator System Availability which offered 0.854 for the no spares case, and 0.931 for the spares case, but it forebodes that the expected availability would be no better than 0.854 since there are no spares for the 15 critical modulators. We are lucky, or we give these modulators more attention when permitted by the schedule.

Finally, we arrive at the comparison of Availability for SLC and the modulator system. Table IV offers this data.

TABLE IV: Availability of SLC and Modulator Systems.

SLC Run Period	1991	1992	1993	94/5
PRR (Hz)	60	120	120	120
SLC Operating Hours	4008	5568	5736	6528
SLC Availability	0.6	0.818	0.828	0.794
244 System Mod "A"	0.884	0.829	0.849	0.863
15 Critical Mod "A"	0.990	0.994	0.992	0.991

IV. CONCLUSIONS

SLC availability increased while the 15 Critical Modulator Availability wavered about 0.99 indicating that the modulator system does not seriously impact SLC performance. We continue to improve the reliability of the system. Presently we are installing a device, an "anode reactor" that extends the life of the pulse cable. It has definitely improved cable lifetimes in six modulators where it has been installed. But even if cable lifetimes improve by a factor of three "Availability" only increases by 0.9%.

V. REFERENCES

[1] A.R. Donaldson and J.R. Ashton, "SLAC Modulator Operation and Reliability in the SLC Era," 1992 20th Power Modulator Symposium, IEEE Conference Record CH3180-7/92/0000-152.

RELIABILITY SESSION SUMMARY

J.C. Sheppard and A.R. Donaldson

The first presentation discussed klystron production, failure modes and lifetime of the SLAC 5045. The MTTF for the 5045 klystron is 50,000 hours. Previously published data on thyratron lifetime at SLAC is also included. Thyratron lifetime in the SLAC modulators is manufacturer dependent, but for the past 3 years of SLC operation, the MTTF has been approximately 14,000 hours.

The remaining addresses were by Linac system managers from LIL/CERN, KEK, PLS/POSTECH, and SLAC. They presented their modulator-klystron system reliability and availability data, as well as their lifetime data for klystrons and thyratrons.

The data in the table below was tabulated by the authors for comparison, but because of mis-interpretation, it may not accurately reflect the actual experience of the facilities listed. Please contact the various system experts for accurate lifetime and availability data. In the "Period of M-K Operation" row, we list the operating hours for physics research. The data extends from one to six years of Linac operation for physics research.

The presentations stressed a common theme, the necessity for preventive maintenance, system modularity, and desirability of an integrated diagnostic scheme to enable fast troubleshooting and repair.

Linac/Laboratory	LIL/CERN	PF/KEK	PLS/POSTECH	SLC/SLAC
M-K Linac Count	6	(1) 53	11	244
M-K Spares Count	0	4	0	(2) 14
Period of M-K Operation [hr]	28,770	58,000	4,752	21,840
M-K Repetition Rate [pps]	100	25 & 50	60	60 & 120
Klystron MTTF [hr]	22,000	17,700	>15,000	50,000
Thyratron MTTF [hr]	12,000		>15,000	14,000
Modulator MTTF [hr]			311	707
Linac M-K System Availability	0.978	0.987	0.910	(3) 0.931

Notes: (1) Count before the increase for KEK-B.
(2) Spares are available for 229 of the 244 modulators.
(3) This value only applies to the modulators.

SMART Modulator Terotechnology

P. PEARCE

* Simple and effective design
* Modular construction to reduce costs
* Ac to RF power conversion efficiency high
* Reliable, available and maintainable
* Transmision of maintenance fault data

(or ANY DATA FOR PERFORMANCE OPTIMIZATION)

TEROTECHNOLOGY

A COMBINATION OF :

- MANAGEMENT SKILLS
- FINANCIAL CONTROL
- ENGINEERING

APPLIED TO PHYSICAL ASSETS
IN THE PURSUIT OF
HIGH PERFORMANCE (AND EFFICIENCY)
WITH ECONOMIC LIFE-CYCLE COSTS

Evolution of accelerator diagnostics - getting SMART

1st Generation

Demonstrate that accelerators work according to theory.
Only fix them when they break.
Downtime has small effect on the physics output.
Operating costs increased only marginally by faults.
Learning on the job necessary.

2nd Generation

Accelerator designs made for higher availability and reliability with longer expected useful lifetimes.
Computer control systems are introduced generally.
Preventive maintenance procedures introduced to reduce downtime.
Operating costs increase sharply with system size and complexity.
Information and documentation systems become necessary.
Specialization of skills required due to wide range of tasks performed.

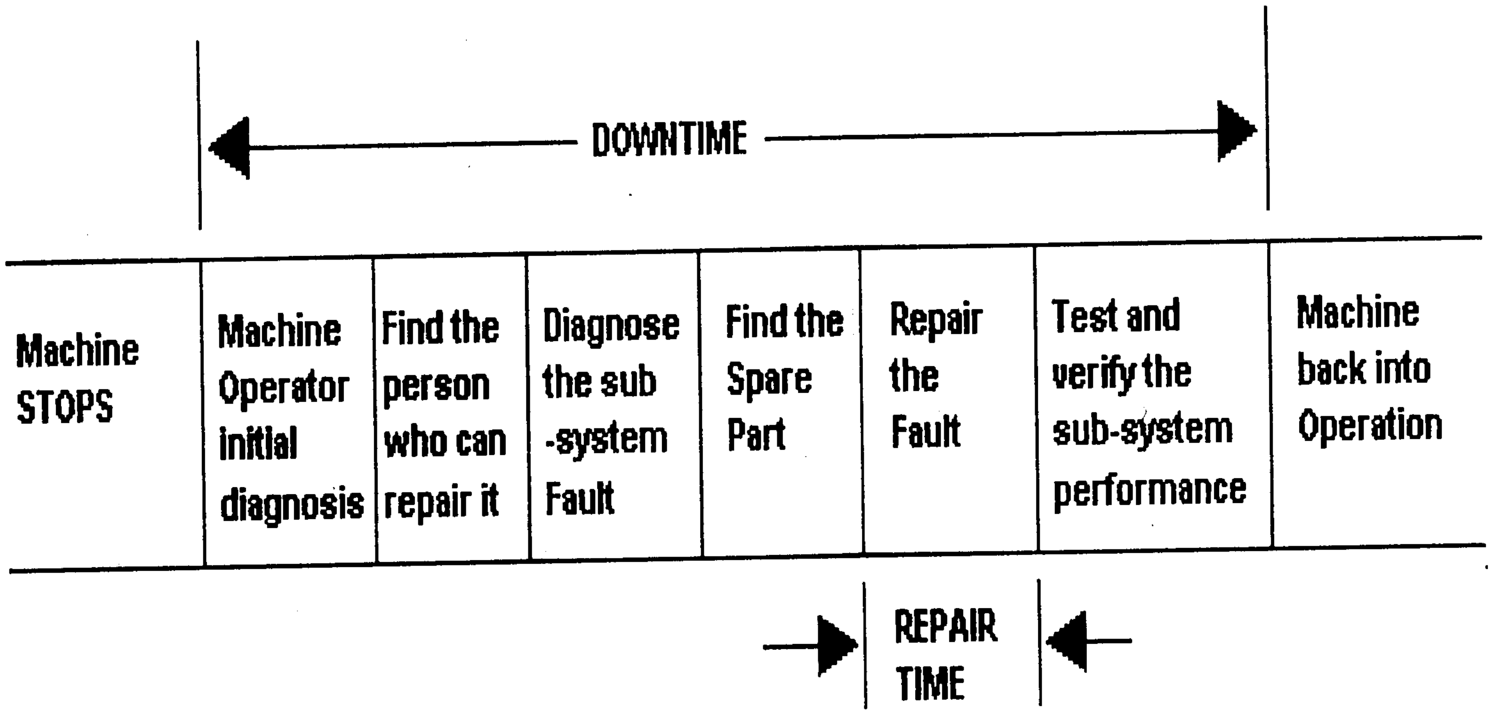
3rd Generation

Greater cost effectiveness from safe, and environmentally friendly accelerators.
Well defined beam quality demanded.
Designed in reliability, availability and maintainability (RAM).
Microprocessors in new equipment add flexibility and "intelligence", but increase system complexity.
Failure modes and effects analyses are made to provide information on all possible failure modes.
Expert systems are being tried out in large accelerators to aid fault finding down to the individual block level.
Smaller maintenance teams with large and complex systems to run look to smart equipment to help them keep operational.

Selected Parameters for Linear Colliders

Parameter	UNITS	TESLA	SBLC	JLC(S)	JLC(C)	JLC(X)	NLC
RF freq	GHz	1.3	3.0	2.8	5.7	11.4	11.4
Rep rate	Hz	10	50	50	150	150	180
Linac length	km	20	29.4	28	15.6	17.7	14
No. of Klys.	n	1202	2450	1944	4356	3400	1945
Klys. power	MW	3.25	150	85	50	70	94
Klys. pulse	μs	1300	2.8	4.5	2.4	0.84	1.5

Machine Down time versus Repair time



SMARTEN UP THE MODULATORS TO IMPROVE THE EFFICIENCY OF OPERATION

RELIABILITY VERSUS REDUNDANCY (HOW MUCH)

WHAT IS THE TRADE-OFF BETWEEN:

ADDED DIAGNOSTICS AND:-

- NUMBERS OF MAINTENANCE PEOPLE
- REDUCTION IN DOWNTIME

ADDED DIAGNOSTIC SYSTEMS HAVE TO BE VERY RELIABLE, LOW COST

AND WILL BE USED FOR

- SELF PROTECTING AND FAULT/PERFORMANCE REPORTING.

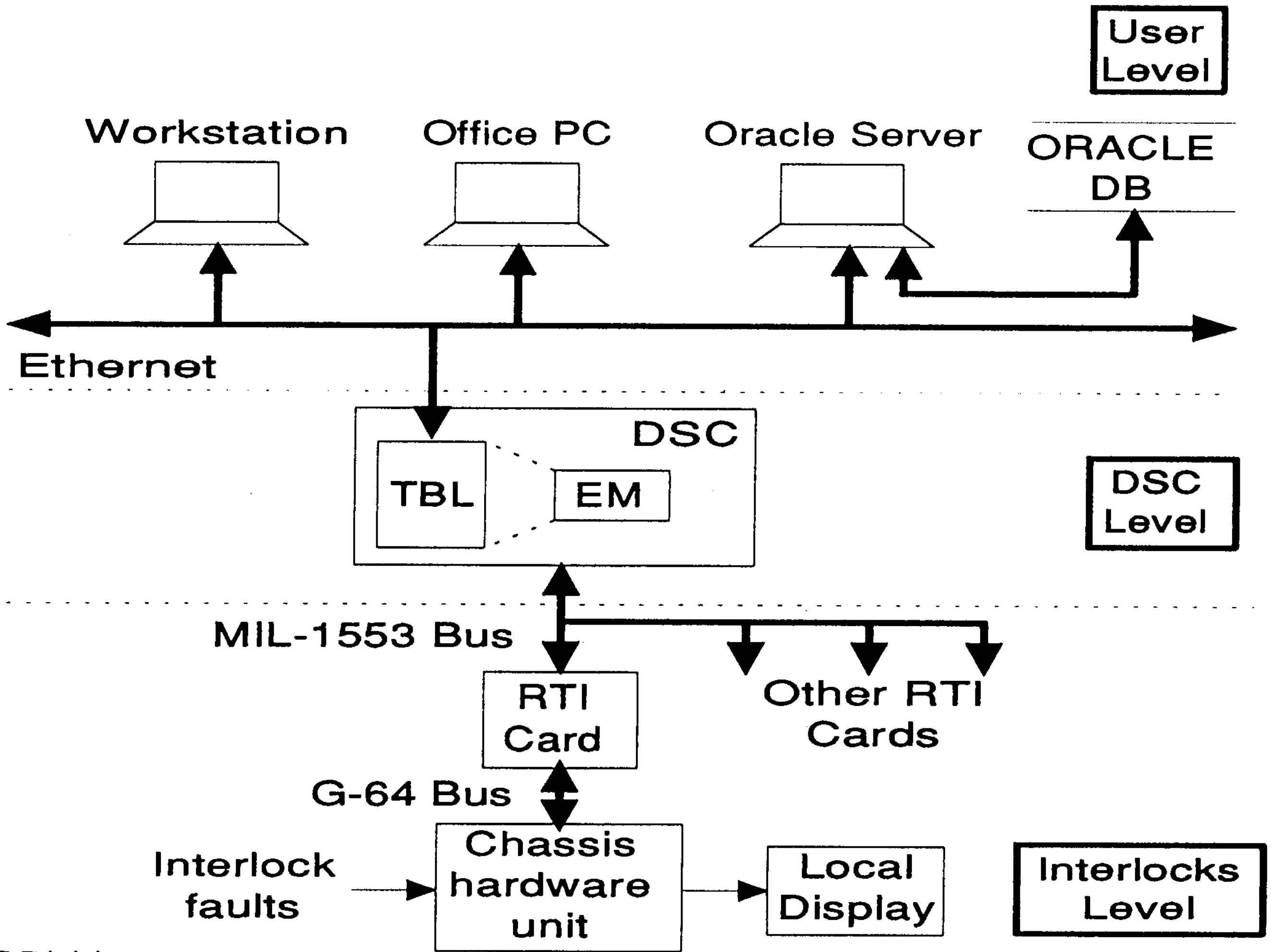
- SELF OPTIMIZATION SYSTEMS TO KEEP EFFICIENCY OPTIMAL AS KLYSTRON/THYRATRON AGING GOES ON.

AREAS TO APPLY
SMART DIAGNOSTIC TOOLS

- HEATER MONITORING AND CONTROL
- RF CONTROL + INTERLOCKS AROUND KLYSTRON'S
- CONTROL OF D'GING LOSSES [COMPENSATION or FEEDBACK]
- ON-LINE MONITORING OF OVERALL MODULATOR EFFICIENCY.
- DIAGNOSTIC HARDWARE AND SOFTWARE TOOLS FOR FAULT INTERLOCK SYSTEM OF MODULATOR
- KLYSTRON / THYRATRON HOURS + PERVEANCE MANAGEMENT
- OFF-LINE DATA ANALYSIS SOFTWARE FOR STATISTICAL ANALYSIS
- . . . . ?

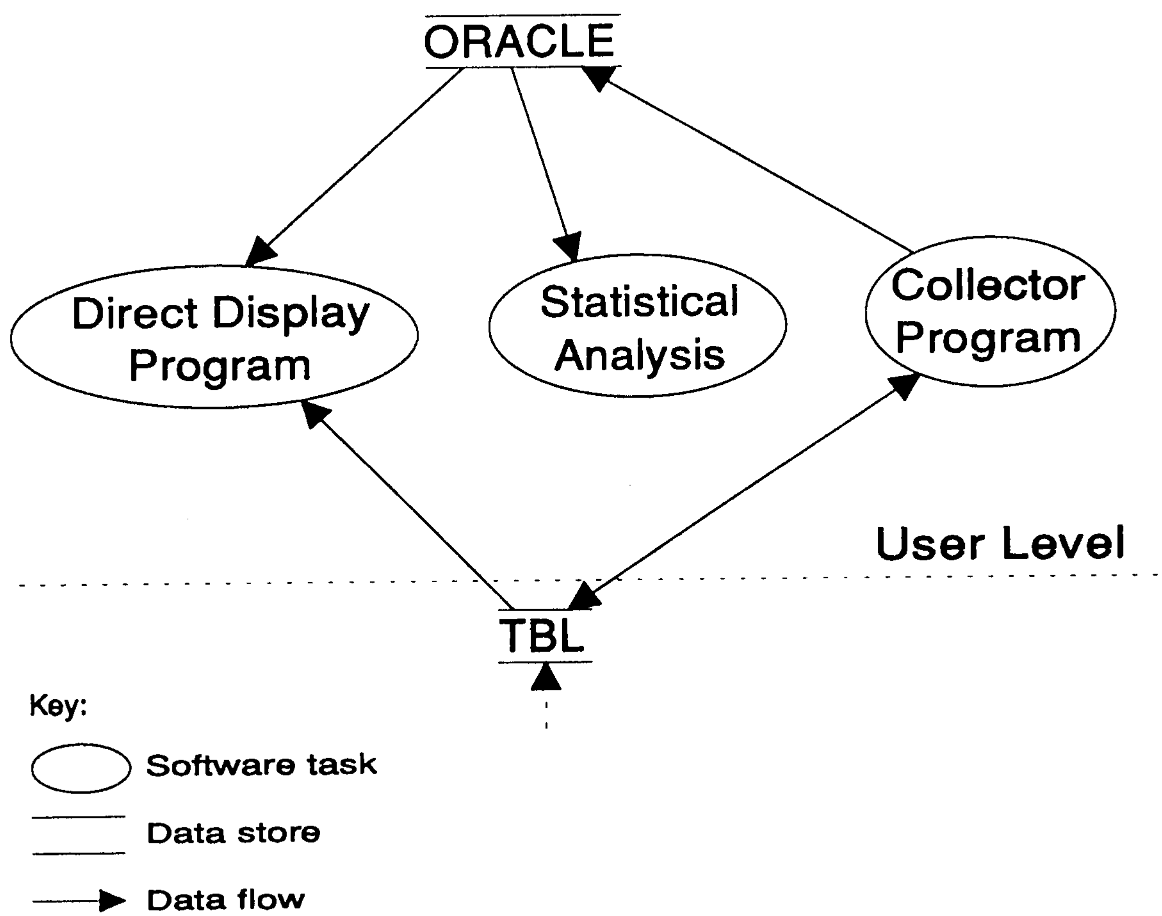
EFFICIENCY MUST BE LOOKED AT AREA BY AREA WITHIN THE MODULATOR TO FIND OUT WHERE DIAGNOSTICS WILL HELP TO KEEP COSTS DOWN.
(CAPITAL COSTS + RUNNING)

Modulator system Interlock fault data network



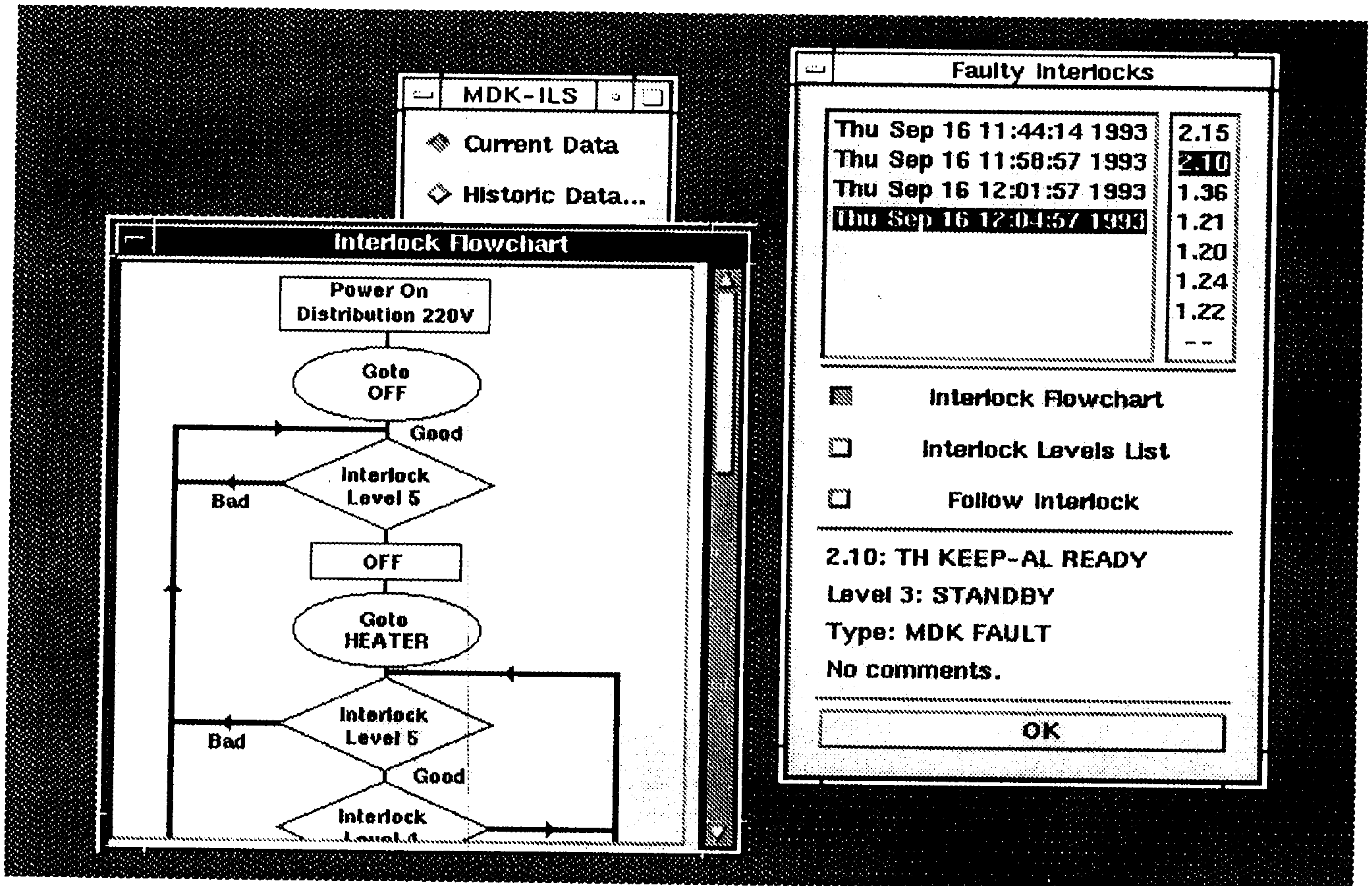
CERN PS Division

Modulator Interlock - Users Software



CERN PS Division

Modulator Interlock Software-Window style



CERN PS Division

Modulator system diagnostics - The "smart modulator"

P. Pearce and G. McMonagle
CERN, PS Division, Geneva, Switzerland

Introduction.

Downtime has always affected the productive capability of accelerator systems, by reducing beam quality, increasing operating costs and causing major pertubations for the experimental teams. As our accelerator systems get larger and more complex (eg. the CERN lepton production which uses four accelerators that are functionally in series) the need for quickly locating the system fault and effecting a repair becomes more urgent. In view of the many proposed linear collider schemes that are being studied by several physics laboratories, and the proposition to use many (up to 4000 in some cases) RF high power pulsed modulators brings home the point of designing in reliability and maintainability from the start. The cost of designing and building reliable modulator systems is not more than the cost of an unreliable system, and in the long term must be considerably less. Nevertheless, even with the best design possible, some faults will always occur and downtime will result. Where large arrays of systems are planned there is also the need to include good diagnostics that really help to have rapid recovery from such situations. These so called smart modulators have some diagnostic tools that will help, along with intelligent maintenance procedures and a sound basic design, to keep large scale accelerator systems productive.

Accelerator maintenance evolution.

It is convenient to divide up the evolution of accelerators and their systems from the point of view of maintenance into three time periods.

1. **First generation.** Period up to 1960.
   This period is marked by the desire to get small accelerator systems working and demonstrate that theory stood up to the practical test. Systems were only fixed when they broke down or burnt out. Downtime had only a small effect on experimental physics output, and operating costs increased only marginally due to faults. Learning on the job was necessary and using much modified prototype equipment was frequently the key to improved accelerator performance.

2. **Second generation.** Period from 1960 up to mid 1970's.
   Component and system selection was made during the design stages to enable a higher availability of the accelerator, and computer control systems started to get into the act in a serious way. Planned equipment overhauls and preventive maintenance procedures were introduced to reduce downtime due to faults.The operating costs increased sharply with system size and complexity, and maintenance documentation methods became very necessary together with the need of specialized personel skills for a wider range of tasks to be performed.

3. **Third generation.** Period from mid 1970's until today.
   Cost effective and safe, environmentally friendly accelerator systems are demanded, along with well defined beam quality to improve experimental physics results. Newer systems design in the required reliability and maintainability in order to achieve desired levels of accelerator availability, using the so called RAM technique. Microprocessors are built into much equipment, including modulators and other pulsed systems to increase user flexibility. Failure modes and effects analyses are made for systems in the design stage as well as for those already in operation, and Expert Systems are being tried out.

Paper presented at the 2nd Klystron-Modulator workshop at SLAC for Future Linear Colliders 9th to 11th October 1995.

The evolution of accelerator equipment shown in Figure 1 shows that increasing the size and complexity of accelerator system installations over the years has brought about a need to maintain and improve their availability for greater cost effectiveness. This has been done by analysing the equipment performance and designing in the reliability required for new systems, and designing out the problems with older systems as well as introducing comprehensive maintenance methods.

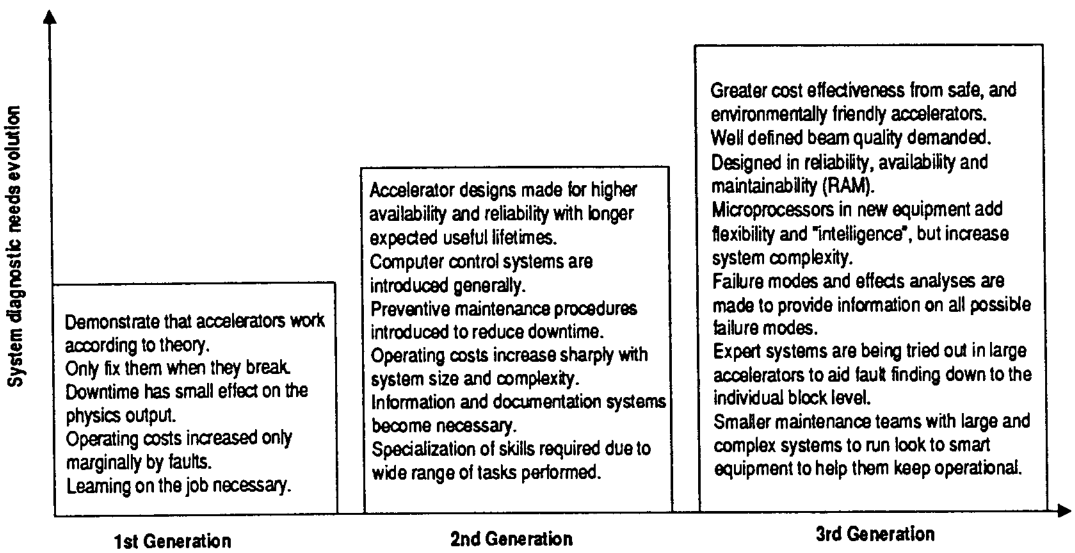


Figure 1

It is recognised that maintenance teams cannot increase in size indefinitely as systems grow to 4000 modulators or more, and the large stocks of spares required for unplug and replace strategies to combat unreliability will also be costly. Building in any extra equipment for redundancy purposes also adds to the initial project costs. In addition the effects of downtime are being aggravated by component and equipment suppliers moving towards just-in-time systems in their own factories. This has increased lead times for spare part items and prompts the build up of a larger than necessary in-house spares stock, just-in-case. However, leaner maintenance teams will require more information from operations people, readily available maintenance data and spare parts, together with smart equipment systems that will help them maintain a high system availability and safety.

Smart modulators.

Important in all modulator systems, is the actual performance in producing pulsed RF power as efficiently as possible, and the minimization of downtime that reduces overall system efficiency.

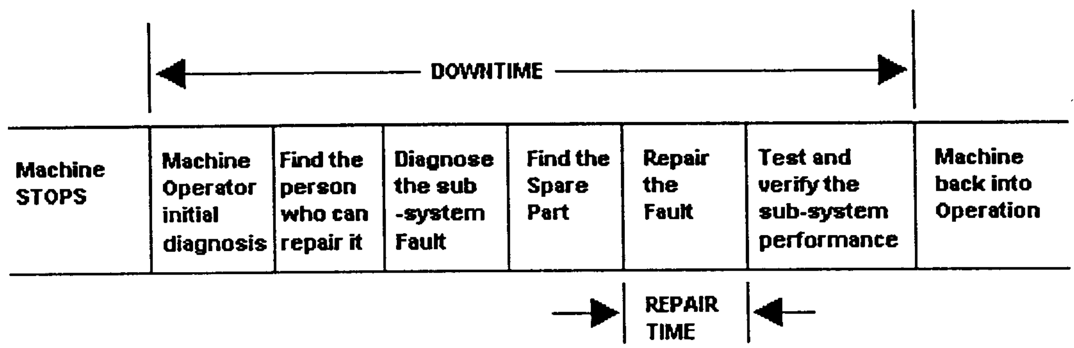


Figure 2

Ways to improve electrical efficiency depend on the equipment design, whilst overall performance efficiency (physics hours per maintenance dollar) depends on reliability and availability. The usually accepted definition of steady-state availability (A) of a system being:

$$A = \text{Uptime}/(\text{Uptime} + \text{Downtime})$$

Downtime reduces physics hours and is usually accounted for in an installation as in Figure 2 above. Reliability can be thought of as an effectiveness parameter which needs to be specified in new systems, and maintained in existing ones, and as a consequence has to be paid for. Diagnosis times can be an appreciable amount of the total downtime as shown and smart modulator systems can help to reduce this and associated maintenance costs by providing timely information.

There are many ways to define what a "smart modulator" system should be doing. Some of the more important functions that can be given to a smart system are the following:

a) A system that prevents operational working outside of well defined maximum or minimum limits by protecting itself. This type of "intelligence"usually resides within the modulators control and interlocking-protection system.

b) A data gathering system that will tell you what faults have occurred and their order of occurance, and in what part of the modulator system, including when they occurred, to speed up the initial fault diagnosis time.

c) Associated computer software that helps diagnose fault situations and provides information memory prompts from previously stored fault scenarios. This approach helps to supplement the lack of skilled modulator maintenance people.

d) An integral hardware and software system that enables the monitoring of pulse performance and also RF power calibration so that the fall-off in the klystron performance over time can be obtained for use with preventive maintenance records.

The first two functions a) and b) above have been successfully implemented in the CERN LIL modulators and give the added support to both the maintenance and operation teams. The second group of functions c) and d) are now starting to be actively developed using commercially available software packages and the results look very promising.

Smart modulator protection scheme.

This smart modulator protection scheme has evolved over the last four years with three distinct levels of development. The initial work concentrated on replacing the old static relay hardware used for protecting each modulator against internal and external faults. The new scheme, shown in Figure 3 relies on a microprocessor based system that provides a much higher reliability and the possibility to add a wide range of functional features that improve greatly the quality of fault information. The second two stages of this systems development focussed on connecting up the microprocessor interlock system from each modulator via a MIL-1553 Bus system and communication software (DSC level) to the controls network, and then providing user functionality to make the modulator smart (the User level) with approriate software.

The main problems with the old relay system were that no storage of interlock status data was made, so that if an interlock were to fail it would not be possible to determine the time of the failure. Also, if further interlocks were to fail as a consequence of the first interlock failure then the order of these 'cascading' failures would not be known. Only an experienced operator would be able to postulate the likely order of failure, and therefore the principle reason for the fault occurring in the first place. By storing all information that is relevant to each fault, and then providing easy to use, powerful software tools at the operator workstation or office PC, on the controls network, downtime has been reduced because faults can be diagnosed more rapidly.

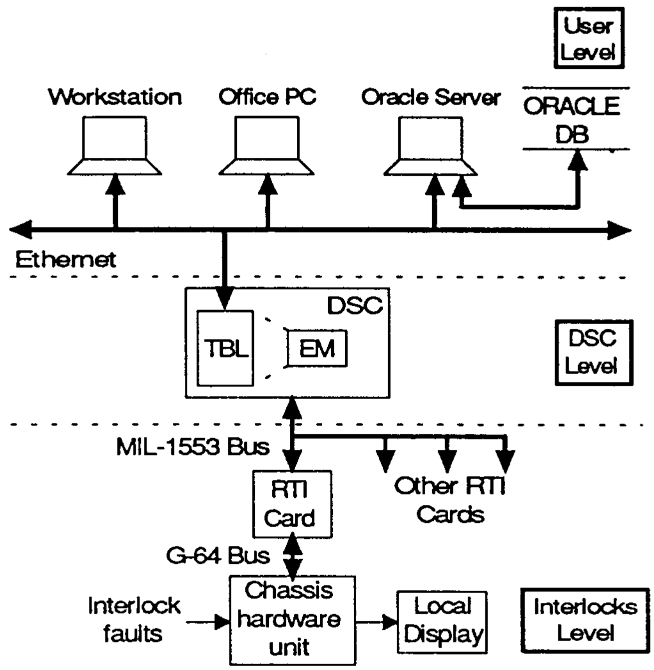


Figure 3

The software programs that do this maintenance and operator support work are:

a) A program to display detailed interlock fault information directly from the modulators local software controls memory (TBL).

b) A program to collect the fault information periodically from the modulators software memory and store it off-line in the ORACLE database.

c) A program to perform statistical analysis on the 'historic' data stored in ORACLE.

The three tasks outlined above were implemented with the connection structure as shown below in Figure 4.

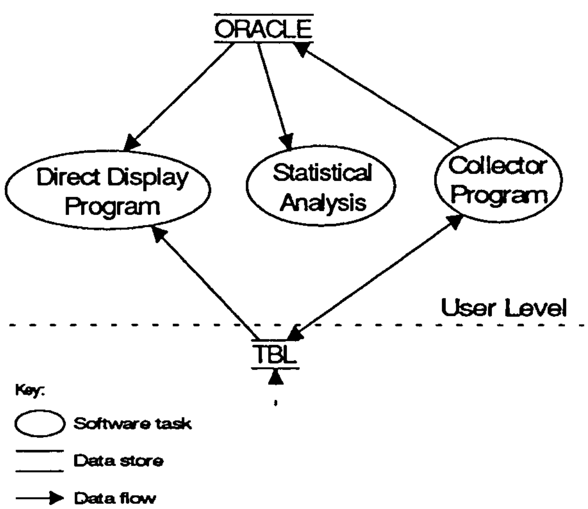


Figure 4

Some of the data windows that are created for the direct display of faulty interlock data are shown below in Figure 5. There is also stored within the program a complete flow chart of the interlock level functioning to add more on-line maintenance and diagnostic information .

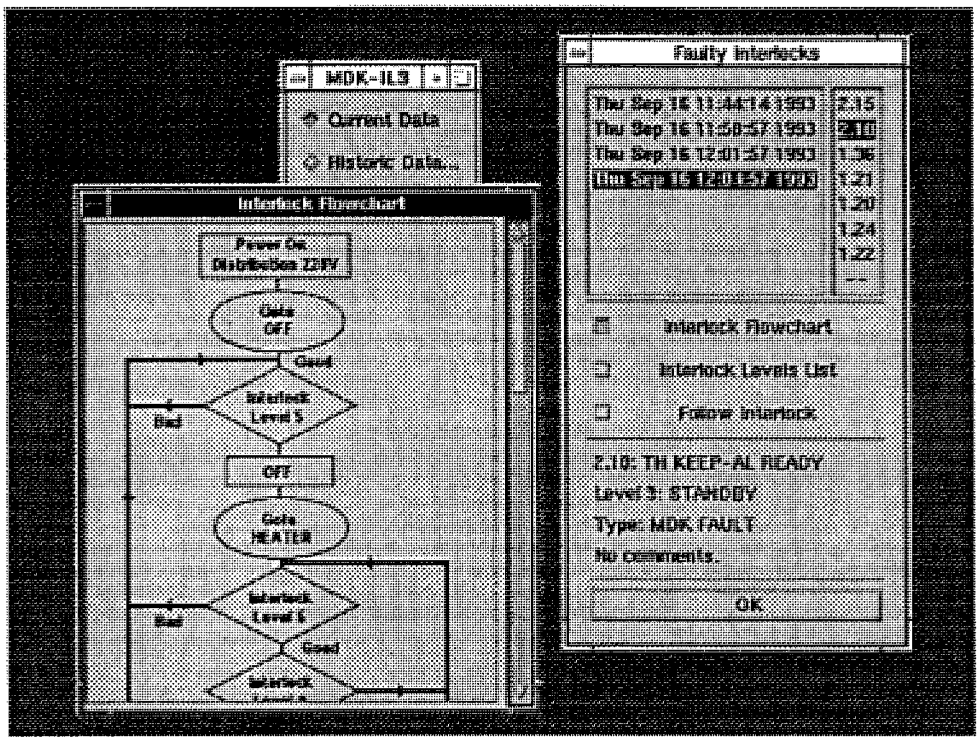


Figure 5

Conclusions.

It seems very clear that in any future linear collider using large numbers of klystron modulators that reliability, availability and maintainability must be placed on a par with wall-plug power efficiency if downtime is to be minimized. The approach used for the small, but important LIL klystron modulator system, which is part of the lepton production process, has been to build in smart fault reporting and protection equipment as described. This has resulted in a reduction of modulator downtime from 8% to less than 1% for a average yearly running time of 6000 hours. This reduction has been achieved over a period of about four years, during which a steady investment of equipment and software has been made.

To complement this development, tests are now being made with NICODEMUS work management software to provide on-line flow-chart checking procedures for fault finding, equipment setting-up and calibration. In addition, LabView programs have been written that enable standard power calibration tests to be quickly made, and the results stored away on computer memory for maintenance recording purposes. All of these areas of system improvement are contributing to a higher equipment availability in having modulators that are Simply Maintained And Reliably Tested (SMART).

References.

Marco Grippeling,1993, "The Design and Development of a G-64 based Interlock System for LPI Modulators", CERN/PS/LP Note 93-01 (Tech).

Alan Campbell, 1993, "Fault Data Acquisition Project for the LPI Modulators", CERN/PS/LP Note 93-66 (Tech).

Ryan Gilmour, 1994, "User Level Software for the New Interlock System of the LPI Klystron Modulators", CERN/PS/LP Note 94-36 (Tech).

Implementation of Diagnostic Hardware and Software Systems for CERN Modulators

P.Pearce, G.McMonagle and G.Rentier

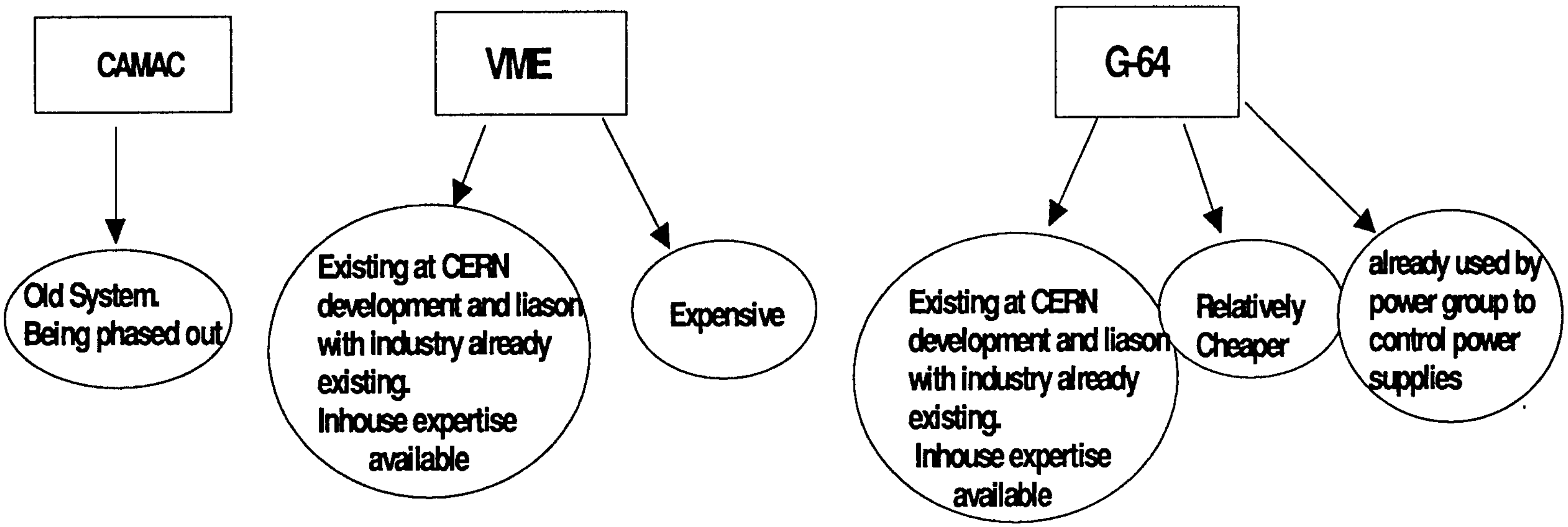
CERN, PS Division, Geneva Switzerland

SLAC Modulator-Klystron Workshop 9th to 11th Octber 1995

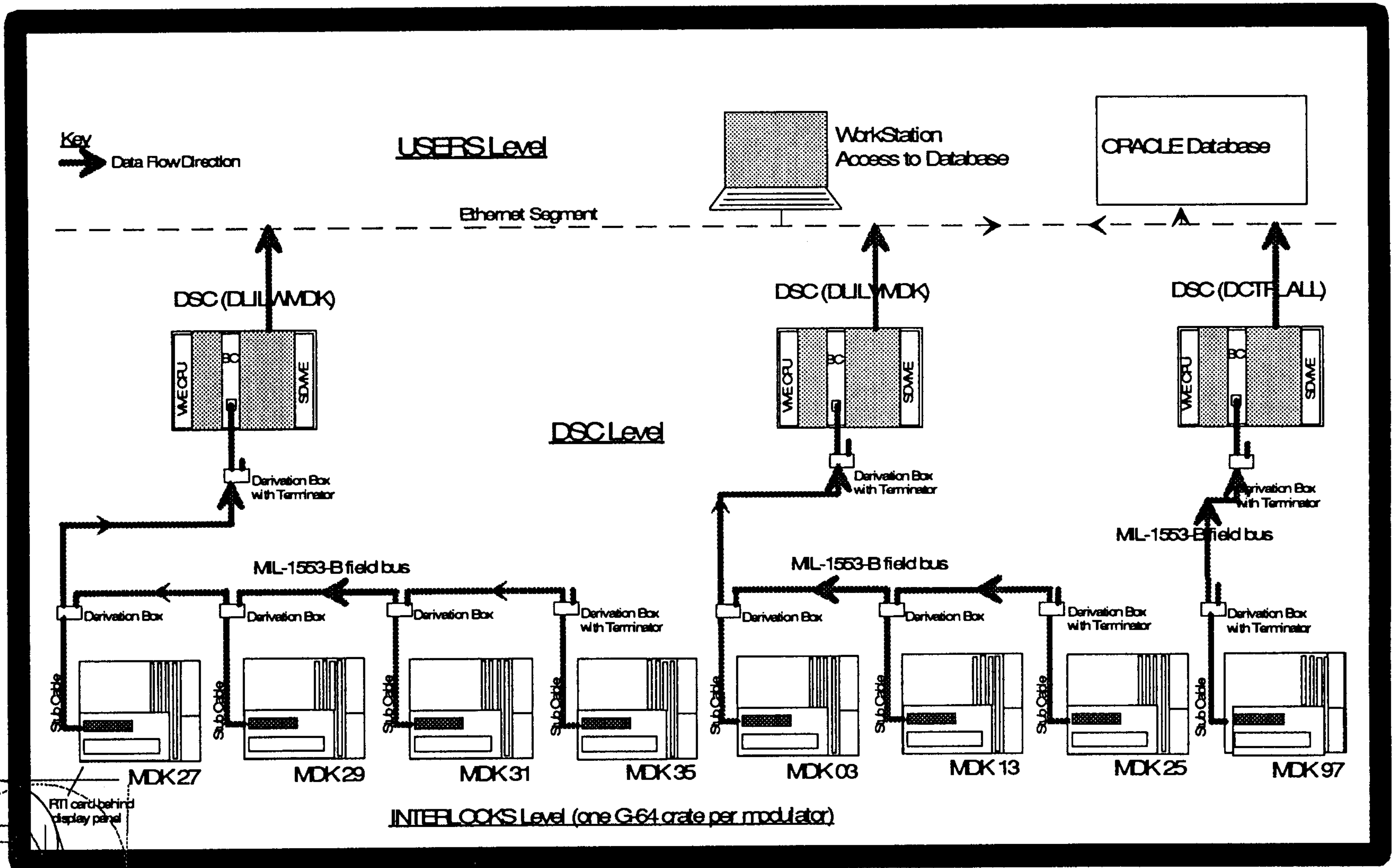
Requirements for New Interlock System

- Memorisation of modulator faults including time and date of failure with local display panel
- High reliability
- Interfacing to control system (and later on to ORACLE database)
- Fail-safe with no ambiguous fault indication
- Complete input signal and data output compatibility with the old interlock system
- Conforming to CERN personnel security requirements

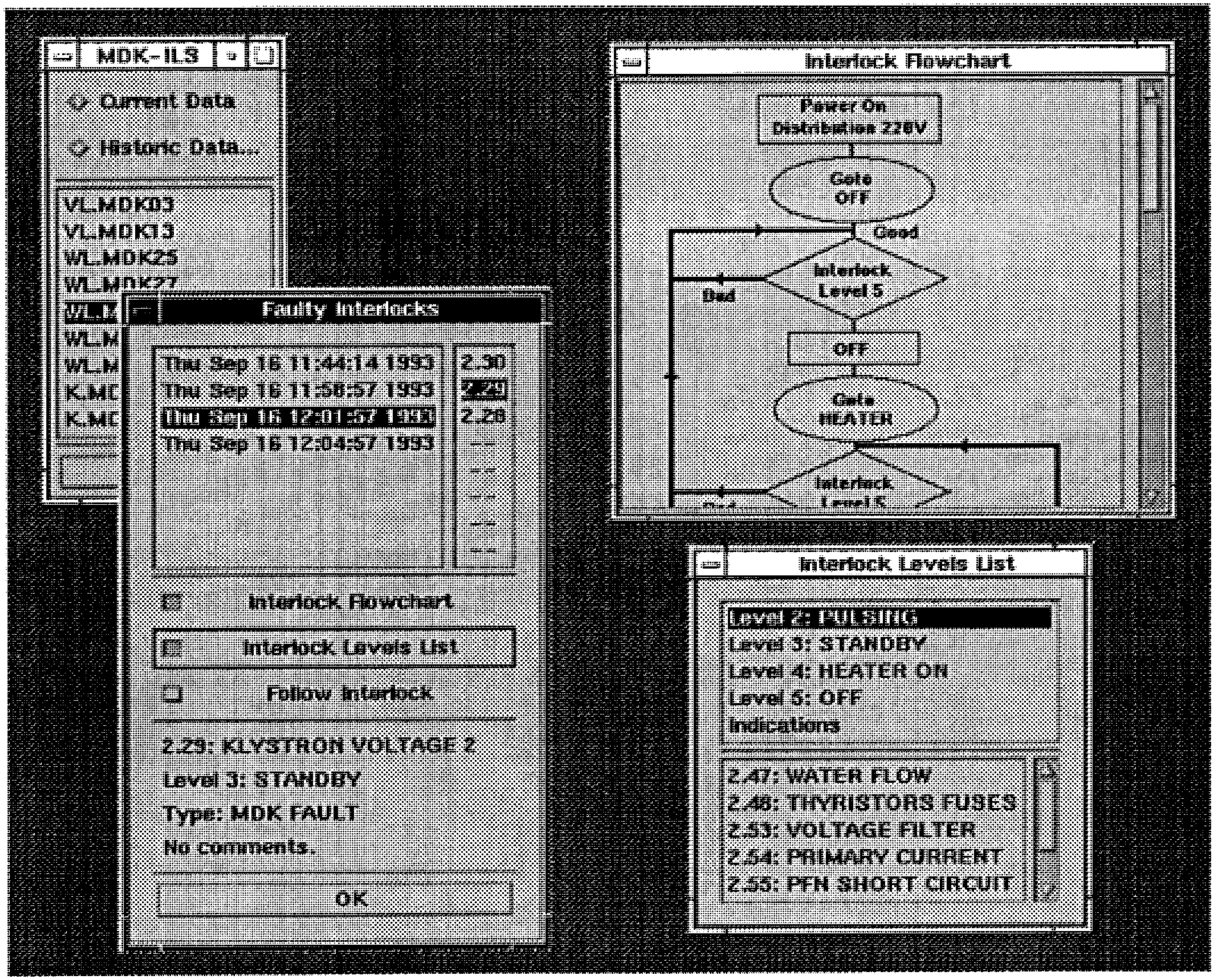
Choice of System



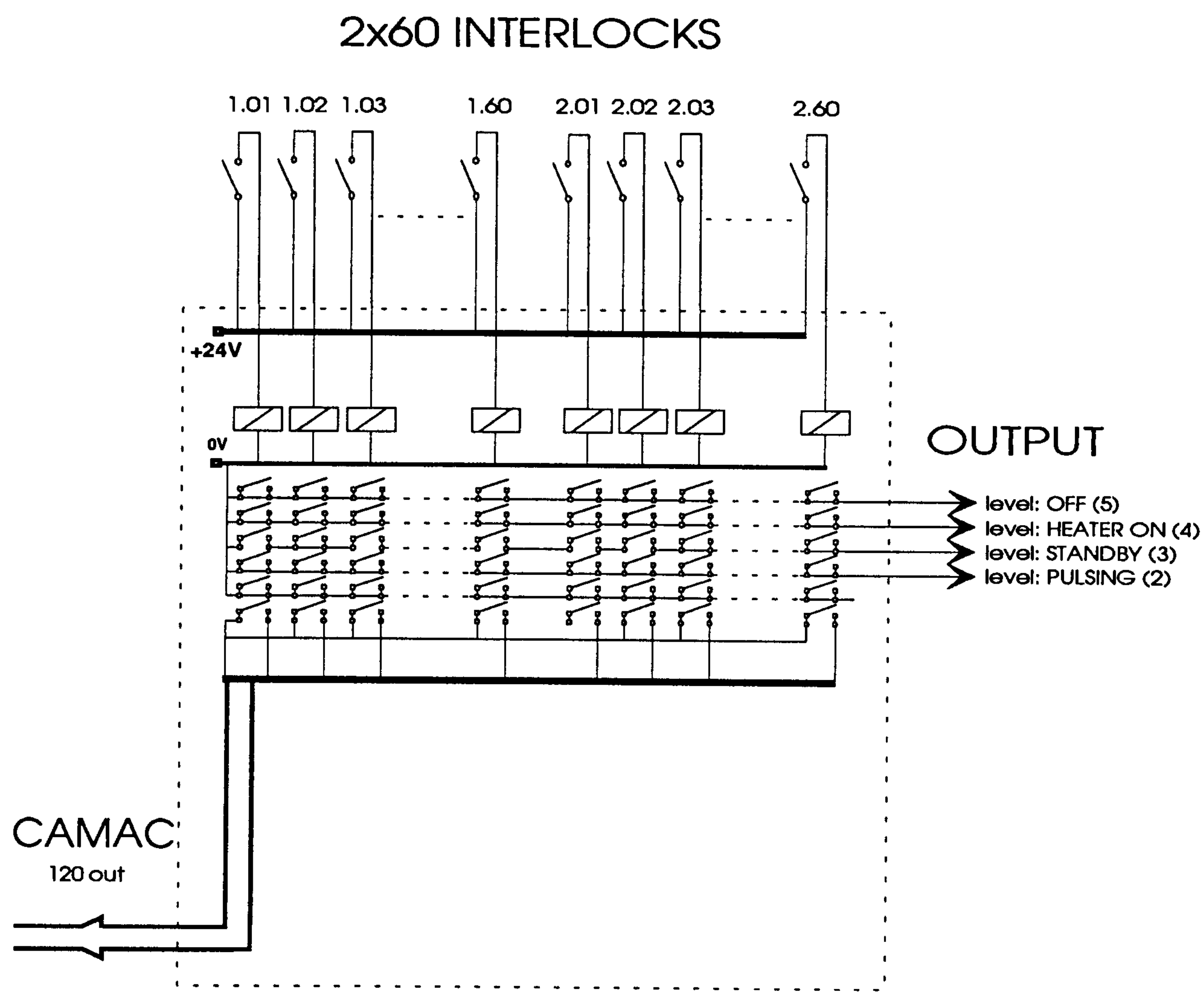
Hardware Details for Full Project Implementation



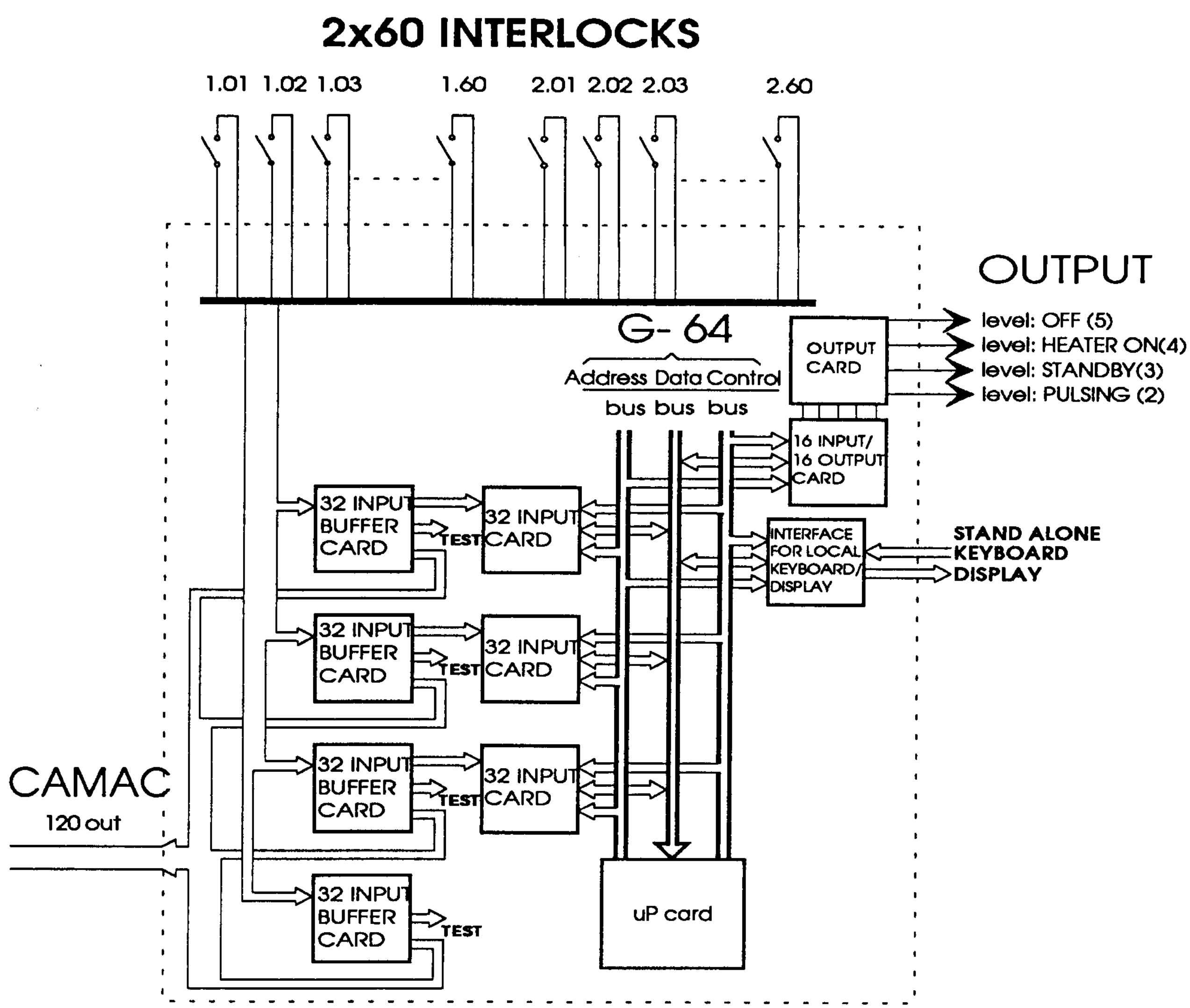
Direct Display Program



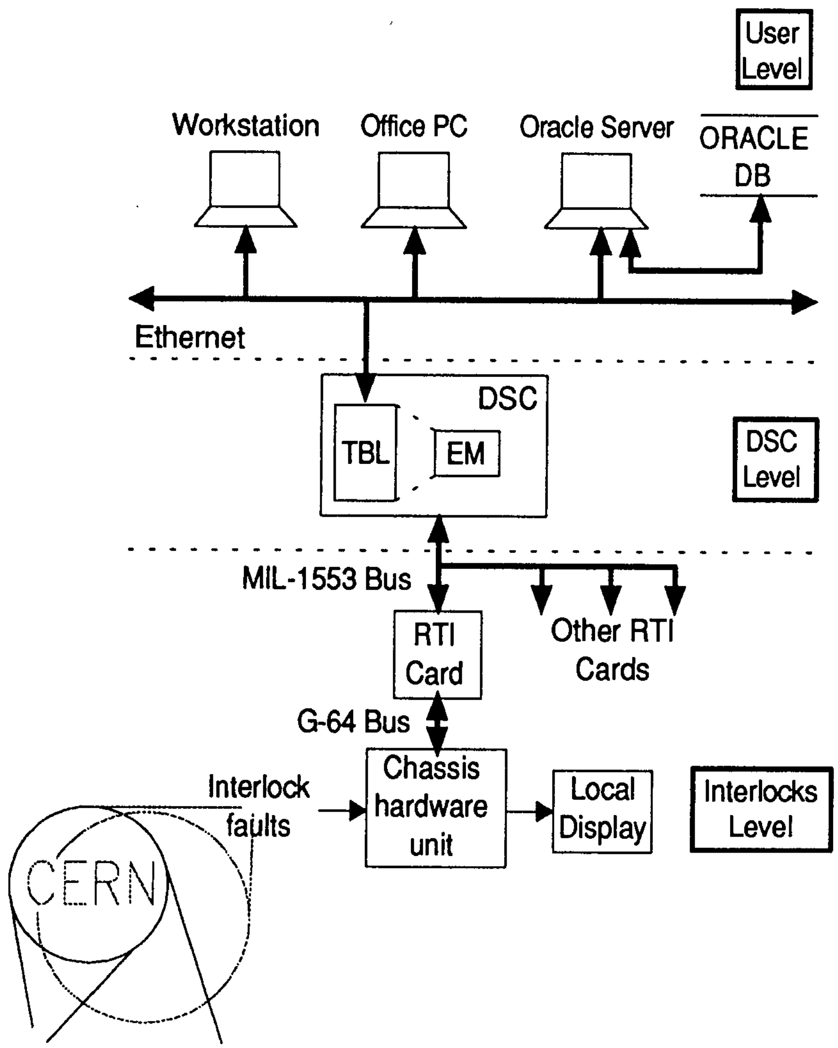
Schematic Diagram of the Old Static Relay Interlock System



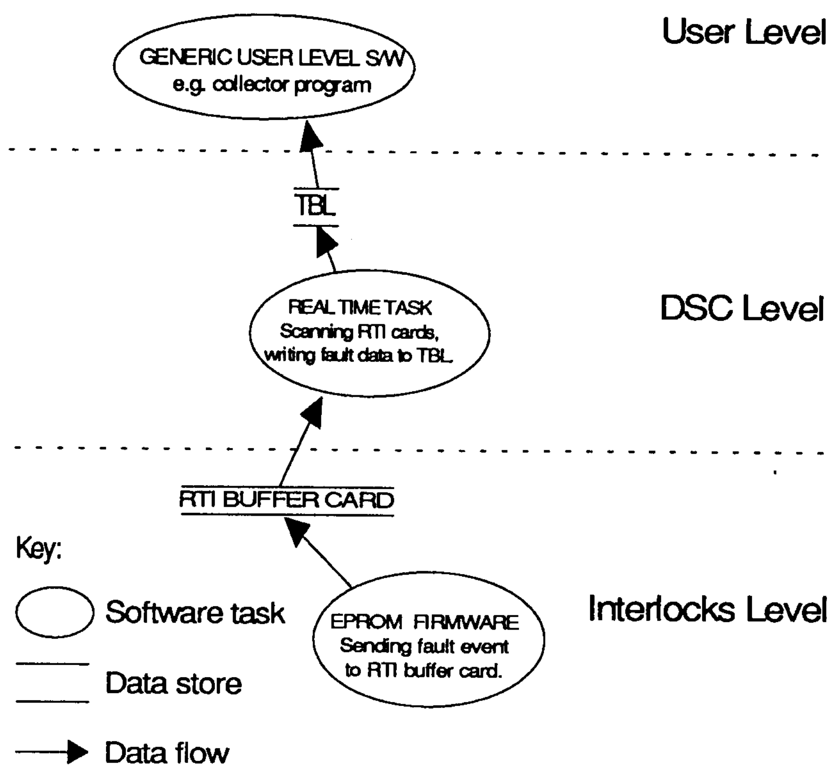
The New G-64 Microprocessor Controlled Interlock System



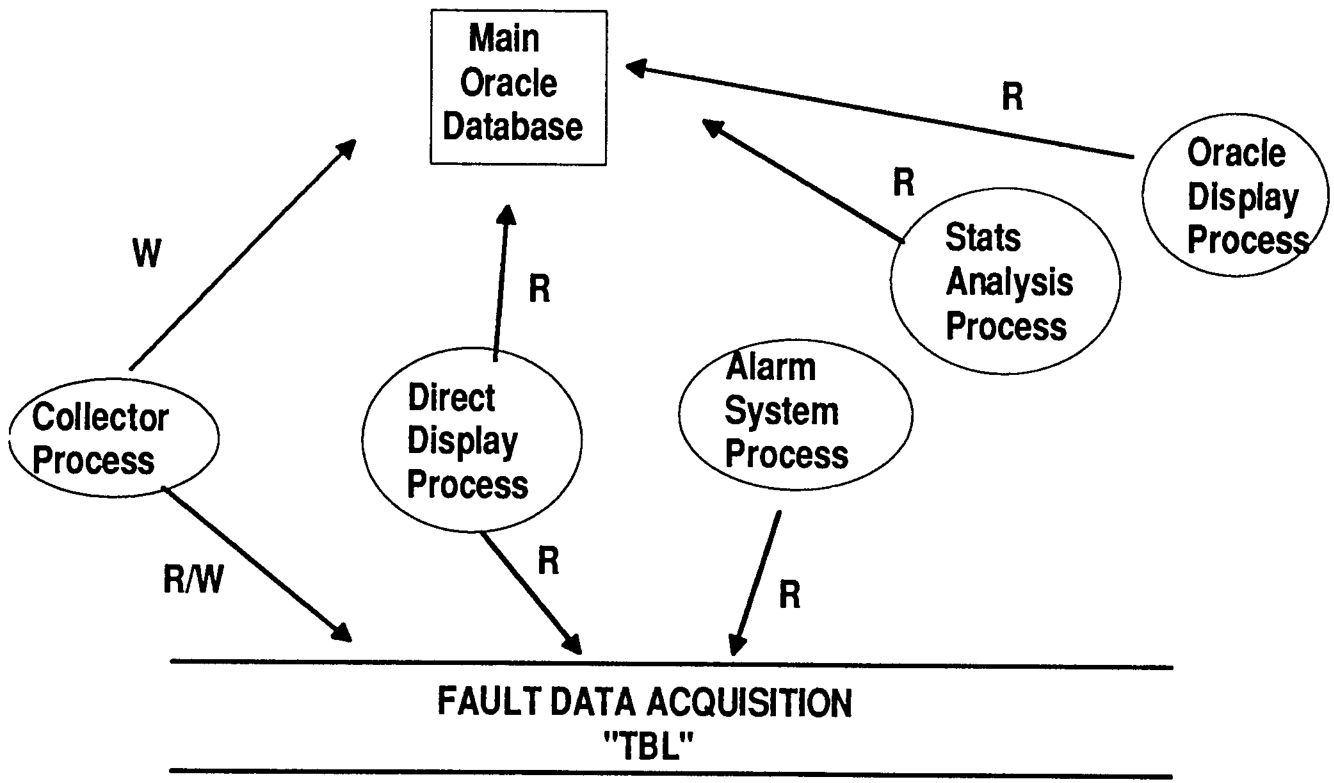
New Interlock system Including User Level



A soft and Firmware View of the New Interlock System

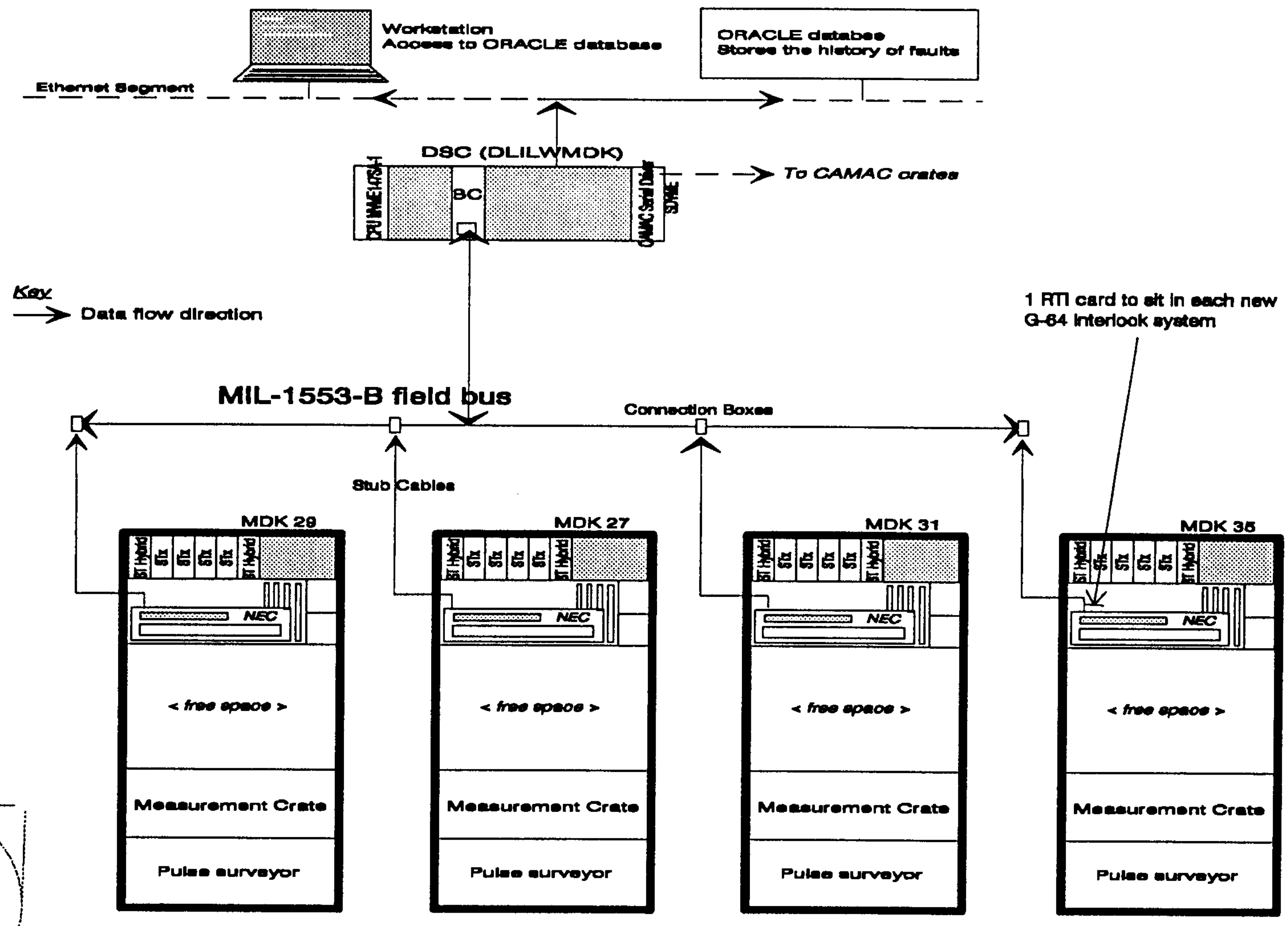


Range of User Level Software

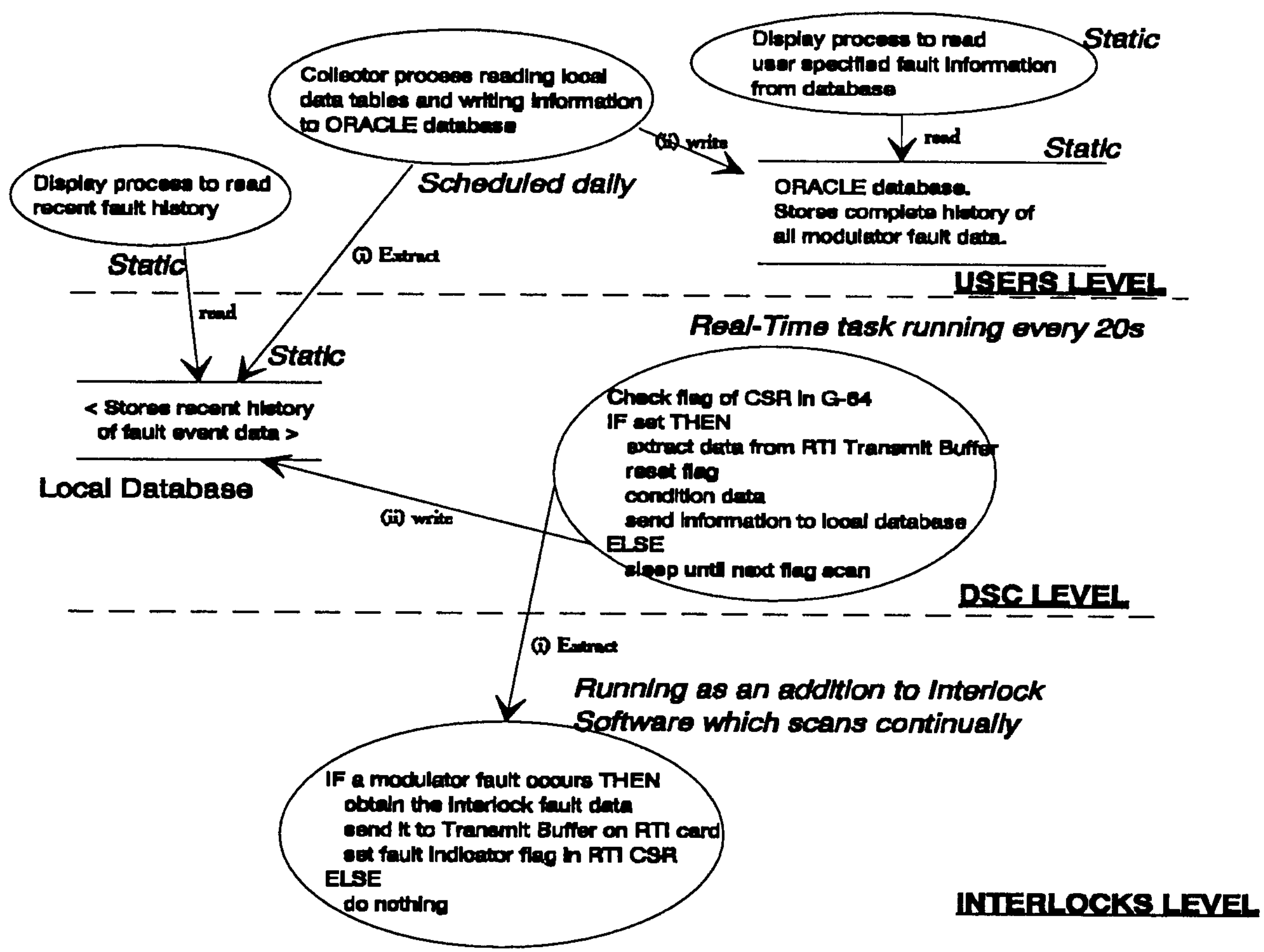


450

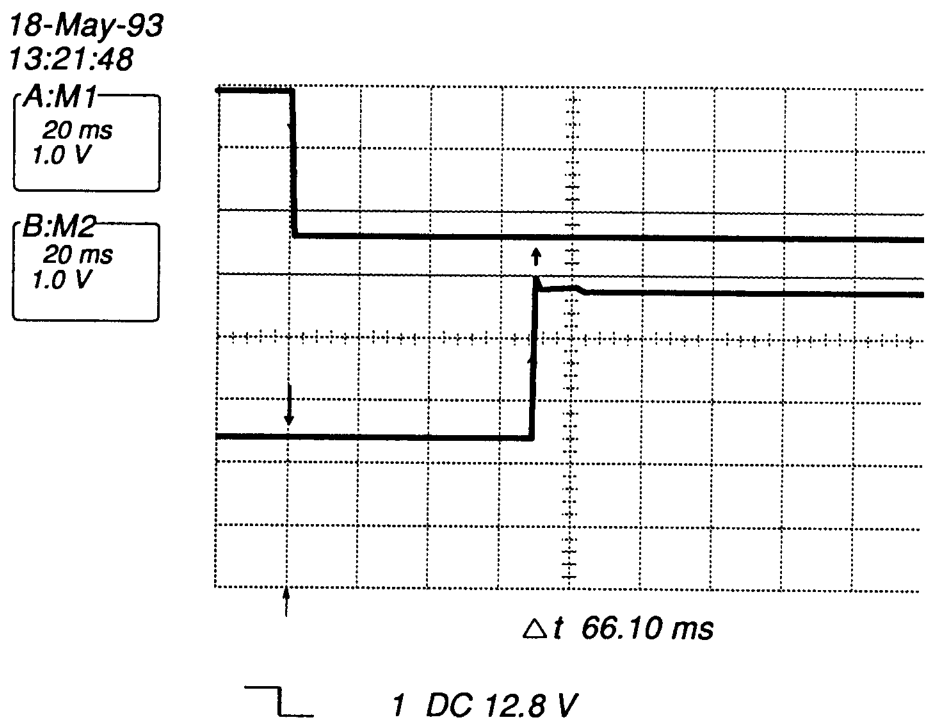
Chosen Design Architecture-VME based using the MIL-1553-B Field Bus Hardware



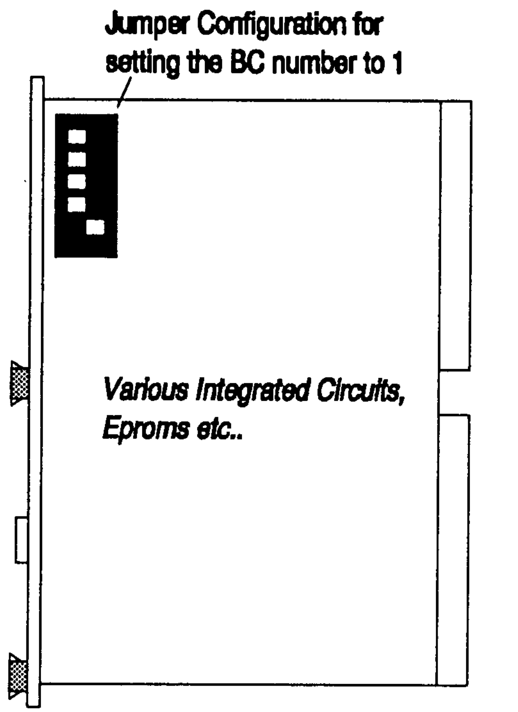
Diagramatic Representation of the Software Algorithm



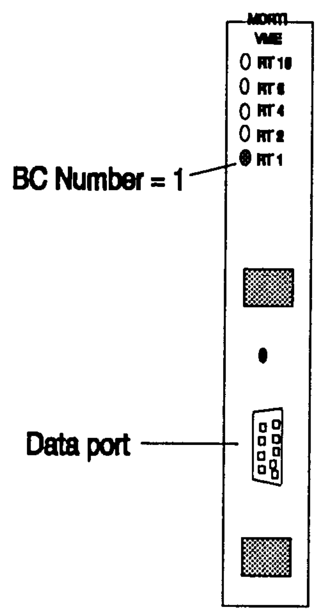
Protection Response Time of Modulator



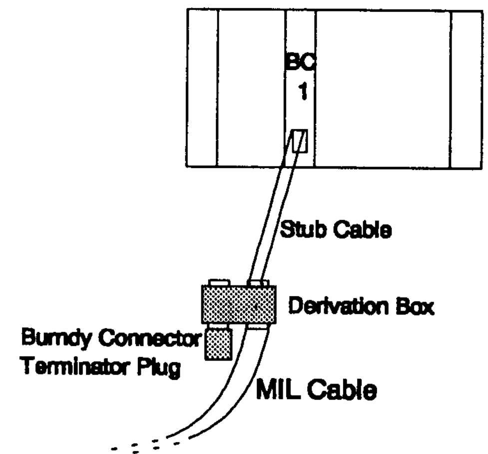
CH1 (A) represents the interlock that goes from a good status to a bad status.
The response time of the output signal is 66.1E10-3 seconds on average

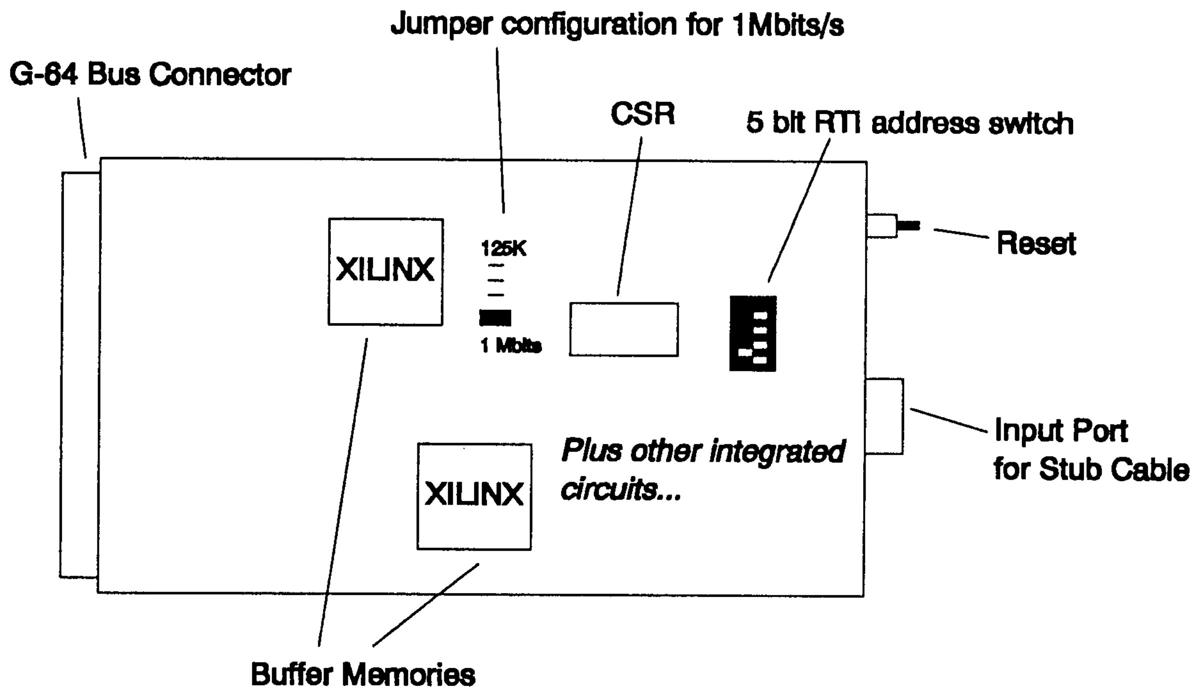


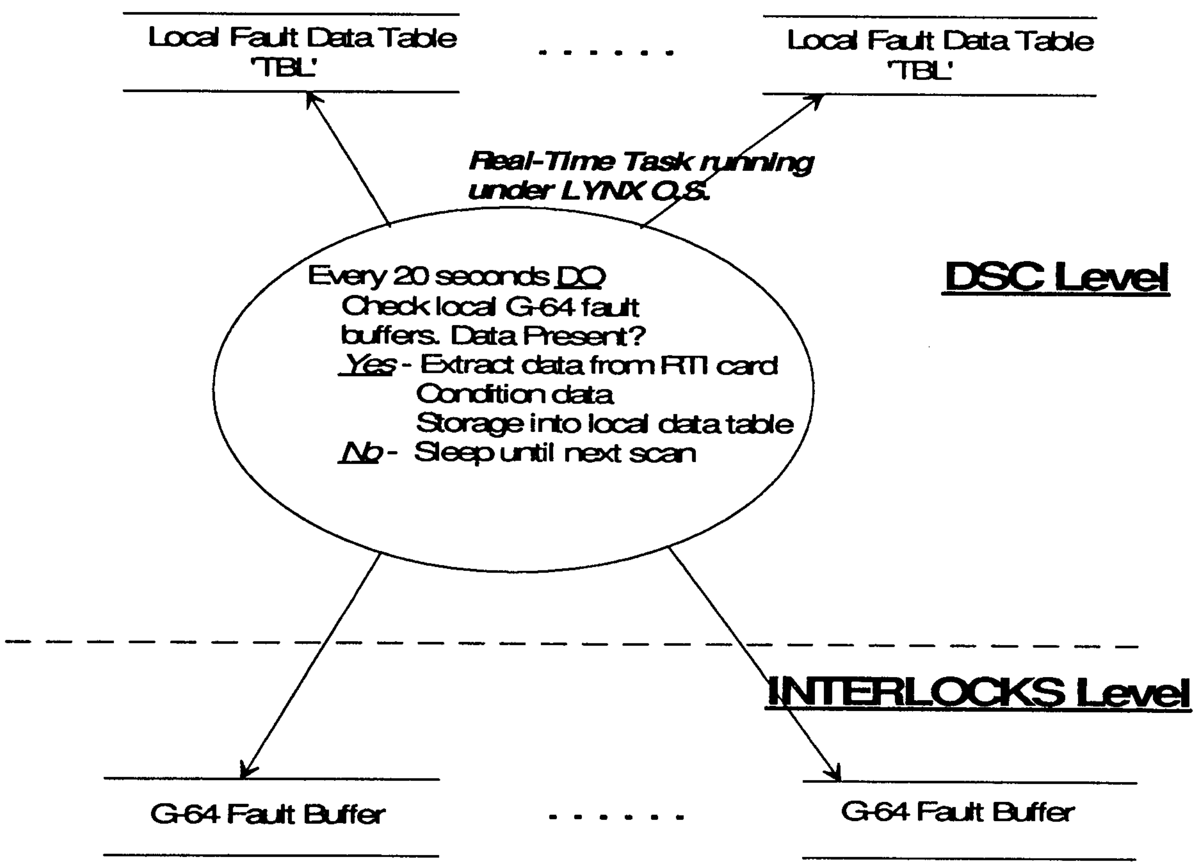
Bus Controller Module (side on view)



BC module (front view)




Jumper configuration for 1Mbits/s
G-64 Bus Connector
CSR
5 bit RTI address switch
XILINX
125K
1 Mbits
Reset
Input Port
for Stub Cable
XILINX
Plus other integrated
circuits...
Buffer Memories


Local Fault Data Table
'TBL'
......
Local Fault Data Table
'TBL'
Real-Time Task running
under LYNX O.S.
Every 20 seconds DO
Check local G-64 fault
buffers. Data Present?
Yes - Extract data from RTI card
Condition data
Storage into local data table
No - Sleep until next scan
DSC Level
INTERLOCKS Level
G-64 Fault Buffer
......
G-64 Fault Buffer

Real-Time task polling every 20 seconds

Check Local G-64 Fault Buffers. Data present?

Yes

- Extract data from RTI card
- Condition data
- Storage into 'TBL'

No

- Sleep

Implementation of diagnostic Hardware and Software systems for CERN modulators[1]

P. Pearce, G. McMonagle and G. Rentier
CERN, PS Division, Geneva, Switzerland

1. Introduction

At the PS Klystron - Modulator Workshop, October 1991, a suggested improvement for the LIL Modulator systems was "An interlock memorisation system/program that will enable intermittent modulator faults to be captured and stored over a period of time." The existing static relay system based upon 120 relays, for one modulators interlocks, would not be able to provide this functionality because it is entirely an analogue system with no memory capacity. As a result of this, a new interlock system was designed in accordance with the following requirements.

- Complete input signal and data output compatibility with the old interlock system
- Fail-safe with no ambiguous fault indication
- High reliability
- Memorisation of modulator faults including time and date of failure with a local display panel
- Interfacing to control system (and later on to Oracle database)
- Conforming to CERN personnel security requirements

A G-64 8 bit microprocessor-controlled system was chosen as similar equipment was already being used by the power group to control power supplies. Thus the development and liaison with industry had already been established and there was considerable expertise already available in the PS Division.

The new interlock system was designed and implemented in 3 stages.

- G-64 microprocessor interlock system with local memorisation of faults
- Fault data acquisition from G-64 system via MIL 1553B bus. allowing the information to be stored in ORACLE data base and giving access to current information from remote terminals.
- User level software for treating data stored in ORACLE data base for creating statistical information of past faults.

At the moment a new ON/OFF co-ordinator, which allows local or remote control of the modulator, is being developed also using a G-64 microprocessor system, which will be linked to the new interlock system and the MIL-1553B data bus.

2. Original interlock system and inherent problems

Each original relay interlock system was designed to protect the modulator hardware from excessive damage if a fault occurred. Up to 120 input signals, coming from semi-static and real time operational sub-assemblies within each modulator were continuously processed. These input signals operated 120 separate d.c. relays in each interlock unit. The output relay contacts were organised into 4 separate interlock chains, corresponding to the 4 output control levels (Off, Heater, Standby, Pulsing). A d.c. current of about 20mA flowed through every contact in each of the series chains of contacts, enabling the four output protection conditions.

During normal production operation the modulator system works continuously for many months at a time. Throughout this period many intermittent faults occurred, mainly due to contact oxidisation since the relays stayed in an activated closed position. This oxidisation build up increased the system downtime in a random fashion. In addition, because individual interlocks were not memorised the fault finding and separation of true external faults from internal contact problems proved difficult.

3. Micro-processor interlock system

To overcome these difficulties a more reliable system has been designed using commercial solid state G-64 micro-processor and opto coupled interface board technology to replace the relay logic. The new scheme apart from improving modulator reliability stores up to eight complete fault sequences in local

[1] Paper presented at the 2nd Klystron-Modulator workshop at SLAC for Future Linear Colliders 9th to 11th October 1995

memory, in a fully time ordered presentation. Within each fault sequence the first eight faulty interlocks are memorised together with a date and time tag to give maximum fault information.

Hardware design

The new stand-alone protection system has been developed that uses the MC6809, 8 bit micro-processor within a G-64 data bus crate as shown in Figure1. This system handles the 120 input signals via purpose designed 32-way input buffer cards. Each input interlock signal generates the following three output signals.

1) A high priority direct interlock connection to the 32-way input card for modulator protection
2) An opto-isolated output for the existing CAMAC data acquisition
3) A TTL level output for on board testing purposes

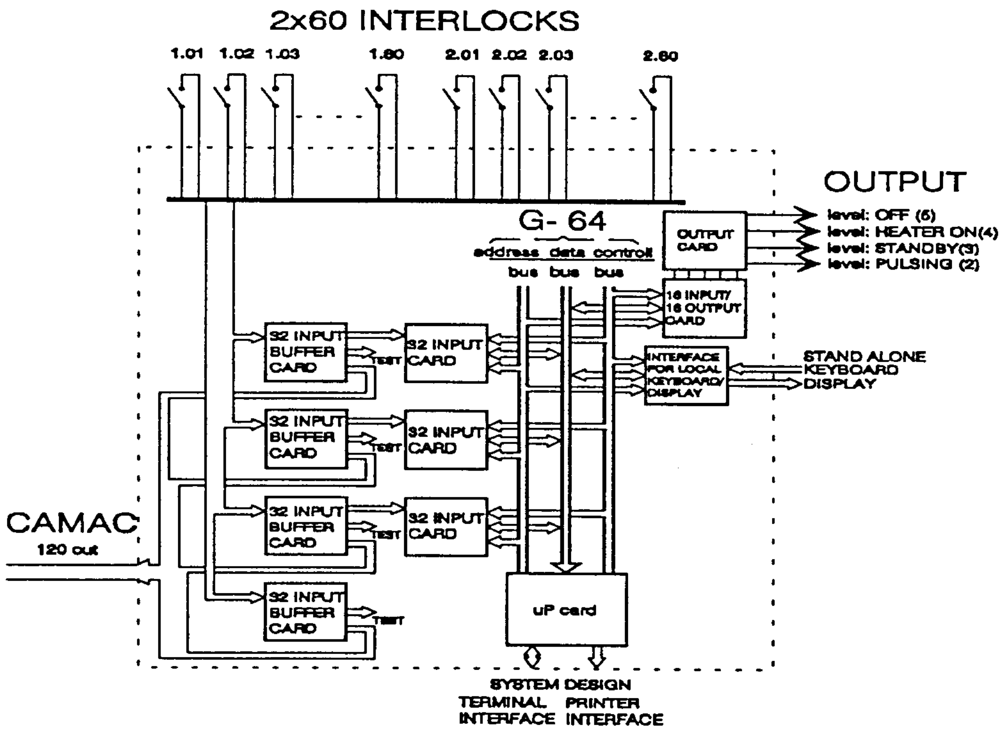


Figure 1 Micro-processor controlled interlock hardware scheme

Four 32 way input cards handle the interlocks in groups of eight and any one of these groups can generate a hardware interrupt for the processor. The failed interlock groups are then collected by the program and stored in a local memory. Any interrupt is processed immediately by an interrupt service routine (ISR), which changes the output status as required. The MC6809 micro-processor can address a total of 64kbytes of memory. The interlock program is stored in EPROM together with the interrupt and start vector addresses. The 16 way output board connects the G-64 system with the modulator via opto-coupled links and a buffer card. Four output levels react directly with the modulators power circuits and control its status. A fifth output level is used as a watchdog and monitors the functioning of the processor via a status line that is toggled by the software. If this line stops toggling, the program has stopped running and the protection system is no longer working and the modulator is immediately put to the OFF state. The machine access control and HV protection doors also provide interlock contacts that are directly connected in series with the output level contacts to give additional personal security.

EPROM software development

The main interlock program is a loop that includes the acquisition and treatment of the 120 input signals and has been written in Pascal. The program 'display' variable is used to make sure that the display screen information is written without interruption from any other keyboard action that occurs during this operation. The initialisation, start-up and interrupt routines have been written in assembler micro-code.Two sources of system interrupt that can occur. One that is generated by a faulty interlock and a second by a key on the units display panel. However the interlock generated interrupts have priority over any display requests. The overall internal response time between the change of input signal and the $\overline{\mathrm{IRQA}}$ line on the G-64 bus due to the oto-couplers is about 14 µs. When a fault occurs the interrupt service routine is immediately executed and any subsequent new interrupts are disabled whilst the input group that caused the first interrupt is traced by means of a polling routine. The output status of the protection system is switched to the assigned operating level and so protecting the modulator. Finally the interrupt flag is cleared and the faulty interlock is stored along with the date and the time tags.

The display screen on each interlock unit allows the following display modes to be selected :

- Mode 1 Checks system memory and is automatically activated when pulsing
- Mode 2 Displays current status of interlocks
- Mode 3 Changes date and time
- Mode 4 Displays information and error messages

Each display mode has a software driver module containing special functions and procedures.

4. The new interlock system implementation.

The new interlock system design uses three different layers of hardware and software. This enables the fault data to be available at the three basic system levels which are :

1) Stand-alone modulator interlock protection
2) Front-end processor (Device Stub Controller) level
3) Operational user level

The system hardware scheme based on these three levels is shown in Figure 2

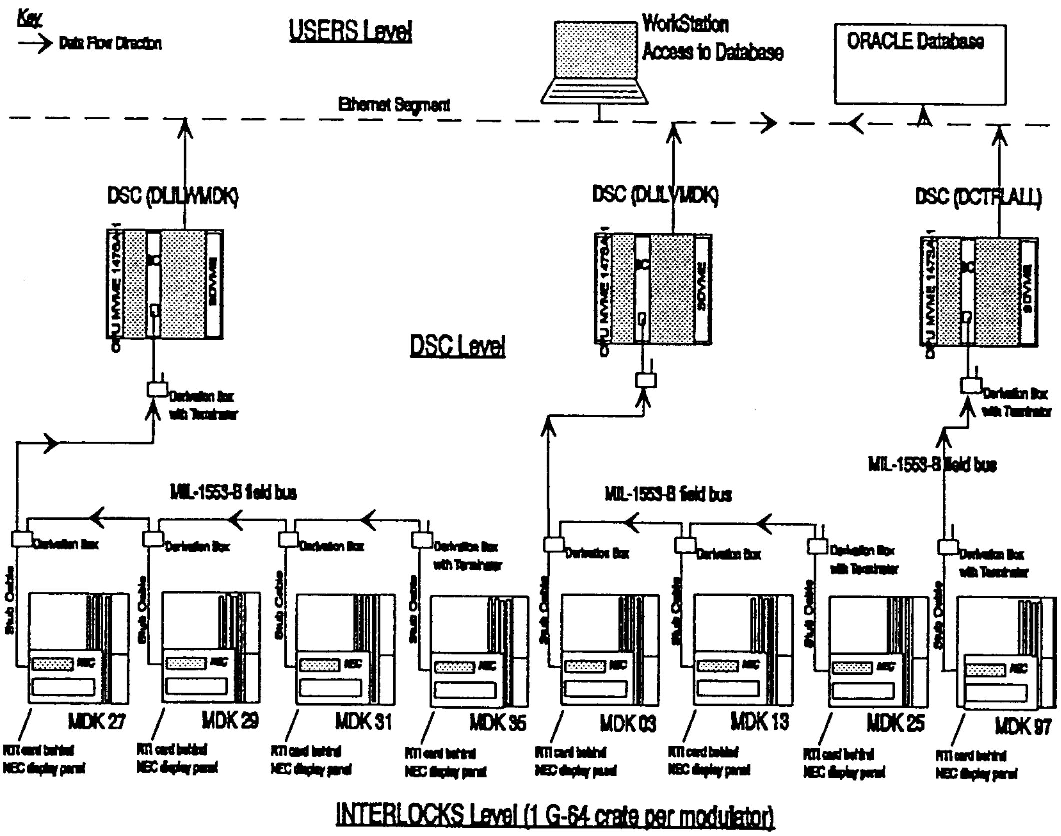


Figure 2 System hardware schematic diagram

Interlock protection level

At the interlock hardware level each G-64 interlock unit has a Remote Terminal Interface (RTI) card plugged into its data bus. The multi drop MIL-1553-B field bus connects this card to the accelerator controls system. This enables the asynchronous exchange of data in response to commands from the Bus Controller (BC) in the front end processor (DSC). The two buffer memories on the RTI card are used as Receive and Transmit FIFO buffer stacks that hold control values and the G-64 acquisition data. A Control and Status Register (CSR) bit (TB) indicates to the BC that the interlock data has been loaded into the transmit buffer memory. The TB bit is only reset after the transmission is complete. A data transmission rate of 1 Mbits/s is used.

The interlock micro-processor has a set of firmware assembler instructions that are used to load the faulty interlock data into the transmit buffer on the RTI card. The EPROM program is triggered into action by hardware interrupt on the occurrence of the first faulty interlock. An internal delay ensures the capture and storage of up to a maximum of seven subsequent cascading interlocks before the RTI transmit buffer is loaded. The worst case acquisition time measured for a complete sequence of cascading interlocks was 116 ms. However, the measured average protection response time to put the modulator to a non pulsing state, after the fault event occurs, is about 66 ms as shown in Figure 3

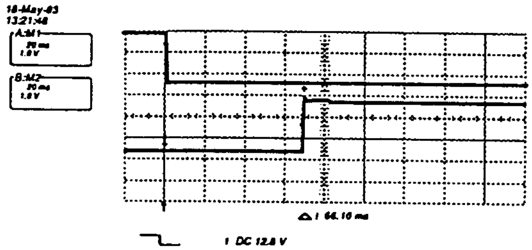


Figure 3 Protection response time of modulator

Front-end processor level

At the DSC level a real time software task has been written in C language and runs under the control of the Lynx (UNIX like) operating system. The RTI buffer cards are scanned every 20 seconds by this task to check for any new data. A representation of the real time task software algorithm is shown in Figure 4. If data is available from the RTI card it is taken, the CSR bit is cleared and the data is reformatted and stored. The reformatting process consists of removing any padding characters and decimal points from the fixed length 32 byte message. The interlock numbers are then converted into corresponding 32 bit integer values and the UNIX system date and time is attached. Finally the position to store the fault message in the data table (TBL) is calculated and the data is stored. One table is used for each modulator. These tables are located within the specific software Equipment Module (EM) drivers used for LPI modulator control and acquisition.

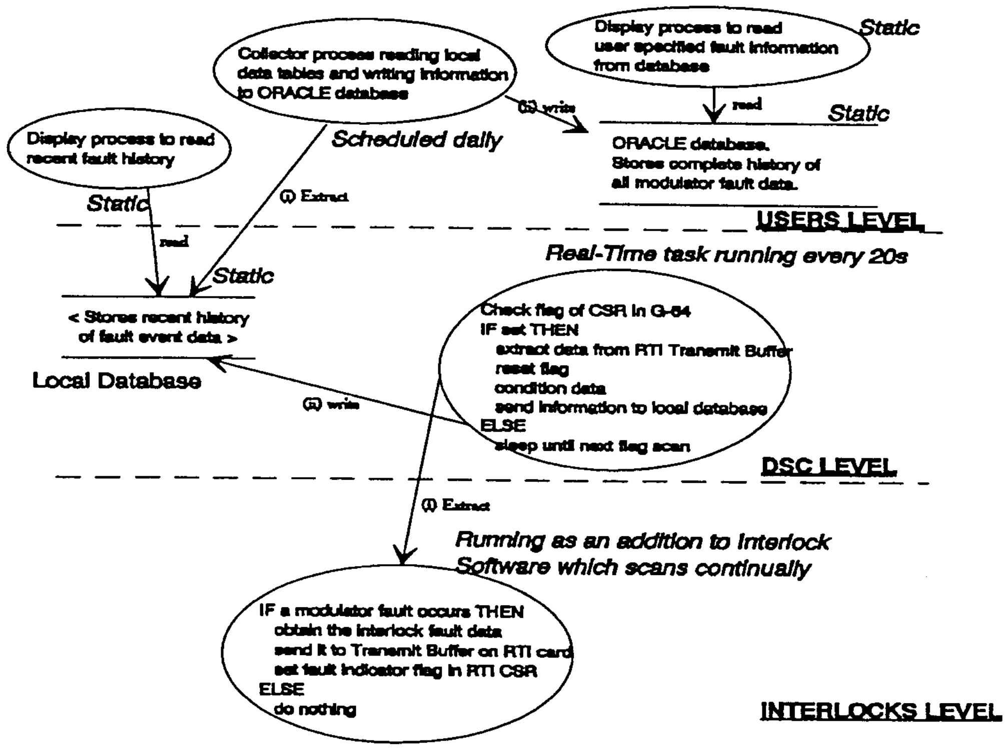


Figure 4 Real-time task algorithm

Operational user level
A direct display program on the controls network enables the operations and maintenance staff to see equipment faults directly from a selected modulator, for a particular date and time. The displayed data is obtained either from the current contents of the data table (TBL), or from the historical data in the Oracle database. The programs interactive display is shown in Figure 5.

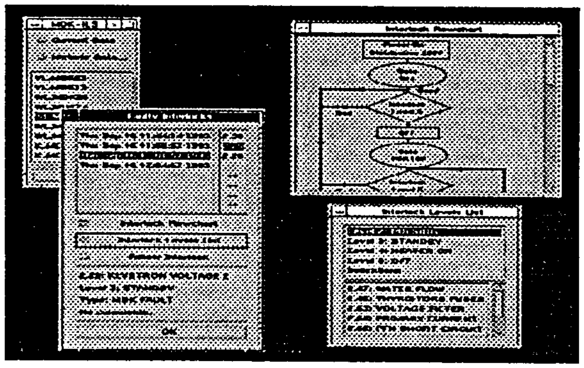


Figure 5 Direct display program : workstation version

A real time task collector program runs daily to extract data from the TBL of each modulator and reformats it before sending it to the Oracle database. A statistical analysis program has been written using Microsoft Access ®, which enables the data in Oracle to be studied in looking for trends of faults due before component failure. The range of existing and future (Alarm System Process) user software is shown in Figure 6.

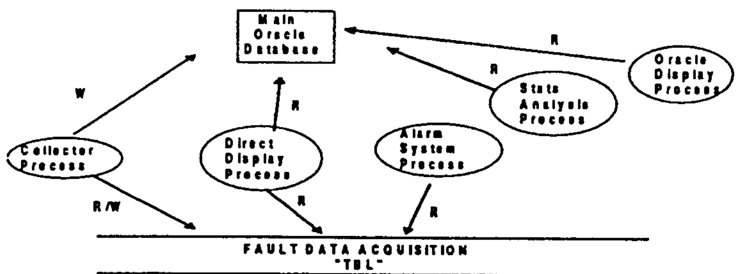


Figure 6 Range of user level software

5. Summary

All LIL modulators have been equipped with the new G-64 interlock system. These have been fully integrated into the accelerator control system, providing detailed fault information for both operators and maintenance staff. The modulator system reliability has been significantly improved as a result of this development. It is expected that the future implementation of the new ON/OFF coordinator units, under development and using the same technology, will further improve the operational features and reliability of the modulator system.

6. References

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SMART MODULATOR SESSION SUMMARY

J. de Lamare

The goals in a SMART modulator/klystron design are to maximize accelerator availability and system efficiency. These goals are more easily accomplished when the modulator and klystron designs are integrated as a system. The design issues can be summarized into three parts:

A. Maximize system reliability and efficiency.
B. Minimize system diagnosis and reset time.
C. Minimize system repair time.

A. Maximize system reliability and efficiency

1. Reduce active components where possible to increase reliability.
2. Explore tradeoffs between system "smarts" and reliability.
3. Maximizing efficiency may increase reliability.
4. Create feedback to maintain high efficiency.
5. Evaluate tradeoffs between redundancy, initial costs, operation costs, and downtime costs.
6. Evaluate tradeoffs in reliability and efficiency for C-band vs X-band accelerators.
7. Interlock system should be fail-safe.

B. Minimize system diagnosis and reset time

1. Provide diagnostics for personnel safety, system safety, feedback, and readback.
2. System should be self resetting for minor faults to minimize reset time.
3. Diagnostics available locally and remotely.
4. Store fault and operation information in database.
5. Record fault information with time, date and sequence stamp.
6. Use digitizer to sample system waveshapes and record anomalies.
7. Diagnostics must be reliable and inexpensive.
8. Klystron processing after a vacuum fault should be automated.

C. Minimize system repair time

1. Sub-systems should be modular.
2. System should provide information necessary to expedite repair.
3. Design system for ease of maintenance.

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