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PROCEEDINGS OF THE INTERNATIONAL WORKSHOP ON NEXT-GENERATION LINEAR COLLIDERS

November 28–December 9, 1988

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

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International Workshop on
Next-Generation Linear Colliders

TABLE OF CONTENTS

INTERNATIONAL WORKSHOP ON NEXT-GENERATION LINEAR COLLIDERS

EXECUTIVE SUMMARY

James M. Paterson

The first International Workshop on Next Generation Linear Colliders was held at the Stanford Linear Accelerator Center between November 28 and December 9, 1988. There were 113 participants including 28 from outside the United States representing Novosibirsk in the USSR; CERN, DESY, Frascati and Orsay in Europe; and KEK in Japan. Such broad participation indicates the growing interest in the technology of linear colliders. The purpose of the workshop was to discuss the research programs on linear colliders around the world, to identify areas that are common or complementary in their goals and to advance these programs by collaboration.

The first two and one half days of the workshop were organized in plenary sessions, where representatives from various laboratories or institutions discussed their latest linear collider design plans and/or their research programs. Subsequently the participants formed seven working groups to discuss in more detail specific programs on subsystems. During these five and one half days, there was a lively exchange of ideas within and between the groups. Their results were summarized and presented in two days of plenary sessions at the end of the meeting. This volume contains copies of the summary-talk transparencies plus brief overviews written by the chairman and scientific secretary of each working group.

In this overall summary we can only highlight a few topics from the proceedings. The Parameters working group examined the existing designs for high-energy linear colliders, which have the acronyms CLIC, ILC, JLC, TLC and VLEPP. They tabulated the design parameters in a consistent form to aid comparisons; these useful data sheets can be found in the proceedings. The working group on Beam Dynamics and Wakefields was very active in interactions with other groups on subjects such as tolerances, the maximum Q's of wakefield modes in accelerator structures, etc. They studied emittance preservation from damping rings through to the final focus and the problems associated with the use of multibunch trains of particles. They discussed some beam dynamics experiments that may be done on the SLC and began a collaboration that will formulate proposed experiments.

The topic of Damping Rings and Sources was studied by a group of specialists who concluded that the desired emittances could be achieved in several different designs, all of which require wiggler magnets as part of the lattice. They noted two areas that need further development of technology: the design of damping ring

RF and vacuum systems with sufficiently low impedances to allow operation with multibunch trains, and the design of extraction systems that can meet the very strict tolerances required to preserve the emittance.

One of the largest working groups concentrated on the topic of RF sources. This key problem in linear collider technology requires a continuing worldwide effort to explore alternate and complementary solutions. The research programs discussed included many "small" sources of "modest" power, sources with peak power outputs of more than a gigawatt, and two-beam accelerators where energy of the drive beam ranged from tens of MeV to several GeV.

Gigawatts of RF power are needed to energize novel Accelerator Structures, a topic which had its own working group. This group discussed new construction techniques, experiments on RF breakdown limits, and designs that damp out wakefields to allow multibunch operation. One new issue that arose was the fatigue limit in structures subjected to short-impulse heat stresses. This topic will require more research to quantify the problem and its impact on structure design.

The working group on Instrumentation explored the precision and tolerances needed in various designs of damping rings and accelerators. The subject of how to measure nanometer beam spots was left to the Final Focus group. Many techniques for component alignment and beam diagnostic measurements were explored, but considerable research is clearly required to achieve the desired level of performance. A problem that was identified is the extreme difficulty in collimating high-power, low-emittance beams.

A large working group studied a variety of issues under the title of Final Focus. Several optics designs with different chromatic correction schemes were compared. The geometry around the collision point using crossing angles and "crab" crossing to provide head on collisions was discussed, and the general problem of beam-beam interaction effects that can cause backgrounds in the detector was explored. It was in this area that the most significant surprise of the workshop appeared. In the very strong beam-beam interaction in linear colliders, the particles radiate in the macroscopic field of the opposing bunch. This "beamstrahlung" process has been extensively studied, and the trajectories and energy spectrum of the degraded electrons is known to be an important background consideration in collider design. Under conditions with large values of the beam-beam strength parameter, the beamstrahlung photons can produce electron-positron pairs either by close collisions with particles of the opposing bunch or in the macroscopic fields of the bunches. The pairs are subsequently deflected by the same fields to large angles and can cause severe background problems. This higher-order process was found to be extremely sensitive to the beam-beam strength parameter, thus effectively limiting the maximum luminosity per crossing that can be used in a design. The

whole subject of both "coherent" and "incoherent" pair production and deflection will need much more study before collider parameters (number of bunches, crossing angles, detector and IR geometry, etc.) can be optimized while keeping the pair-production problem under control.

The proposed Final Focus Test Beam at SLAC using the SLC beam as input, was well received and much discussed. Many groups expressed interest in collaboration on both construction and use of this beamline. Its unique capabilities make it an important part of a linear collider R&D program where optics ideas, hardware and beam instrumentation can be developed and tested. After the workshop, the beamline design will be refined to include many new suggestions, and there will be further discussions on the organization of an international collaboration to construct and use it.

Overall, the workshop was a great success and contributed much to advancing our knowledge of future linear colliders. The excellent technical and social interactions which took place augur well for our continuing collaboration.

PARAMETERS WORKING GROUP

Chairmen: J. Rees/P. Wilson SLAC

Secretary: T. Mattison SLAC

Members and Contributors

C. Sinclair	CEBAF
D. Rubin	Cornell
M. Castellano	Frascati
A. Hutton	SLAC
T. Knight	SLAC
R. Palmer	SLAC/Brookhaven

Summary of the Parameters Group Discussions

John R. Rees, Tom Mattison

The purpose adopted by the group was to collect parameter sets — self-consistent ones if possible — for the colliders under study at the participating laboratories, to compare the parameter sets and to point out the major differences in philosophy and style implicit in those differences. The enterprise was moderately successful; such differences do exist.

Parameters were collected through questionnaires, which were completed for CLIC, ILC, JLC, TLC and VLEPP. One was also prepared for SLC for comparison. These were summarized and evaluated in the summary session on the final Thursday of the workshop. The following very general conclusions were drawn:

1. The Japanese design (JLC) is similar in spirit to the SLAC designs (TLC and ILC).
2. The SLAC designs are shorter overall than the others. One consequence is that TLC has a considerably higher energy gradient than that of any other design, and it requires a higher peak RF power.
3. CLIC and VLEPP have larger vertical beam-spot sizes at the interaction point than JLC, ILC and TLC. In the case of CLIC, the larger interaction area is compensated for by means of a higher repetition rate. In the case of VLEPP the compensation is achieved primarily by a larger bunch population. ILC, JLC, TLC and VLEPP all depend on extremely "flat" beams compared to CLIC, but VLEPP is content with more nearly customary values of the beta-function than those contemplated for the other machines.
4. The CLIC and VLEPP designs call for longer bunch lengths than the other designs. In consequence, those two machines are faced with especially severe problems in controlling the effects of transverse wake fields.

List of Parameters Talks

1. C. Sinclair, "Superconducting RF Approaches"
2. R. Palmer, "Description of PC Program for Linear Collider Evaluation"

INTERNATIONAL WORKSHOP ON
NEXT GENERATION LINEAR COLLIDERS

PARAMETER QUESTIONNAIRE

December 1, 1988

Project Name: Stanford Linear Collider

E_{cm} (GeV): 100

Design luminosity ($cm^{-2}sec^{-1}$): 6×10^{30}

Source and Damping ring parameters:

Damped $\gamma\epsilon_x$ (m-rad): 1.5×10^{-5}

Damped $\gamma\epsilon_y$ (m-rad): 1.5×10^{-5}

Damped $\sigma E/E$ (percent): .073

Damping ring energy (GeV): 1.21

Damping ring circumference (m): 35.3

Damping time τ_x (msec): 3.36

Damping time τ_y (msec): 3.36

Damping time τ_z (msec): 1.5

Buncher, pre-acceleration: One stage compression in ring to linac, S-band

Positron source: Second e^- bunch in main linac, extracted at 33 GeV

Polarization: 45% polarized e^- from laser photocathode (planned)

Main linac parameters:

Wavelength λ (mm): 105.0

Peak gradient (MV/m): 17

Filling time (nsec): 800

Iris radius (a/λ): .1

Group velocity (V_g/c): .012

Repetition rate (Hz): 180 (120 achieved)

Power source: 70 MW klystron + SLED cavity, 240 stations

Bunch population: 7×10^{10} (3×10^{10} achieved)

Bunches per fill: $e^+e^-e^-$ separated by 60 nsec

Final σE/E (percent): 0.5 (0.2 now)

Final focus parameters:

Final focus length (m, 1 beam): 150

Chromatic correction: 2 families of 4 sextupoles

Final quadrupole: Iron and copper $\rightarrow$ superconducting upgrade

Crossing angle (mrad): 0

Linear β_x^* (mm): 7.5

Linear β_y^* (mm): 7.5

σ_x (nm): 1600 (3000 achieved)

σ_y (nm): 1600 (3000 achieved)

σ_z (microns): 1000

INTERNATIONAL WORKSHOP ON
NEXT GENERATION LINEAR COLLIDERS

PARAMETER QUESTIONNAIRE

December 1, 1988

Project Name: CLIC

E_{cm} (GeV): 2 TeV

Design luminosity ($cm^{-2}sec^{-1}$): 10^{33} cm^{-2} sec^{-1} with one bunch per linac and pulse

Source and Damping ring parameters:

Damped $\gamma\epsilon_x$ (m-rad): 15.9×10^{-7}

Damped $\gamma\epsilon_y$ (m-rad): 5.3×10^{-7}

Damped $\sigma E/E$ (percent): 0.172

Damping ring energy (GeV): 2

Damping ring circumference (m): ~ 200

Damping time τ_x (msec): 1.1

Damping time τ_y (msec): 2.7

Damping time τ_z (msec): 5.8

Buncher, pre-acceleration: 5 to 10 GeV/c

Positron source: e^- linac on rotating wheel target

Polarization: not studied

Main linac parameters:

Wavelength λ (mm): 10

Peak gradient (MV/m): 80

Filling time (nsec): 12 ns

Iris radius (a/λ): 0.2

Group velocity (V_g/c): 0.07c

Repetition rate (Hz): 1700

Power source: Two-beam, Superconducting RF drive linac

Bunch population: 5×10^9

Bunches per fill: 1 (ten "later", if possible)

Final σE/E (percent): a few tenths

Final focus parameters:

Final focus length (m, 1 beam): $\sim$ 500 m

Chromatic correction: 0.2%

Final quadrupole: $\ell \approx 2$ m, $\sim$ 1T/mm aperture radius = 1 mm ($\sim 6\sigma$)

Crossing angle (mrad): $\gtrsim$ 3 mrad

Linear β_x^* (mm): 30

Linear β_y^* (mm): 0.4

σ_x (nm): (goal: 12) 15

σ_y (nm): (goal: 60) 125

σ_z (microns): 200

ℓ^* (m): ~ 2

INTERNATIONAL WORKSHOP ON
NEXT GENERATION LINEAR COLLIDERS

PARAMETER QUESTIONNAIRE

December 1, 1988

Project Name: ILC

E_{cm} (GeV): 500

Design luminosity ($cm^{-2}sec^{-1}$): 1.7×10^{33} (with dilutions)

Source and Damping ring parameters (R. Palmer, AAS-Note 39)

Damped $\gamma\epsilon_x$ (m-rad): 1.85×10^{-6}

Damped $\gamma\epsilon_y$ (m-rad): 1.85×10^{-8}

Damped σE/E (percent): 0.072

Damping ring energy (GeV): 1.08

Damping ring circumference (m): 143

Damping time τ_x (msec): 2.1

Damping time τ_y (msec): 2.1

Damping time τ_z (msec): 1.1

Buncher, pre-acceleration:

Positron source: Polarization: polarized e^- from laser photocathode (planned)

Main linac parameters:

Wavelength λ (mm): 17.5

Peak gradient (MV/m): 93

Filling time (nsec): 60

Iris radius (a/λ): 0.20

Group velocity (V_g/c): 0.082

Wall Plug Power: $\simeq$ 52 MW

Repetition rate (Hz): 360

Power source: Rel. klystron or conventional tube with RF pulse comp.

Bunch population: 6.9×10^9

Bunches per fill: 10

Final σE/E (percent): 0.20

Final focus parameters:

Final focus length (m, 1 beam): $\approx$ 250 m

Chromatic correction: 2 families of 4 sextupoles

Final quadrupole: $\hat{B}_p = 1.4$ T, $\ell^* = 0.36$ m, aperture = 0.18 mm

Crossing angle (mrad): 4.2

Linear β_x^* (mm): 28

Linear β_y^* (mm): 0.087

σ_x (nm): 422

σ_y (nm): 2.35

σ_z (microns): 70

INTERNATIONAL WORKSHOP ON
NEXT GENERATION LINEAR COLLIDERS

PARAMETER QUESTIONNAIRE

December 1, 1988

Project Name: JLC

E_{cm} (GeV): 1000

Design luminosity ($cm^{-2}sec^{-1}$): 1.7×10^{33}

Source and Damping ring parameters:

Damped $\gamma\epsilon_x$ (m-rad): 3×10^{-6}

Damped $\gamma\epsilon_y$ (m-rad): 1×10^{-7}

Damped $\sigma E/E$ (percent): 0.15 ?

Damping ring energy (GeV): 1.5

Damping ring circumference (m): 180

Damping time τ_x (msec): 5

Damping time τ_y (msec): 5

Damping time τ_z (msec): 2.5

Buncher, pre-acceleration:

Positron source:

Polarization:

Main linac parameters:

Wavelength λ (mm): 26

Peak gradient (MV/m): 100

Filling time (nsec):

Iris radius (a/λ):

Group velocity (V_g/c):

Repetition rate (Hz): 510

Power source:

Bunch population: 4×10^9

Bunches per fill: 15

Final σE/E (percent):

Final focus parameters:

Final focus length (m, 1 beam): 200

Chromatic correction: TLC type flat-beam

Final quadrupole: 1.4T/0.5 mm

Crossing angle (mrad): $\sim$ 4 mrad

Linear β_x^* (mm): 30 mm

Linear β_y^* (mm): 0.09 mm

σ_x (nm): 300

σ_y (nm): 3

σ_z (microns): 79

INTERNATIONAL WORKSHOP ON
NEXT GENERATION LINEAR COLLIDERS

PARAMETER QUESTIONNAIRE

December 1, 1988

Project Name: TLC

E_{cm} (GeV): 1000

Design luminosity ($cm^{-2}sec^{-1}$): 7.9×10^{33} (with dilutions), 3.3×10^{34} (no dilutions)

Source and Damping ring parameters:

Damped $\gamma\epsilon_x$ (m-rad): 2.7×10^{-6}

Damped $\gamma\epsilon_y$ (m-rad): 2.7×10^{-8}

Damped $\sigma E/E$ (percent): 1.0×10^{-2}

Damping ring energy (GeV): 1.8

Damping ring circumference (m): 155

Damping time τ_x (msec): 2.5

Damping time τ_y (msec): 4.0

Damping time τ_z (msec): 2.82

Buncher, pre-acceleration: Compress at DR energy, accelerate to $\approx$ 15 GeV in $\lambda = 10.5$ cm structure, compress again

Positron source:

Polarization:

Main linac parameters:

Wavelength λ (mm): 17.5

Peak gradient (MV/m): 186

Filling time (nsec): 60

Iris radius (a/λ): 0.200

Group velocity (V_g/c): 0.082

Wall Plug Power: $\approx$ 210 MW

Repetition rate (Hz): 360

Power source: ? Rel. klystron/conventional, cluster or strip beam klystron with RF pulse comp.

Bunch population: 1.4×10^{10}

Bunches per fill: 10

Final σE/E (percent): 0.14

Final focus parameters:

Final focus length (m, 1 beam): $\sim$ 350 m

Chromatic correction:

Final quadrupole: $\hat{B} = 1.4$T, $\ell^* = 0.68$ m, aperture = 0.32 mm

Crossing angle (mrad): 3.9

Linear β_x^* (mm): 27

Linear β_y^* (mm): 0.085

σ_x (nm): 388

σ_y (nm): 2.2

σ_z (microns): 70

INTERNATIONAL WORKSHOP ON
NEXT GENERATION LINEAR COLLIDERS

PARAMETER QUESTIONNAIRE

December 1, 1988

Project Name: VLEPP

E_{cm} (GeV): 1000×2

Design luminosity ($cm^{-2}sec^{-1}$): 10^{33}

Source and Damping ring parameters:

Damped $\gamma\epsilon_x$ (m-rad): 6×10^{-6}

Damped $\gamma\epsilon_y$ (m-rad): 6×10^{-8}

Damped $\sigma E/E$ (percent): 0.3

Damping ring energy (GeV): 1.542

Damping ring circumference (m): 77

Damping time τ_x (msec): 1

Damping time τ_y (msec): 1

Damping time τ_z (msec): 0.5

Buncher, pre-acceleration: yes

Positron source: Undulator

Polarization: yes

Main linac parameters:

Wavelength λ (mm): 21.4

Peak gradient (MV/m): 100

Filling time (nsec): 70

Iris radius (a/λ): 0.156

Group velocity (V_g/c): 0.05

Repetition rate (Hz): 100

Power source: Relativistic gyrocon, klystron

Bunch population: 10^{11}

Bunches per fill: 1

Final σE/E (percent): 1

Final focus parameters:

Final focus length (m, 1 beam):

Chromatic correction:

Final quadrupole:

Crossing angle (mrad):

Linear β_x^* (mm): 100

Linear β_y^* (mm): 1

σ_x (nm): 1000

σ_y (nm): 10

σ_z (microns): 700

THE PARAMETERS WORKING GROUP

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1) PARAMETER LISTS FOR ALL (?) MACHINES
   (UP TO VERSION N-7 FOR TLC !!)

2) ATTEMPT TO INTERCOMPARE PARAMETER SETS
   a) GENERAL OVERVIEW
   b) USING BOB PALMERS PROGRAM (UNBIASED?)

3) GENERAL LAYOUT CONSIDERATIONS
   a) NON-LINEAR COLLIDER
   b) GENERIC 50 GeV COLLIMATION INSERTION
   c) GENERIC 180° BEND

DAMPING RINGS

		SLC	CLIC	ILC	JLC	TLC	VLEPP
ENERGY	GeV	1·21	2·0	1·08	1·5	1·01	1·542
CIRCUMFERENCE	m	35	200	143	180	96·1	77
DAMPING TIMES τ_x	ms	3·36	1·1	2·1	5·0	2·3	1·0
τ_y	ms	3·36	2·7	2·1	5·0	2·3	1·0
τ_z	ms	1·58	5·8	1·1	2·5	1·5	0·5
UNCOUPLED EMITTANCE	mmr	30	2·1	1·87	3·1	3·2	6
EMITTANCE RATIO	ϵ_x/ϵ_y	1	3	100	30	100	100
RF FREQUENCY	GHz	0·7	3·0	1·4	–	1·4	0·5
ENERGY SPREAD	$\partial E/E$ %	·073	·172	·072	·15	·069	·3
BUNCHES PER FILL		2	1 (10)	10	15	10	1

CAN WE COMBINE ADVANTAGES OF DIFFERENT DAMPING RING DESIGNS ?

PERHAPS – IF WE GO TO PRE-DAMPING RING BEFORE DAMPING RING (e.g. ACOL, AA)

PRE-DAMPING RING

TOP PRIORITY – FAST TRANSVERSE DAMPING

HIGH FIELD WIGGLERS

- EXCHANGE OF DAMPING PARTITION NUMBERS
- FULL COUPLING
- → FAST VERTICAL DAMPING

DAMPING RING

TOP PRIORITY – SMALL FINAL EMITTANCE

WEAKER BENDING

- EXCHANGE OF DAMPING PARTITION NUMBERS ?
- NO COUPLING
- → TIME IN RING LIMITED BY VERTICAL DAMPING

MAY BE NEEDED IF WE GO TO HIGH REP RATE TO SOLVE PAIR PRODUCTION PROBLEM

LINACS

		SLC	CLIC	ILC	JLC	TLC	VLEPP
ENERGY c-m	GeV	100	2000	500	1000	1000	2000
WAVELENGTH	mm	105	10	17.5	26	17.5	21.4
PEAK GRADIENT	MV/m	17	80	93	100	186	100
LENGTH (EACH)	Km	3	13	3	5	3	10
PEAK POWER	MW/m	13	177	147	–	586	217
IRIS RADIUS	a/λ	0.1	0.2	0.2	–	0.2	0.16
GROUP VELOCITY		.012	.070	.082	–	.082	.05
FILLING TIME	ns	800	12	60	–	60	70
BUNCH POPULATION	10^{10}	7	0.5	0.7	0.4	1.4	10
ENERGY SPREAD	10^{-3}	5	few	2	–	1.4	10
REP RATE		180	1700	360	510	360	100

COMPARISON OF PROJECTS USING BOB PALMERS PROGRAM

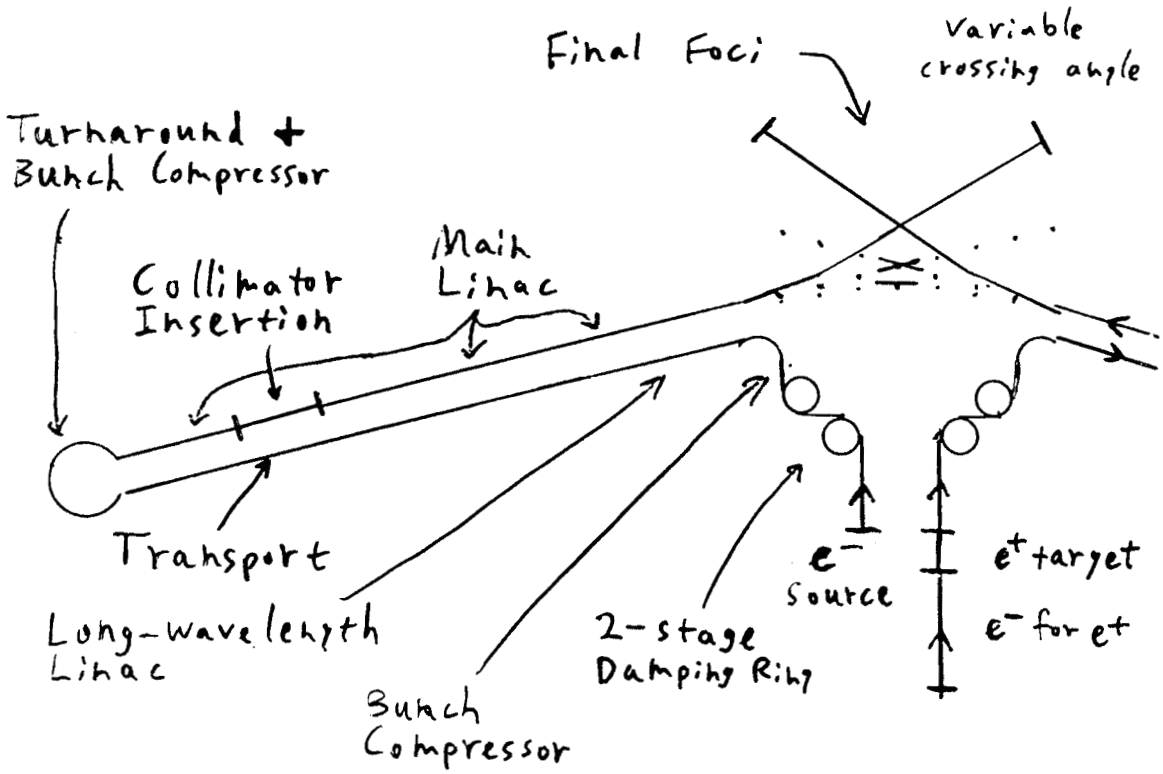
	CLIC HEAD-ON	CLIC CRAB	ILC	JLC	TLC	VLEPP
LUMINOSITY (10^{33} cm^{-2}sec^{-1})	0·6	0·5 ×5	0·17 ×10	0·18 × 15	0·8 ×10	1·2
FINAL QUAD POLE FIELD (T)	15	0·9	1·4	1·4	1·4	1·4
PHASE EXTENT OF BUNCH (rad)	11	10	0·8	0·15	1·2	43
QUAD TOLERANCE (μ)	3	2	20	106	31	1
DAMPING RING Z/n (Ω)	0·6	0·3	0·5	0·5	0·5	0·5
DILUTION	NO	YES	YES	NO	YES	NO

NLC ~ Nearly Linear Collider

- Crossing angle <u>may</u> be larger than maximum permissible final focus bend.

→ Non-collinear main linacs may be required!

- Collimator power density and muon spoiling may require most collimation be done at a fraction of full linac energy and length.



≈ 50 GeV COLLIMATOR INSERTION

REQUIREMENTS

TRANSVERSE CUT IN X PLANE (Y IMPOSSIBLE?)

2 SETS OF COLLIMATORS 90° APART

β VALUE LARGE ENOUGH FOR 'SAFE' COLLIMATION

(MULTIBUNCH TRAIN EQUIVALENT TO SINGLE BUNCH FOR SHOCK-EXCITED THERMAL STRESS)

$\beta_x \approx$ 500 - 1000 metres

(β_y WOULD HAVE TO BE $\approx$ 50000 - 100000!!)

ENERGY CUT

1 SET OF COLLIMATORS FOR DEBRIS CLEAN-UP

(MORE IS ALWAYS BETTER!)

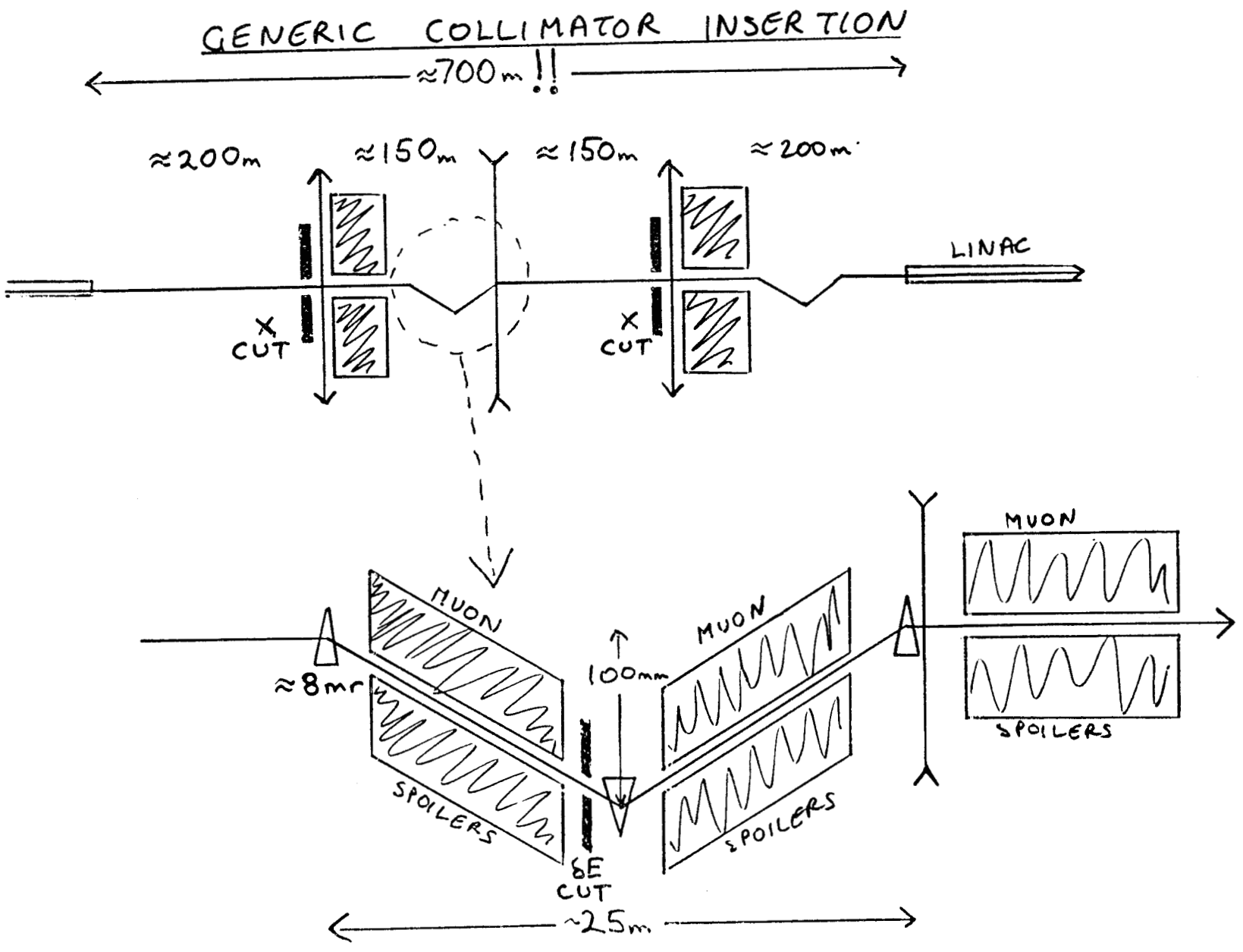
100mm DISPERSION & 1mm SLIT GIVES 1% ENERGY CUT

(SLC CHROMATIC CORRECTION REGION $\eta_x \approx$ 200mm

MUON CLEAN-UP

BEND AFTER COLLIMATION

MUON SPOILERS AFTER BEND


GENERIC COLLIMATOR INSERTION
≈700m !!
≈200m
≈150m
≈150m
≈200m
LINAC
X
CUT
X
CUT
MUON
MUON
≈8mr
100mm
SPOILERS
SPOILERS
δE
CUT
~25m
MUON
SPOILERS

Often-Neglected Subsystems

Turnaround / bunch compressor / collimation at injection into main linac.

Collimation / muon spoiling insertion into main linac, at moderate energy.

Collimation / muon spoiling insertion at end of main linac + interleaved into final focus [Not obviously possible!]

Beam phase space monitoring insertions.

Beta, eta, skew matching sections.

→ Parameters not well defined

→ Generic designs welcome!

PROBLEM AREAS

THE PARAMER GROUP TRIED TO COME UP WITH A LIST OF 'GENERIC' PROBLEMS THAT WERE COMMON TO ALL DESIGNS AND COULD BE TACKLED INDEPENDENTLY OF THE PROJECT.

SPECIFICALLY THEY COULD BE TACKLED BY SMALL INDEPENDENT GROUPS AS A VITAL CONTRIBUTION TO THE FIELD

1) COLLIMATOR DESIGN

2) COLLIMATOR INSERTION DESIGN

3) 180° BENDS

4) POSITRON TARGET DESIGN

FINAL FOCUS

		SLC	CLIC	ILC	JLC	TLC	VLEPP
LENGTH/SIDE	m	150	500	250	200	350	–
CROSSING ANGLE	mrad	0	≥3	4.2	4	3.9	–
FINAL QUAD POLEFIELD	T	1.2 2.7	1.0	1.4	1.4	1.4	–
DIAMETER	mm	40 4.4	2	0.18	0.5	0.32	–
LINEAR β_x^*	mm	7.5	30	28	30	27	100
β_y^*	mm	7.5	0.4	0.087	0.09	0.085	1
SPOTSIZE σ_x^*	nm	1600	125 (60)	422	300	388	1000
σ_y^*	nm	1600	15 (12)	2.35	3	2.2	10
SPOT ASPECT RATIO		1	8 (5)	180	100	176	100
BUNCH LENGTH σ_z	mm	1	0.2	0.07	0.078	0.07	0.7
NO OF MICROBUNCHES		1	1	10	15	10	1
LUMINOSITY	$cm^{-2}sec^{-1}$	6×10^{30}	10^{33}	1.7×10^{33} (dil)	1.7×10^{33}	7.9×10^{33} (dil)	10^{33}

BEAM DYNAMICS AND WAKEFIELDS WORKING GROUP

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Secretary: K. Thompson SLAC

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Summary of the Beam Dynamics and Wakefields Group Discussions

Ronald D. Ruth, Kathleen Thompson

This working group took as its task to look at the preservation of the emittance of the beam from the exit of the damping ring to the entrance of the final focus. There were a total of 13 talks given, with 3 in the plenary sessions and 10 in the working groups.

To prepare the long bunch from a damping ring for the accelerating structure, it is necessary to compress it longitudinally. The bunch must be short enough to control longitudinal and transverse wakefields in the linac, and its length must be less than β^* at the interaction point. Bunch compression can be done in two stages if very short bunches are desired. A design was presented for a second stage of compression having a 180° bend, using very strongly focussing, combined-function magnets as in the SLC arcs.

In the main linac, the transverse wakefields cause a single bunch to grow a large tail. This can be controlled by using a correlated change in focussing strength along the bunch, either with energy spread or RF focussing (BNS damping). Different designs use the technique differently due to large differences in bunch length and transverse wakefields. There were discussions and calculations presented as to the interaction of BNS damping with required tolerances. Qualitatively, large spreads in transverse oscillation frequency improve jitter tolerance by causing a loss of memory down the linac. By the same token, they decrease orbit tolerances due to filamentation in transverse phase space. Smaller spreads lead to tight tolerances on magnet jitter, but loose tolerances on alignment. Accelerator structure alignment seems always to be less severe than quadrupole magnet alignment because only the tail of the bunch is kicked by an offset accelerator structure. Of course, for cases with stronger wakes, this tolerance is tighter.

Emittance growth due to quadrupole errors was found to be rather easy to control. Direct coupling due to quadrupole rotations is only a problem for flat beam designs, but the tolerances are not severe.

There is a general consensus that to achieve high luminosity, we need many bunches per RF fill to extract more energy from the RF. Keeping the bunch-to-bunch energy constant requires tight tolerances on the number of particles per bunch.

Analytic models and simulations show that multibunch beam breakup can be a severe problem in the main linacs, and also in the drive beam of a two-beam accelerator scheme. It seems possible to control this by using structures with slots that damp the transverse modes (where necessary, combined with the tuning of the dipole mode relative to the accelerating mode). The effects of a spread in the transverse mode frequencies were also examined, as well as the use of BNS damping.

Two talks were presented, using relatively simple models to examine the high-frequency

limit of the impedance of azimuthally symmetric structures. A diffraction model shows that a series of irises gives approximately the same result as a resistive tube, for very short bunches. Looking at the effects of wakefield kicks due to collimators, we found that the collimators should be at a small value of the β-function. Even so, the wakefield kicks are comparable to the beam divergence. This led to suggestions of dynamical collimation using nonlinear lenses. The effect of the jitter of transverse kicks due to dark current was quickly examined. The damping of the transverse modes was found to help this considerably.

List of Beam Dynamics and Wakefields Talks

1. V. Balakin, "Landau Damping, Autophasing"
2. D. Chernin, "Single Bunch Dipole Beam Break-up in the Presence of Random Transverse Magnet Displacements"
3. S. Heifets, "Simple Models for High Frequency Impedance"
4. H. Henke, "Resistive Wall Effects"
5. R. Helm, "What is the 'Best' Phase Advance for Linac Transport System?"
6. S. Kheifets, "Bunch Compression for TLC"
7. R. Palmer, "Diffractive Model for High Frequency Impedance"
8. M. Sands, "Emittance Growth From Random Focussing Errors"
9. K. Thompson, "Multibunching—Beam Break-up Control"

Other talks jointly done with other groups:

1. J. Seeman, "Transverse Wakefield Damping in the SLC Linac" (Instrumentation Group)
2. Y. Y. Lau, "Beam Break-up" (RF Group)

Beam Dynamics and Wakefields Working Group

Chairman: Ron Ruth
Scientific Secretary: Kathy Thompson

1. Main linacs (high energy, high frequency)
   (a) Lattices
   (b) Wake fields
   (c) BNS damping (strong vs. weak)
   (d) Tolerances on magnet misalignments, BPMs, accelerator structures
   (e) Jitter
      (i) Magnets: Correlated and uncorrelated
      (ii) Accelerator sections
   (f) Flat beams; coupling of vertical and horizontal emittance
   (g) Drive-beam issues for two-beam accelerators
   (h) Multibunching
      (i) Control of ΔE, including higher order effects, tolerances, etc.
      (ii) Control of beam break-up
2. Bunch compression
   (a) Parameters, designs
   (b) Tolerances on magnet misalignments, BPMs
   (c) Tolerances for matching β, β', η into preaccelerator or main linac
   (d) Wake field effects

3. **Preaccelerators**

   (a) **Lattices, acceleration gradient**

   (b) **RF parameters — T_{fill}, v_g, etc.**

   (c) **Wake fields**

   (d) **Is BNS damping necessary?**

   (e) **Tolerances on magnet misalignments, BPMs, accelerator structures**

   (f) **Multibunching — Control of ΔE and beam break-up; tolerance issues**

Other issues.

1.) Wake field kicks due to collimators

2.) Dark Current deflections

3.) Higher mode frequency spread for helping multi-bunch BBU.

Bunch Compression.

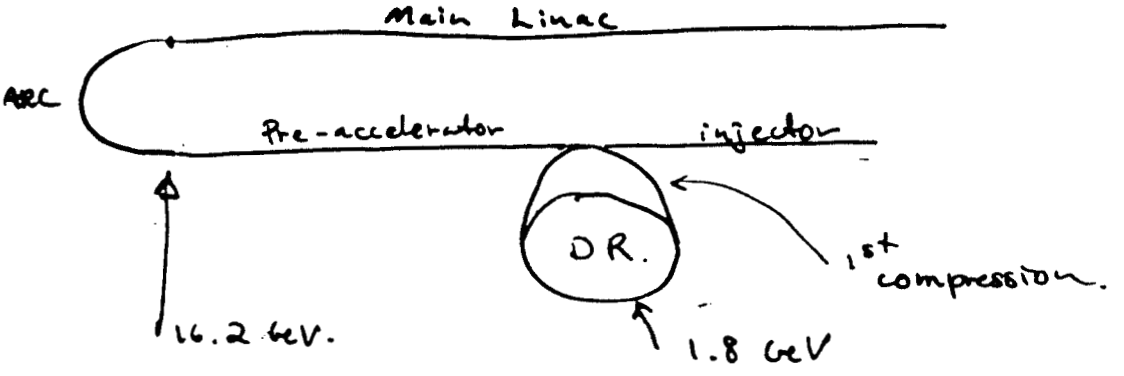
Talk by S. Kheifets.

TLC needs two compressions.

CLIC may need only one.

etc.

Basic Layout.



Basic Idea.

	σ_z	$\Delta p/p$
Energy 1.8 GeV	5mm	10^{-3}
compress 1.8 GeV	.5mm	10^{-2}
Accelerate 16.2 GeV	.5mm	1.2×10^{-3}
compress in ARCS 16.2 GeV	.05mm	1.2×10^{-2}

S. Kheifets

180° bend Compressor
THC

Issues.
emittance dilution (OK)
tolerances (not yet finished)

Table 9.

180 degrees Compressor Main Parameters (Common)

N	Parameter	Value
1	Bend Angle per Half-magnet (°)	0.268
2	Number of Achromats	21
3	Number of Cells per achromat	8
4	Number of Half-Magnets per cell	4
5	Betatron Phase Advance per cell (°)	135
6	Total Angle Bend (°)	180
7	Compressor RF (GHz)	17.0
8	λ (cm)	1.76
9	$\theta = 2\pi l/\lambda$	0.164
10	$\Delta(\Delta p/p) = \theta^2/6$	$4.48 \cdot 10^{-3}$

Table 10.

180 degrees Compressor Main Parameters (Particular)

N	Parameter	Version G	Version I	Version H
1	Total Arc Length (m)	703.32	501.72	367.32
2	Radius of curvature (m)	213.6	149.5	106.8
3	Half-Magnet length (m)	1.000	0.700	0.500
4	Correlation $(\Delta p/p)/l$ (%/mm)	1.37451	1.95971	2.69622
5	V_o (MV)	640	900	1230
6	Δl_{out} (mm)	0.086	0.061	0.044
7	$\delta p/p_{out}$ (%)	0.648	0.915	1.254
8	$\Delta\epsilon/\epsilon$(%)	2.12	2.22	3.12

S. Kheifets cont.

Table 5.

Arc Compressor Transverse Beam Size

N	Parameter	Version G	Version I	Version H
1	$\sqrt{\epsilon_x \beta_x}$ (μm)	24.4	20.0	17.1
2	$\sqrt{\epsilon_y \beta_y}$ (μm)	1.20	0.450	0.385
3	$\sqrt{\epsilon_x / \beta_x}$ (μrad)	2.33	2.845	3.32
4	$\sqrt{\epsilon_y / \beta_y}$ (μrad)	0.475	1.262	1.476

Table 11.

Focusing and Dispersion Functions for 180 degree Arc

N	Parameter	Version G	Version I	Version H
1	$\beta_{x,max}$ (m)	9.83	7.02	5.15
2	$\beta_{x,min}$ (m)	0.50	0.36	0.26
3	$\beta_{y,max}$ (m)	9.83	7.02	5.15
4	$\beta_{y,min}$ (m)	0.50	0.36	0.26
5	$\eta_{x,match}$ (m)	0.032	0.023	0.017

Wake fields in final compressor (R. Ruth)

In the final compressor

RF = linac RF $\Rightarrow$ 17.1 GHz (THC)

<u>Half spread</u> for BNS δ_{BNS}

Given by.

$$\frac{e^2 N W_1(2\sigma_z)\beta^2}{8E} = \delta_{BNS}$$

from two particle Model

<u>1st</u> Assume No BNS in compressor.

2 part. Model.

$$\frac{x_2 - x_1}{\hat{x}} = \frac{e^2 N W_1 \beta}{4E} s$$

distance.

$$= 2\delta_{BNS} \frac{s}{\beta}$$

Wake parametertized by amount of spread which would be necessary for BNS.

In compressor bunch is 10 times long $\Rightarrow$

$W_{comp} = 10 W_{linac}$, $s = 12\,m$, $\beta = \beta_{linac}$

$E = E_0$ (linac) δ_{BNS} (THC) $\approx 10^{-3}$

$$\Rightarrow \frac{x_2 - x_1}{\hat{x}} \lesssim .1$$

Also correlation put in for compression is $\sim \delta_{BNS}$ $\Rightarrow$ <u>No Problem</u>

1.) Main Linacs

(a) Lattices

Question: How do we scale the lattice vs γ?

1.) We must focus as hard as possible at the beginning of linac to control wakes.

Possibility 1 : Keep cell fixed

Bad Idea. $\Rightarrow$. $\beta \propto \gamma$, cells at end have small phase advance $\rightarrow$ inefficient use of quads.

Possibility 2: scale cell length $\propto \gamma^{1/2}$
scale Magnet length $\propto \gamma^{1/2}$
fix B' at maximum.

$\Rightarrow$. $\beta \propto \gamma^{1/2}$ much better!

Two Part. BNS $\quad \dfrac{e^2 N \; W(2\sigma_z)\, \beta^2}{\gamma E} = \delta_L$

(No Acceleration)

Scaling. $\beta \propto \gamma^{1/2}$ keeps δ_L fixed along accelerator.

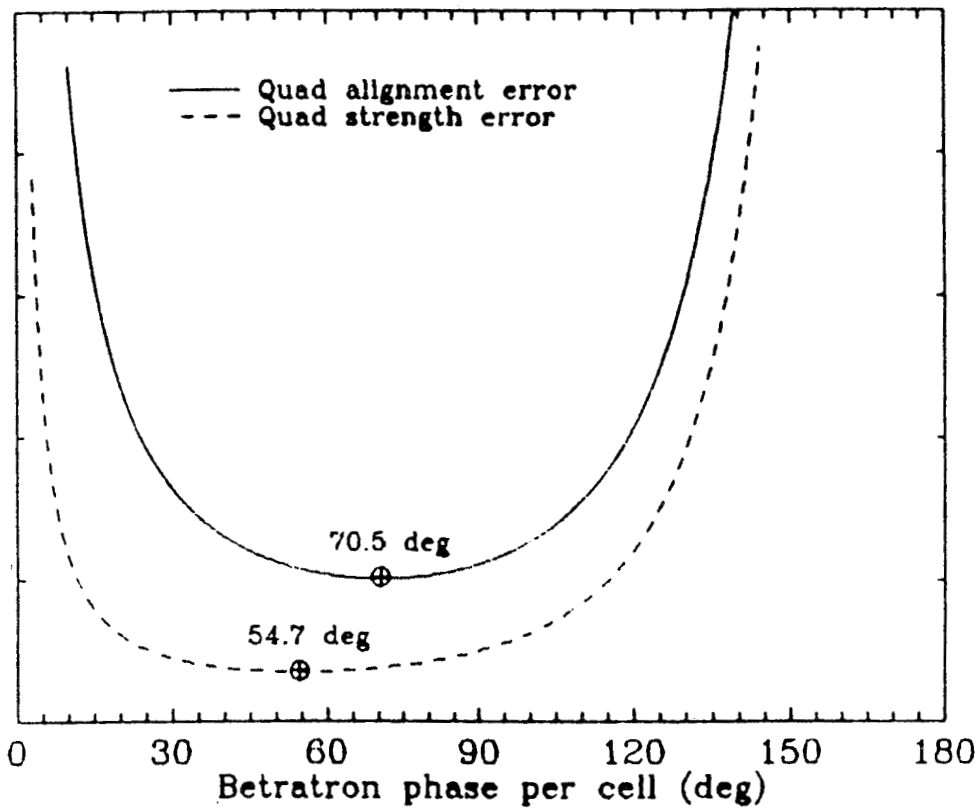
However since quads will <u>interrupt</u> Acc. structure spacing is quantized. $\gamma^{1/2}$ scaling approximated by discrete steps.

Need more work here.

(a) Lattices R. Helm.

Sensitivity of FODO array to misalignment and focusing

R. Helm.



Quad Alignment $\langle \delta a^2 \rangle = \frac{L}{\bar{\beta}^2} \boxed{4 \frac{\left(1 + \frac{2}{3}\tan^2 \mu/2\right)^2}{\tan \mu/2}} \langle \delta x^2 \rangle$

Quad Strength $\langle \delta \mu^2 \rangle = \frac{L}{\bar{\beta}} \boxed{\frac{\left(1 + 2\tan^2 \mu/2\right)\left(1 + \frac{2}{3}\tan^2 \mu/2\right)}{\tan \mu/2}} \left\langle \left(\frac{\delta k}{k}\right)^2 \right\rangle$

b.) Wake fields

The tools which exist to calculate wake fields are extensive. Even for slotted structures we have various 3-D codes (MAFIA ...) We do not yet have calculations of the Q's of cavities with damping slots However, D. Yu did talk about new work which uses MAFIA + analysis to calculate Q approximately. Initial results are encouraging.

<u>Single Bunch Wakes</u>

For very short bunches the wake fields are difficult to calculat in the "frequency domain" and in time domain.

Question: $Z(\omega)$ $\omega \to \infty$.
$W(\tau)$ $\tau \to 0$.

Single Cavity $Z(\omega) \sim \omega^{-1/2}$

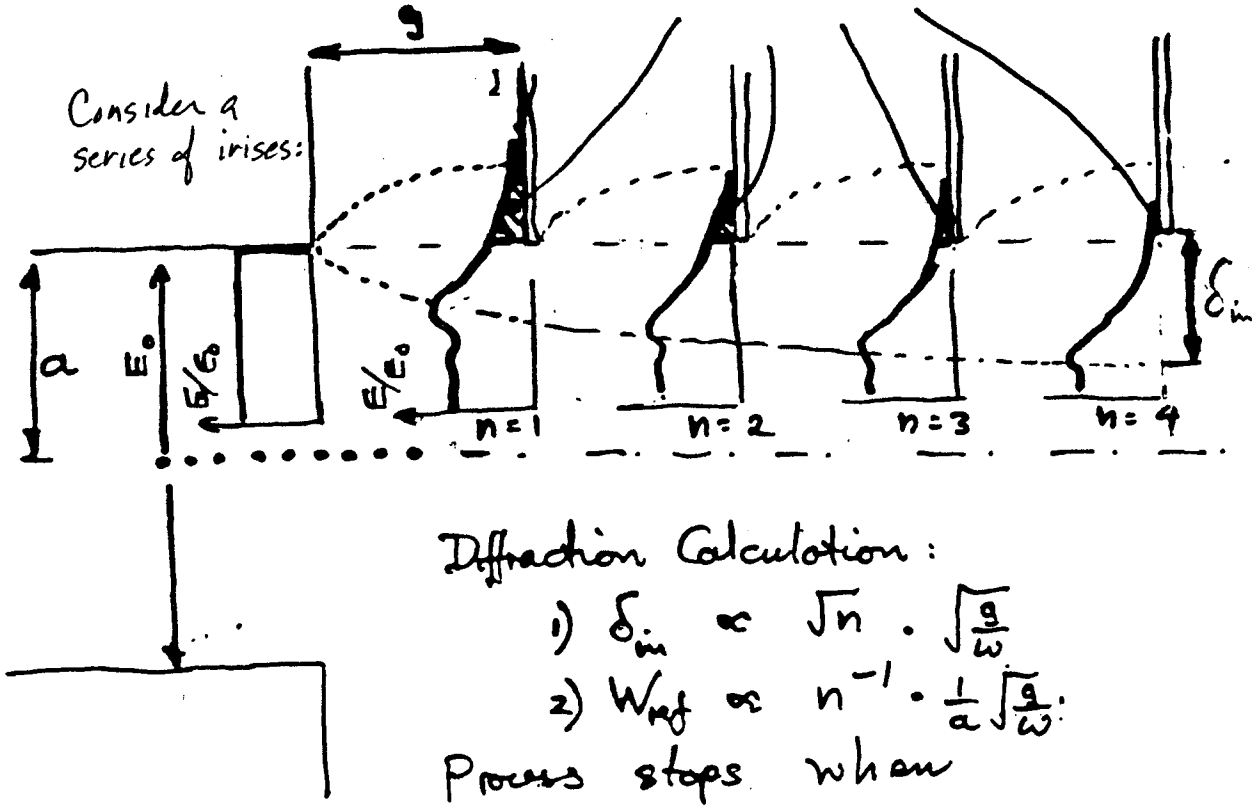
Periodic Structure. $Z(\omega) \sim \omega^{-3/2}$

what is the transition for structures of finite length.

B. Palmer, SLAC

Reflected power W_{ref}

Consider a series of irises:



Diffraction Calculation:

1) $\delta_{in} \propto \sqrt{n} \cdot \sqrt{\frac{g}{\omega}}$

2) $W_{ref} \propto n^{-1} \cdot \frac{1}{a}\sqrt{\frac{g}{\omega}}$

Process stops when

$\delta_n \lesssim a$

$$n_{crit} \approx \frac{a^2\omega}{g}$$

$Z_{1\ cell} \propto \omega^{-1}$

$$Z \propto W_{ref} = n_{crit}^{-1} \cdot \left(\frac{1}{a}\sqrt{\frac{g}{\omega}}\right)$$

$$Z_{n \gg n_{crit}} = \frac{1}{a^3} g^{3/2} \omega^{-3/2} \propto \omega^{-3/2}$$

Integrate for short bunch $\rightarrow$ $k \approx \frac{1}{\pi\epsilon_0}\frac{1}{a^2}$ independent of σ_z, g

This is the same (approx at least) as k for short bunch in resistive wall tube (indep of σ_z, ρ).

The high-frequency impedance of arbitraty azimuthal symmetric structures.

S. Heifets
CEBAF

periodic array of Irises.

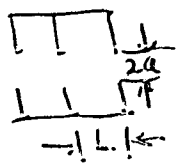
$$\mathrm{Re}\, Z = \frac{Z_0}{\pi}\left(\frac{L}{\pi K a^2}\right)^{3/2} \propto \omega^{-3/2}.$$

(1°) Start with a straight pipe:

$$\vec{E}_\omega = \vec{E}_\omega^{\,part} + \vec{E}_\omega^{\,rad}$$

where $\vec{E}_\omega^{\,part}$ = synchronous component of the field of a free particle

$\vec{E}_\omega^{\,rad}$ = radiated wave which gives the impedance

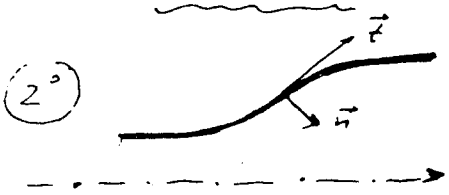


The normal component $E_{\omega,n}^{part} = \frac{e}{cr} e^{ikz}$

$$B_{\omega,\varphi}^{rad} \sim E_{\omega,r}^{rad} \sim E_{\omega,z}^{rad} \sim 1/r^2$$

Conclusion: $\vec{E}_{n,\omega}^{\,part}$ does not generate $\vec{E}_\omega^{\,rad}$

(2°)



Arbitrary boundary $r = a(z)$

Boundary conditions

$$\vec{E}_{n,\omega}^{\,rad} = 0; \quad \vec{B}_{t,\omega}^{\,rad} = 0; \quad \vec{E}_{\omega,t}^{\,rad} = -\vec{E}_{\omega,t}^{\,part}$$

$$E_{\omega,z}^{rad} = -\int dS' \frac{\partial G}{\partial r'} E_t^{part};$$

where

$$G = \frac{i}{8\pi}\int_{-\infty}^{\infty} d\tau\, e^{i\tau(z-z')} J_0\left(r\sqrt{k^2-\tau^2}\right) H_0^{(1)}(r'\ldots$$

(3°) Examples:

- A cavity (Z_ℓ, Z_r)
- Transition cavity $\Leftrightarrow$ step regimes
- Periodic structure
- Taper

the conjecture works O.K.

c) BNS damping.

the basic idea: To Arrange the focusing forces to compensate for wake field forces when the bunch is rigidly offset.

For an offset $\hat{x}$ of both head and tail.
(short bunch)
dipole deflecting wake (away from axis)

$\Rightarrow$ More focusing on tail so that $\Delta K \hat{x}$ cancels wake force.

Two part Model.

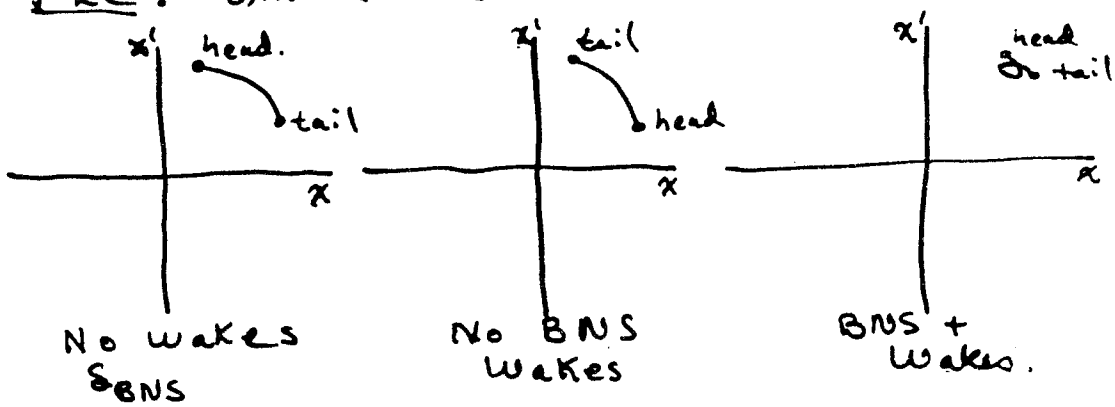
$$\frac{e^2 N\, W(2\sigma)\, \beta^2}{8E} = \delta_{BNS}.$$

δ_{BNS} = 1/2 spread in $\frac{\Delta p}{p}$ (correlated)

= " " " $\frac{\Delta k}{k}$ "

$k = 1/\beta$

<u>ILC</u>: small wake ~ SLC at 1×10^{10}



phase space at end of linac. for a coherent oscillation Oscillation stays coherent, very linear wakes $\Rightarrow$ ~ 2 part Model.

V. Balakin

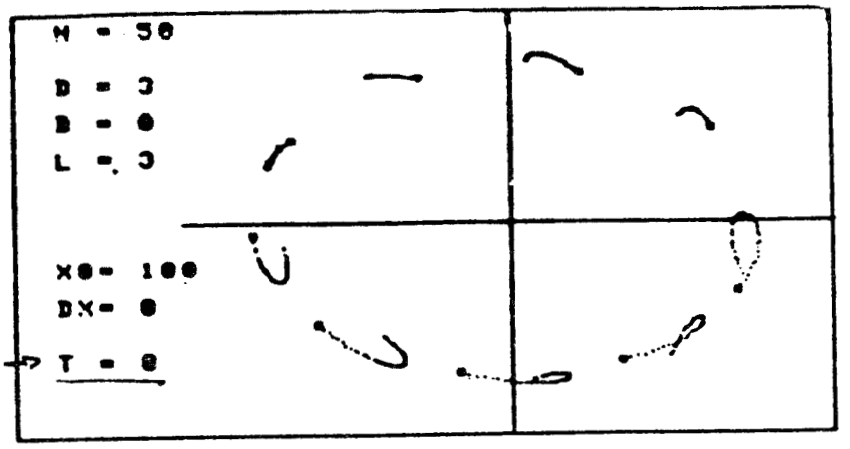
BNS damping

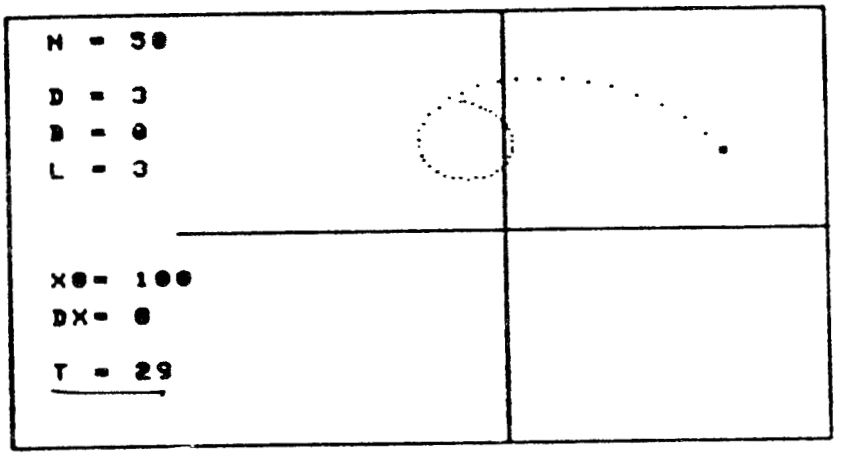
Long bunch. rather nonlinear transverse wakefield.

+

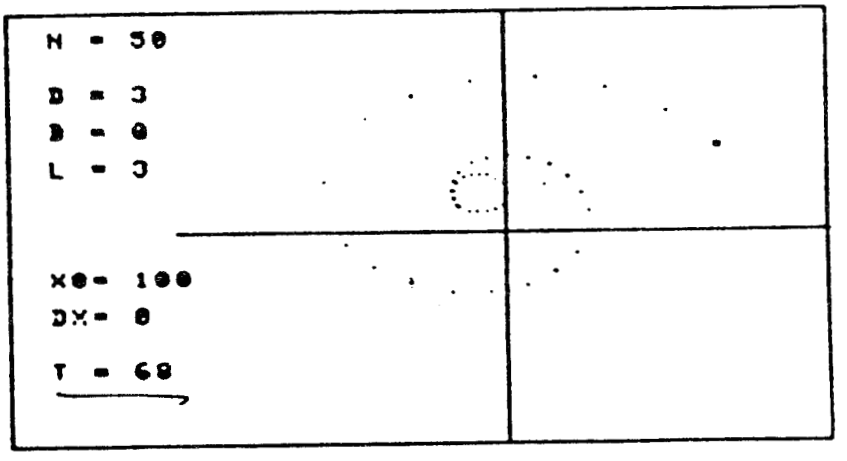
Linear energy correlation.

time →



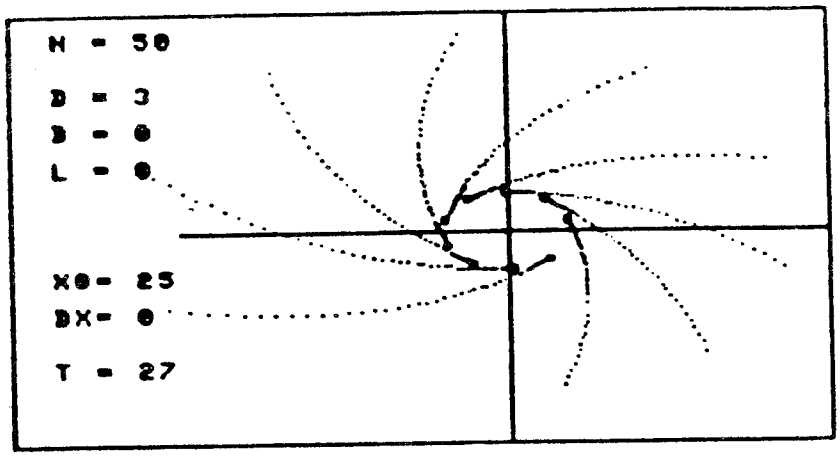


Dilution shown here leads to tight tolerances

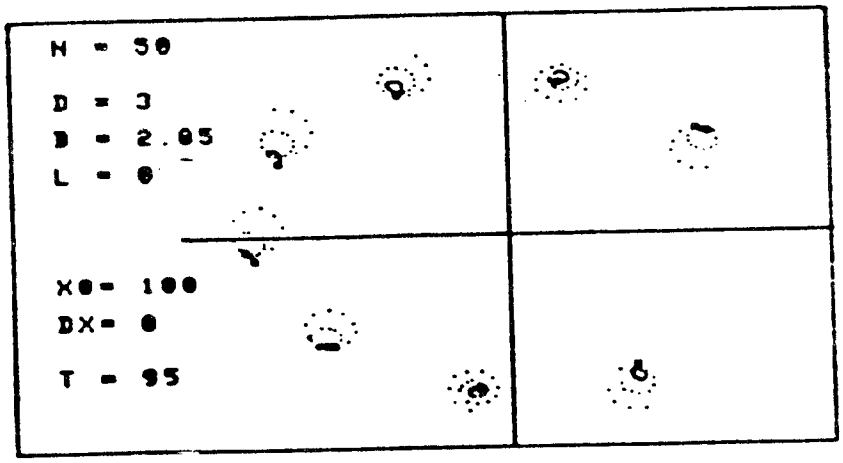


V. Balakin, cont'

No BNS damping → large tail growth

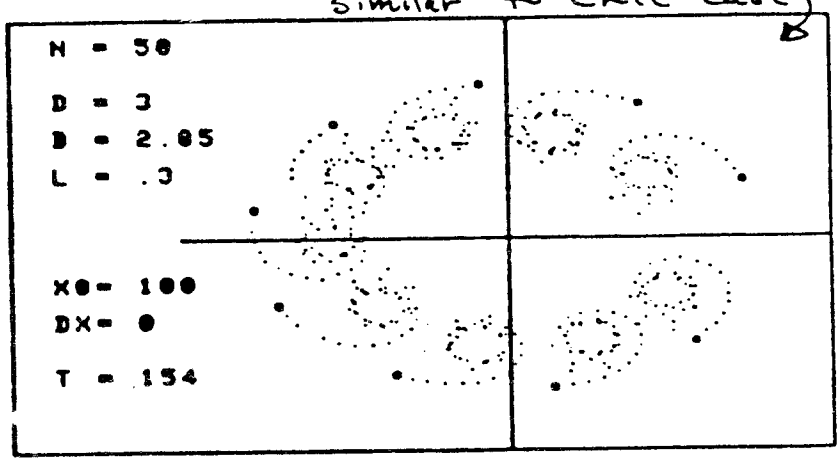


Quadratic correlation to match wake field "autophasing" → coherence remains



ADD Linear correlation to the quadratic part. → coherence + damping

similar to CHIC case)



D. Chernin, SAIC, McLean, VA

Wakefields + Jitter + BNS

Linear Wakefield
uniform bunch.
Magnet jitter
BNS damping
due to energy spread

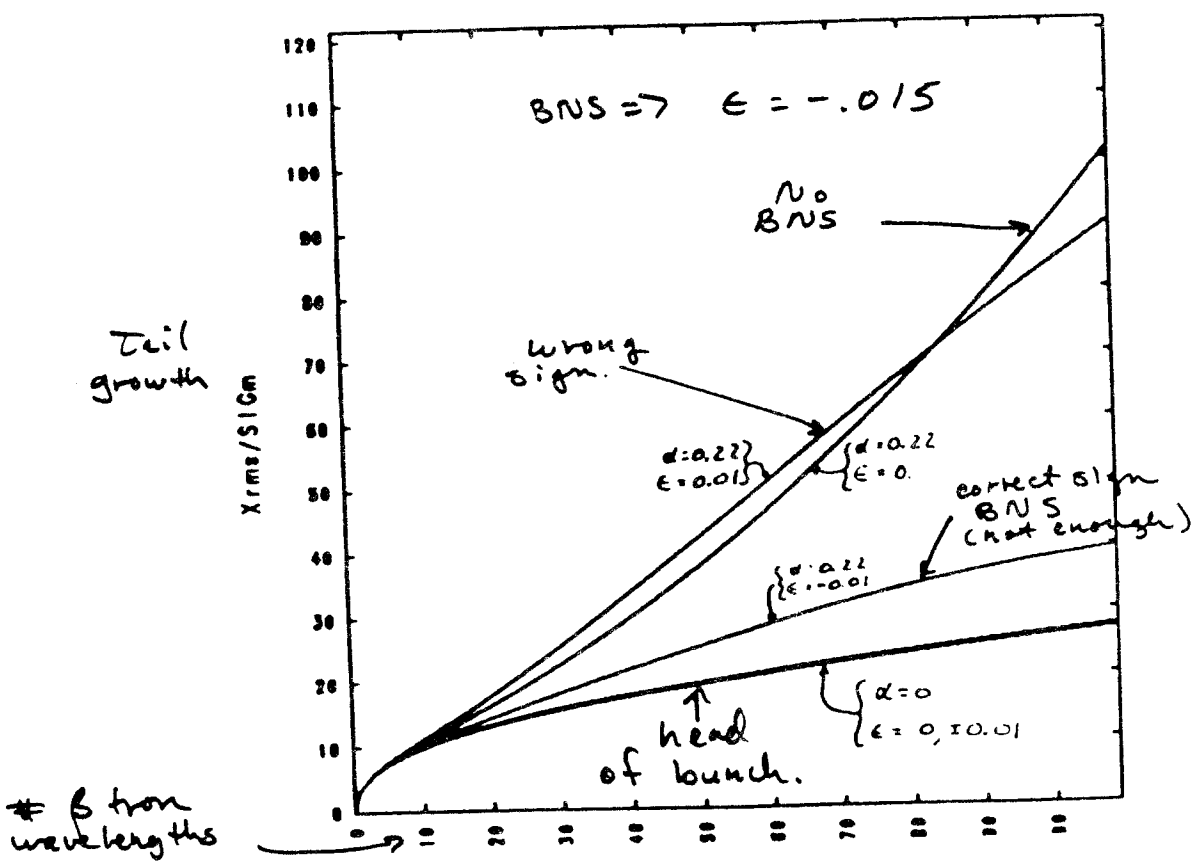
Numerical Example

Linac: 5 - 500 GeV in 3 km
$f_q = 4 \times 2.856$ GHz

Bunch: $N = 10^{10}$
$l_b = 1$ mm
$E = E_0 (1 + G\xi)(1 + \epsilon \xi / l_b)$
within bunch.

Focusing: $\mu = \pi/2$
$\lambda_\beta = 5\,\mathrm{m}\,[E/5\,\mathrm{GeV}]^{1/2}$

Wake field: $W(1\,\mathrm{mm}) = 2.36 \times 10^{17}$ V/C-m^2
$\alpha = 0.22$



Simulation Results for SLC (K. Bane)

To obtain detailed results it is useful to slice the bunch at many points along its length to simulate this behavior.

You see the dramatic improvement from → $\Delta K = 0$, No BNS → to → $\Delta K \neq 0$ BNS →

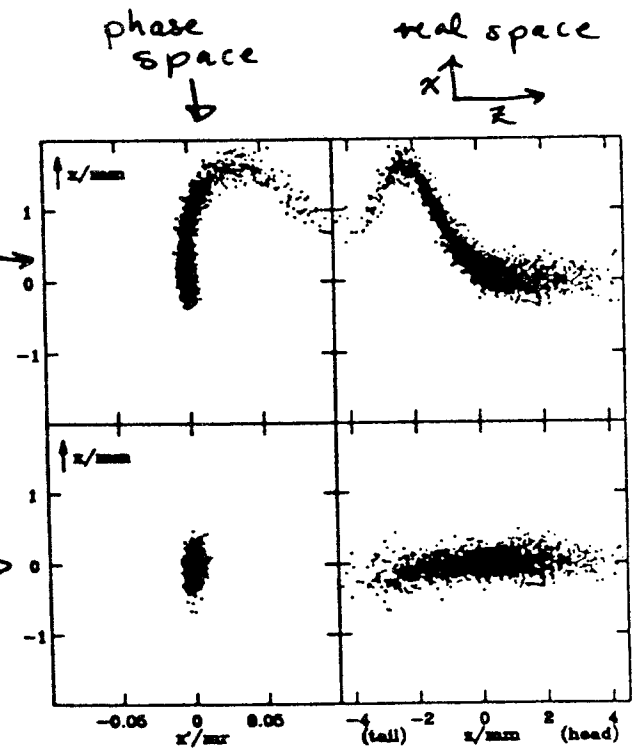
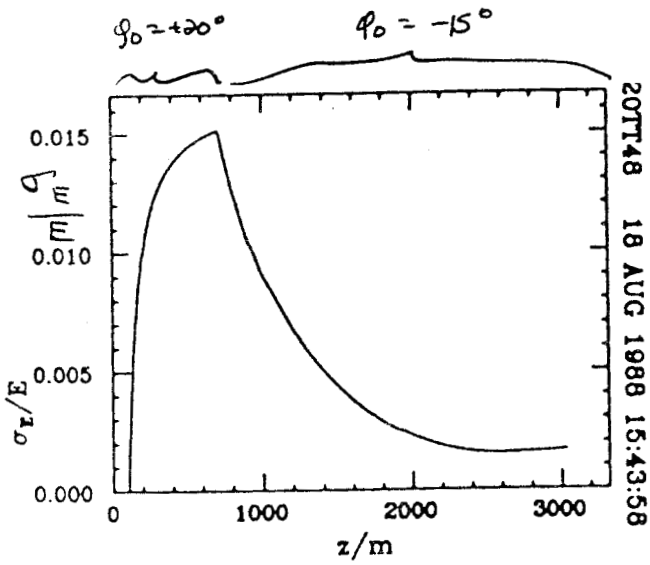
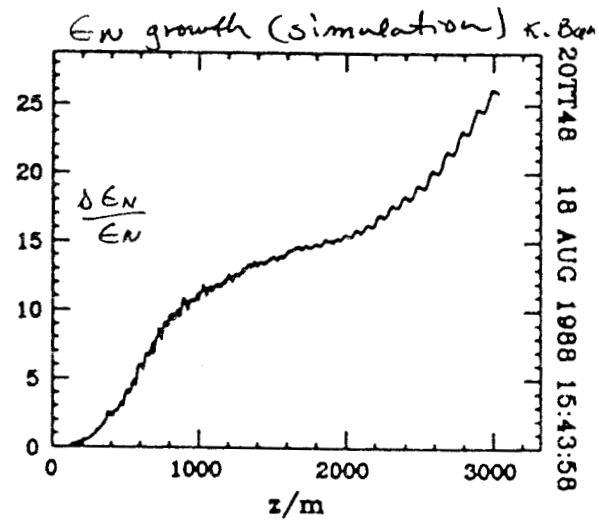


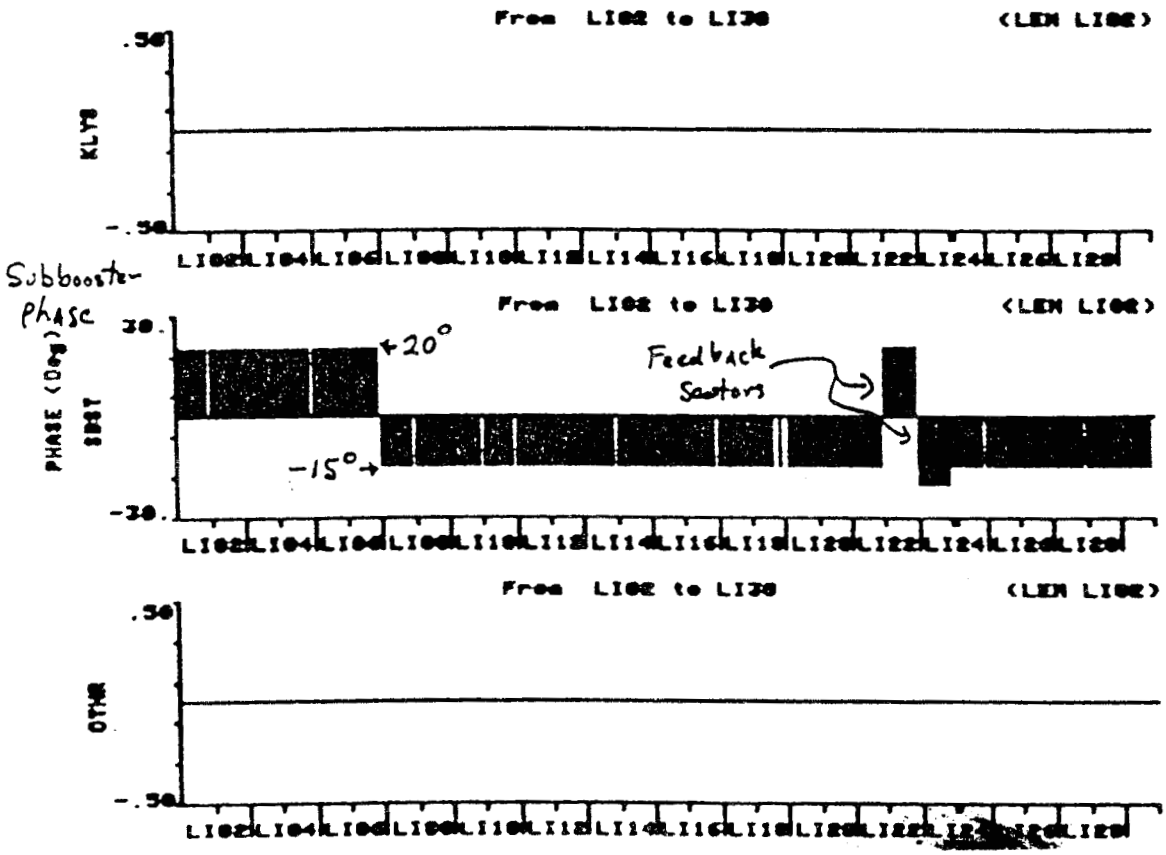
Fig. 11. Scatter plot of two beams at a point near the end of the SLC linac where r is at a minimum; one beam has not been Landau damped (the top two frames), the other has been (the bottom two frames). In both cases $N = 5 \times 10^{10}$ and $\sigma_z = 1.5$ mm; both beams were launched with the offset $x_0 = 0.1\sigma_{x0}$. In the Landau damped case $\Delta E = 1.0$ GeV, $\phi_0 = -20°$. The two left frames display the beams in phase space; the right two frames show them projected in the $x - z$ plane (the head is to the right).

SLC experiment: the set-up of BNS phases and predicted ϵ growth.
(J. Seeman et al)





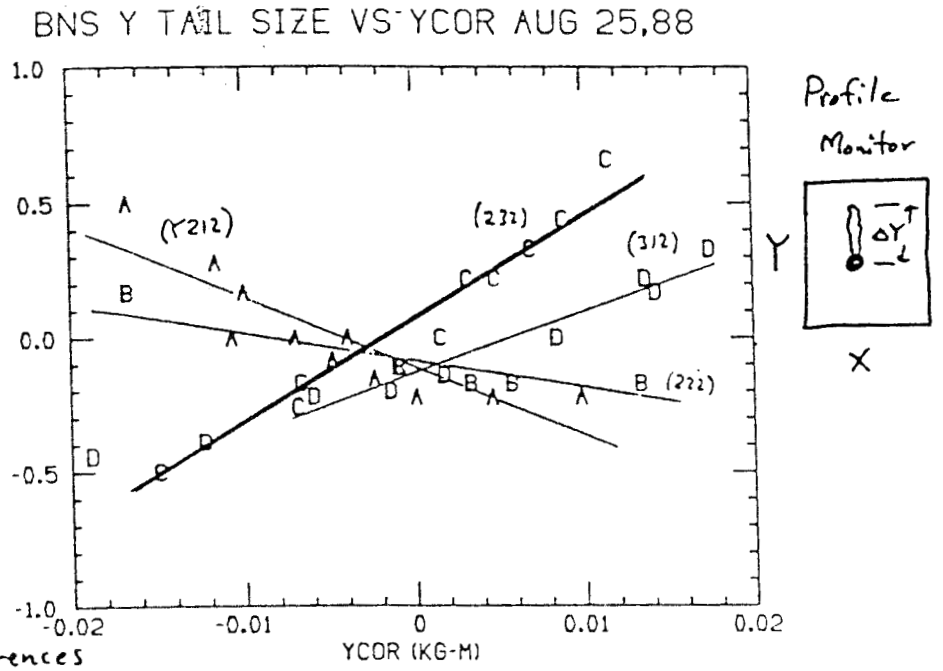
LEM KLYSTRON AND SUBBOOSTER PHASE



SLC experiment: The effect of correctors (trajectory) on the growth of the tail.
(T. Seeman, et al)

BNS

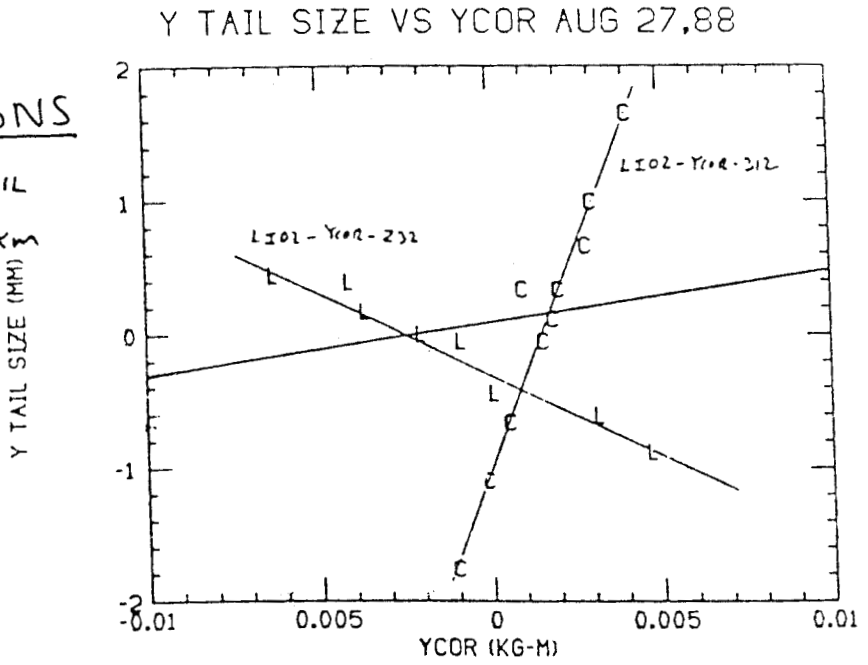
ΔY_{TAIL} at 3 km



Note differences in scale.

No BNS

ΔY_{TAIL} at 3 km



Y Dipole Strength

d.) Tolerances on magnet misalignments, BPMs, accelerator structures.
These are "fixed" in time or correctable with feed back systems.

a.) Magnet misalignments, BPMs.

1.) Weak wakefields, small $\frac{\Delta K}{K}$,

a.) coherent β-tron oscillation must not dilute beam.

initial offset $\hat{x}_0 \ll \frac{2\,\sigma_\beta^{final}}{(\delta\psi)\,N_f}$ size at end of linac.

chromatic phase advance/cell; # quads

or $\hat{x}_0 \ll \sigma_\beta$ if $\frac{N_f\,\delta\psi}{2} \geq 1$

THC $\hat{x}_0 \ll 2\sigma_\beta$

b.) chromatic dilution due to orbit correction.

$$\Delta x_{rms} < \frac{\sigma_\beta^f}{\delta\psi}\sqrt{\frac{2}{N_f}}$$

chromatic effect on orbit → dispersion dilutes phase space, may be very nonlinear dispersion & difficult to correct. Above estimate is for linear term. If linear, may be able to correct.

THC: $\Delta x_{rms} \ll 45\,\sigma_\beta \simeq 30\,\mu m$.

2.) Strong wakefields, large $\frac{\Delta K}{K}$.

a.) coherent β-tron oscillation.

BNS damping can improve situation here. Must do simulation of particular case.

Example CLIC + RF quads

$$\Delta x_0 \approx 44 \mu m.$$

b.) "chromatic" dilution due to orbit correction (any $\frac{\Delta K}{K}$ will do!)

Interpret $\delta\mu$ as variation of phase advance/cell due to anything.

$$\Delta x_{rms} < \sigma_\beta \quad \text{if} \quad \delta\mu = \sqrt{\frac{2}{N_q}}$$

Need more simulations to test orbit correction strategies.

If trajectory does not stay coherent, difficult to measure + correct. Wake fields compound the problem.

Large spreads in β-tron focusing tend to decrease orbit tolerances to $\lesssim \sigma_\beta$

(c) Jitter

1) Magnets. (QUADS)

[Injection jitter for weak wakes.

$$\hat{x}_0 \ll \sigma_\beta(0)$$

For strong wakes. + BNS damping

$$\hat{x}_0 \gtrsim \sigma_\beta$$]

QUADS: weak wakes. d_{rms} = rms jitter focal length

uncorrelated $\Rightarrow$ $d_{rms} \ll \sigma_\beta^f \frac{F}{\beta} \sqrt{\frac{3}{N_b}}$

β function.

THC $d_{rms} \ll .02\,\mu m = 20\,nm$
uncorrelated

for correlated effects. $\sim \beta$, $2\pi s_0 < \lambda < 2\pi\beta_f$

correlated $\rightarrow$ $\boxed{d < \left(\frac{\gamma_f}{\gamma_i}\right)^{1/2} \left(\frac{\beta_f}{L}\right)^{1/2} \sigma_\beta^f}$

THC $d \ll .7\,\mu m$

Strong wakes + BNS damping.

CLIC simulation. $d_{rms} \lesssim 1.4\,\mu m$.

Physics: phase space is diluted $\Rightarrow$.
loss of memory of early kicks. If this happens only over a few QUADS

$$d_{rms} \ll \sigma_\beta \frac{F}{\beta}$$

(e) Jitter (& Alignment)
2.) Accelerator Sections

Alignment. (offsets)

<u>Weak wakes:</u> less servere than QUADS.

Offset Structure Kicks tail for $L_{structure}$.

Offset QUAD Kicks head $\Rightarrow$ wake for L_{linac}!

Also chromatic effects of QUADS.

<u>Strong wakes</u>

Alignment of accelerator structures more important.

CLIC : $d_{rms} \simeq 11\mu m. \sim \sigma_\beta$

Jitter is similar to alignment error here.

except <u>Jitter of RF Kicks</u>

<u>Weak wakes.</u> $\frac{(\delta p_\perp)_{rms}}{\Delta p_\parallel} << \frac{\sigma_\beta^f}{\beta_f} \sqrt{N_s} <$

jitter

momentum gain / section.

# of section

TLC : $\frac{(\delta p_\perp)_{rms}}{\Delta p} << 3\times10^{-6}$

(SLC : 6×10^{-5})

<u>Tilt of Structure.</u>

$$\Delta p_\perp = \theta \Delta p$$

For Jitter $\delta \Delta p$, $\delta p_\perp = \theta\, \delta(\Delta p)$

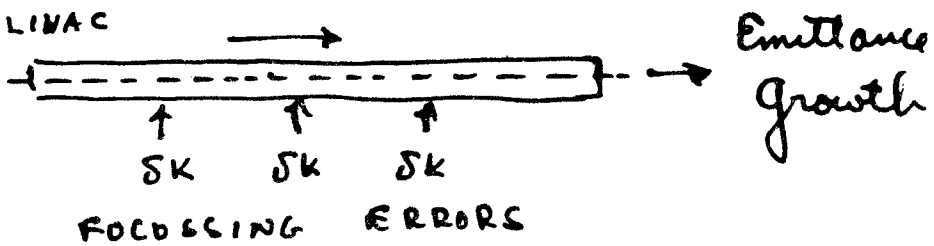
For $\frac{\delta(\Delta p)}{\Delta p} \simeq 10^{-2} \Rightarrow \boxed{\theta \lesssim 3\times10^{-4} \text{ rad.}}$

$\Rightarrow \boxed{300\mu m \text{ over } 1m}$

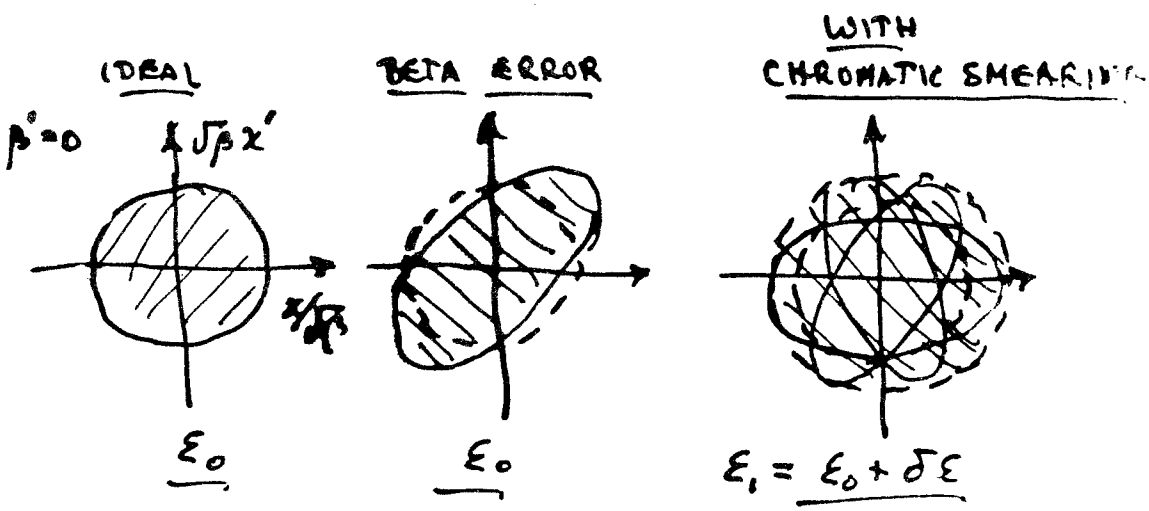
M. Sands
08/12/88

EMITTANCE GROWTH from RANDOM FOCUSSING ERRORS

THE PROCESS



GROWTH MECHANISM



CAN SHOW

$$\left\langle \frac{\delta\epsilon}{\epsilon_0} \right\rangle = \left\langle \left(\frac{\delta\beta}{\beta} \right)^2 \right\rangle$$

[Expectation value for random sample]

QUADRUPOLE TOLERANCE FOR TLC

Say $\frac{\delta\varepsilon}{\varepsilon} \approx 0.1$

with $N = 500$

Tolerance: $\frac{\delta k}{k} = 7 \times 10^{-3}$

---

ok for magnetic quads.

FOR CLIC

Is such a tolerance reasonable for r.f. quads?

OTHER SOURCES

(1) Energy "mismatch" --- looks ok.

(2) Quadrupole wake fields.

? ? ?

L) Flat beams: Coupling

After the developements in the Final Focus group we are probably stuck with flat beams to some degree.

But everybody worrys about them!

Stop worrying & start calculating.

Big Problems: Damping Ring
Final Focus

Why? sextupoles + vertical offsets yield skew quads

still effects are very linear => skew quads can correct.

Why so linear? Beam is tiny!

Linear Coupling in Linac (rotated quads)

$$\theta_{rms} \ll \frac{\sigma_y}{\sigma_x} \frac{2F}{\beta} \frac{1}{\sqrt{N_\gamma}}$$

THC $\theta_{rms} \ll 3$ mrad.

$\lesssim$ 1 mrad will do.

Why? $\frac{\sigma_y}{\sigma_x} = \frac{1}{10}$

what is the real problem? The absolute size (σ_y) vertically sets all tolerances. Direct vertical dilution not so much skew effects. Final Focus needs skew knobs.

(h.) Multibunching.

(i) Must control energy from bunch to bunch.

⇒. Strategy to get it about right.

⇒. Measurements

⇒. fine tuning strategy.

Tolerance on $\frac{\Delta E}{E} \lesssim 10^{-3} \simeq \frac{\Delta p}{p}$ in a bunch

Need much more work here. Nice to have knobs to vary the timing of the RF pulse for each (or a few) sections.

⇒ Tolerance $\frac{\delta N_{TOT}}{N_{TOT}} \leq \frac{\Delta E/E}{\text{loading}}$.

$$\lesssim 10^{-2} = \frac{10^{-3}}{.1}$$

individual bunches might vary by larger amounts. Most severe for <u>last</u> bunch.

Beam Breakup.

1.) Drive beams.

2.) Main Linac.

H. Henke — inverse Laplace transform (using residue calculus)

CERN

$$X_n(z) \sim \frac{C_1^{n-1}}{(n-1)!}\left[\frac{d^{n-1}}{ds^{n-1}}\frac{s e^{sz}}{(s+jk)^n}\Big|_{s=jk} + \frac{d^{n-1}}{ds^{n-1}}\frac{s e^{sz}}{(s-jk)^n}\Big|_{s=-jk}\right]$$

Multibunch BBU in CLIC drive beam due to resistive wall of transfer cavities.

$\Downarrow$

term of highest order in z

$$= \frac{jk\, e^{jkz}}{(j2k)^n} z^{n-1}$$

$$X_n(z) \sim \mathcal{O}\left[\left(\frac{C_1 z}{j2k}\right)^{n-1}\frac{1}{(n-1)!}\begin{Bmatrix} j\sin kz \\ \cos kz \end{Bmatrix}\right] \quad \text{for } n = \begin{Bmatrix}\text{even}\\ \text{odd}\end{Bmatrix}$$

magnitude

$$\boxed{|X_n(z)| \sim \frac{1}{(n-1)!}\left(\frac{C_1 z}{2k}\right)^{n-1}}$$

CLIC: $n = 10$

$z = 10\ \text{km}$

$C_1 = 2.7\cdot 10^{-3}\ \text{m}^{-2}$

$k = 0.126\ \text{m}^{-1} \quad \hat{=} \quad \lambda_\beta = 50\ \text{m},\ 2L = 12.5\ \text{m},\ B' = 6\ \frac{T}{m}$

in a 90° FODO with $m = 0.1$

Note $C_1 \propto \frac{1}{h^3}$

Cure: increase h + BNS.

$$\boxed{\frac{C_1 z}{2k} = 107} \rightarrow \boxed{|X_n| \sim 5\cdot 10^{-13}}$$

! don't forget that's only the highest contribution of bunch 1. !

two-particle model gives $\left|\frac{X_2}{X_0}\right| = \frac{C_1 z}{2k}$

Control of multibunch beam breakup in TLC subsystems

Injection accelerators (0.2 → 1.8 GeV) 2.856 GHz

strong focusing sufficient; would not need to use damped acceleration cavities

25 MeV/m $\beta = 2.0$ m (constant)

Damping rings (1.8 GeV) 1.428 GHz

Damped acceleration cavities

$Q = 30$, $\bar{\beta} = 1.2$ m

Preaccelerators (1.8 → 16 GeV) 2.856 GHz

Damped acceleration cavities

or

Very strong focusing

20 MeV/m $\beta_0 \approx 2.0$ m $\beta = \beta_0 \left(\frac{\gamma}{\gamma_0}\right)^{1/2}$ $Q \lesssim 30$

Main linacs (16 → 500 GeV) 11 to 17 GHz

Damped acceleration cavities + placing bunches near wake zero crossings

A spread in transverse mode frequencies in different cavities can help, too. (see next page)

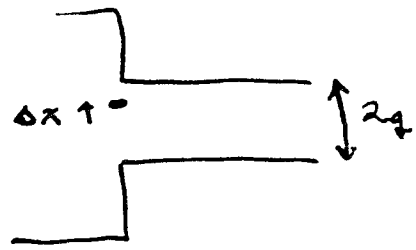
170 MeV/m $\beta_0 \approx 3$ m $\beta = \beta_0 \left(\frac{\gamma}{\gamma_0}\right)^{1/2}$

$Q \lesssim 25$, fundamental $\perp$ mode within 0.5% of zero crossing

Misc Topics

1.) RF Kicks due to collimator. (K. Bane)

$$\Delta\theta_{max} = \frac{2 N r_e}{\sqrt{2\pi}\,\gamma\,\sigma_z}\left(\frac{\Delta x}{g}\right)$$



locally $\propto I(z)$

$$\Delta\theta = .6\,\mu\text{rad}\left(\frac{\Delta x}{g}\right)$$

$N = 1.5\times10^{10}$
$\gamma = 10^6$
$\sigma_z = 50\,\mu m$

Scraper $\pm 5\sigma = g = 10\sigma$

Δx (typical) $\sim \sigma$
$\Rightarrow \frac{\Delta x}{g} \simeq \frac{1}{10}$ no matter the σ

perhaps can do $\frac{\Delta x}{g} \simeq \frac{1}{100}$ but thats about it.

$$\Delta\theta < \frac{\sigma_{beam}}{\beta}$$

THC $(\sigma_x, \sigma_y) \sim (1\mu m, 10\mu m)$
$(\beta_x, \beta_y) \sim (20m, 20m)$

$$\Rightarrow \left(\frac{\sigma_y}{\beta}, \frac{\sigma_x}{\beta}\right) = (.5\times10^{-7}, .5\times10^{-6})$$

Larger $\beta \Rightarrow$ effect get worse. $\propto \beta^{-1/2}$

In the case above. $\Delta\theta_y \sim \frac{\sigma_y}{\beta}$

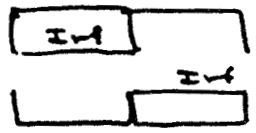
$\Delta\theta_x \sim \frac{1}{10}\frac{\sigma_x}{\beta_x}$ ~ OK.

Gets worse for bigger beams & bigger jaws.

but we may gain a bit on steering accuracy.

Misc

2.) Jitter of transverse kicks due to dark current



Consider an rf dark current.

I_{rf} at radius a = iris radius

at one location azimuthally.

random positions & magnitudes.

Jitter of Rf kicks yields

a tolerance on $\Delta E_\perp$ or

$$V_\perp = V_\perp^{Tol}.$$

$$V_\perp^{Tol} = I_{rf}^{Tol} R_\perp$$

$$\frac{R_\perp}{Q} = \frac{K_\perp}{4\omega_\perp}$$

$$\Rightarrow \quad I_{rf}^{Tol} \leq \frac{V_\perp^{Tol} 4\omega_\perp}{K_\perp Q}$$

$$eV_\perp^{Tol} = 3\times10^{-6}\,\Delta E_{gain}.$$

$$V_\perp = \sqrt{N_{cell}}\, V_{cell}$$

Add up effect for 1 section. use tolerance section by section

$$V_{cell} = \frac{3\times10^{-6}\,\Delta E_{gain}}{\sqrt{N_{cell}}} = 2\times10^{-7}\,\Delta E_{gain} = 70 \text{ Volts.}$$

For ThC

$$\boxed{\frac{I_{rf}^{Tol}}{cell} = \frac{.5}{Q} \text{ Amp}}$$

DAMPING RINGS AND SOURCES WORKING GROUP

Chairman: L. Rivkin SLAC

Secretary: T. Raubenheimer SLAC

Members and Contributors

C. Sinclair	CEBAF
J. P. Delahaye	CERN
M. Serio	Frascati
A. Mikhailichenko	Novosibirsk
F. Couchot	Orsay (LAL)
W. Vernon	UCSD
K. Bane	SLAC
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M. Lee	SLAC
P. Morton	SLAC
R. Warnock	SLAC
K. Thompson	SLAC

Summary of Damping Rings and Sources Group Discussions

Lenny Rivkin, Tor Raubenheimer

We first discussed the SLC experience and what could be learned from it. Our conclusion is that the SLC damping rings and electron gun work well. The biggest problems are: (1) the tight tolerances on the extraction elements, in particular the kickers, and (2) the mode of operation, namely, the use of the same linac for acceleration of both e^- and e^+.

Next we tried to compare the merits of the three damping ring designs presented in the plenary sessions: CLIC, VLEPP, and the TLC. We decided upon a few functions of merit: T_0/τ_y, $\gamma\epsilon_x$, $\alpha_p \frac{J_x}{J_\epsilon}\frac{I_3}{I_5}$, and $\gamma\epsilon_l$. See the summary talk (Lattice comparison) for details. We found that the CLIC and TLC designs were fairly similar, CLIC is optimized for faster damping and lower currents than the TLC, as it should be. The VLEPP lattice differed. It is a very small ring where the low emittance is achieved using a Chasman-Green type structure with strong, short-period wigglers. In this ring, the longitudinal emittance was 3 to 4 times that of the other two designs. We did not find any great advange of any of the specific lattices. We did conclude that wigglers are desirable if not essential. An example of a completely wiggler-dominated ring, designed at Frascati, suggests that much higher repetition rates are possible. Furthermore, high-field, short-period wigglers, such as those in the Novosibirsk design, would be the most helpful.

While discussing the rings, we also talked about the tolerances on the extraction system, specifically the kicker magnets. Fatin Bulos presented two kicker designs with 100 nsec pulses (off-on-off) that when used in a cancellation scheme would achieve the necessary tolerances. These designs are roughly 1 meter long. It was obvious, from this discussion and the previous talks on experiences with the SLC, that we would have to consider the kickers when designing the ring and not attempt to fit them in afterwards.

Next we turned our attention to e^+/e^- production, discussing two approaches. CLIC and TLC are considering conventional production schemes using an intense e^- beam with an energy $\sim$ 1 GeV. VLEPP plans to generate both e^- and e^+ with a method using undulator magnets.

Finally, we concluded with a discussion on impedances. Bob Warnock explained his work on the "free space" impedance and Karl Bane talked about the calculations and measurements of the longitudinal impedance of the SLC damping rings. At this time the SLC rings have an "effective" longitudinal impedance of roughly 1Ω; this is only a factor of 3–4 higher than what is desired for the next generation rings. Next, A. Mikhailichenko discussed the BEP storage ring under construction at Novosibirsk. This ring is designed to test techniques of achieving very low longitudinal impedances, and is calculated to have an impedance of 0.1Ω; it should become operational in the spring of 1989.

List of Damping Rings and Sources Talks

1. J. P. Delahaye, A. Mikhailichenko, T. Raubenheimer, "Comparison of Ring Proposals"
2. T. Raubenheimer, "Extraction Systems—Tolerances"
3. F. Bulos, "Extraction Systems—Kickers"
4. C. Sinclair, W. Herrmannsfeldt, "Electron Guns"
5. F. Couchot, W. Vernon, "Positron Production"
6. J. P. Delahaye, "Injector Systems"
7. S. Ecklund, J. Clendenin, "SLC Positrons"
8. R. Warnock, "High Frequency Impedance"
9. K. Bane, "SLC Ring Impedance"
10. A. Mikhailichenko, "BEP Model Ring"

DAMPING RING & SOURCES
for future LINEAR COLLIDERS

Working group:

K. Bane
F. Bulos
F. Couchot
J. Clendenin
* J.P. Delahaye
S. Eckhund
W. Gabella
P. Grosse-Wiesman
A. Kulikov
* A. Mikhailichenko
P. Morton
K. Thompson
** T. Raubenheimer
*** L. Rivkin
M. Serio
C. Sinclair
W. Vernon
R. Warnock

*** chairman ** secretary * permanent member

Summary:

1. Lessons from the SLC
2. Injector complex
   positron production

} J.P. Delahaye

3. Comparison of Damping Rings Proposals

} A. Mikhailichenko

4. Optics lattices comparison
   Extraction schemes and Tolerances
   Pre-Damping Ring ?

} T. Raubenheimer

5. Collective Effects
   Impedances
   Multibunch operation
6. Conclusion and Recommendations

} L. Rivkin.

Lessons from SLC experience

→ We can produce beams:

$$\gamma\varepsilon_x = (1.5 - 3.0)\times 10^{-5} \text{ m rad}$$
$$\gamma\varepsilon_y = (.07 - 1.5)\times 10^{-5} \text{ m rad}$$
Damping time = 3 msec

$N = 2\cdot 10^{10}$	$N = 3\cdot 10^{10}$
$\frac{\Delta E}{E} = 7\cdot 10^{-4}$	$\frac{\Delta E}{E} = 8\cdot 10^{-4}$
$\sigma_z = 7$ mm	$\sigma_z = 8$ mm
$\gamma\epsilon_z = .01$ m	$\gamma\epsilon_z = .016$ m

→ We can achieve the effective impedance

$$\left|\frac{Z}{n}\right| \simeq 1\,\Omega$$

$\left|\frac{Z}{n}\right|_{eff}$ found from long. microwave instability threshold

→ Small aperture vacuum chamber (high field magnets) with low impedance

What has to be improved in a future design

① <u>Extraction Tolerances</u>

- Relax tolerances on elements ($\frac{\Delta B}{B}$ kickers :
- Space for elements / compensation scheme!
- Special optics insertions

② <u>Overall Ring Impedance</u> :

- Constant cross sections of the vacuum pipe
- Minimize the number of bellows
- Beam Position Monitor optimization
- RF cavity optimized for small impedance

$$\left|\frac{Z}{n}\right| \sim 0.3 \text{ to } 0.5\ \Omega \qquad (f < 20\,GHz)$$

③ <u>Operability issues</u>

- Decoupling of e^+ production from main linac operation
- Avoid simultaneous acceleration of both kind of particles in the same linac.

TLC / CLIC Injector Complex

<u>Goal</u>: Production of two trains of k bunches for e^+ and e^- with N_b particles per bunch separated by a time interval τ (corresponding to an RF frequency F_{RF}) at a repetition rate f_R.

	k	N_b	σ_z	$\gamma\varepsilon_x$	$\gamma\varepsilon_y$	τ	F_{RF}	f_{rep}
	(-)	(10^9)	(μm)	(10^{-6} rad m)	(10^{-8} rad m)	(psec)	(GHz)	(Hz)
TLC	10	14	70	3.2	3.2	714	1.4	360
CLIC	10	5	200	3	100	333	3.0	1690

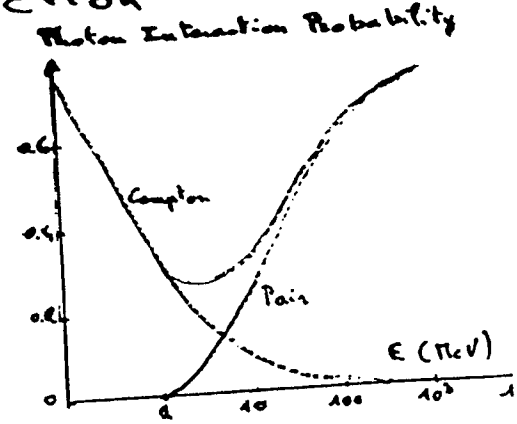
<u>Recommendation</u>: Injector complex and positron production separated as much as possible from main linac operation.
(SLC experience)

<u>Composition</u>: (for both kind of particles)

electrons : High Brightness guns in development
Damping Ring not obviously necessary

positrons : Various methods
Can we produce enough positrons at fast rate (accumulator?)
Pre damping ?

Positron Production



Basic process:

e^+/e^- pair production by interaction of photons in electromagnetic fields (nucleus of a target)

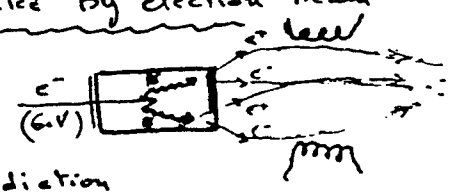
S. Echlund SLAC-PUB 4484

Creation of photons by:

① Electromagnetic shower initiated by electron beam

most common: SLC experience

Thick Target (6 wavelengths)

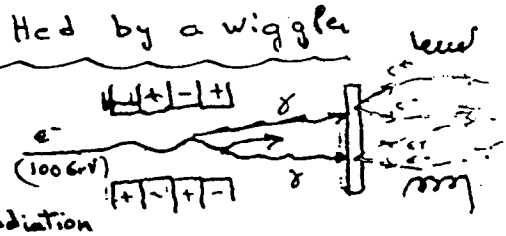


at fast rep. rate { High Power deposited - Radiation
⇒ Rotating Targets (Reliable?)

② Synchrotron Radiated emitted by a wiggler

Foreseen on VLEPP

Thin target (1 wavelength)



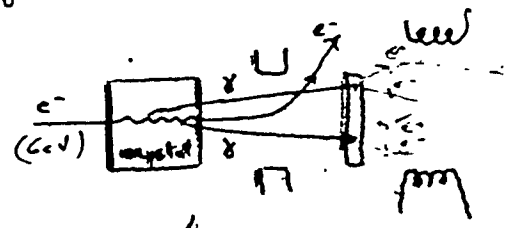
Small Power deposited and radiation

Needs large beam energies (> 100 GeV)

strong wiggler magnets (> 300 Tm!)

③ Channeling:

Same as above but using crystal channels as a wiggler with equivalent field of 3.10^4 T



Small beam energy, no strong wiggler necessary

Promising but crystal damage to be studied

Theoretical and Experimental study in progress at CA.

TLC / CLIC Position Production

Basic Process based on e^+/e^- pair production by photons generated by an electron beam hitting a target (e^- to e^+ converter)

Assuming a yield (following SLC experience)

for TLC : $N^+/N^- = 1.10^{-1}$ GeV $\Rightarrow N_b^- = 1.4\,10^{11}$ e^- GeV
as ~~theoretical~~ in SLC at 200 MeV and $\Delta p/p \sim \pm 5\%$

for CLIC : $N^+/N^- = 2.5\,10^{-2}$ GeV $\Rightarrow N_b^- = 2\,10^{11}$ e^- GeV
as available in the D.R. of SLC at 1.2 GeV and $\Delta p/p \sim \pm 1\%$
and observed in low energy (<1 GeV) e^+ production like LIL

Total beam power on the converter:

$$P = k\, N_b\, f_r\, E = \begin{cases} 80 \text{ kW} & (\text{TLC}) \\ 540 \text{ kW} & (\text{CLIC}) \end{cases}$$

~ 2 to 12 times P for SLC (47 kW)

Rotating Target (P. Sievers)

Electron guns performances

	Thermoionic (SLC)	Laser Driven Photocathode (BNL / Los Alamos)
N_b/bunch	10^{11}	5.10^{9}
Number of bunches	2	1
σ_z (mm)	3	1.5
$\gamma\varepsilon_{x,y}$ (rad m)	10^{-4}	5.10^{-6}
	Meets e^+ production requirements provided 1.4 to 2 GeV beam on converter	Could be used for e^- production thus possibly avoiding need for D. Ring.

Damping Ring found necessary for e^+ and e^-
(emittance ratio control for flat beams)

SLC Positron Production

Primary Electron Beam on Converter

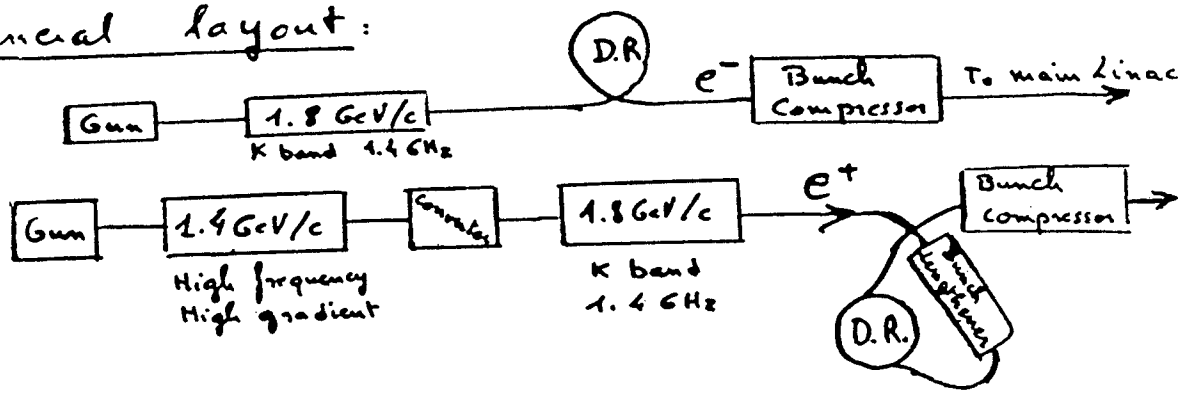
$E = 33$ GeV/c $\quad \sigma_x = \sigma_y = 0.6$ mm $\quad \sigma_t = 3$ psec

	Exit of the Converter	Flux Concentrator	Positron Capture	Return Line	Damping Ring
Energy (MeV)	–	–	54	200	1210
Limitations	–	$p_\perp < 1.3$ MeV $r_0 = 3$ mm	$p_\perp < 1.1$ MeV Geometry	$\frac{\Delta p}{p} < \pm 5\%$ $\frac{p_\perp}{p_z} < 4.6$ m	$\frac{\Delta p}{p} < \pm 2\%$ $\Delta t < 15$ ps
$\frac{N e^+}{N e^-}$ (calculated)	60	8.7	5.72	3.20	2.73
$\frac{N e^+ \text{ (calculated)}}{N e^- \text{ GeV}}$	1.8	0.26	0.17	0.097	0.082
$\frac{N e^+ \text{ (measured)}}{N e^- \text{ GeV}}$	–	–	–	0.075	0.027

The SLC still has large losses entering the DR.

TLC injector

General layout:



Primary Electron Beam on converter

$N_b^- = 1.0\ 10^{11} e^-$/ bunch at 1.4 GeV/c

$\sigma_x = \sigma_y = 0.6$ mm

$\sigma_z \leq 7.5$ psec (2.25 mm)

Positon beam acceptance

$\Delta p = 20$ MeV (between 5 - 25 MeV)

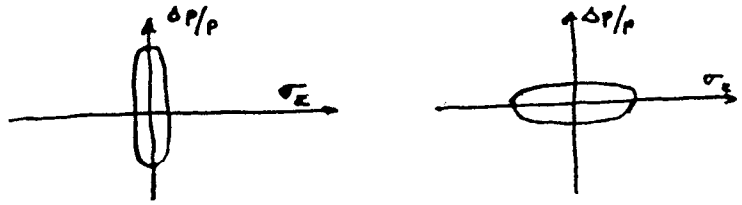
$\frac{p_\perp}{p_z} \leq 4.6$ mrad

} theoretical for $\frac{N_b^+}{N_b^-} = 0.1$ GeV

Phase spread improvement of the K band linac

$\Delta t \leq 30$ psec (15 psec for S band)

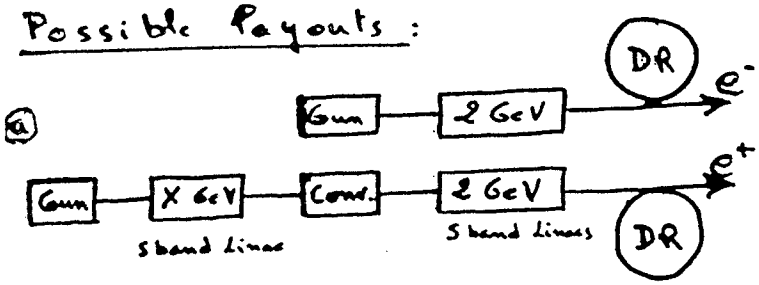
Reduction of momentum spread by Bunch Lengthener in the Linac to Damping Ring Line



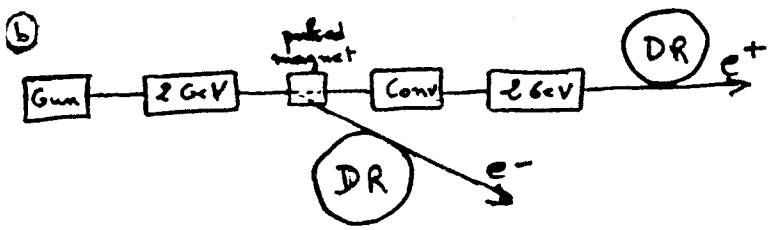
$\frac{\Delta p}{p} \leq \pm 1\%$

CLIC INJECTOR

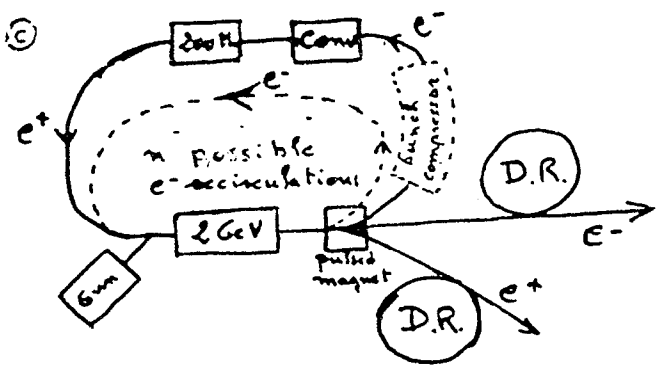
Possible layouts :



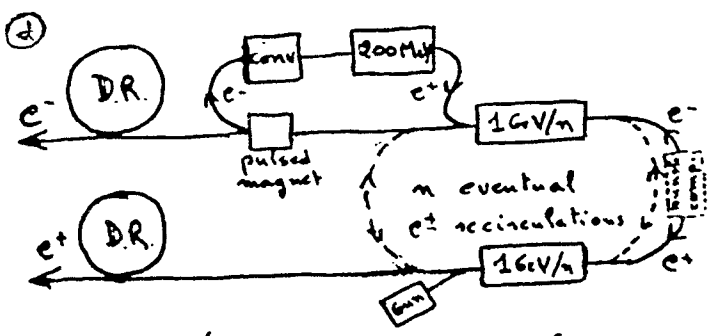
Simple operation
2 necessary guns
(4+X) GeV linacs
$N_b^- = 2.10^{11} e^-/X$



1 gun only
4 GeV linacs
$N_b = 1.10^{11} e^-$
1 fast pulsed magnet (1.7 kHz)
Gun intensity modulation
First linac pulsing at 2 f_r



1 gun only
2.2 GeV linacs
n possible e- recirculations
$N_b^- = 1.10^{11} e^-/n$
Same as above
200 MeV e+ return line



1 gun only
n possible e± recirculations
(2/n + 0.2) GeV linacs
$N_b = 1.10^{11} e^-$
Same as above
Standing Wave Acc. Struct.

Beam characteristics along injector chain

	Gun		Linac		Damping Ring	Bunch Compressor
	e^-	e^+	e^-	e^+		
N/bunch	5.10^9	1.10^{11}	5.10^9	5.10^9	5.10^9	5.10^9
σ_z (psec)	9	9	9	9	3	0.6
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	$\sim 10^{-6}$	$\sim 10^{-6}$

Preliminary Conclusions

Studies Recommendation

1. Injector complex and e^+ production separated from main linac are feasible for TLC and CLIC

2. Possible use of conventional (thermoionic) guns similar to SLC injector :
   Train of 10 bunches with $10^{11} e^-$/bunch (σ_z = 15 psec) ?

3. Unique gun facility for e^+ and e^- production is envisageable.
   Gun intensity modulation at a fast rate (1.7 kHz) ?

4. Conventional TW (SW) S or K band accelerating structure can be used.
   Beam loading of the 10 bunches of $1.10^{11} e^-$?

5. Fast repetition rate at 1.7 (3.4) kHz of RF power.
   Are Klystrons and Modulators available ?
   C W superconducting linac ?

6. Recirculation schemes allow reduction of beam intensity and accelerating structures.
   Study of e^+ return line and recirculation.

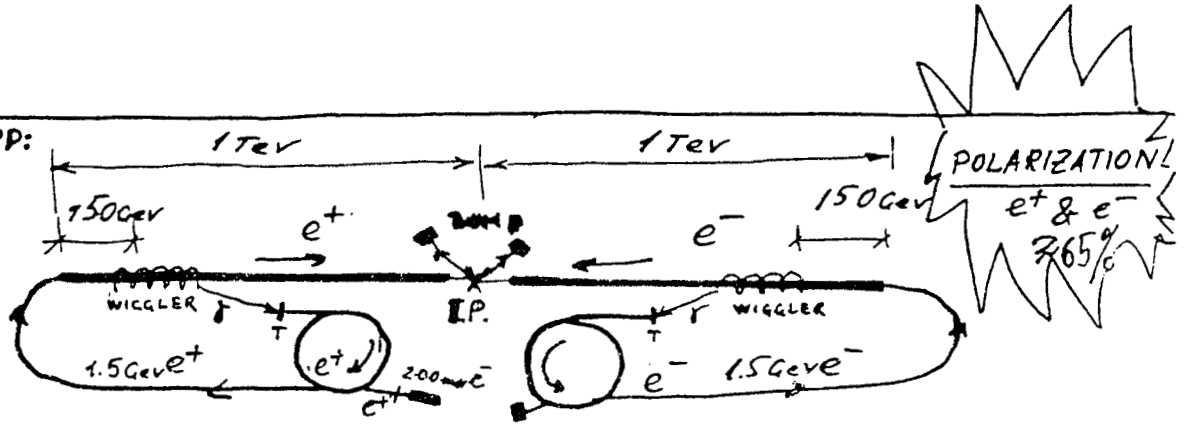
7. What is a realistic positron yield ?
   Influence of primary e^- beam energy and bunch length

8. The intensity fluctuation from train to train should not exceed 1% for energy stability in the linac.
   Intensity regulation schemes to be studied.

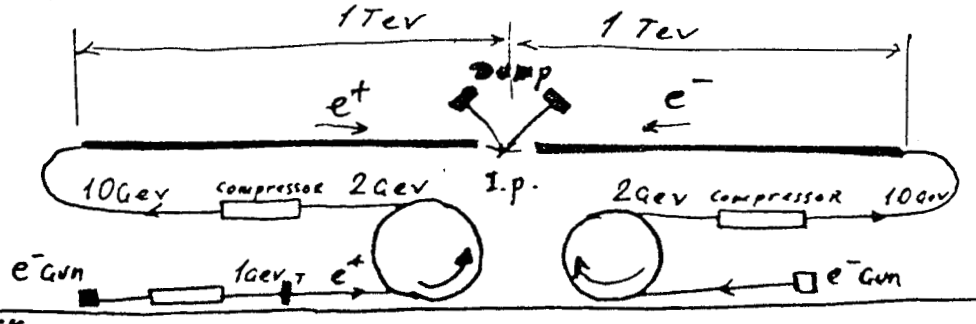
Projects: at now

LC:

VLEPP:



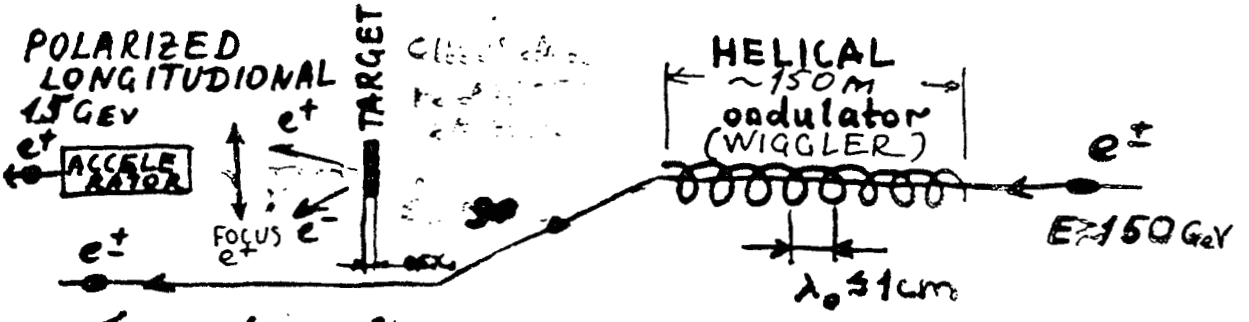
CLIC: + TLC



KEK:

[redacted]

(originally propozed in 1978, Balakin, Mikhailichenko)



loss of $E < 2\%$

~150 GeV

no perturbation of emittance

$$E_\gamma \sim \frac{2\gamma^2}{\lambda_0} \sim 20 \div 30 \text{ keV}$$

AFTER TARGET:

e^+, e^-, γ

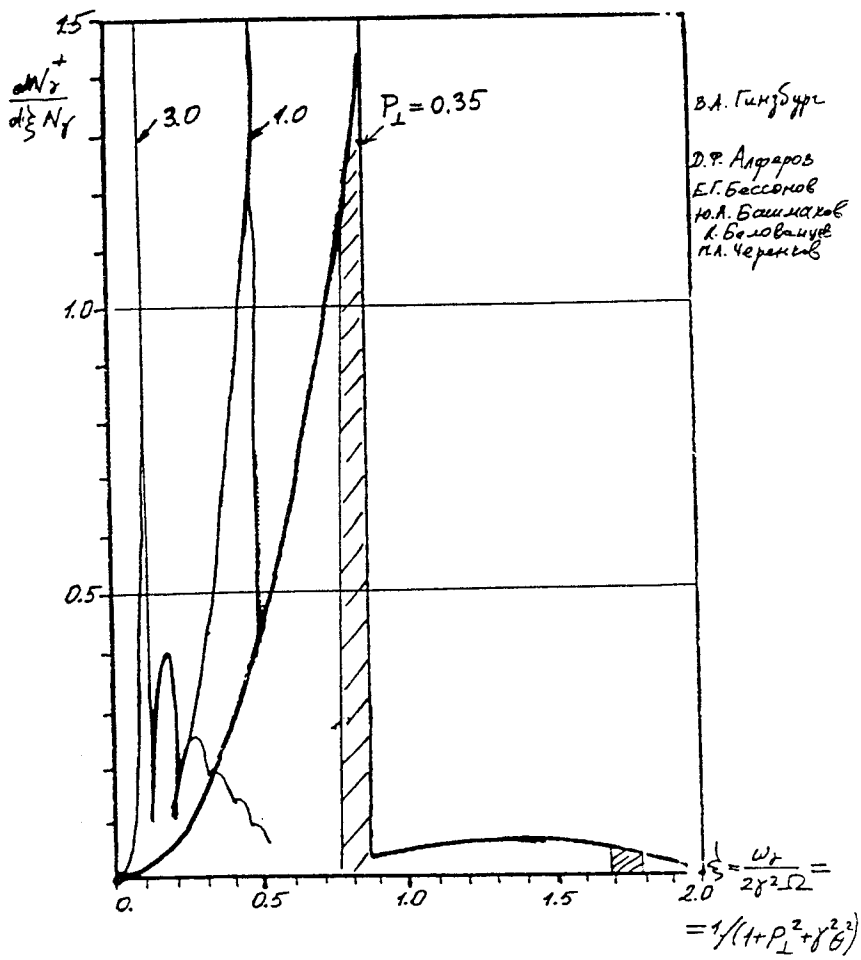
$e^+ \; e^-$ IS FULLY POLARIZED AT THE HIGH BOUNDARY OF ENERGY SPECTRUM

* FOCUSING & SEPARATION of $E^{+/-}$

** ACCELERATION

Spectral distribution of radiation

Спектральное распределение излучения



В.Л. Гинзбург

Д.Ф. Алфаров
Е.Г. Бессонов
Ю.Л. Башмаков
К. Болованцев
П.А. Черенков

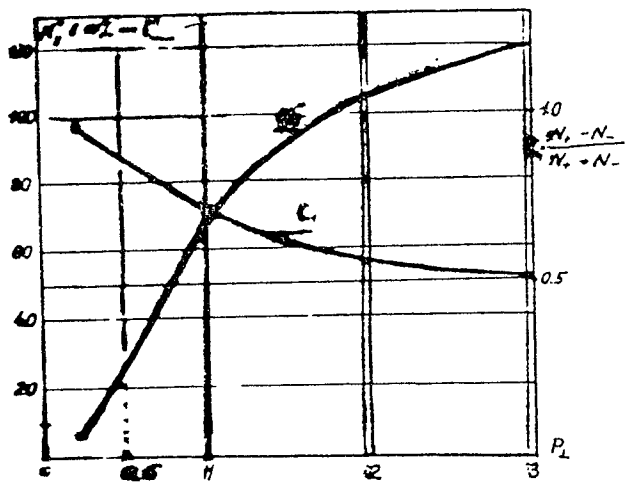
$$P_\perp = \frac{eH_\perp\lambda_0}{2\pi mc^2}, \quad \Omega = \frac{2\pi\beta_\parallel c}{\lambda_0}$$

$$E_\gamma = \frac{4\pi\hbar c\,\gamma^2\cdot k}{\lambda_0(1+P_\perp^2+\gamma^2\theta^2)}$$

Polarization

[redacted]

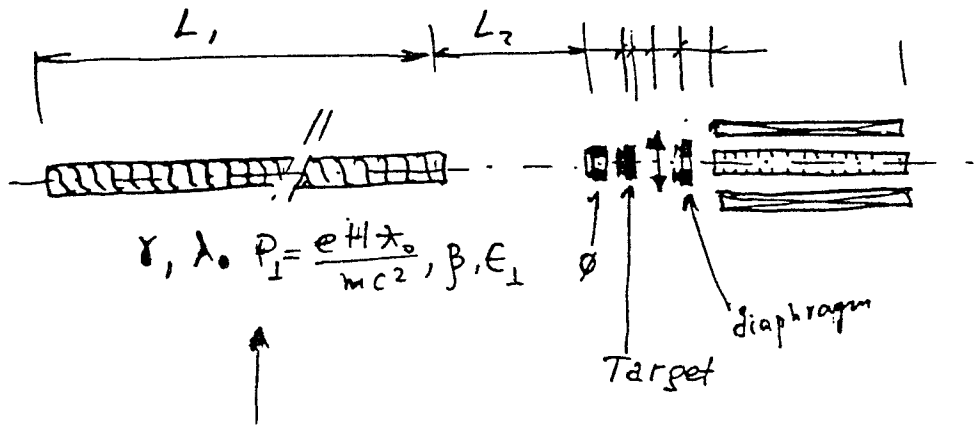
[redacted] Number of right-polarized [redacted] in 10% interval [redacted] maximum of the first harmonic.



$$P_\perp = \frac{e H_\parallel \lambda_0}{2\pi m c^2} = \beta_\perp \gamma = [\text{ГВ}\cdot\text{м}\cdot\lambda_0]$$

TESLA METER

Parametres for e^+/e^- production



Parametres

$\epsilon_\perp$ – emittance

β function

length

$\gamma = E/mc^2$

$P_\perp$

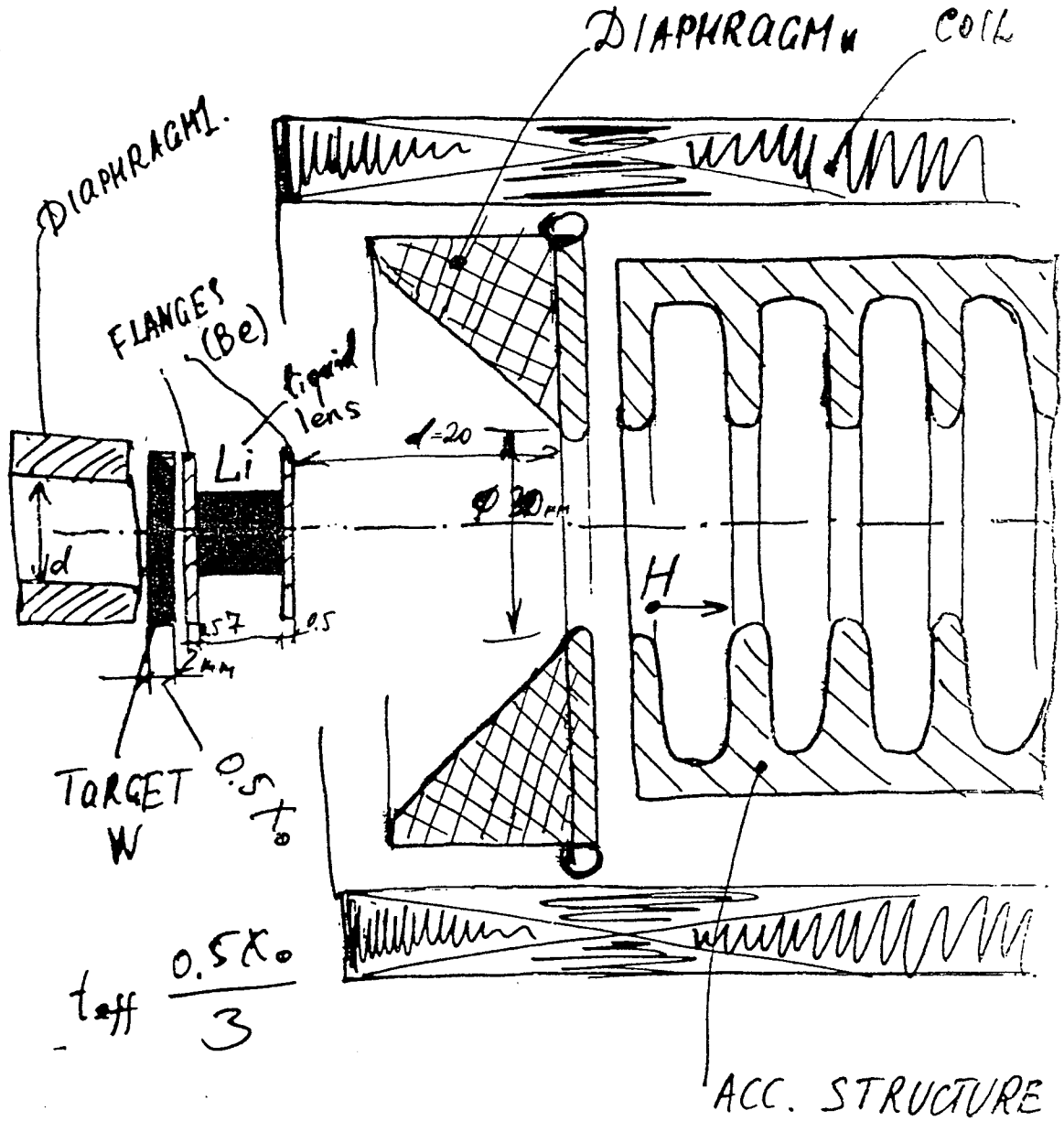
distances...
diametres...
gradient of lithium lens
long. field.

Yields: per incident particle

N_γ ..... ≈ 10

$N_{e^+e^-}$ after target ≈ 6
after lens ≈ 3
after diaphragm and acceleration ≈ 1.5

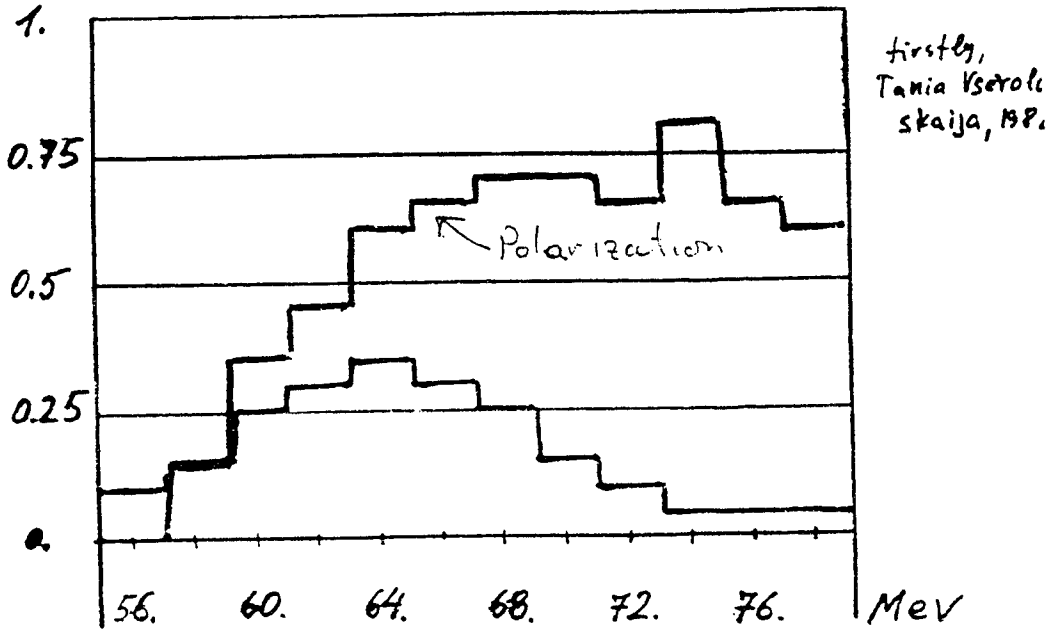
MODEL (P11).
(detalised)



After acceleration up to 50 MeV

— $\frac{2}{N_0}\frac{dN^{\pm}}{dE}$, MeV^{-1}

— polarization

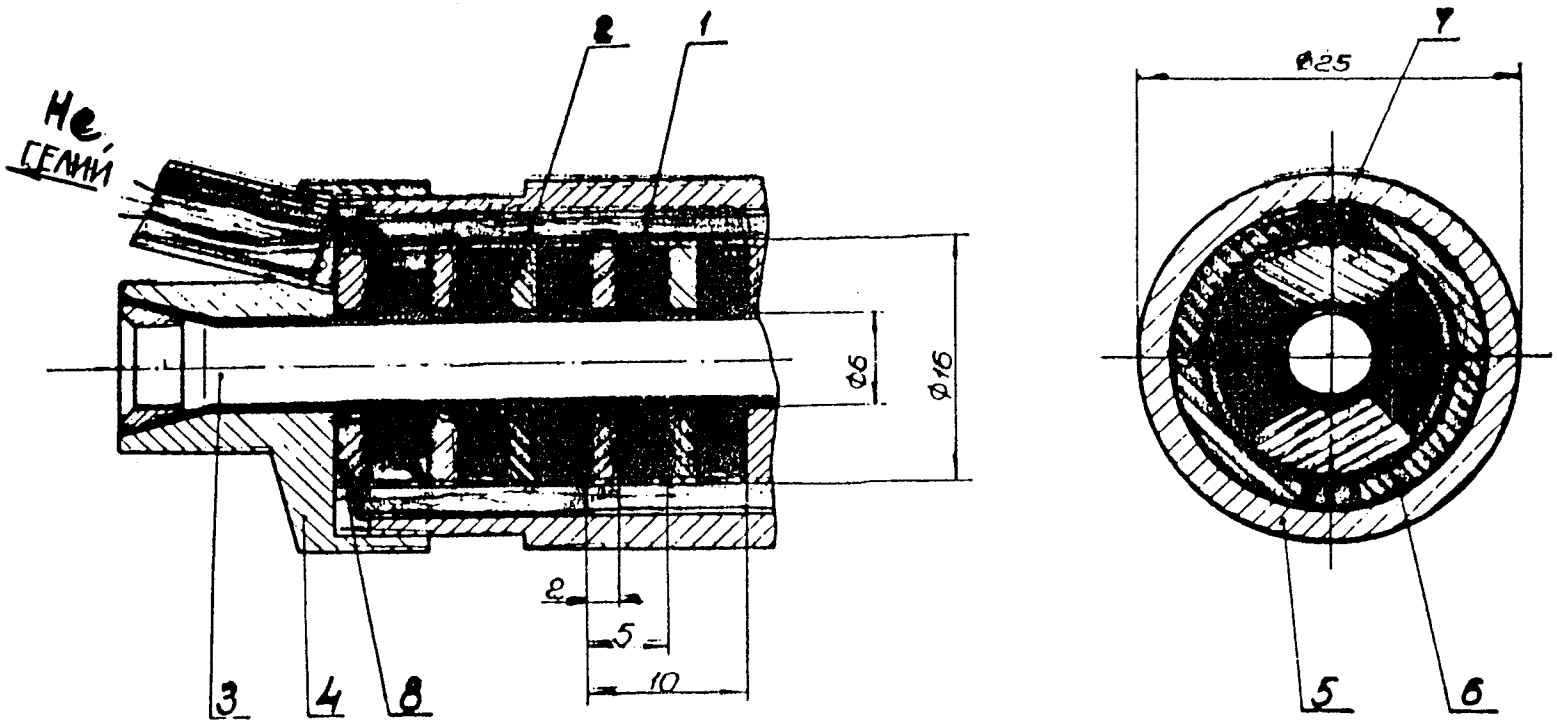


TARGET — W $0.5 X_0$ (2 мм)

фокусировка литиевой линзой

$G = 150 \frac{кG}{см}$ $H_{\parallel} = 2T$

сепарация по энергии — фокусировка и диафрагмирование


Не
ЦЕЛИЙ
2
1
Ø6
Ø16
2
5
10
3
4
8
Ø25
7
5
6

Main parametres of conversion system

E ..... 150 ÷ 500 Gev

Number particles .... $2 \cdot 10^{11}$

Length of *) undulator .... 150 m

$P_\perp^2$ ..... ~ 0,1 $(H_\perp = 0.5T)$

λ_0 ..... 0.6 ÷ 1 cm

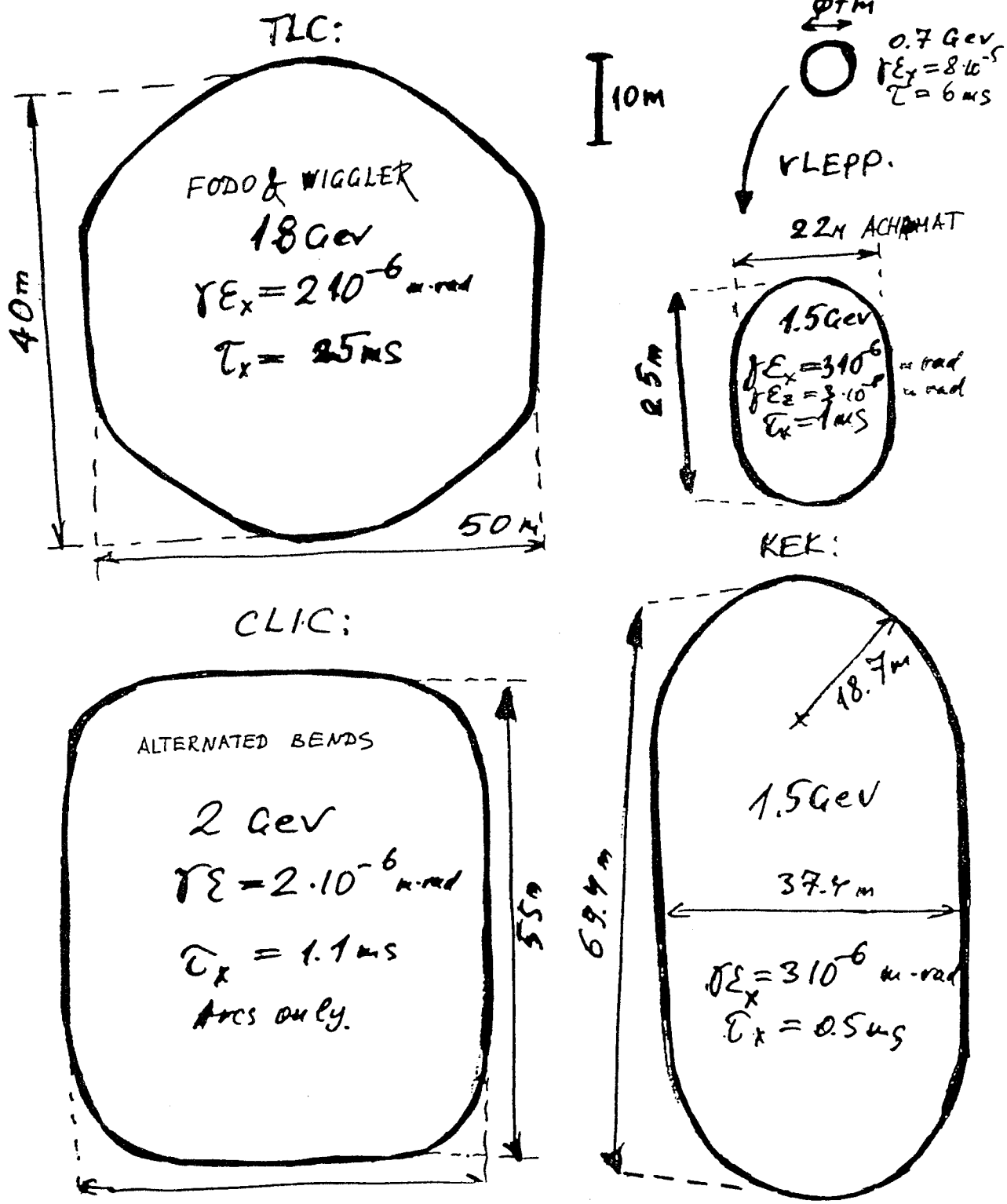
Thinkness of target ..... $0.5 X_0$

The mean Degree of polarization ..... 65 %

N^+/N ..... 1.

*) For nonpolarized particles Length → Length/10

Projects for injectors



Storage rings for linear colliders

	Units	TLC	CLIC	VLEPP	JLC
Keyword		FODO & WIGGLERS	Alternated Bend	ACHROMAT	
E	Gev	1.8	2.0	1.54727	1.5
Circomference	m	155.	162. (arcs only)	77. (70.)	180.
$\gamma\epsilon_0$	10^{-6} m·rad	2.	2.1	3.	3
Nparticles	10^{10}	10x10x1.4	22x10x0.5	20.	
$\gamma\epsilon_{INBS}$	10^{-6} m·rad	2.74	2.1	6.	
τ_x	msec	2.5	1.1	1.0	0.5
τ_y	msec	4.0	2.7	1.0	
URad/TURN	KV	468.	793.	760.	
RF voltage	MV	0.8 (1)	2.	0.85	
f	GHZ	1.46	3.0	0.5	
$\Delta E/E$	10^{-3}	1.	1.7	3.0	
σ_z	mm	5.	1.35	8. (6)	
$\gamma \frac{\partial \nu_x}{\partial \gamma}$		-28.	-20.78	-25.	
$\gamma \frac{\partial \nu_y}{\partial \gamma}$		-22.	-21.77	-21	
α	10^{-3}	1.2	0.23	0.6	
ν_x		24.37	22.4	18.35 (25)	
ν_y		11.27	15.2	5.69 (12)	
B_0, G_0	T, T/m	1.3 ; 30 Bend	1.6; 35	1.73; 0.	
G quads	$\frac{T}{m}$	94.	31.	65. (90.)	
$\int$sext x,y	$\frac{T}{m}$	310. ; -410.	420; -480	380; -253.	
L WIGGLER	m	22.	0.	0.6x20	
B peak	T	2.4	0.	6.	
ϵ_{inj}	10^{-3} m rad	3.	10.	$1.5\ 10^{-2}$	

Lattice Comparisons

The DR must achieve

(1) High current

(2) Low emittance

(3) Fast damping per unit length

(4) Large dynamic aperture

Functions of merit:

damping time $\longrightarrow \frac{\tau_y}{T_0}$ – measure of damping per unit length

Revolution period of the ring

$\alpha_p \frac{J_x}{J_e} \frac{I_2}{I_5}$ – measure of maximum stable current per emittance

Synchrotron integrals

Why?

First we are interested in the damping per unit length. We can fill the ring with batches until limitted by the kicker speed or multibunch instabilities. We consider τ_y since we have to damp more in the vertical than horizontal.

For fast damping maximize $\frac{T_0}{\tau_y}$ ← Circumference / damping time

Second, we want to use a lattice that has the highest current threshold for the long. microwave instability at a given impedance.

form factor

$$I_{th} \sim \frac{\mathcal{F}\,(2\pi)^{3/2}\,E}{Z/n\;e^2 C}\,\sigma_z\,\alpha_p\left(\frac{\sigma_\epsilon}{E}\right)^2$$

Plug in for σ_ϵ/E.

$$I \propto \gamma^3 \frac{\sigma_z \alpha_p}{J_\epsilon}\frac{I_3}{I_2}$$

Synchrotron integrals

Damping Partition

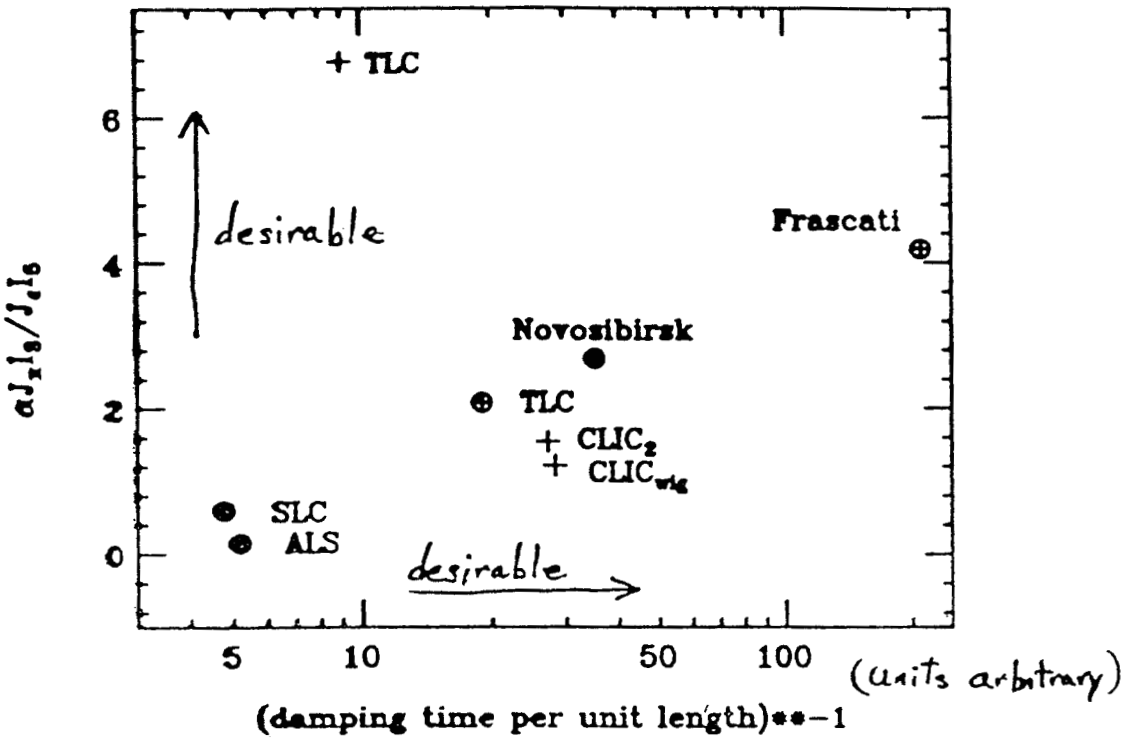
Wish to maximize current and minimize the emittance where

$$\gamma\epsilon_x \propto \frac{\gamma^3}{J_x}\frac{I_5}{I_2}$$

$$\Rightarrow \quad \text{Maximize} \quad \alpha_p \frac{J_x}{J_\epsilon}\frac{I_3}{I_5}$$

Do not consider σ_z since it is RF dependant.

Lattice Comparison: $\alpha J_x I_3 / J_\epsilon I_5$ vs. T_0/τ_y



(units arbitrary)

⊕ Is a complete ring w/ insertions

\+ Just cell structure

TLC ring uses 22 meter of 24 KG wiggler

Novosibirsk uses 12 meters of 60KG wiggler

Frascati uses 433 meters of 17KG wiggler

TLC, Frascati, $CLIC_{wig}$ have $\gamma\epsilon_{xo} \sim 2\times10^{-6}$ m-rad

Novosibirsk, $CLIC_2$ have $\gamma\epsilon_{xo} \sim 3\times10^{-6}$ m-rad

ALS - synchrotron light source $\gamma\epsilon_{xo} \sim 1\times10^{-5}$

SLC has $\gamma\epsilon_{xo} \sim 3\times10^{-5}$ m-rad

Other Considerations

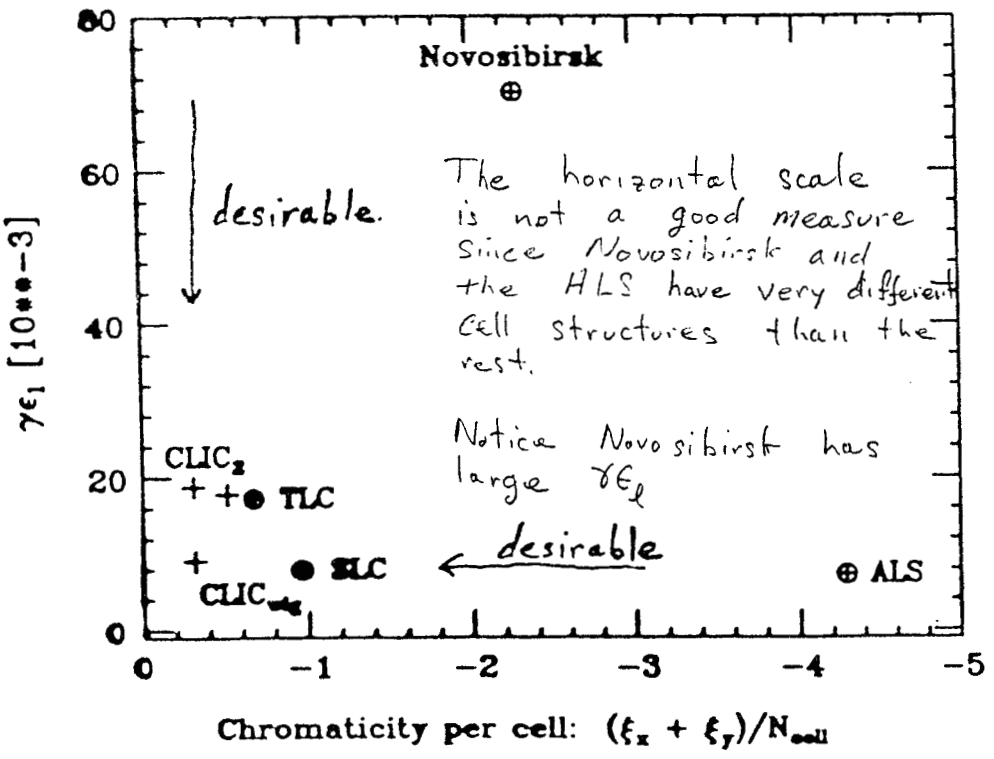
- Longitudinal emittance
- Chromaticity ~ measure of dynamic aperture. → for want of aperture measurements
- Size ~ measure of cost

Circumference.

ALS	200 m	
CLICwig	162 m	+ insertions
CLIC2	300 m	+ insertions
Frascati	720 m	
Novosibirsk	77 m	
SLC	35 m	
TLC	155 m	

longitudinal emittance

Lattice Comparison: $\gamma\epsilon_l$ vs. Chrom. per cell



Alternate Approaches

- We all use conventional Type rings and use wigglers to improve the performance slightly.

Pre-Damping ie. use two rings.

- Rings designed for function
  first use wiggler ring for damping
  Then a ring w/ better α_p/ϵ_{x_0} for emittance

- One gains a factor of 2 in the damping times.

- Not much gain for the cost of an additional ring. Can do the same with wigglers in one ring. Stability?

Wiggler Ring

- Frascati type ring has 100 times The damping. Is it stable? → wiggler dominated

Lattice Summary

- Different machines have different needs - very hard to compare.

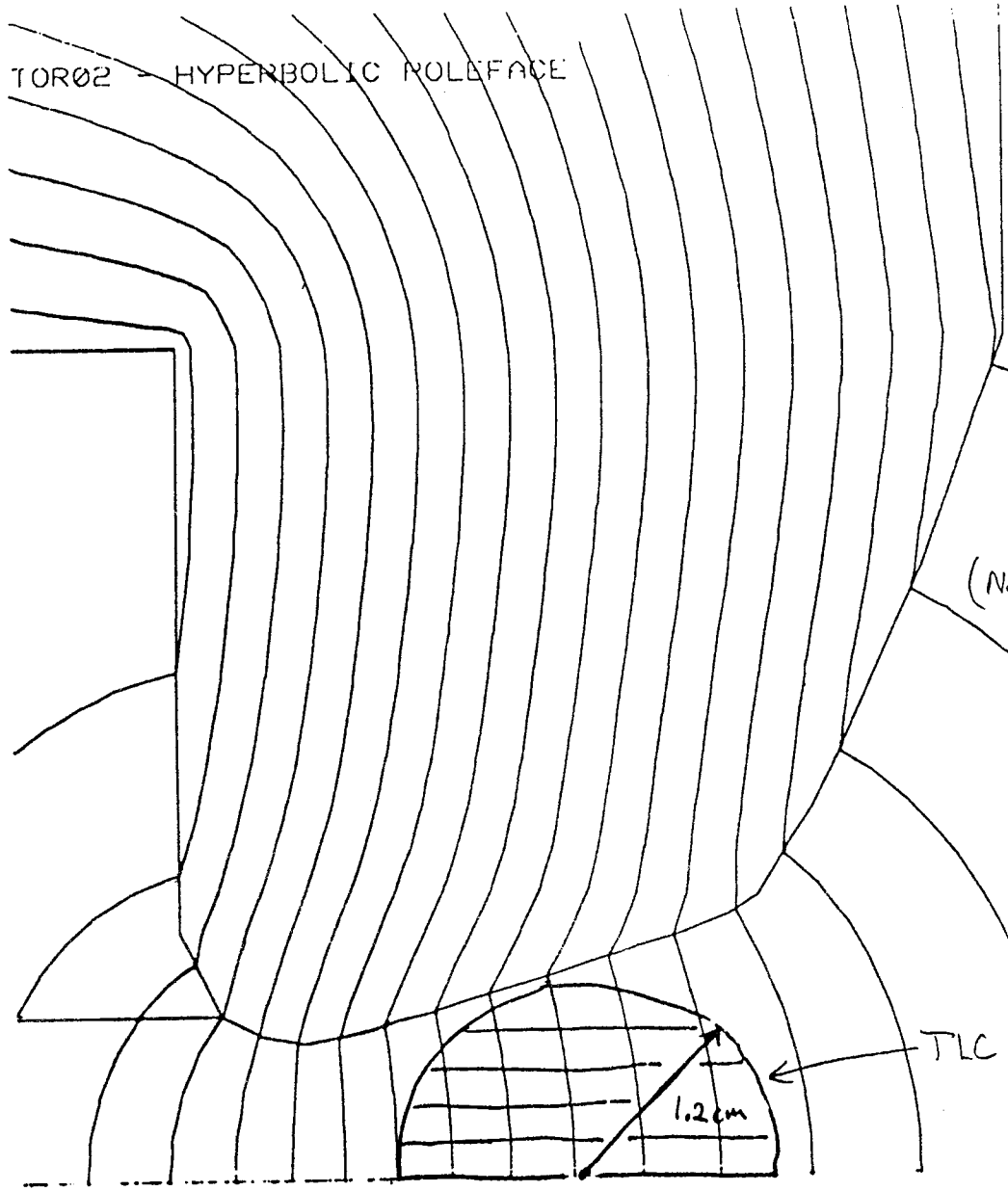
- Both CLIC and TLC seem interested in CF bends - what sort of gradients are possible?
  (See next page)

Combined function

- Novosibirsk calls for very short period wigglers $\lambda_w = 12\,cm$ $B_0 = 60\,KG$. These should be investigated further. (See plot in two pages)

- The stability of wiggler based rings like Frascati's should be checked It might be overkill for TeV colliders, but a smaller version would be great.

Combined Function Bend



Tor 11

$B_0 = 13.1$ kG

$\frac{dB_y}{dx} = 300$ kG/m

$\cancel{\frac{d^2B_y}{dx^2}} = 4$ kG/m²

$B_{peak} = 23$ kG

(Needs vanadium permandur poles)

Strong Short Period Wigglers

⊕ Complete ring with insertions

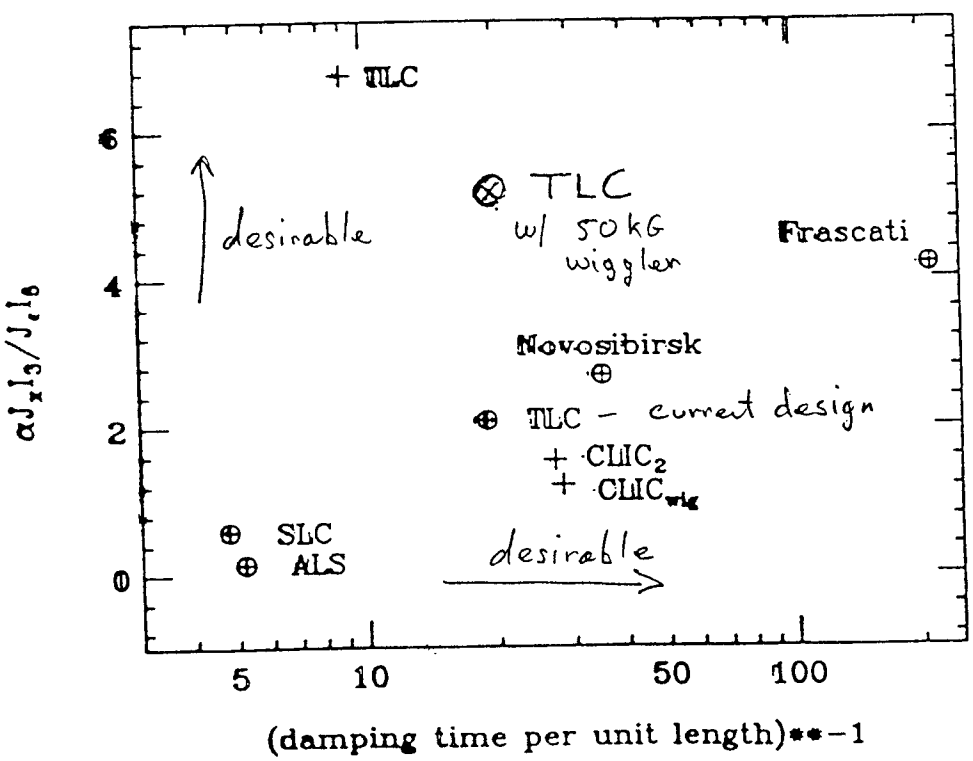
+ Just cell structure

⊗ TLC with 5 meters of 50 KG short period ($\lambda_w = 12$cm) wiggler instead of 22 meters of 24KG wiggler w/ $\lambda_w = 20$cm.

Changes to TLC

Length	155 →	115 meter (fewer insertions)	
ξ_x, ξ_y	decrease		
$\gamma\epsilon_{xo}$	Constant	2×10^{-6}	
$\gamma\epsilon_\ell$	Constant	2×10^{-2}	
τ_y/T_o	decrease	slightly	

Lattice Comparison: $\alpha J_x I_3/J_\epsilon I_5$ vs. T_0/τ_y



Flat Beam Issues

- Our (SLAC) initial calculations indicated that intrabeam scattering does not prevent flat beams in the TLC DR.

$\Rightarrow$ ϵ_x/ϵ_y determined by coupling and residual vertical dispersion.

		Coupling
Quad rotations Sextupole misalignments Vertical orbits in sext.	$\Rightarrow$	Increases y_β directly Increases η_y

Bend Rotations Quad misalignments Vertical orbit in quads	$\Rightarrow$	Increases η_y directly which is coupled to y_β via S.R.

Flat Beam Tolerances

- For TLC ring $\epsilon_x/\epsilon_y = 100$

  $\Rightarrow$ Quad Rotations $\lesssim 0.25$ mrad

  Sextupole misalignments $\lesssim 80\,\mu m$

  Vertical Closed orbit $\lesssim 100\,\mu m$

- These are less than the linac requirements (but still tight)

Another issue is that we must measure the damped beam for diagnostics and correction of coupling.

Beam Measurement

- Beam is $30 \times 3\,\mu m$.
- Unfortunately the energy is low in the bends $\rightarrow \lambda_c \sim 5\,\mathring{A}$ (~ 2 keV)
  critical photon wavelength
- Need to be able to resolve spots.

This is done at PEP but 10 times larger beams.

Flat Beams

Jitter Tolerances

Another issue for flat beams are the jitter Tolerances.
just because the beam is smaller.

In addition because of the larger β_y in the rings they are more sensative to vertical kicks.

Assymetric tunes $\nu_x \gg \nu_y$ $\Rightarrow \beta_y \gg \beta_x$

Correctors

Assuming linear optics

$$\Delta\theta \lesssim 2\times10^{-4}\ \text{mrad} \quad \text{for } \frac{1}{10}\sigma_y \text{ jitter}$$

$$\Delta B_0 \ell \lesssim 1\times10^{-2}\ \text{Gauss-meters}$$

Quads

– Assume $y_c \sim 150\mu m$ tolerances previous page.

In the arcs of the ring most errors cancel.
Assume the variation of a string acts like a single quad.

length

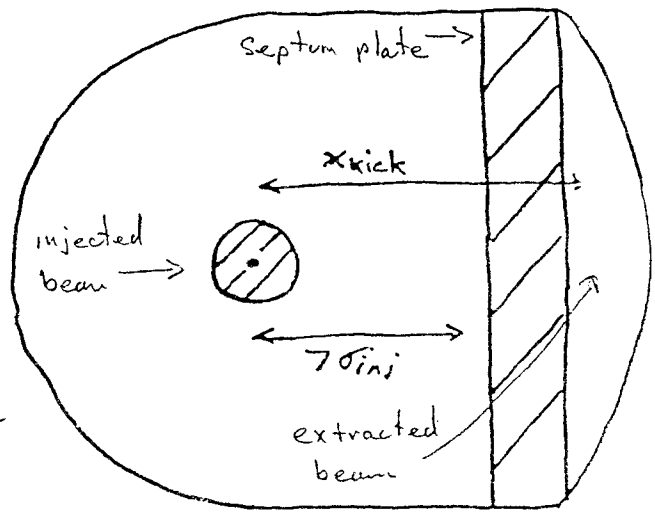
$$\Delta K \ell\, y_c \lesssim 2\times10^{-4}\ \text{mrad}$$

$$\Delta K \ell \lesssim 10^{-3} \quad \text{or} \quad \frac{\Delta K}{K} \lesssim 3\times10^{-4}$$

Extraction Systems

Kickers

- Fast – damp more batches at once
- Strong $\theta \sim 5$ mrad same as SLC DR's
- stable



$$N_s = \frac{\text{beam pipe radius}}{\text{injected beam size}}$$

$$\theta \simeq \frac{N_s\sqrt{\epsilon_{inj}} + 4\,mm/\sqrt{\beta x\ \text{septum}}}{\sqrt{\beta x\ \text{kicker}}}$$

For TLC with $N_s = 7$ to prevent particle loses and $\gamma\epsilon_{inj} = 3\times10^{-3}$

$$\theta \sim 4-5\ \text{mrad}$$

$\Rightarrow$ Current for the kicker

gain by having small $\beta y/\beta x$ @ kicker ie. flat beam pipe.

$$I \propto B_0\,\text{gap} \propto \theta\sqrt{\frac{\beta y\ \text{kicker}}{\beta x\ \text{kicker}}}$$

Stability — assume linear optics from septum → IP, ie. no wakes.

$$\frac{\Delta\theta}{\theta} \simeq \frac{1}{10} \frac{\sqrt{\epsilon_{ext}\,\beta_{x\,septum}}}{\left(N_s\sqrt{\epsilon_{inj}\,\beta_{x\,septum}} + 4\,mm\right)}$$

for 1/10 σ jitter @ IP. septum plate + extra distance

For TLC $\Delta\theta/\theta \sim 3\times10^{-4}$

Ferrite kickers with thyratrons are typically good for $\Delta\theta/\theta \sim 0.1\% - 1\%$

Solutions

(1) Check our assumptions ($N_s = 7$) – tracking
(2) Reduce incoming emittance $\theta\downarrow$
(3) Special insertion for kicker $\theta\downarrow$
(4) Cancel jitter w/ Two kickers

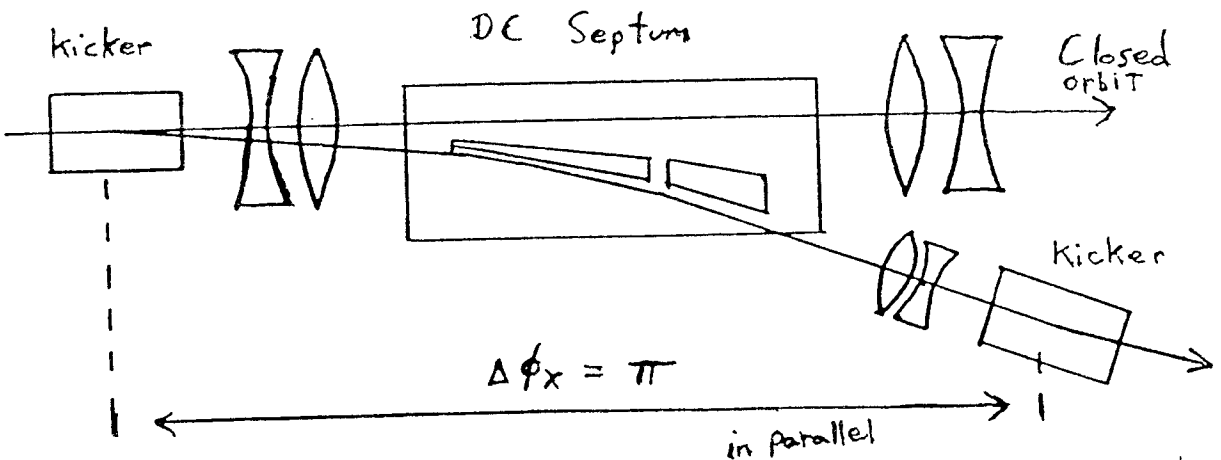
Other advantage of a pre-damping DR:
Rings could be optimized for function, ie fast damping vs. low emittance

Kickers

- 100 ns full pulse Off-On-Off
- $\theta \sim 5$ mrad @ 1.8 GeV w/ 2.4cm pipe
- Tolerance $\sim 10^{-4}$

Parameters from Fatin Bulos

	Ferrite	Air - Capacitive loaded
Length	0.75 m	1.25 m
Segments	3 of 0.25 m	2 of 0.62 m
Power Source	3 Thyratrons	2 Thyratrons
Tolerance	Use cancellation scheme	Cancellation scheme



The two kickers are driven in parallel from same thyratron

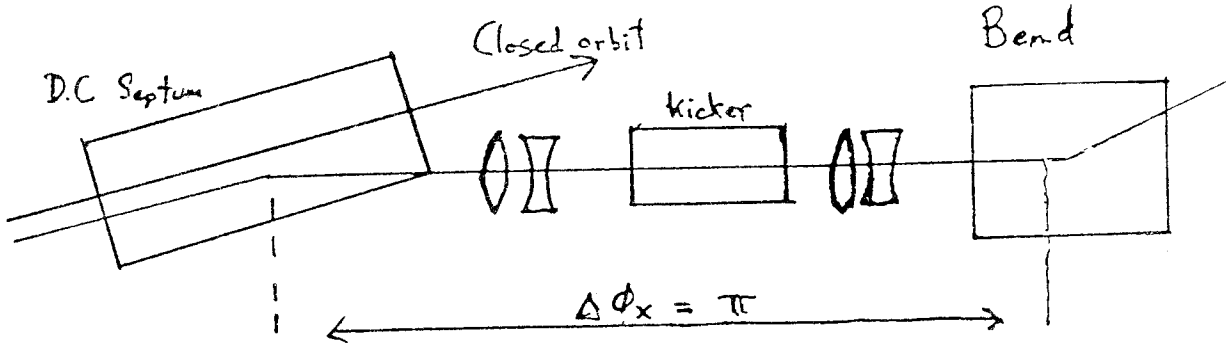
Septum

- DC Septum – stability
- Horizontal bending – looser tolerances because of flat beams.

Naively $\Delta x \simeq \Delta\theta \sqrt{\beta_{sept}\beta}$ ← R_{12} matrix element

$$\Rightarrow \frac{\Delta\theta}{\theta} \lesssim 10^{-5} \quad \text{for } 10^\circ \text{ septum}$$

a. Need to use same cancellation scheme as kicker:



The septum and bend are connected in series.

Impedance questions (Longitudinal)

I. Requirements on impedance

TLC / CLIC / VLEPP / Frascati / SLC

- bunch lengthening
- energy spread

> long. emittance, bunch length compression

II Calculations and measurements

1. SLC case (talk: Karl Bane)
   - calculations
   - measurements with beam
   - estimates

2. "Free space" impedance (talk: Bob Warnock)
   - estimates of impedance (high frequency)
   - low frequency contribution is small
   - stability analysis in progress

3. BEP model ring in Novosibirsk (talk: A. Mikhailichenk
   - careful engineering of the vac. chamber, of the RF cavities, insertion
   - estimated impedance $\left|\frac{Z}{n}\right|_{eff} \lesssim .1\,\Omega$

Impedance requirements

Definition:

Turbulent bunch lengthening threshold

$\parallel$

Design current

$$\left|\frac{Z}{n}\right|_{eff} = 2\pi \frac{E\,\alpha_p}{e I_p}\left(\frac{\Delta E}{E}\right)^2$$

	TLC	CLIC	VLEPP	Frascati	SLC
$N\,[10^{10}]$	1.4	.5	20	2	2
$\alpha\,[10^{-3}]$	1.2	.23	.6	2.7	14.7
$\frac{\Delta E}{E}\,[10^{-3}]$	1	1.7	3.0	.9	.71
$\sigma_z\,[mm]$	5.2	1.35	8 (6)	4.1	7.0
$\left\|\frac{Z}{n}\right\|_{eff}\,[\Omega]$	.3	.1	.1	.3	1.0

BEP model ring (estimate) $\left|\frac{Z}{n}\right|_{eff} \simeq .1\Omega$
(Novosibirsk)

SLC Damping Rings Experience

I. Calculations of longit. impedance (K. Bane)

- pseudo Green function for all objects in the vacuum chamber was calculated with the code TBCI (T. Weiland) W_z
- potential well bunch lengthening is calculated using the total W_z (K. Bane, R. Ruth)

II. Measurements with the beam

- longitudinal bunch charge distribution as $f(I)$
  ↳ bunch length
- equilibrium energy spread as $f(I)$

III. Good agreement between the measurements and the calculations

Effective impedance (from turbulent threshold)

$$\left|\frac{Z}{n}\right|_{eff} \simeq 1\ \Omega \qquad N_{th} \sim 2\cdot 10^{10}/\text{bunch}$$

Simulations indicate for the RF cavities only

$$\left|\frac{Z}{n}\right|_{eff} \simeq .2\ \Omega \qquad N_{th} \sim 8.5\cdot 10^{10}$$

Finally we point out that the inductance formulas of this section may be used to estimate the imaginary part of the transverse impedance $\Im m(Z_\perp)$ at the origin for these structures. Using a well-known formula[4] for estimating the transverse from the longitudinal impedance for a cylindrically symmetric structure, with tube radius a, we find near the origin

$$\Im m(Z_\perp) \approx \frac{2c}{a^3} L \quad . \tag{5}$$

Layout of the Damping Ring Vacuum Chamber

The damping ring vacuum chamber is divided into 8 girders (see Fig. 2). Girders 2, 3, 6 and 7 are almost identical. Each of these girders contains 4 1/2 FODO cells, with the quadrupole vacuum chambers — which are cylindrically symmetric — separated by the roughly rectangular bend vacuum chambers (see Fig. 3). Girders 5 and 8, in addition to half a FODO cell on each end, contain kickers, septa, rf cavities and other vacuum chamber elements not found in the rest of the ring.

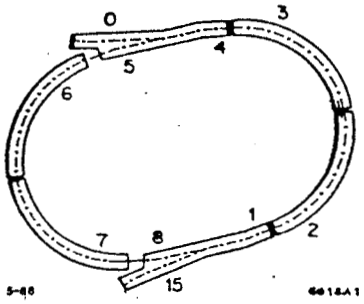


Fig. 2. The girders of the SLC north damping ring.

DR vac. Chamber

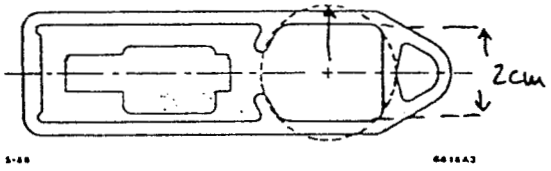


Fig. 3. The cross section of the bend chamber. The dashed circle shows the size of a quad chamber.

The vacuum chamber of the FODO cells can be divided into two groups of objects, each of which is repeated 20 times in the ring. One group, which we will call a "QD vacuum chamber segment" is centered on a defocusing quadrupole vacuum chamber, with each end at the middle of the neighboring bend chamber. The "QF vacuum chamber segment" is similar, though centered on a focusing quadrupole. The vertical profile of these segments is sketched in Fig. 4, with the ends truncated. Nonsymmetric portions are shown dashed. The figures are drawn to scale. The total length of each type is about 60 cm; the half-length of the bend chamber is 15 cm.

A QD segment (see the top sketch) begins with the roughly rectangular bend chamber (1), which is connected by a tapered transition (2) to the cylindrically symmetric defocusing quadrupole (QD) chamber. The QD chamber contains a 1 inch beam position monitor (1" BPM) (3), a QD bellows (4), a serf gasket (5), and a QD mask (6). Finally there is another transition (7) into the next bend (8). The ends of a QF segment are similar (see the bottom of Fig. 4). The cylindrically symmetric QF chamber, however, contains a 1" BPM (3), a flex joint (4), and a QF mask (5).

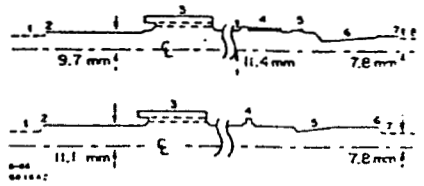


Fig. 4. The vertical profile of a QF segment (top) and a QD segment (bottom). The noncylindrically symmetric portions are drawn with dashes.

Ring girders 5 and 8 include two kickers, two septa, a two cell rf cavity, two 1" to 2" transitions, four 2" BPM's, four 1.4" BPM's, an optical monitor and a dielectric gap.

Inductances of Individual Vacuum Chamber Elements

We have divided the damping ring vacuum chamber into a number of recognizable pieces, for which we have then calculated the effective inductance L (as described earlier), in order to get an estimate of their relative importance for bunch lengthening. Such an approach is reasonable so long as neighboring pieces are not too near each other and so long $\sigma \gtrsim a/2$, with a the tube radius. Whenever possible noncylindrically symmetric objects were modeled by cylindrically symmetric ones that were deemed suitable. Table 1 gives the results for the elements that are inductive to a 6 mm bunch — the nominal bunch length at a ring voltage of .6 MV. The factor in column 3 is an azimuthal filling factor used to account for the contribution of noncylindrically symmetric objects. We see that the QD bellows, the masks, and the bend-to-quad chamber transitions account for roughly 60% of the ring inductance at a bunch length of 6 mm.

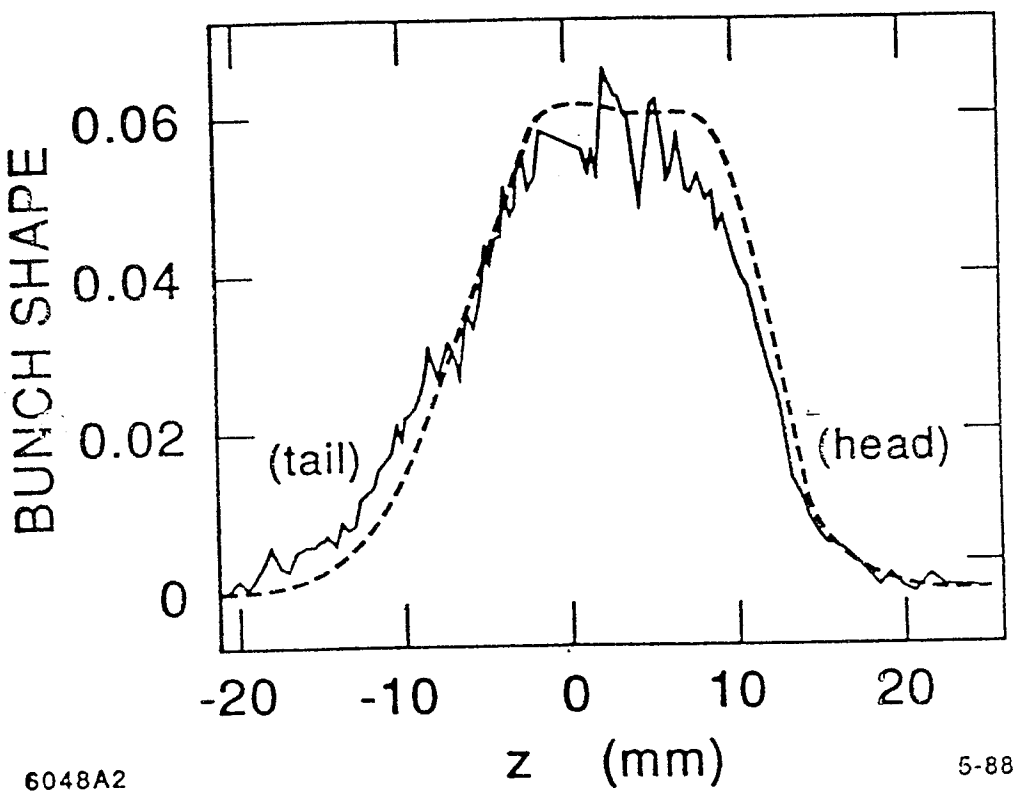
Table 1. The inductive vacuum chamber elements.

Single Element Inductance		Contribution in Ring		
Type	L/(nH)	Factor	Number	L/(nH)
QD bellows	.62	1.0	20	12.5
QD & QF masks	.47	1.0	20	9.5
QD & QF trans.	.52	.9	20	9.3
ion pump slots	1.32	.1	40	5.3
kicker bellows	2.03	1.0	2	4.1
flex joint	.18	1.0	20	3.6
1" BPM trans.	.10	.8	40	3.3
other				2.4
		Total		50.0

Not included in the table are the septa, each of which is a complicated obstruction in a 25 mm ID tube, and is therefore inductive. Using the computer program MAFIA[5] on a simple three-dimensional model we estimate that $L \approx 2$ nH for each septum.

There are objects in the ring which are resistive, most important of which are the two 2-cell rf cavities and the forty 1" BPM cavities. At a bunch length of 6 mm the rf cavities contribute 5.8 V/pC to the ring loss factor k; we estimate that the 1" BPM's contribute 3.2 V/pC. Other objects that are resistive at this bunch length, but contribute little to the ring

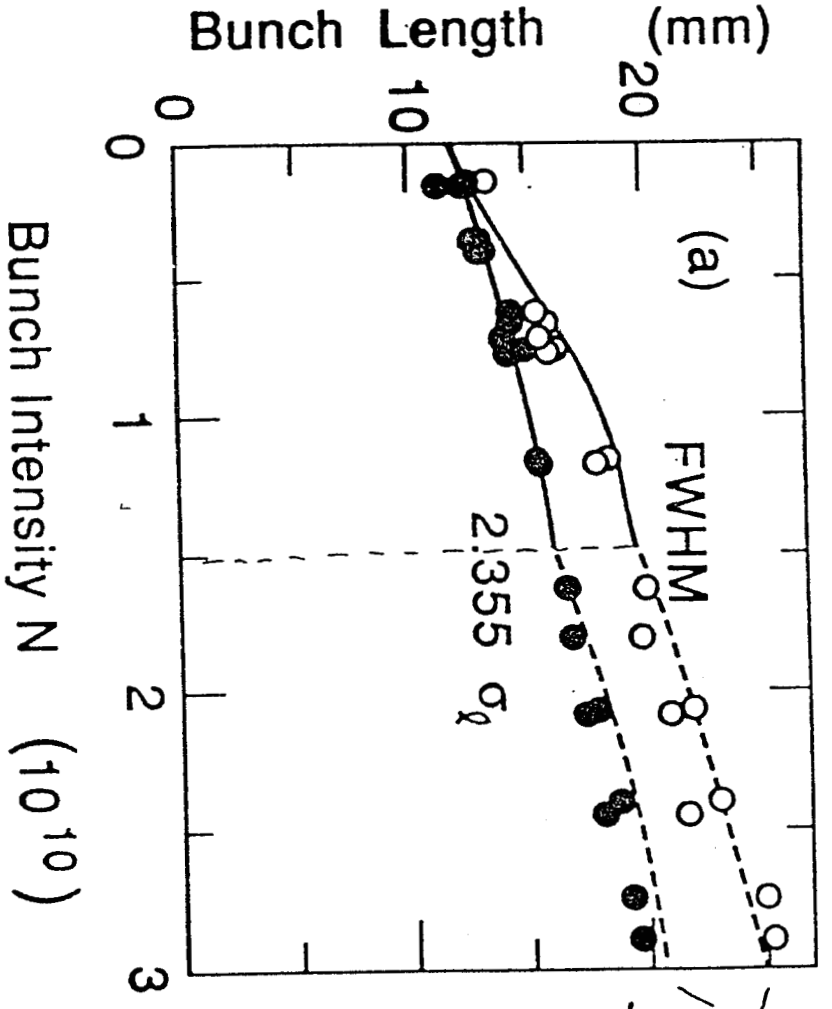
Longitudinal bunch shape in SLC DR's



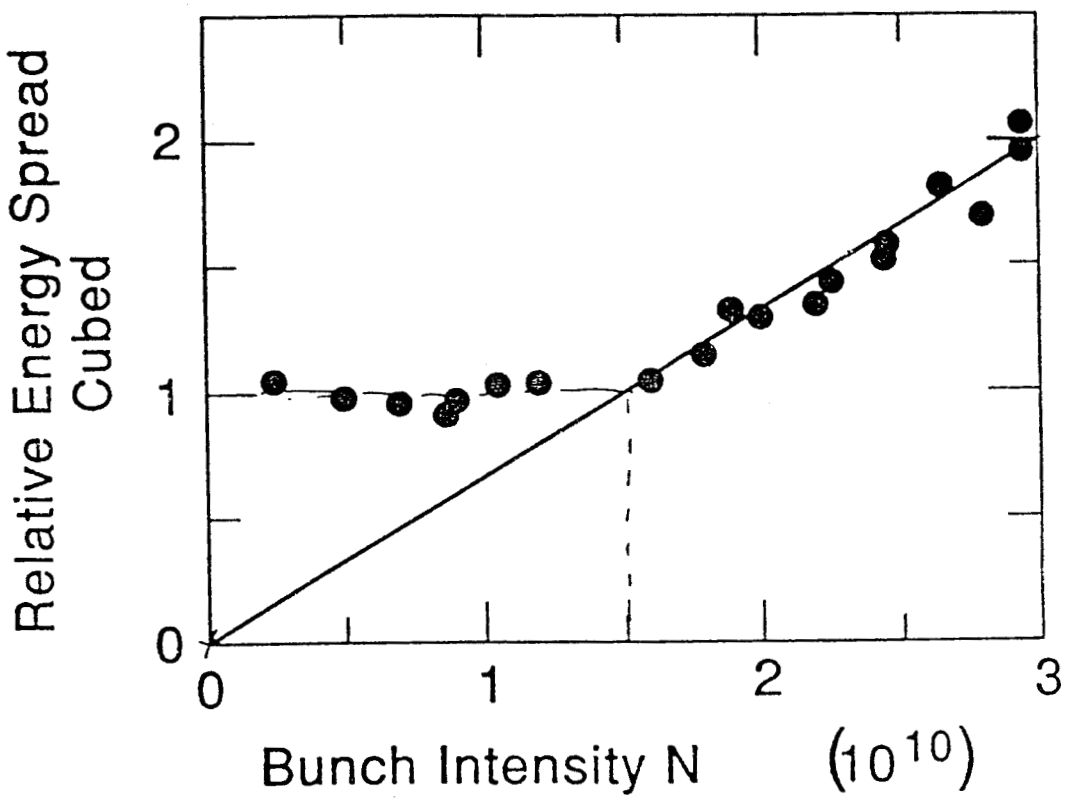
---- predictions from potential well bunch lengthening calculations

N.B - the asymmetry of the longitudinal charge distribution

Measured Bunch length vs. current in SLC DR



Asymmetry of the distribution

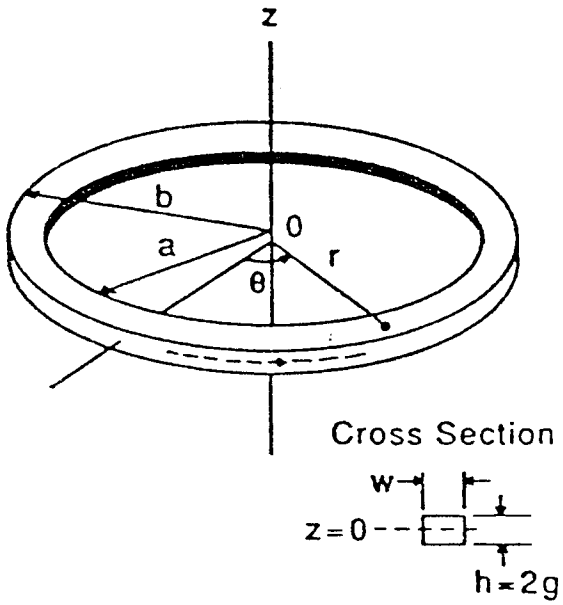


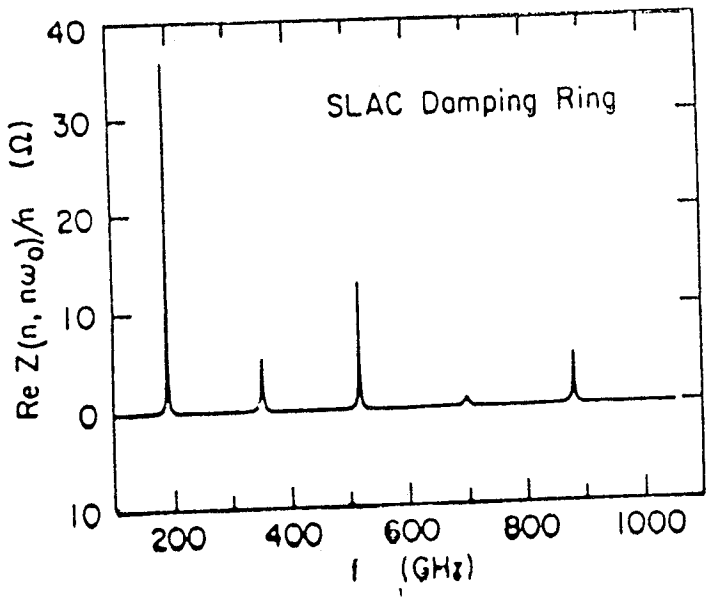
Scaling in turbulent regime

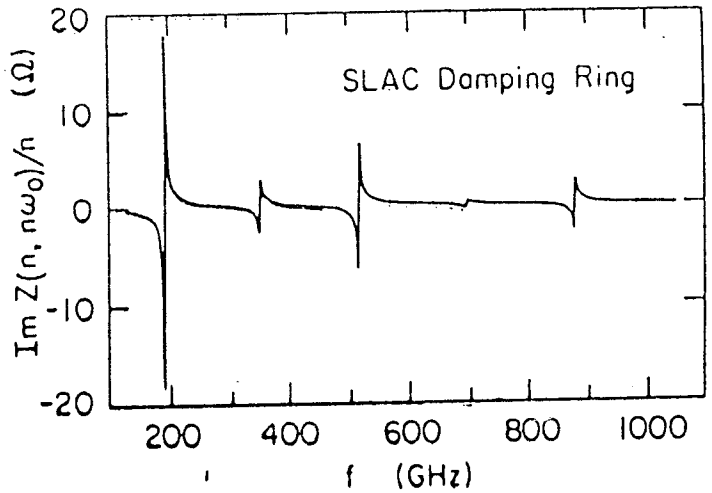
$$\left(\frac{\sigma_\epsilon}{E}\right)^3 \propto N$$

R. Warnock
P. Morton
K.-Y. Ng

High frequency impedance of a toroidal vacuum chamber




SLAC Damping Ring
Re Z(n, nω0)/n (Ω)
40
30
20
10
0
10
200
400
600
800
1000
f (GHz)


SLAC Damping Ring
Im Z(n, nω0)/n (Ω)
20
10
0
-10
-20
200
400
600
800
1000
f (GHz)

Vac. Chamber in Bep - Novosibirsk

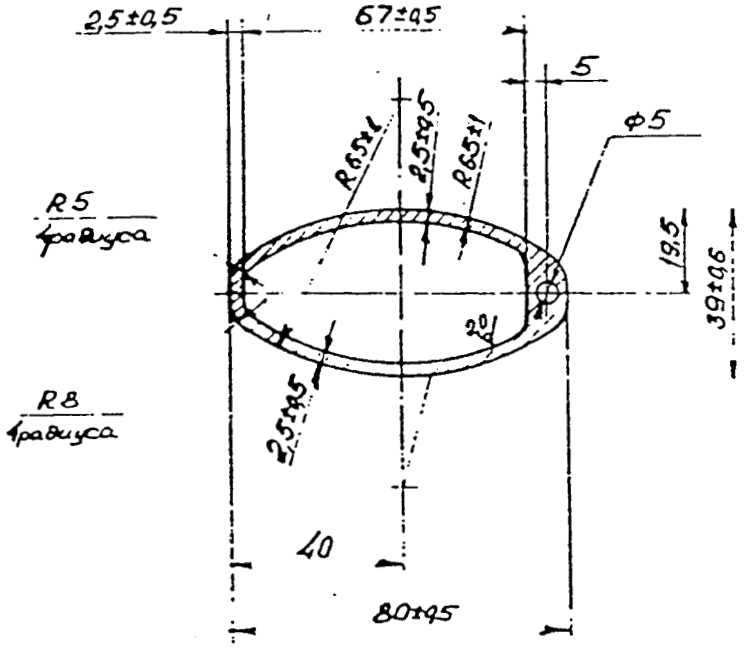


Fig.16. View and cross section of the aluminium vacuum chamber.

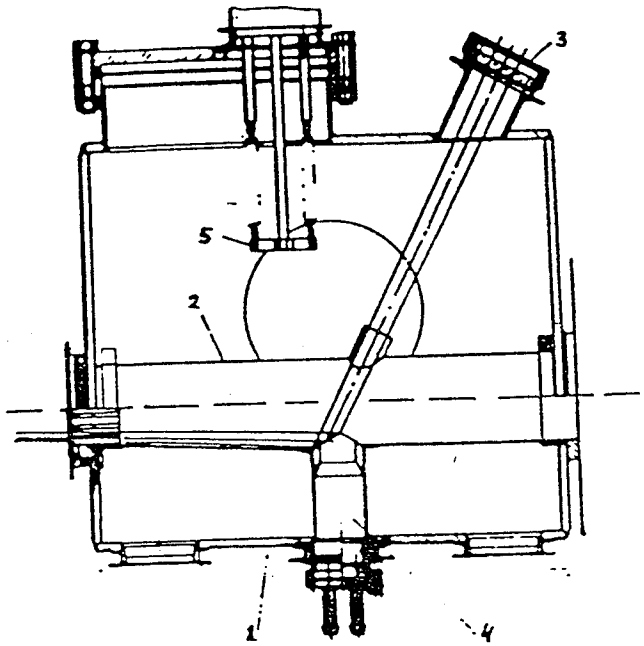


Fig.17. The plan view of the standard straight section.

1 - outer shell, 2 - perforated tube; 3,4 - the window and the mirror-absorber for the synchrotron radiation, 5 - titanium-evaporation pump

Multi bunch Effects

Kathy Thompson

10 trains of 10 bunches

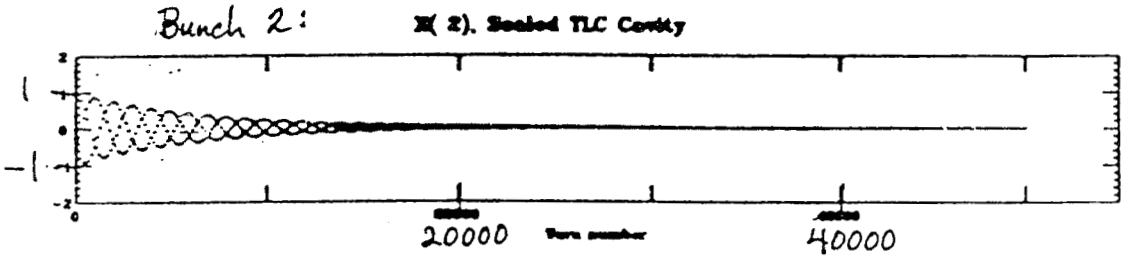
Use damped acceleration cavities — for example below, $Q = 30$

Turn-to-turn and train-to-train wakes negligible

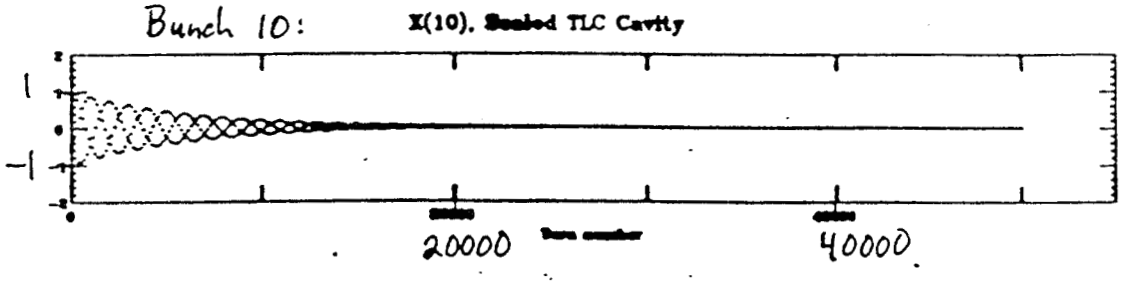
All bunches initially offset 1 unit

Bunch offsets as function of turn number:

Bunch 2:



Bunch 10:



Used damped RF cavities Q's ~ 20 for 1st deflecting mode

Conclusions and recommendations

I e^-/e^+ sources seem possible

- need: high intensity (~SLC), high repetition rate, short bunch length } e^- gun for e^+ product (CLIC/TLC

- important to optimize the yield

$$\frac{e^+}{e^-}/\text{GeV} = .025 \text{ (CERN)} - .08 \text{ (SLAC)}$$

- wigglers, channeling radiation seem attractive
  - more study on the crystal damage

II Current sets of parameters can be satisfied with the present design of the rings

1. We cannot make a clear choice of one lattice over the others
2. Extraction system tolerances can be kept reasonable
   - leave plenty of space for the kickers
   - work is needed on more stable kickers
     (- hard tubes
     - cap. loaded transm. lines (Bulos)
3. Wigglers can be very useful
   - costs, manufacturing, beam-wiggler interacti
   - influences strongly lattice design
   - if feasable, Frascati design indicates a way to the high rep. rate.
4. Pre-damping rings at present seem to give small gains needs further study

III with careful engineering of the vacuum chamber we may be able to achieve

$$\left|\frac{Z}{n}\right|_{eff} \lesssim .3\Omega$$

- detailed comparisons between calculations and measurements for transverse impedance
- design of the high RF frequency cavity
  low impedance + damped
- short bunches : - simulations
  - experiments
- BEP model ring experiment in Novosibirsk
  (spring '89 , $\left|\frac{Z}{n}\right|_{eff} \simeq .1\,\Omega$)

IV Multi-bunch instabilities in the ring given damped RF cavities seems O.K. (Kathy Thompson)

RF POWER SOURCES WORKING GROUP

Chairmen: M. Allen—SLAC/J. Le Duff—Orsay (LAL)
Secretary: T. L. Lavine SLAC

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Summary of RF Power Sources Group Discussions

Matthew A. Allen, Theodore L. Lavine

RF power sources were recognized as one of the key problems to be solved for the next collider. No solutions exist that simultaneously meet all the requirements of peak power, repetition rate, efficiency and cost. Demonstrations of each of the first three requirements have been made separately. Research efforts up to now have come under two main headings. The first is single or multiple sources using power-generating beams in the 1–10 GW power and up to 10 MeV energy ranges. The second is two-beam accelerators with the power-generating beam in the 10 TW and 100 MeV ranges. The primary emphasis of the R&D program at each of the major laboratories makes use of existing technologies developed at that lab. The directions being pursued are:

- klystrons at SLAC and KEK
- induction linacs at LBL and LLNL
- gyrocons and separatrons at Novosibirsk
- superconducting RF at CERN
- lasertrons at Orsay.

Some smaller laboratories are pursuing other power sources for linear colliders. Examples of some of these are: gyroklystrons at the University of Maryland, gigatrons at Texas A&M, and intense, relativistic electron-beam sources at the Naval Research Lab.

There are many unresolved questions relating to the two-beam accelerator that would benefit from a test facility — extraction, reacceleration, etc. Among other applications which merit exploration is the cross-field amplifier, which has been used successfully in phased-array radars and could be a possible power source. It has many superior features compared to the relativistic klystron in its lower voltage operation and cold cathode feature.

The ongoing, complimentary, and international effort in RF power source development has great promise for success.

List of RF Power Sources Talks

1. Y. Y. Lau, "Intense Relativistic Electron Beams and Beam Break-up"
2. R. Miller, "SLAC, LBL, LLNL Experiments on Relativistic Klystrons"
3. A. Vlieks, "Future Development of Relativistic Klystrons"
4. W. Panofsky, "Scaling Law for Induction Accelerators"
5. R. Ryne, "2-D Klystron Simulations"
6. J. Haimson, "Chopped Beams"
7. W. Barletta, "Cost Scaling for Induction Linacs"
8. G. Bowden, "Problems With Magnetic Pulse Compression"
9. R. Koontz, "MV, kA Beam Generator"
10. W. Lawson, "Gyrotrons and Other Cross-Field Devices"
11. S. Kazakov, "RF Sources for VLEPP"
12. P. McIntyre, "Gigatrons"
13. T. Lee, "Design Considerations for a 100 MW, X-Band Klystron"
14. J. Feinstein, "Magnetron Amplifier"
15. G. Loew, "Klystrinos"
16. A. Mondelli, "Cost Scaling of Gyroklystron Amplifiers in Linear Colliders"
17. H. Mizuno, "Strategy for TLC—Quality of Mass Production"
18. W. Schnell, "Two-beam Accelerator—CLIC"
19. A. Sessler, "Two-beam Accelerator—FEL"
20. D. Hopkins, "Two-beam Accelerator—FEL"
21. R. Palmer, "RF Pulse Compression"
22. D. Farkas, "Radio Frequency Pulse Compression and Structures"

23. G. Spalek, "Realization of Full Size RF Compressor"

24. M. Chodorow, "High Perveance Klystrons"

25. R. Miller, "Efficiency as a Function of Perveance"

26. R. Palmer, "Cluster Klystron"

27. K. Eppley, "Condor Program"

28. J. Le Duff, M. Yoshioka, "Lasertrons"

RF POWER SOURCES WORKING GROUP SUMMARY

J. LeDuff

with assistance from
Matt Allen, Ted Lavine, Roger Miller,
and the RF Working Group

December 8, 1988

Division of Discussions

Category	Talks	%
Klystrons (longit. modul.)	12.5	43
Pulsed Power Beam Production	4	14
Crossed Field Devices (Gyro-klystron, -con, CFA)	3.5	12
RF Pulse Compression	3	10
RF Guns and Lasertrons	3	10
Two-Beam Accelerators	3	10
Total	29	100

How to Compare Sources ?

Poor Candidate
Good Candidate

Cheap
Expensive

Improved Conventional
Novel

Multiple Beam Acc
Two Beam Acc

State of the Art : easier and safer

TYPES OF RF Power Sources

1 - Improved conventional sources

***	Klystrons :	relativistic	SLAC, LLNL, Novosibirsk
		separatron	Novosibirsk
		Hollow beam (IREB)	NRL Washington D.C.
***	Gyrocons :		Novosibirsk
**	Gyro klystrons :		Un. Maryland
*	Magnetron amplifier :		Stanford
***	Pulse compression :	magnetic	LLNL
***		RF	SLAC

2. Novel devices

**	Chopped beam amplifier		HAIMSON, LLNL
*	Gigatron		Texas Un.
***	Lasertron		SLAC, KEK, ORSAY, Los Alamos
***	TBA :	induction linac + FEL	LBL, LLNL
**		induction linac + transfert structure	LBL, LLNL
*		S.C. linac + transfert structure	CERN

* under consideration
** under design or construction
*** experimented

Classification of the main approaches ⇒ L.C.

I- Multiple Beams Accelerator.

I-1 Space modulation devices $\vec{B} \parallel \vec{E}$

bunched beam $v_\perp \ll v_\parallel$

RF cavity | RF chopper | Pulsed laser

RF extraction from a resonant cavity

- The challenge is high peak power at high frequencies
  cathode size $P \propto \lambda^2$

I-2 Cross field devices $\vec{B} \perp \vec{E}$ (almost)

Continuous beam $v_\perp \sim v_\parallel$

phase modulation

Transverse energy extraction

- In principle good for high frequencies
  The challenge is the cathode loading
  $P \propto \lambda$

Modulator klystron occupancy versus H.G. linac

II Two Beam Accelerators.

II-1 Continuous beam. RF produced in a wiggler (FEL amplifier)

Good for high frequencies

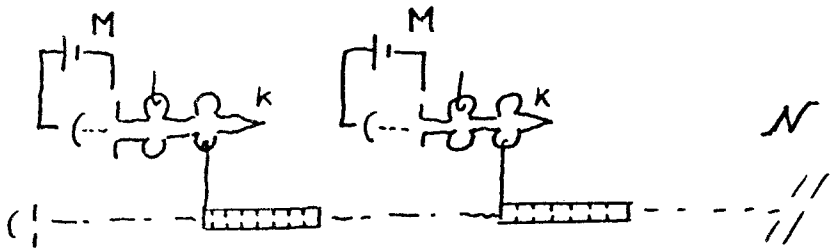
The problem is to keep beam quality after each FEL pass

II-2 bunched beam:

Problems → keep beam quality after transfer structure

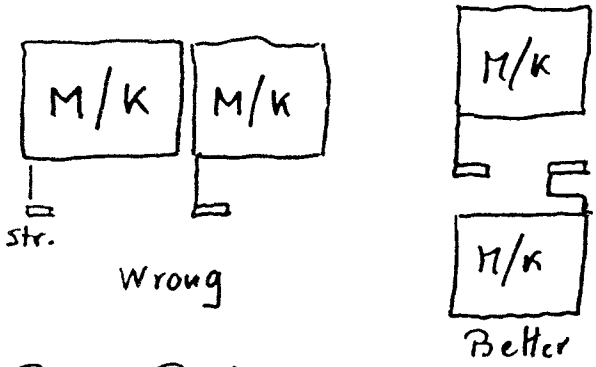
→ Generation of beam at high frequenc

Multiple Beam Devices.



Goal : 1000 MW/m peak

Problem : Modulator/klystron size compare to structure length for each accel. unit.

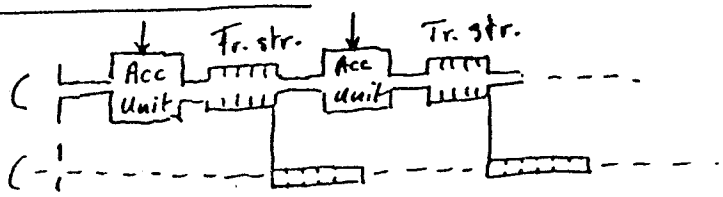


How does the M/K unit scale with $\hat{P}$?

If faster than linear then look for an optimum $\hat{P}$.

Klystrinos versus Rel. Klystr.

Two Beam Devices



Goal is the same

Has the previous problem been solved ?

Is it easier to maintain the performances of a single driving beam than to produce many driving beams; The cost question comes a bit later.

Status of Relativistic Klystrons

Relativistic $\Longrightarrow$ $V \geq 500$ kV

SLAC - LBL - LLNL collaboration

X band experiments (11.4 GHz)
Voltage ~ 1 MV (50-60 ns pulses)
Current ~ 1 KA (induction accel.)

Goal ~ 1 GW obtained : 80 MW, $\eta = 50\%$

↓

above → pulse shortening
multipactor

↙

Development continuing : input cavity (shield) (fingers)
output cavity (TW str.)

Problem to solve : High beam loading from high currents

NRL - WASHINGTON, d.c.

L band experiment (1.3 GHz)
voltage ~ 500 kV (140 ns pulse) PFN
Current ~ 5-20 kA (Hollow beam, cathode + field emission)

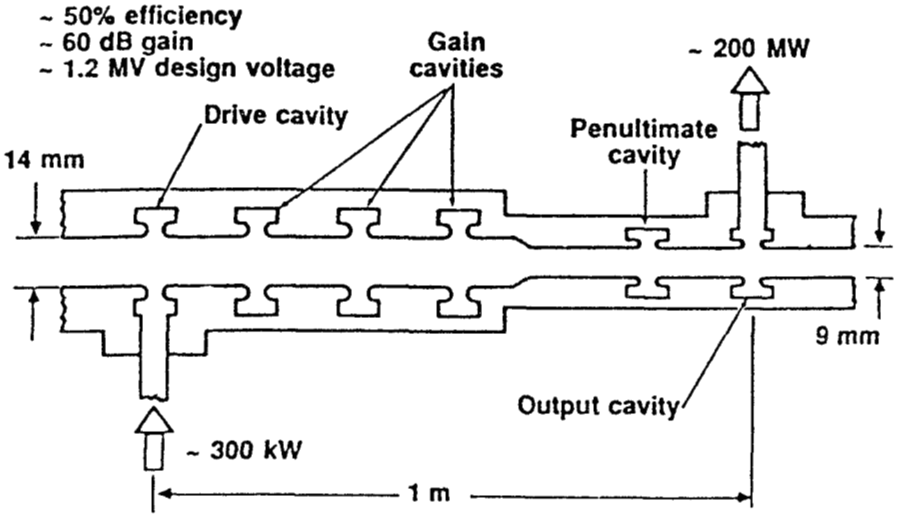
3 GW measured { RF pulse shortening but not current } → no BBU
$\eta = 35\%$

Problems : extrapolate to X band high repetition rate (cathode)

<u>Interesting</u> : Intense Relativistic Beam can help bunching (virtual cathode)

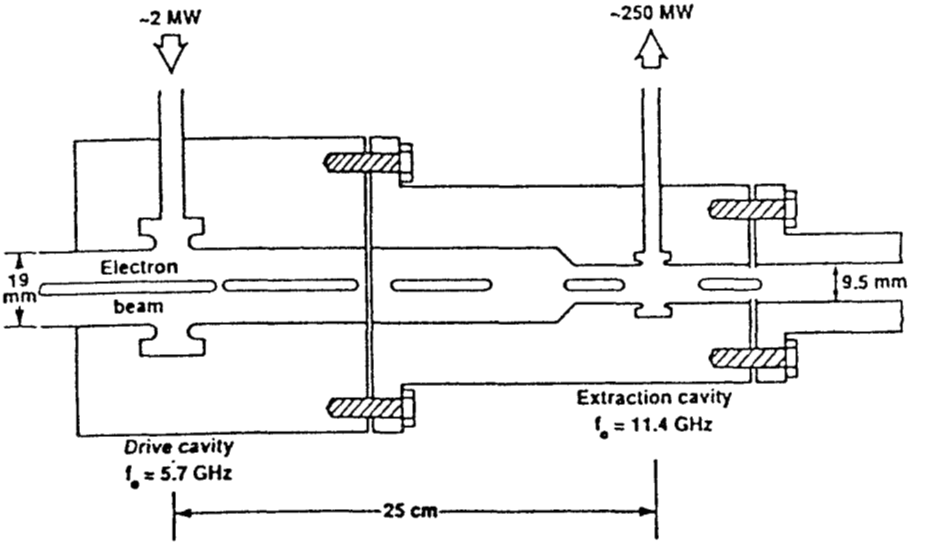
SLAC-LBL-LLNL
Lavine, Miller, Vlieks

11.4 GHz klystron experiment (SL4)



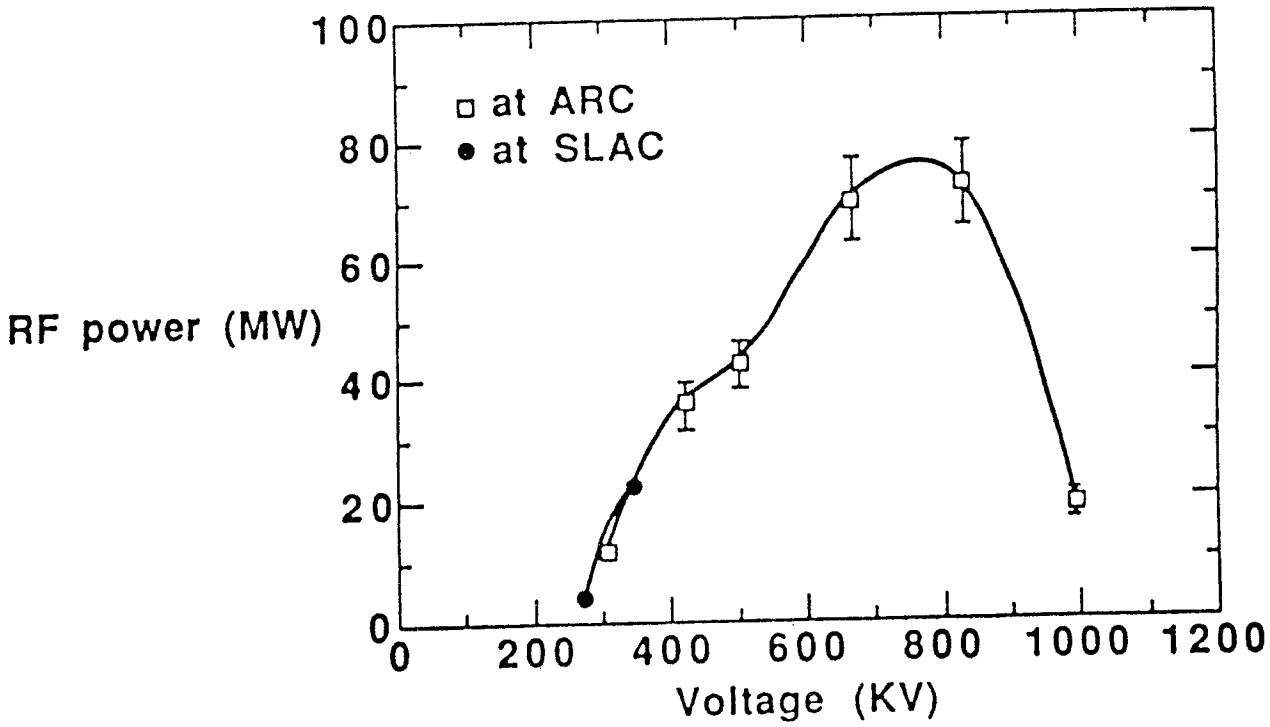
90-E-1067-1091C
MM

Subharmonic drive experiment (SS1)

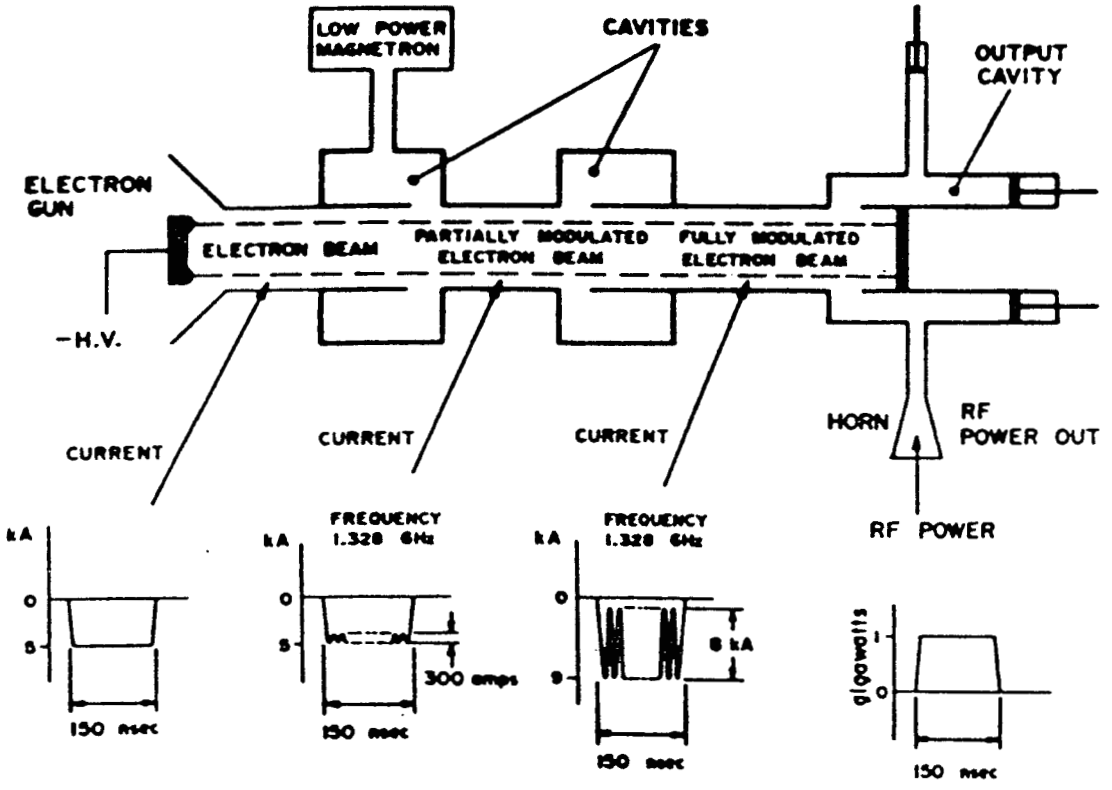


RF output from 8.57 GHz Klystron

SLAC-LBL-LLNL
Lavine, Miller, Vlieks



INTENSE RELATIVISTIC ELECTRON BEAM MODULATION



3372 J. Appl. Phys., Vol. 64, No. 7, 1 October 1988

Y.Y. Lau (Naval Res. Lab)

Novosibirsk

5 years ago have experimented following klystron :

$I = 100\ A$ $\qquad f_{RF} = 7\ GHz$

$V = 1\ MV$ $\qquad \tau = .8\ \mu s$

rep. rate ~ 1 - 3 Hz

obtained : 20 MW

15% efficiency

Not yet a good experience in high peak power klystron , but good experience in producing relativistic beams of medium currents (at least at low rep rate)

KEK

An extensive program has been launched.

Philosophy very close to SLAC's one

+ collaboration with Japan. Industries.

GO TO
SLAC

Back to Normal klystrons

It is interesting to notice that though the SLAC - LBL - LLNL collaboration has been producing very good experimental results with Relativistic Klystrons, SLAC is making at the same time one step back in pushing the development of a non relativistic klystron: together with "Compression".

So SLAC is designing:

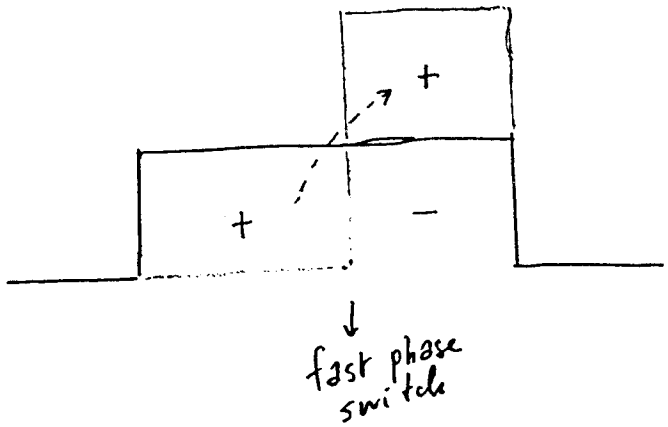
X band klystron	11.4 GHz
output peak power	100 MW
Beam voltage	440 KV
Beam current	511 A
efficiency	45 %
RF pulse length	400 ns
Focussing field	6 kG

The major problem is to keep the cathode loading at reasonable level (7 A/cm²) → good life

This klystron is to be used with RF compression

100 MW ⟹ 1.3 GW

RF compression scheme -



100 MW ↓ 600 MW

400 ns ↓ ~ 50 ns

A full ~~scale~~ size (11.4 GHz) RF compressor has been built at SLAC - (low power level)

Good : efficiency 84 %

fast switch (15 ns)

Cheap delay line.

half good : length of delay line ~ 60 m for 1 m acc. section

Not good: EXPENSIVE TO INSTALL AND EVACUATE!

Nothing really wrong in low power tests (mW)

Next step : combined the 100 MW x-band klystron with this compressor

---

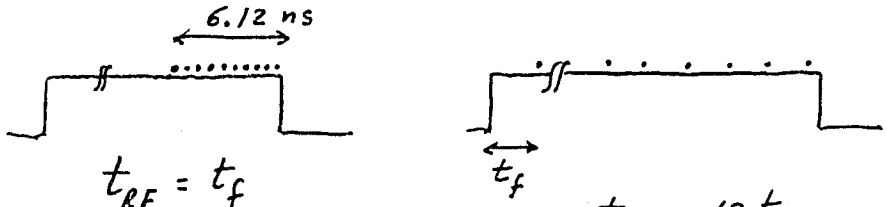
Rel. Kl. Alternative : magnetic compression (modulator)

Problems: Low impedance system - Difficult to couple High Current - low voltage to klystron.

modulator/klystron efficiency 25 %

Multibunching with Long RF Pulses

Idea (G. Loew)	Present TLC		TLC variant
	360 pps		30
	10 bunches/pulse		120
	3600 bunches/sec	=	3600



$t_{RF} = t_f$
$= 60$ ns

$t_{RF} = 12\, t_f$
$= 720$ ns

Consequenses :

bunch spacing 11 x longer → an advantage
circumference of D.R. larger → inconvenient
overall machine rep rate ↘ → an advantage
modulator efficiency ↗ → "
Longer modul. pulse - more Cap. → inconvenient
more energy per klystron pulse → "
General problems of long pulse (BBU, etc.) "

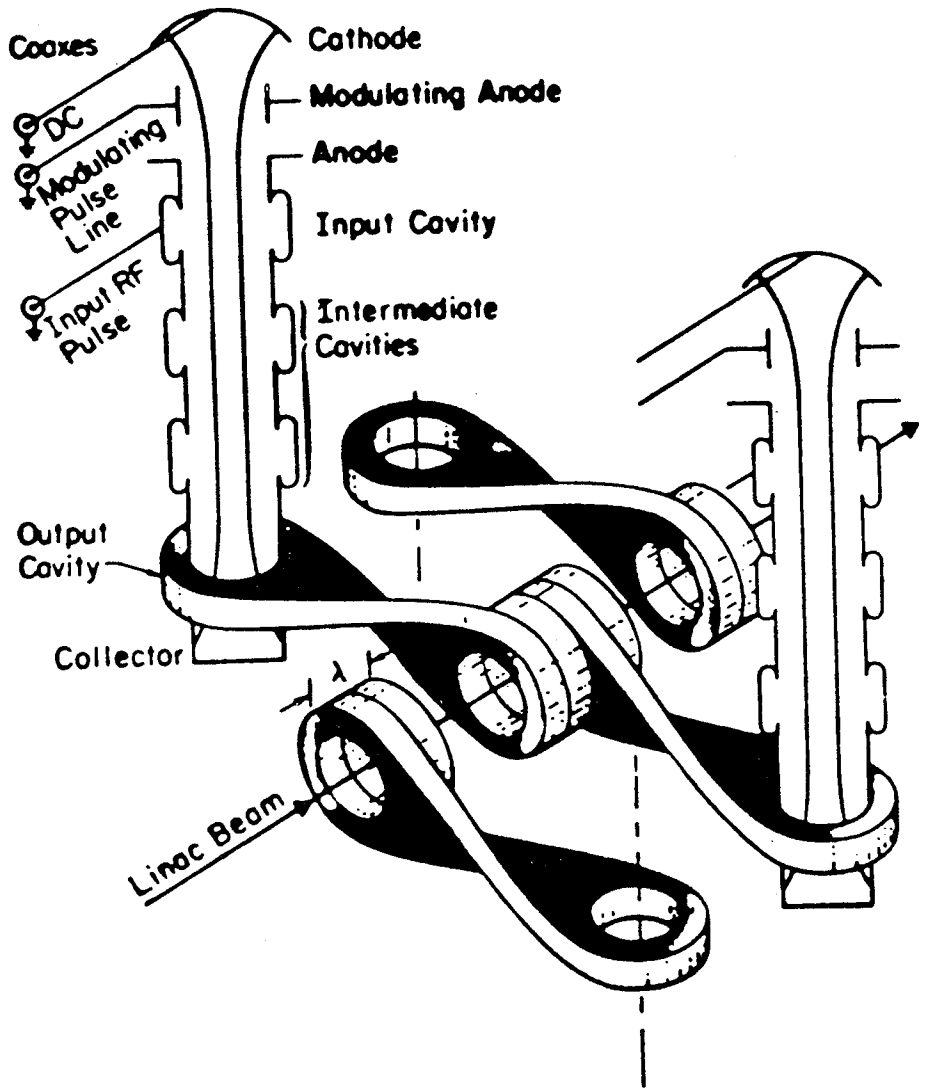
but may be not cheaper

One more step back with Klystrons:

"KLYSTRINOS"

G. Loew
(SLAC)

"Small is Beautiful" (Schumacher)



Klystron Variants

(Chopped beams)

Novosibirsk : SEPARATRON

experimental results : $V \sim 500\,kV$, $I \sim 300\,A$, $P_{out} \sim 40\,MW$

efficiency 26 %, breakdow output cavity, reflected electrons.

[Try to improve modulation by loss of particles]

RF chopper – HAIMSON Cie.

Transverse RF deflection + collimator ⇒ beam modulation

RF Power extraction through TW structure.

advantages :

Short bunching distance for Relativistic beam

High order mode regime → large cavity → high $\varepsilon_\perp$

Inconvenients

A fraction of the beam is lost

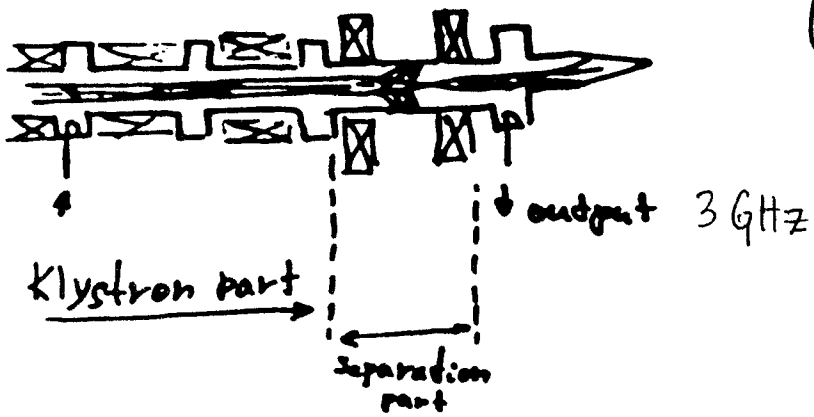
Efficiency is not the issue

Design Parameters.. 6 MV 1 kA 45 ns $\varepsilon_n = 584 \cdot 10^{-6}$

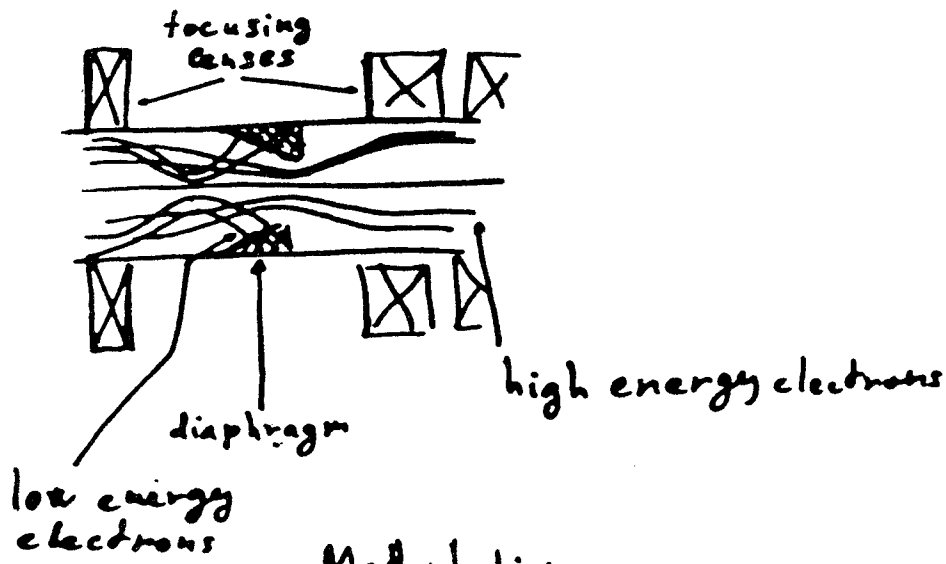
Separatron

Balakin, Kazakov (Novosibirsk)

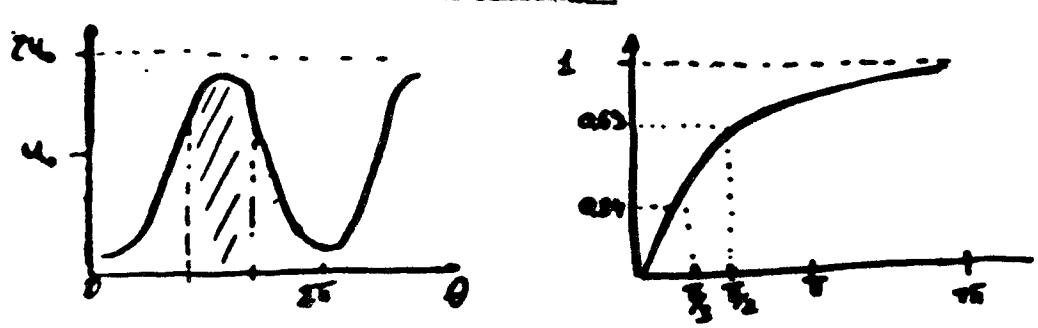
Idea (Balakin, Skiadt, 1974.)



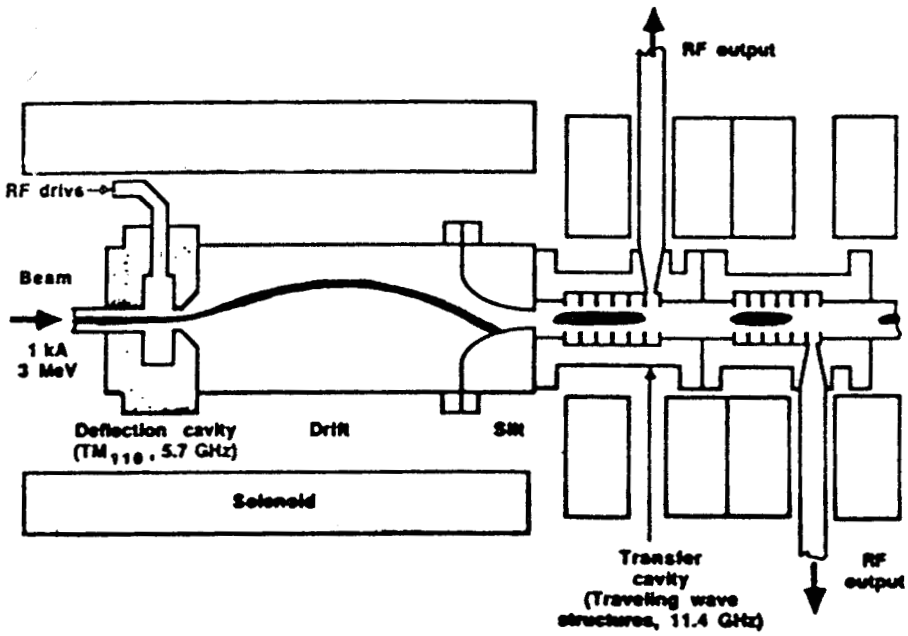
Separation parts



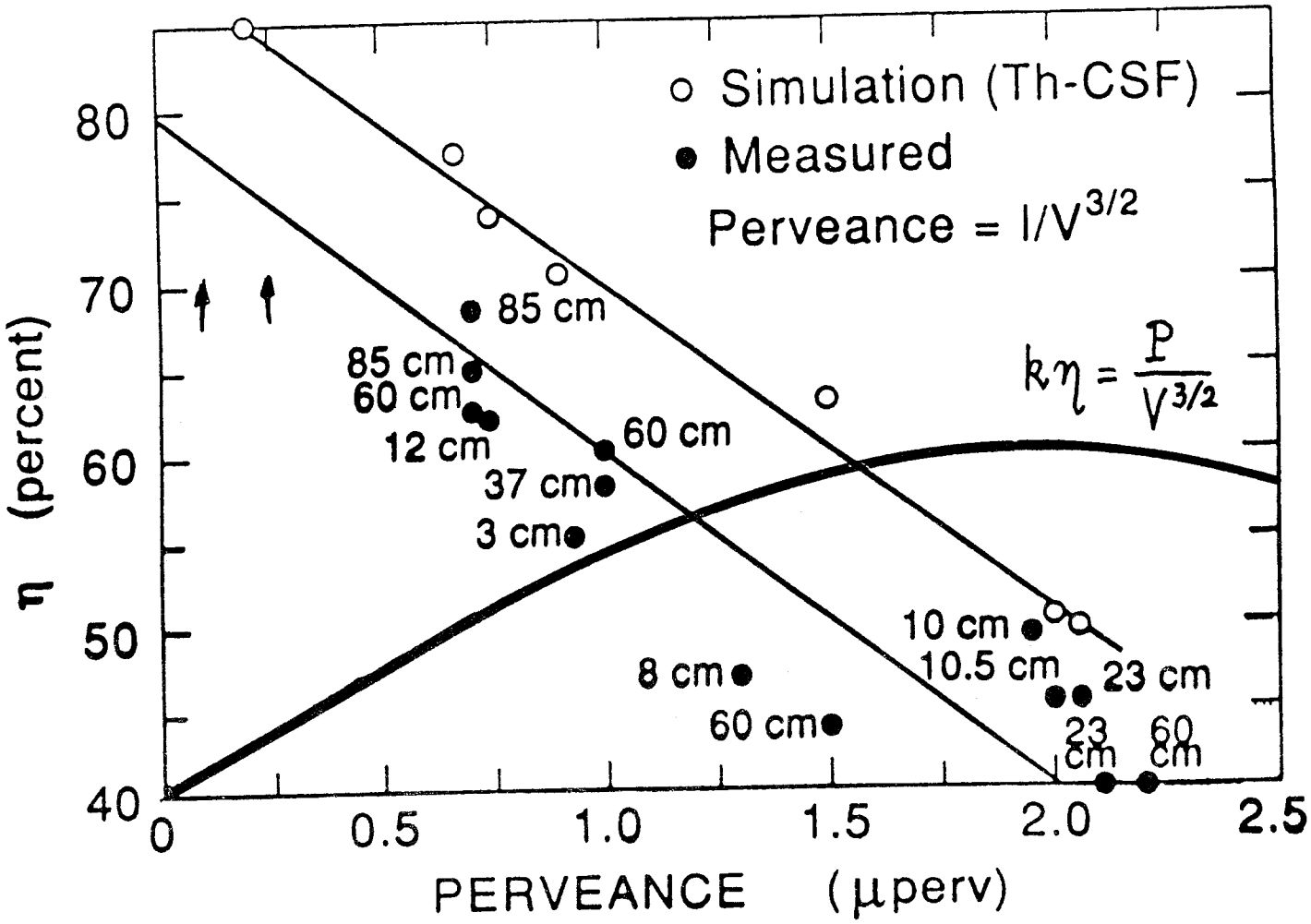
Modulation:



Relativistic klystron using transverse chopper



Haimson
(Haimson Research Corp.,
LLNL)


Simulation (Th-CSF)
Measured
Perveance = I/V^3/2
kη = P/V^3/2
85 cm
85 cm
60 cm
12 cm
60 cm
37 cm
3 cm
10 cm
10.5 cm
23 cm
8 cm
60 cm
23 cm
60 cm
80
70
60
50
40
0
0.5
1.0
1.5
2.0
2.5
η (percent)
PERVEANCE (μperv)

Magnetron gun

Chodorow (Varian).

1300 M.C.

Drift tube Dia.	1.50 inches
Beam Out. Dia.	1.25 inches
Beam In. Dia	1.09

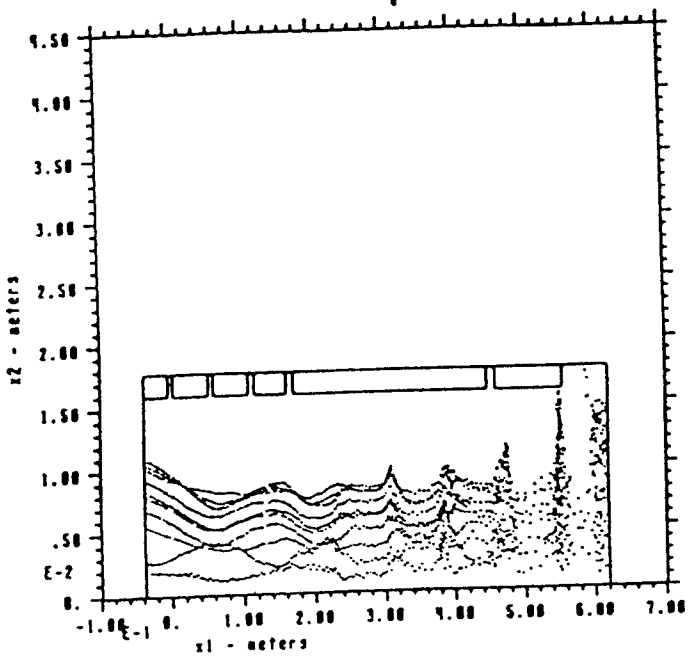
6 cavities Hollow Beam

Voltage	50 KV.
Current	93 A.
* Perveance	8.3×10^{-6} *
Power Out	2.0 MegaWatt
Efficiency	43%

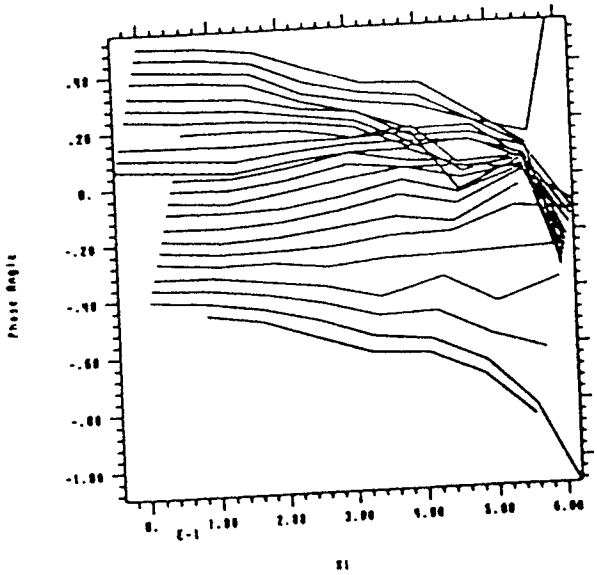
$$\frac{V_{(gap)}}{V_0} \approx .85 - .92$$

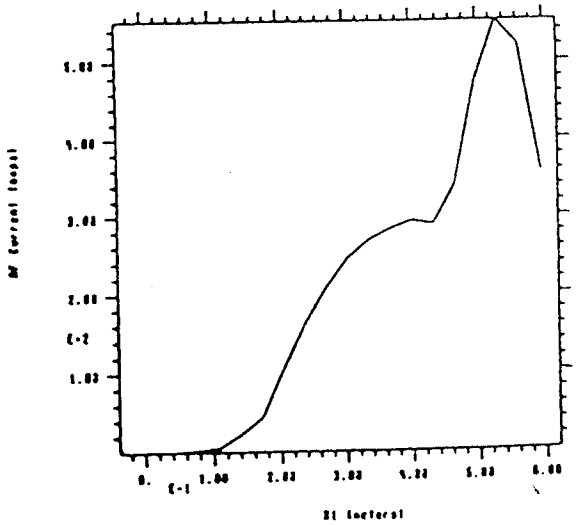
TUBE OPERATED AT EIMAC.
THEORY BY KINO & TALYOR.

SLAC 5045 Klystron Simulation



Eppley
(SLAC)





Status of Gyrocons

Results

$U = 1.2$ MV

$I = 100 - 500$ A (200 A typical)

$\tau = 1\ \mu s$

$f_{rep} = 1 - 2$ Hz

$f_{in} = 3.5$ GHz

$f_{out} = 7$ GHz

$P_{in} = 50$ W

$P_{out} = 60$ MW

Gain : 60 db → 100 db { 3 to 5 passive cavities

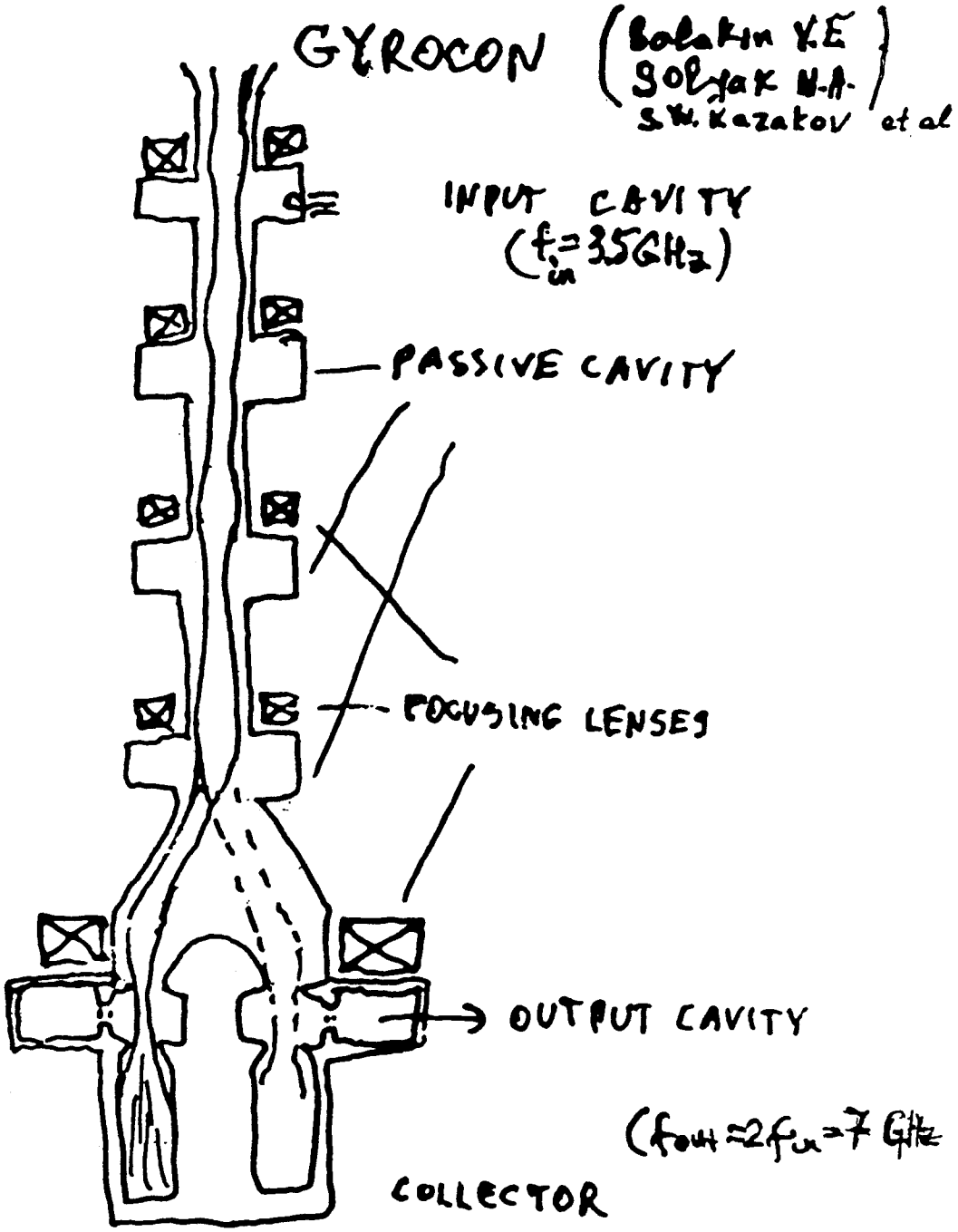
$\eta = 25\ \%$

Limited by breakdown in OUTPUT CAVITY

Notes: Gyrocons have not reached Klystron performances.

- More emphasis on klystrons at Novosibirsk in next future (may be)
- Very good experience in high voltage Power Supplies

collaboration { What about Combining SLAC klystrons with Novosibirsk high voltage Power Supplies



Balakin, Kazakov
(Novosibirsk)

Status of Gyro-klystrons

Gyrotrons are well known to give high C.W. power at high RF frequencies (Plasma)
The gyro-klystron is the Amplifier version of gyrotron

Advantages :

- Beam Power scales like λ (λ^2 for klystrons)
- High order cavities $\rightarrow$ High current

Problems :

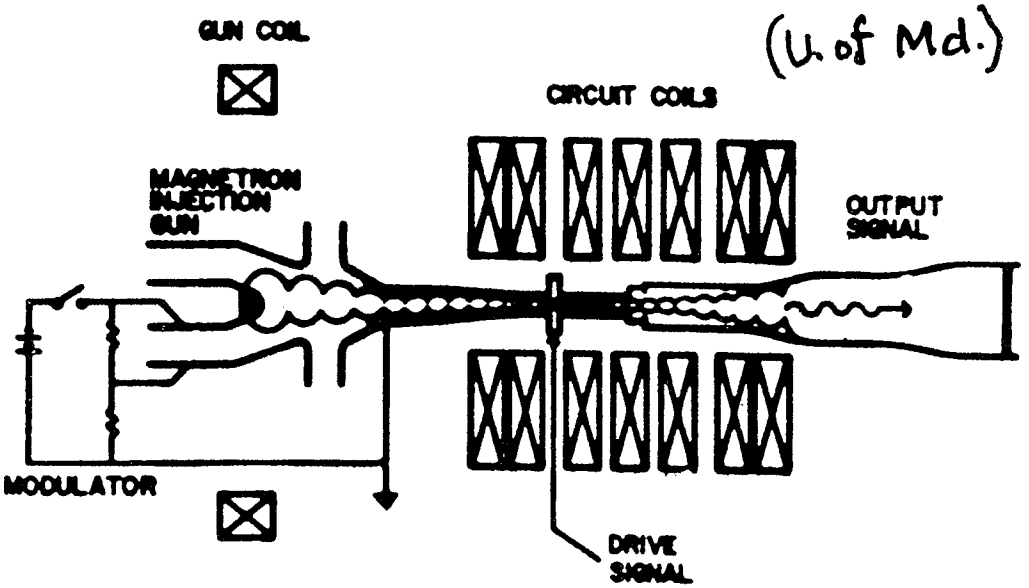
- Complicate gun
- Lower maximum possible efficiency
- Not much data at the moment

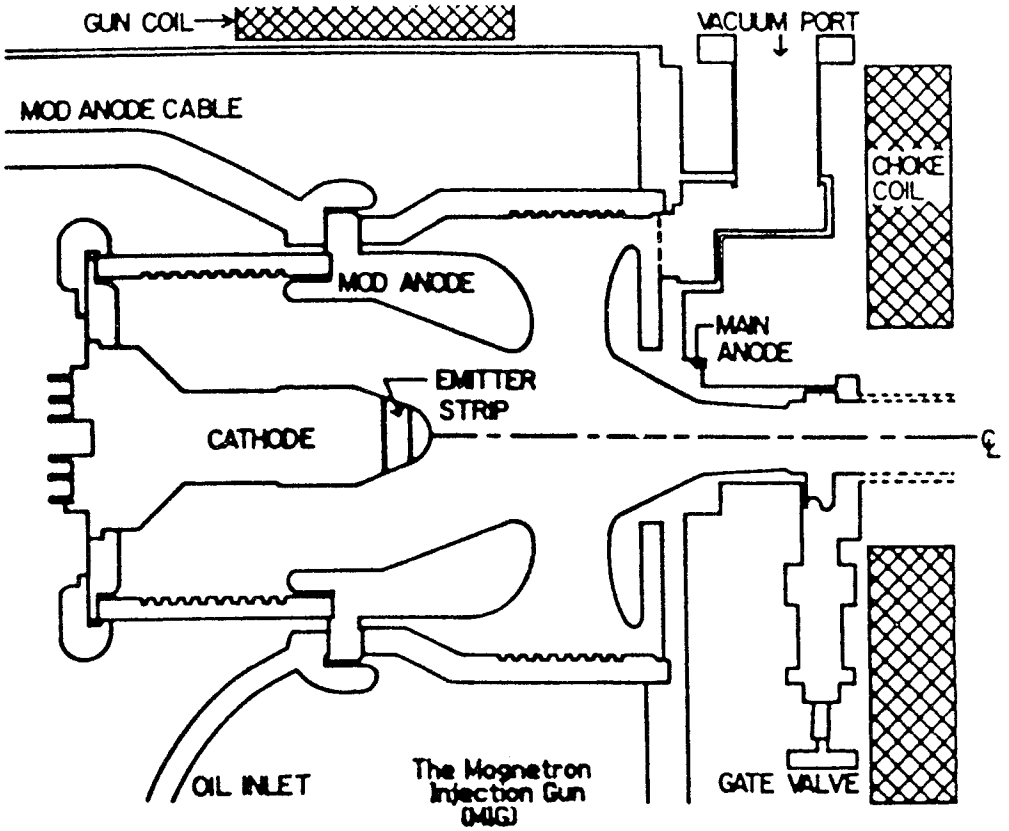
Prototype under construction at Un. of Maryland :

frequency	10	GHz	
voltage	500	kV	Let's wait
Current	200	A	for
P_{out}	30	MW	experimental
η	~ 30	%	results
Gain	27	db	

Design extrapolation predicts Gyro-klystron might be better than Klystrons at 6 × SLAC frequency but not at 4 × SLAC

GYROKLYSTRON SCHEMATIC Gramatstein Lawson (U. of Md.)





Magnetron Amplifier

Main features

- A Low Power version is used in a phased array radar

- Phase stability proven to be very good

- High perveance device
  300 kV compare to 1.2 MV (Klystron)
- Low impedance device
  better match to modulator
- RF triggered cold cathode →
  modulator simplification
- Expected manufacturing cost low compare to klystron

Challenge

Establish experimentally that a muti hundred Megawatt device can work

SLAC is going to investigate

May be SLAC should start by buying one (present version) → perhaps commercially available ?

CROSS-FIELD AMPLIFIER

(magnetron)

Design Parameters for

1 GW at 10 GHz - 50 nsec pul

$V = 300$ KV.

$I = 10$ KA.

$G_{am} = 30$ db

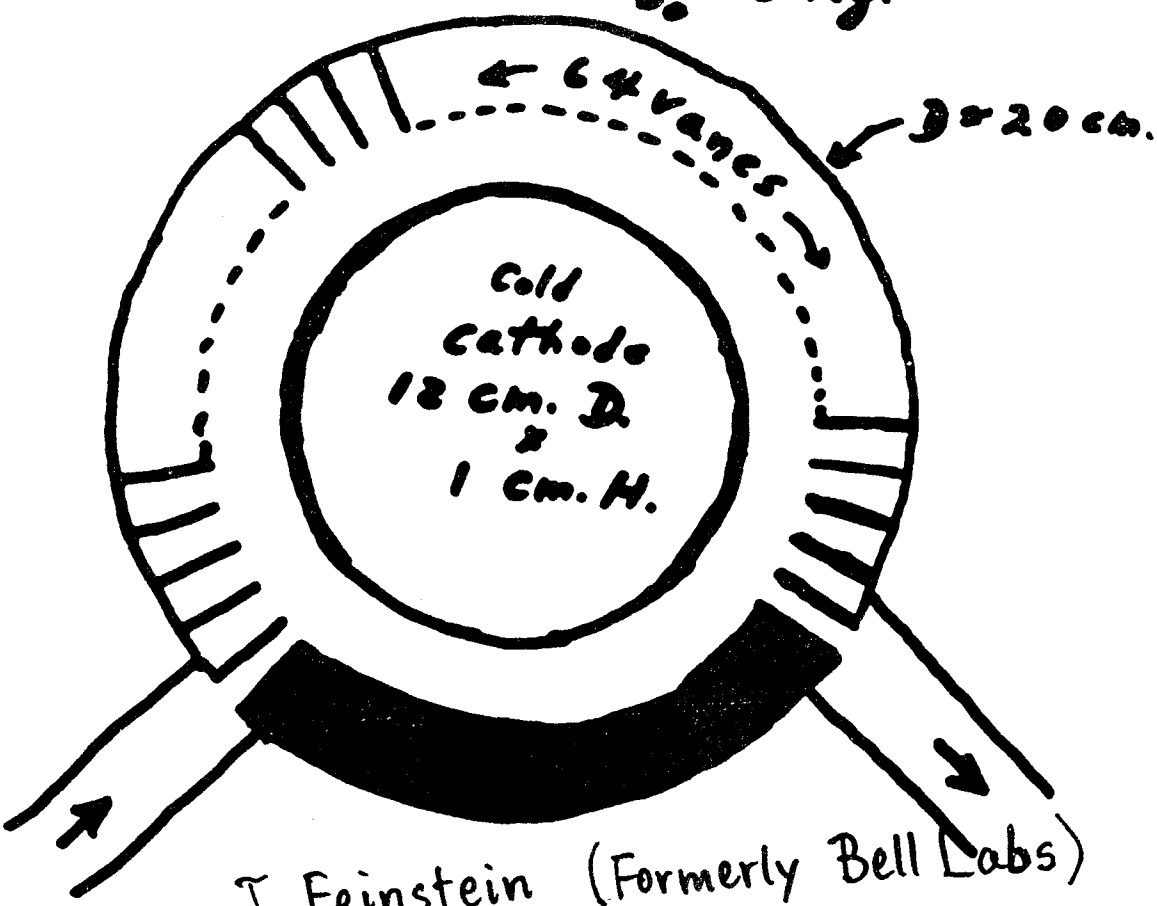
$BW = 1\%$

$V_{sync} = 30$ KV.

$I/A = 200$ A/cm^2

$E_{max} = 500$ KV/cm ($\perp B_0$)

$B_0 = 5$ Kg.



J. Feinstein (Formerly Bell Labs)

Lasertron

This RF power Source has had a very short life considering that SLAC and KEK abandoned their prototype developments :

3 GHz 50 MW $\eta \sim 70 - 80\%$

Notice that the programs were quite ambitious :

bring the lasertron technology at the level of klystron technology in a couple of years

At the moment ORSAY and Los Alamos are still persuing a lasertron program :

The problems :

- photo cathodes breakdown at relatively medium peak current under high d.c. voltages and laser pulses .
- Laser performances (stability)

Partial solutions :

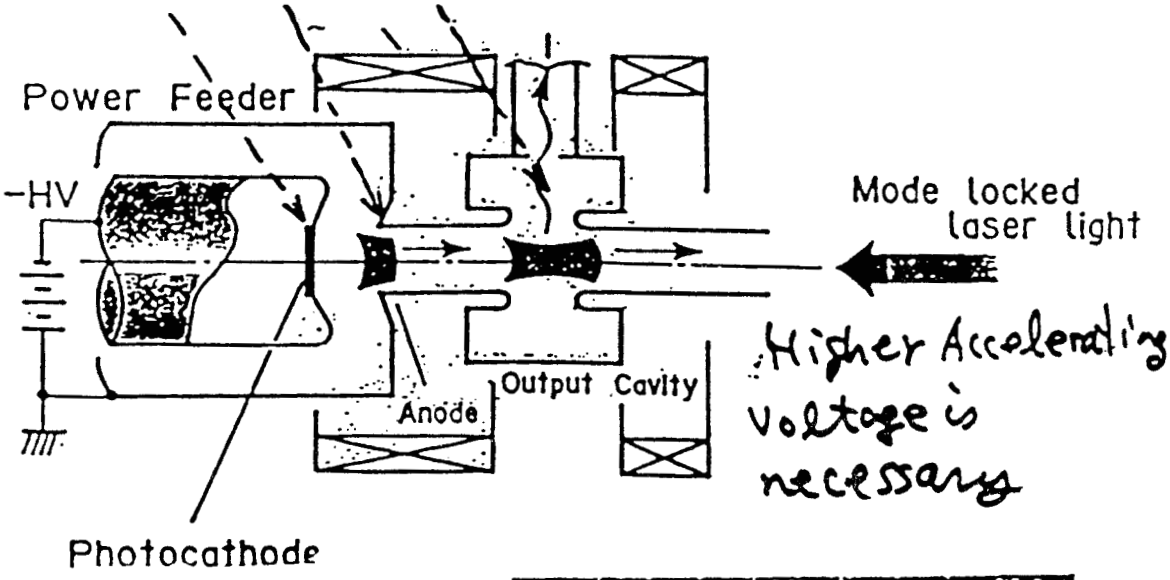
- bi alcaline photocathodes $Sb + Cs + K$ (los Alamos)
- metallic field emitter arrays (orsay + BNL)
- oxyde and dispenser cathodes (orsay)
- c.w. mode locked laser + compression + multiplex. (already good results at KEK + los Alamos)

Next steps

- d.c. laser triggered gun (first part of ORSAY program)
- RF gun laser triggered (KEK , ORSAY ; already los Al.)

Remark - The lasertron , according to the necessity of fundamental research should continue at the level of University Groups if High Tech Lab. give up. (For ex: ORSAY , Tokyo , Stanford Universities)

LASERTRON (Yoshioka, KEK)



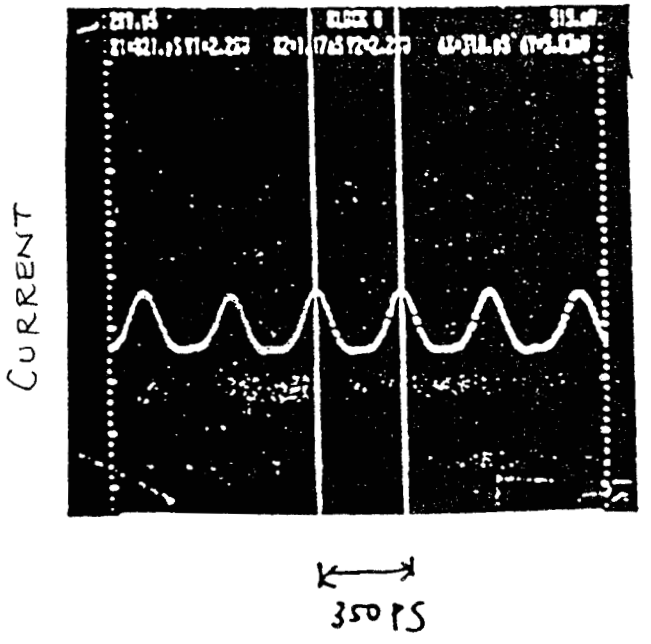
Higher Accelerating voltage is necessary

Cathode

$\begin{cases} Cs_3Sb \\ GaAs \end{cases}$

obtained results

150 kV
20 A
80 kW
2.7 %



Gigatron

An interesting, sophisticated, innovative idea from a small University Group.

It is an extension of the lasertron and sheet beam klystron Concepts

Interesting features:

1) Uses a gated field emitter array

2) Suppress the laser (and related problems) as the trigger –
   uses a coupled lumped resonant circuit to propagate a low level triggering signal

3) Uses a TW output coupler

4) Uses a ribbon beam (space charge ↓)

Present stage

A proposal for a prototype device (start with cathode developments)
Look for money and collaborations

Gigatron McIntyre (Texas A&M)

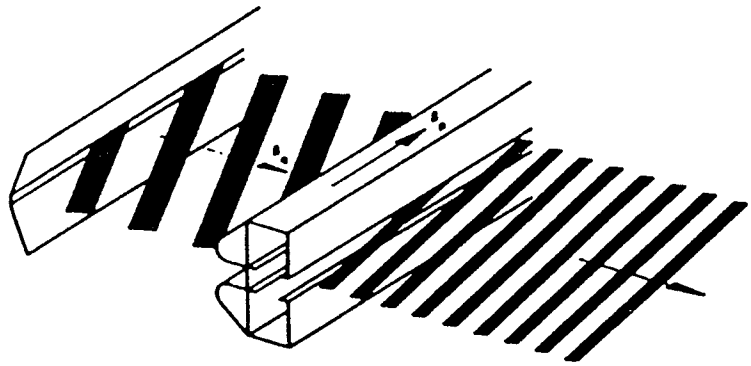


Figure 9. Isometric view of ribbon electron beam and traveling wave coupler.

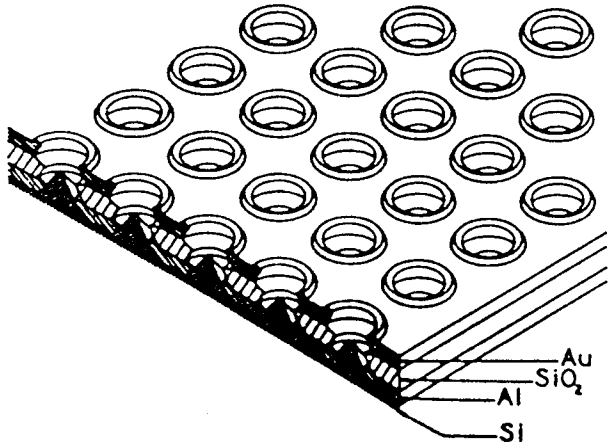


Figure 4. Isometric view of gated field emitter array (FEA).

Two Beam Accelerator Scheme

At first look it is probably one of the most attractive scheme

simple in the principle
A single drive beam

But simple in principle ≠ easy in practice

Present status (from an RF source point of view)

TBA - FEL	1.8 GW	(input 30 kW)
	34.6 GHz	
1 TBA	0.5 Hz	
unit	3.6 MeV	
Wiggler 1.3 m	1.1 kA	

TBA - S.C.

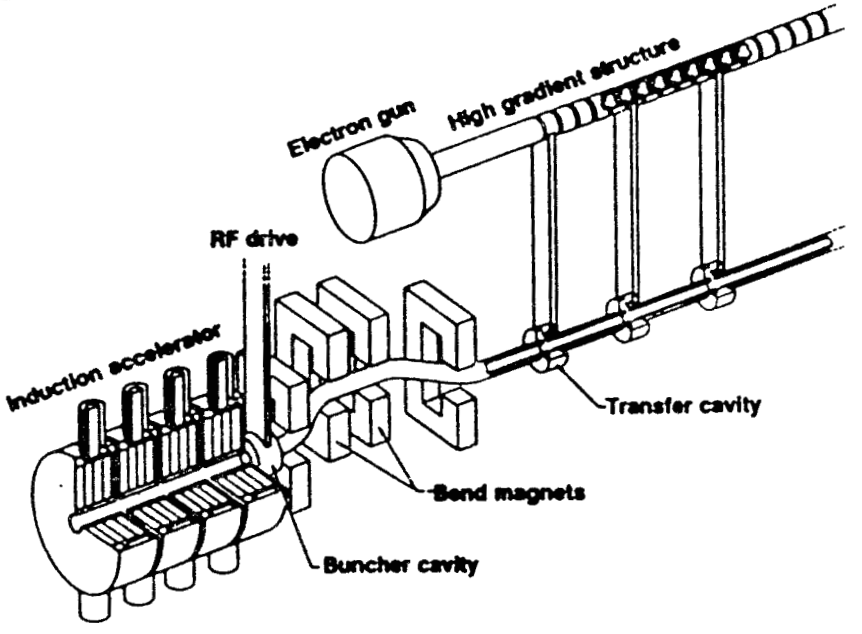
- Transfert structure being experimented at CERN - LIL [3 GHz]
- Laser triggered gun work at ORSAY

Next stage

At LBL - LLNL → 10 MeV 3 kA 3 GW (1 period, New extraction system

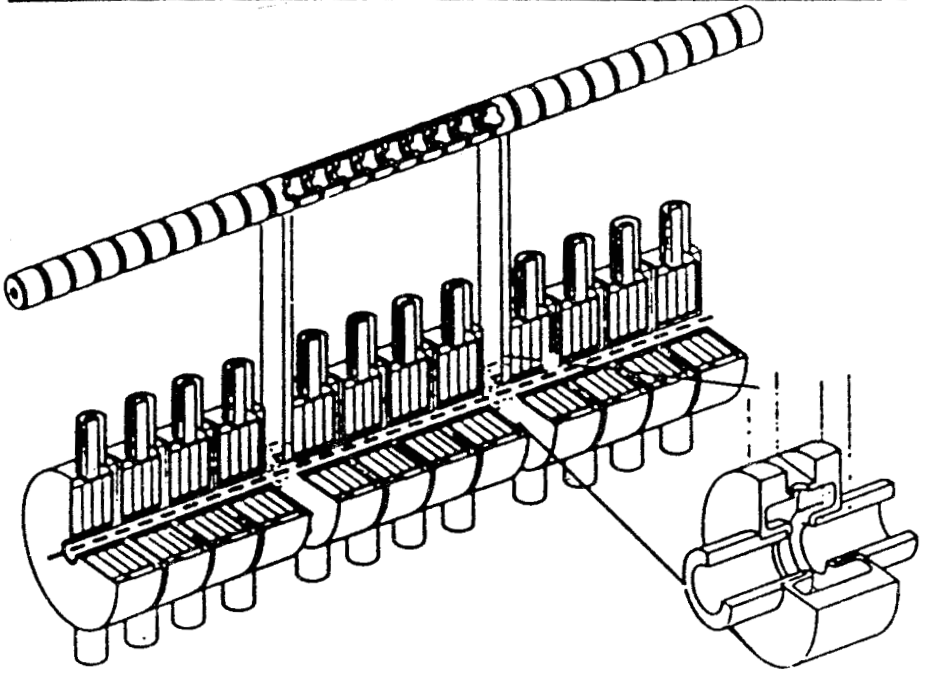
At CERN → Drive linac injector test station

Schematic of a relativistic klystron

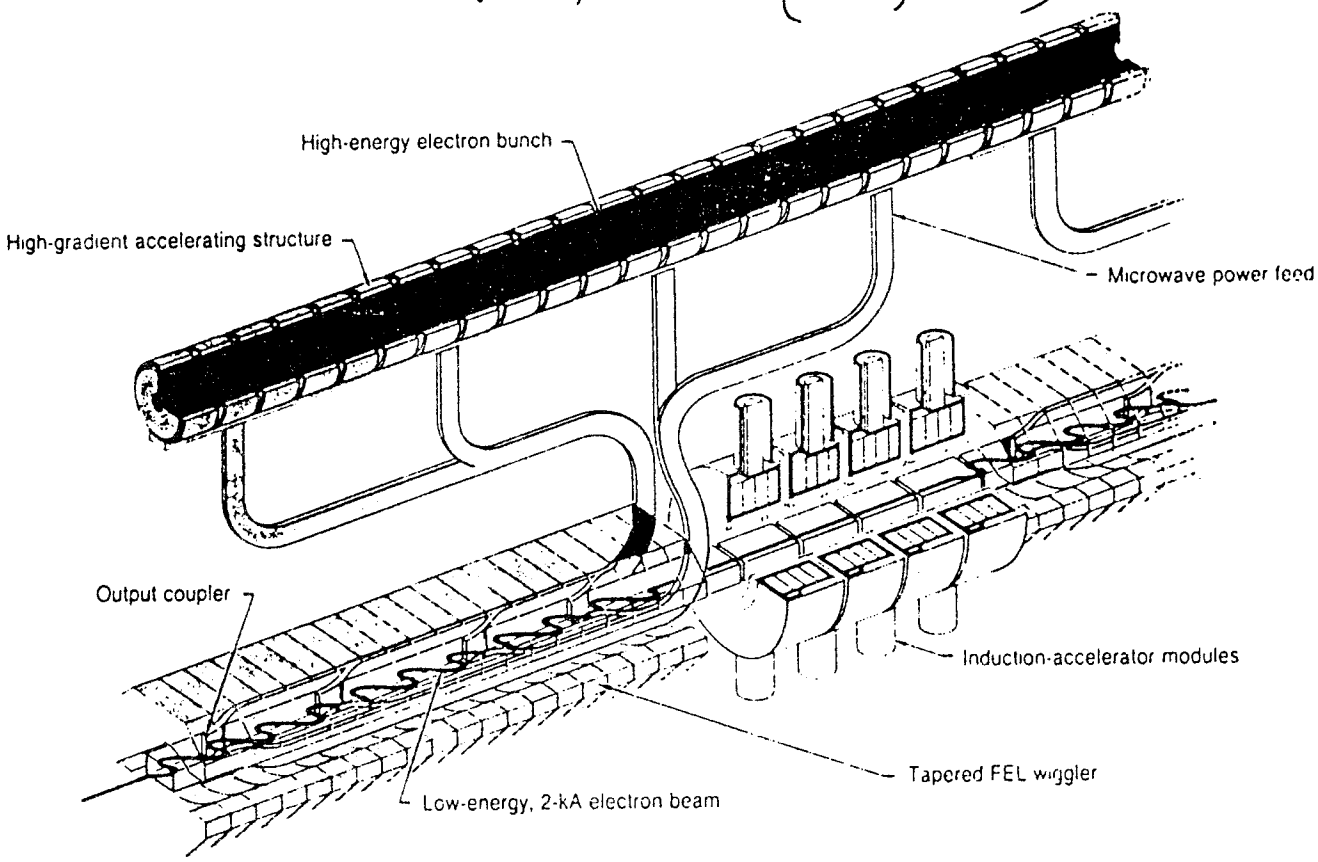


Sessler, Hopkins (LBL)

Schematic of a relativistic klystron



FEL/TBA Hopkins, Sessler (LBL, LLNL)

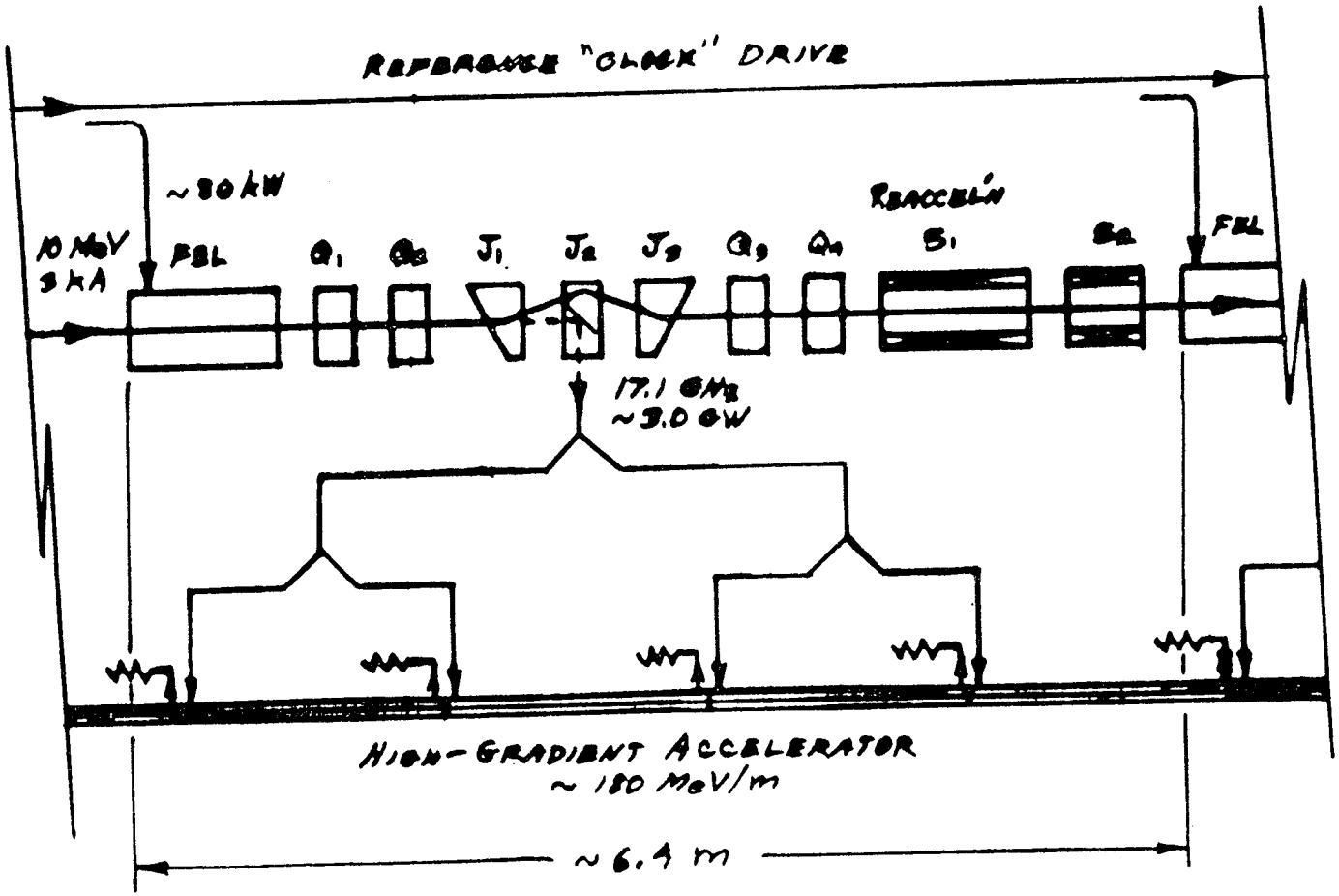


Two-beam accelerator envisioned by the Berkeley-Livermore group. A high-gradient miniature of a conventional rf accelerating structure is fed short-wavelength microwave power from an adjacent high-current beam of low-energy electrons serving as a free-electron laser as it undulates through wiggler magnet arrays. The energy this driving beam gives up to the high-energy electron beam is replenished by induction-linac modules along the way. Figure 5

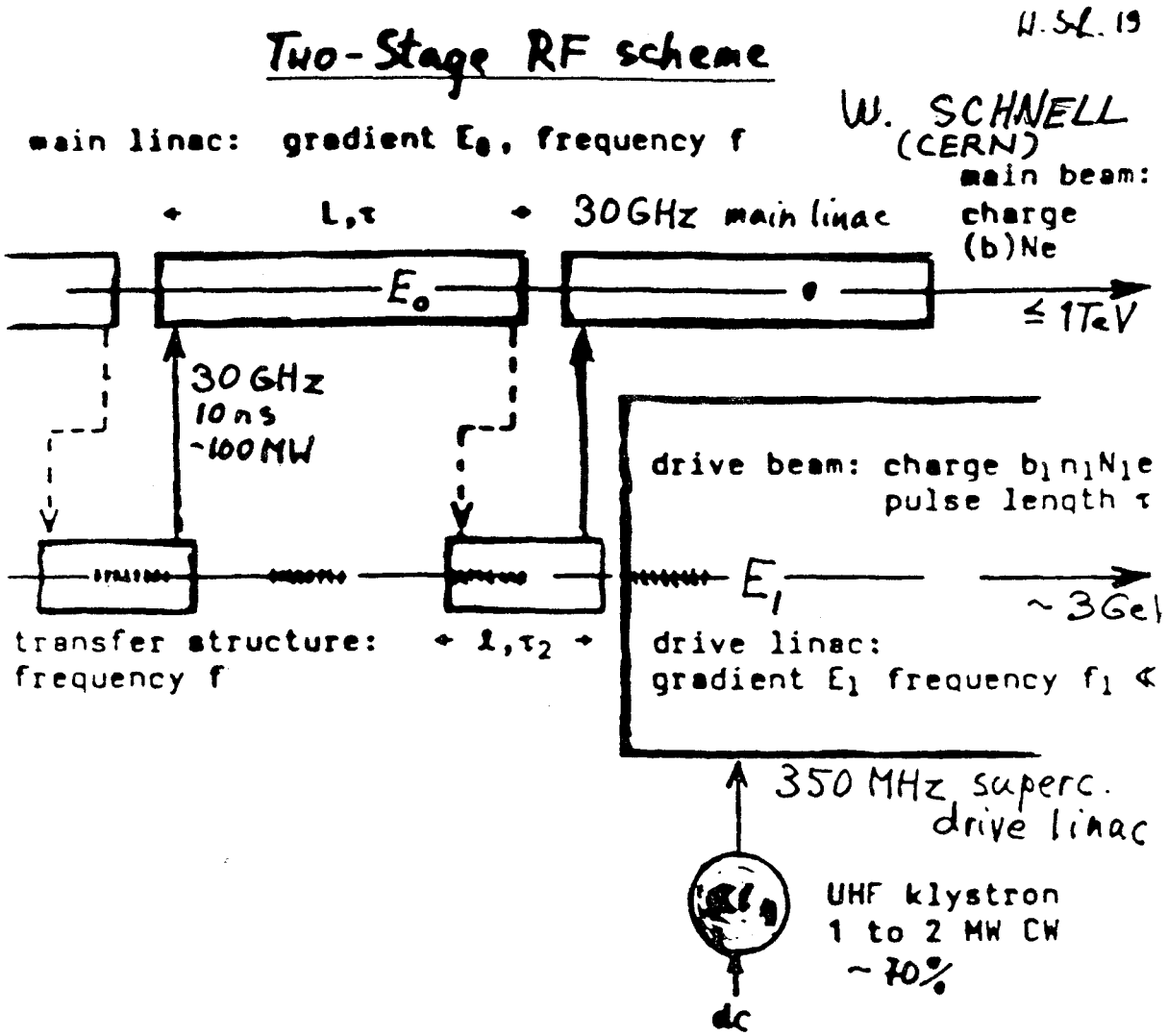
FEL/TBA

Hopkins
(LBL)

NEW VERSION OF FEL/TBA SHOWING A SINGLE PERIOD



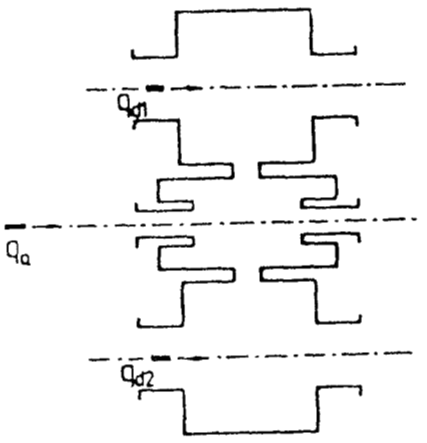
CERN LINEAR COLLIDER

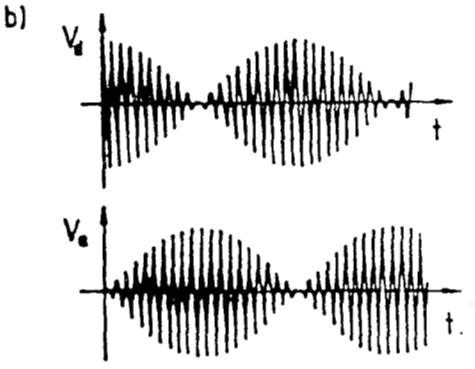


ENERGY RECUPERATION SCHEME FOR A TWO-BEAM ACCEL.

— Henke (CERN)

b)





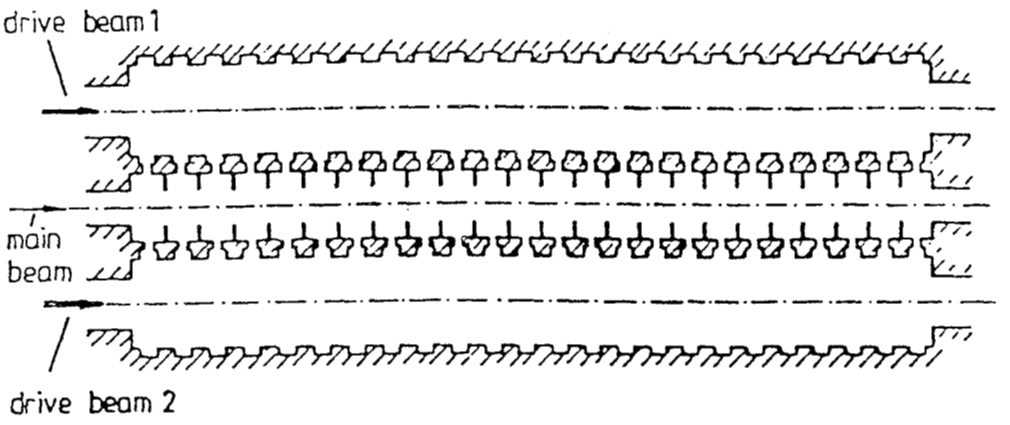


Fig. 5 Multicell cavity beat-wave transformer with two symmetrically arranged drive beams.

COST

INVARIANT

1 B$

Conclusions

Present situation

No solution which fulfill all constraints : Peak Power
rep. rate
high efficiency
realistic cost

However two non dedicated sources have reached $\hat{P} > 1$ GW
(FEL, IREB, Vircator oscillator, and Rel. Magnetron oscill.)

Next stage

Two Beam or not Two Beam, that is the question.

At the moment the different choices are more a matter of existing high tech in each lab.

In the case of TBA there is need for a real test facility : a few stages of beam manipulation [extraction, reacceleration]

There is still room for innovation
Any good new ideas will be helpfull
Don't be discourage - Think of your child

ACCELERATOR STRUCTURES WORKING GROUP

Chairman: G. Loew SLAC

Secretary: J. Wang SLAC

Members and Contributors

I. Wilson	CERN
N. Soliak	Novosibirsk
M. Yoshioka	University of Tokyo
T. Higo	KEK
E. Haebel	CERN, HEPL
D. Yu	DULY Consultants
J. Haimson	Haimson Research
E. Paterson	SLAC
H. Hoag	SLAC
A. Lisin	SLAC
C. Rago	SLAC

Summary of the Accelerator Structures Group Discussions

Gregory A. Loew, Juwen Wang

Thirteen people in the workshop participated in the working group on linear accelerator structures. The following topics were considered and conclusions were reached:

1. All laboratories described their respective structure programs, which are summarized in the section on recent and planned experiments for calendar years 1988, 1989 and 1990.
2. The choice of RF frequencies ranges between 11.4 GHz for KEK and possibly SLAC, and ~30 GHz for CLIC. Novosibirsk has chosen 14 GHz. At the present time, all structures are of the disk-loaded traveling-wave type ($2\pi/3$-mode) although standing-wave structures (π-mode) are also being considered. The latter have the advantage that they do not require loads and allow for easier multi-bunch energy control, but have the disadvantage that they generally exhibit higher peak-to-accelerating field ratios. The lengths of the sections range between 25 cm (CLIC) and about 1.5 m (SLAC), and the corresponding gradients range between 80 and 186 MV/m. For single-bunch wakefield control, the ratio of iris radius to wavelength is invariably chosen to be 0.2. The resulting group velocity is about 10% of the velocity of light, which results in filling times in the range 10–50 nsec. The peak input power per section ranges between 37 MW (CLIC) and 1450 MW (SLAC). Structure efficiencies turn out to be about 50%.
3. For Physics reasons, CLIC and especially SLAC are considering multi-bunch operation with injection of each bunch train before the end of the filling time. An alternative to this scheme was also discussed whereby each RF pulse would last several filling times and the bunch spacing could be increased accordingly. In any case, multi-bunch beam break-up seems to require that the Q of the deflecting mode (HEM_{11}) in these structures be reduced below 20, dictating the need for slotted-disks with lossy transverse waveguides. Considerable effort was spent discussing the calculations (MAFIA), spurious modes, tests, construction, lossy materials, cost, etc., pertaining to these slots. While they present many difficulties, they at least have the advantage of increasing the pumping speed of the structure, which is important.
4. Other important subjects discussed were high-gradient breakdown, dark currents, and RF processing (possibly using argon), fatigue damage from impulse RF heating, water cooling and the potential vibrations caused by the flow, brazing techniques (preferred above all other alternatives including electroforming), alignment tolerances (on the order of 10 to 50 μm) and the desirability of built-in beam position monitors.

List of Accelerator Structures Talks

1. I. Wilson, "Design and Fabrication Studies of the High Gradient Accelerating Structure for the CERN Linear Collider (CLIC)"
2. G. A. Loew, "SLAC Structure Work"
3. T. Higo, "High Gradient Accelerator Structure Research at KEK"
4. N. Soliak, "High-Gradient Accelerator Structure Research at Novosibirsk"
5. H. Henke, "Multi-bunch Requirements and Wakefields"
6. D. U. L. Yu, "Computer Aided Design of 3-D Waveguide Loaded Cavities"
7. I. Wilson, "Summary of Structures Working Group"
8. G. A. Loew, "Laboratory Activities on Structures, Recent and Planned Experiments"

STRUCTURES
TOPICS

1. Experiments done recently and planned in near future, including materials and fabrication methods

   Novosibirsk
   KEK
   ORSAY
   CERN
   SLAC / LLNL / LBL / HRC

   } SEE SECTION BELOW

2. Multibunch requirements
   Alignment tolerances
   Wakefields from dark currents

3. Slotted structures
   Effect of slots on E_z
   Length of slots, lossy materials
   MAFIA calculations and other experiments
   Q measurements

4. Other structures

5. Breakdown
   Dark current
   RF processing

   } Evidence
   Theory

6. Fatigue damage from impulse RF heating

7. Fabrication techniques & cooling

8. Vacuum, pumping speed.

9. Built-in beam position monitors

10. Structure dimensions and calculations
    (made by D. Farkas)

NOVOSIBIRSK

ACTIVITIES	88	89	90
14 GHz TW $2\pi/3$ MODE	DESIGN	FABRIC. TECHNOL. STUDIES 0.3 m AND 1.0 m SECTIONS MACHINING BRAZING	CONT.
RF — LOW POWER		PARAM. MEASMTS.	
RF — HIGH POWER		NEW KL. OR GYR. 14 GHz $P \geq 10$ MW	RESONANT STRUCTURE $E_{ACC} = 100$ MV/m TESTS WITH BEAM

KEK

ACTIVITIES	88	89	90
2.856 GHz HIGH GRADIENT TW STUDIES	RESONANT RING 65 MW $E_{ACC} \sim$ 150 MV/m		
	0.6 m + 1.5 m SECTION STUDIES FOR	TAF	
TEST ACCELERATOR FACILITY (TAF)	2 5045 KL. (SLAC) 200 MW ↓ ~100 MV/m	1 5045 KL. SLAC 100 MW ↓ ~ 50 MV/m	REGULAR OPER. AT 50 MV/m
	WITHOUT /	WITH BEAM	
11.4 GHz STUDIES	STRUCT. DESIGN	CONT. DESIGN MACHINING BRAZING	PROTOT. FABRIC. FOR TAF
ALIGNMENT STUDIES		DISPL. STR. 10 μm RES. 10 nm FEEDBACK → 100 Hz	CONT.

ORSAY

ACTIVITIES	88	89	90
3 GHz HIGH POWER TESTS	2π/3 * 4π/5  DARK CUR.	INCREASED KLYSTRON POWER CONT. WITH BEAM	CONT.
LASERTRON "HYBRID" CATHODES	MEASUREMENTS	→ CONT.	

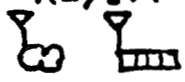
* 2π/3 : FORWARD-WAVE STRUCTURE

4π/5 : BACKWARD-WAVE STRUCTURE

CLIC

ACTIVITIES	88	89	90
FABRICATION STUDIES	BRAZING TESTS ON CUPS	ELECTROF. TESTS MACHINING + BRAZING	CONT.
RF MEASUREMENTS		30 GHz 5 6-CELL 2 72-CELL STRUCTURES	COUPLER STUDIES
TEST BEAM FACIL. USING 3 GHz LINAC AT 100 MeV ONE BUNCH, 2×10^{11} e^-		e^-	PHOTO-CATHODE SOURCE TRANSFER STRUCTURE ACCEL. STRUCTURE
BEAM POSITION MONITOR STUDIES	e^-	INTEGRAL WITH ACCEL. SHAPE SIGNAL PROCESSING	CONT.
MECHANICAL TESTS		WATER VIBRATION FATIGUE ALIGNMT.	CONT.

SLAC

ACTIVITIES	88	89	90
2.856 GHz HIGH POWER	10-40 MW KLYST.  π 2π/3 150 MV/m	10-40 MW KLYST  SLOTTED STRUCTURE	10-40 MW KLYST CONT. WITH DAMPED PORT
2.856 GHz RF PROCESSING BREAKDOWN DARK CURRENT	EFFECT OF GASSES	 SINGLE CAVITY DEMT.	
2.856 GHz SLOTTED STR. DESIGN	CONCEPT.	ACTUAL TESTS AT LOW POWER LOSS Q MEASMT	
11.4 GHz STRUCTURE	30 CAVITY SECTION ~200MW ~140 MV/m INTERIM	CONT. WITH RK AT LLNL OR WITH K. AT SLAC	CONT. WITH BEAM
11.4 GHz 17.1 GHz STRUCTURE	EARLY MODELLING	FABRICATION STUDIES	
MULTIBUNCH BBU TESTS ?		POSSIBLE TESTS ON LINAC	

HRC - LBL - LLNL

ACTIVITIES	88	89	90
33 GHz HIGH GRADIENT STRUCTURE FOR TBA	NOT YET TESTED	WAITING FOR RF AT LLNL OR MIT	
11.4 GHz β<1 RK STUDIES TW OUTPUT FOR SHARK	INSTALL. OF TW TRANSFER STRUCTURE	EXPERIMT AT LLNL	
11.4 GHz "CHOPPERTRON" $v_g/c = \frac{1}{6}$ $\beta = 1$ EXTRACTION		TO BE INSTALLED AND TESTED AT LLNL	
17.1 GHz HIGH GRADIENT DESIGN		DESIGN AND POSSIBLE FAB. FOR FEL PROG. IF REQUIRED	

MULTI BUNCHING

- Luminosity increase
- more recently final focus problems
- however beam breakup if no damping of wakefields

With bunch spacings typically 10–20 RF cycles
— need Q_s of 10 or 20

- most efficient way – slot the irises
- however considerably complicates structure design

Considerable discussion this week on ways to avoid beam break up without having to have slots.

Step in right direction – G. Loew scheme with N bunches/shot spread thinly over extended pulse (M individual pulses end to end). Saves M−1 filling times
Allows much larger bunch spacings
Reduces repetition rate by factor M.

Disadvantages :

<u>SLAC</u> (i) Flat top long pulse from klystrons (×M)
(ii) For M = 10 say, repetition rate approaches ground motion frequencies (30 Hz)

<u>CLIC</u> (i) SC cavities unable to provide enough stored energy for extended pulse.

- Considerable discussion with beam dynamics people – would the 2–3 % $\Delta f/f$ for higher modes which could be built into acc. structure – varying cell/cell dimensions
  – const. grad. type structure
  be any help in easing the problem?

Message from beam dynamics people LOUD & CLEAR

- neither of these contributions individually sufficient
- do really need SLOTS !

$\Delta f/f \doteqdot 2\%$ however might help to get closer to zero resultant for scheme with trailing bunch placed close to zero crossing (SLAC scheme) since amplitudes are much smaller and mixing might improve things.

<u>CONCLUSION</u>

If you want multibunching – you need SLOTS.

This is bad news for the fabrication people.

ALIGNMENT TOLERANCES

- Difficult to get precise values
- Depends on various design approaches adopted & in particular frequency

Following values INDICATIVE only (ball park values) and are constantly being revised (usually in wrong direction).

		TLC	CLIC
Alignment	structures.	50 μm	10 μm
"	quads.	30 μm	few μm
Jitter	quads.	0.02 μm	0.2 μm

- *properly* engineered feedback systems – *possible*

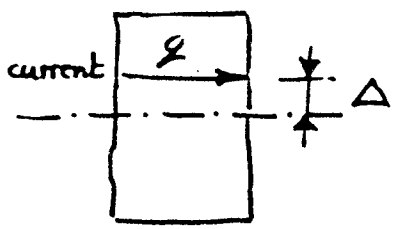
WAKEFIELDS FROM DARK CURRENTS

- basic problem – field emitted electrons produce a flow of charge off axis
  – excites transverse modes

- Beam dynamics group is looking at this problem
  – later session hopefully will give an upper limit for current which starts to give problems

Model

Field emitted current



All charge concentrated at distance Δ from axis
Excites TM_{11} mode.

RF absorbed POWER – FIELD EMITTED ELECTRONS

- RF absorbed power due to RF focussed field emitted electrons along axis of accelerator – basically beam loading – apparently NOT a problem
  – SLAC : no measured effect on test structures (G. Loew)*

- Since $I \propto 1/f$
  helps to go to higher frequencies.

*NOTE ADDED BY G. LOEW :
"EFFECT NOT MEASURABLE SO FAR".

OTHER STRUCTURES

- not found attractive alternative to DLWG geometry

- Jungle Gym invoked – simpler cavity to fabricate
  – large a/λ requirement $\rightarrow$ very unfavourable geometry $\rightarrow$ substantial reductions in R' & R'/Q

- Must mention that BEATWAVE TRANSFORMER scheme proposed by H. Henke – many attractive features
  – uses SW coupled π-mode cavities
  – deserves further consideration

  Presented at this workshop – copies available.

  – 2 coupled π mode cells with individual feeds – proposed for klystrino approach of G. Loew.

SURFACE DAMAGE FROM RF IMPULSE HEATING

- VERY large peak powers required for LCs produce
  LARGE PULSED DISSIPATED POWER DENSITIES
  (CLIC 80 MV/m $P \doteqdot 170$ KW/cm^2
  160 MV/m $P \doteqdot 680$ KW/cm^2)
- Shown to produce
  thermally induced cyclic stressing of Cu surface
- Concern – lifetime of accelerator (10^{11}-10^{12} cycles)
  surface damage due to fatigue may occur.
- Fatigue data for $\sigma^* \doteqdot 0.1\sigma_Y - 0.5\sigma_Y$
  not available in literature.

- THEREFORE RECOMMENDED THAT A
  FATIGUE TEST made
  – carefully prepared copper test piece
  – realistic working conditions
  – periodic checks on surface quality

FABRICATION TECHNIQUES

This is dominated by the well-known saying

" TO SLOT OR NOT TO SLOT – that is the question

- SLAC (TLC) are committed to slots
  JLC (KEK) – not decided
  Novosibisk – have no slots
  CERN – would like to incorporate slots if possible.

- SLAC structure (4 quadrants – individually machined & radiused) – although complicated (5 parts per cell) looks technically feasible at X-band using very precise 3-D milling machines or grinders.
- At 30 GHz – not obvious such approach technically possible.

- There is LITTLE ENTHOUSIASM for electroforming.
  All labs. represented at workshop envisage machine + braze solutions
  – CERN & KEK never-the-less have electroforming studies in progress.

- Relax TOLERANCE requirements on machining
  → use of less sophisticated machines
  – many more available
  – then DIMPLE TUNE.

- Must <u>continue searching</u> for <u>simpler</u> ways of making these structures !!

COOLING OF STRUCTURES

- main concern not to get $\overline{P}_d$ out but
- to avoid excessive temperature differentials
  - lead to thermal distortion & associated frequency changes

- Thermal distortion can be limited to some extent by judicial placing and dimensioning of water cooling channels
- Detailed stress & deformation analysis needed to assess seriousness of problem.

- concern over water flow induced vibrations in the structures
  - tests are required to establish freq. / amplitude spectrum for reasonable flow rates on real structures.

BEAM POSITION MONITORS

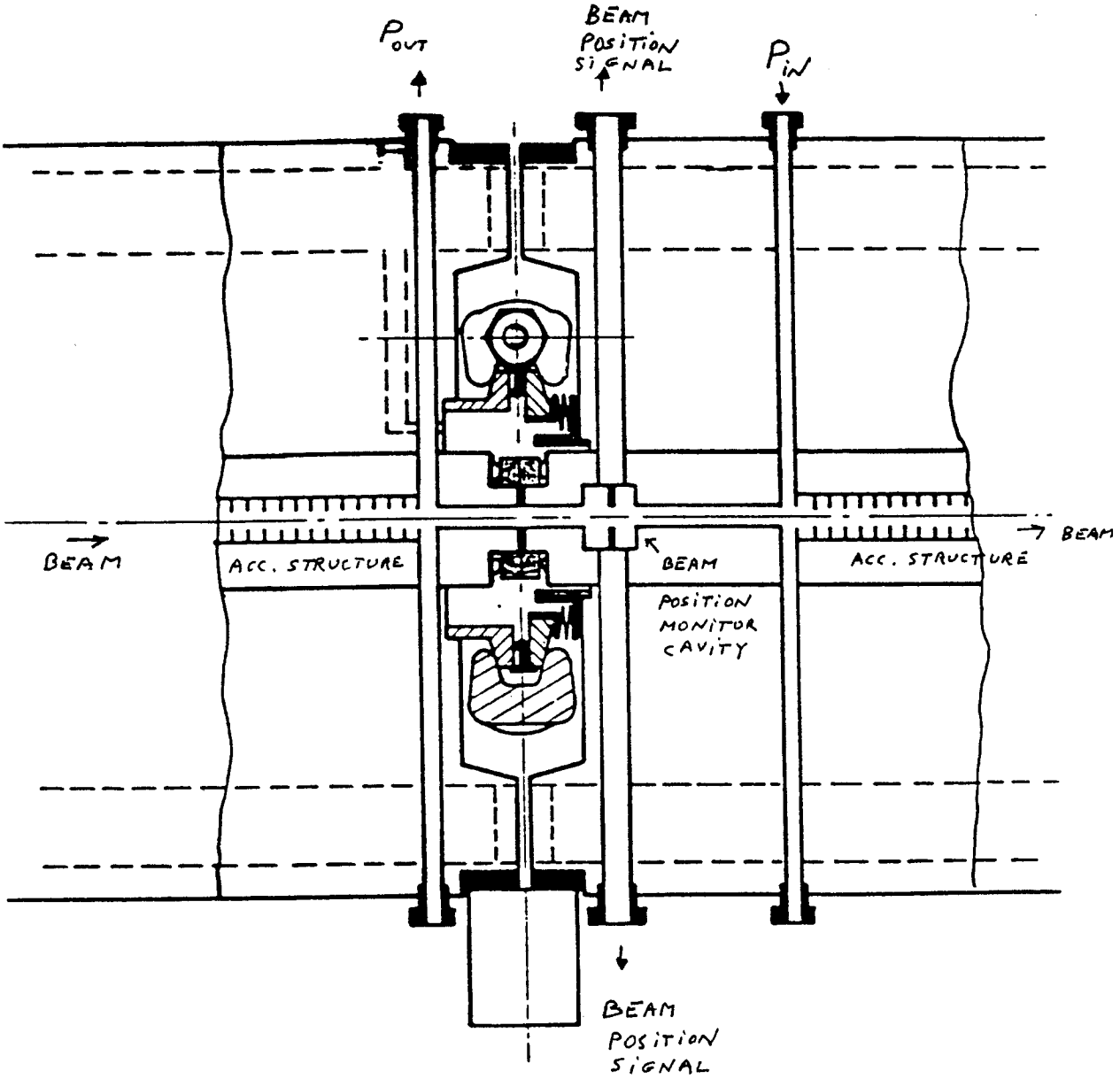
- given tight tols. on alignment
- require accurate measurement of transverse beam position
- essential BPM whose output signal
  - reliably zero if beam on axis, otherwise $\propto q \cdot \Delta$ – be incorporated into acc. structure as integral part during fabrication.

- one possibility to get μm resolution + zero point definition → microwave structures picking up EM energy from beam.

- shown (CLIC Note 70) that
  - simple circular cavity
  - co-axial to beam axis
  - E_{11} mode excitation by off-centre beam

  ⟹ forms excellent position pick-up with POTENTIAL of micron resolution.

- avoid beam break up with multiple bunches
  - cavity must be slotted
  - E_{11} signal coupled out of one of damping slots then passed thro' narrow-band receiver to filter the required signal.



JUNCTION OF TWO ACCELERATOR SECTIONS WITH ALIGNMENT AND BEAM POSITION MONITOR INTEGRATED INTO CONSTRUCTION

STRUCTURE DIMENSIONS & CALCULATIONS
(D. Farkas).

D. Farkas – calculated a reference subset of structure parameters with TWAP TW PROGRAM
– produced expressions (by curve fitting reference subset) which allow all important parameters to be calculated without running the computer program

Copies of his results have been distributed and are available on request.

INSTRUMENTATION WORKING GROUP

Chairman: J. Seeman SLAC

Secretary: G. Fischer SLAC

Members and Contributors

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M. Serio	Frascati
V. Parkhomchuk	Novosibirsk
A. Lumpkin	LANL
R. Pitthan	SLAC
K. Bane	SLAC
M. Ross	SLAC
R. Ruth	SLAC
C. Johnson	SLAC
T. Lavine	SLAC
D. Walz	SLAC
M. Lee	SLAC
P. Morton	SLAC

Summary of the Instrumentation Group Discussions

John Seeman, Gerhard E. Fischer, Colin Johnson

The subject "Instrumentation and Controls" for the next linear collider covers a broad spectrum of topics. Included among them are system packages, flexible on-line models, beam position monitors, beam size and emittance measurements, energy and energy spectrum control, alignment of components and mechanical vibration control, control system philosophy, collimation, and the complications arising from multiple bunch operation. Overall reviews of selected topics were presented (see list of talks) and discussed in terms of their application to the next linear collider. Final focus instrumentation was not discussed in this group because it depends on details of final focus design as well as being somewhat unique compared with the nominal parameters of the accelerator complex. The large scope of this group's activities prevented in-depth development of any single topic, but several general conclusions could be drawn. They are :

1. Comprehensive instrumentation packages must be incorporated into the accelerator design for the next linear collider at strategic locations from the very outset. Such strategic locations might, for example, be at the territorial, or better, at the optical boundaries between system functions. Whatever the case, such monitoring points must be clearly defined.

2. The accelerator complex will be significantly more complicated than in the past so that comprehensive on-line model and application programs will be essential for problem diagnosis.

3. Arguments can be made for either RF or stripline position monitors. At this time, which design concept is better depends on details yet to be studied and the choice is best be left to the taste of the user. Dark currents in the linac or common mode problems will need to be considered.

4. In the linac, beam size measurements will likely have to be made with wire scanners ($\sigma \approx 2$ to $20\mu m$). Problems with linac dark current may contaminate the readings.

5. Devices using the properties of transition radiation work well at "low" energies ($< 100MeV$) . Their usefulness at the "high" energies of a linear collider is less clear, but warrants further study.

6. Energy and energy spectrum control must be incorporated into final focus design. Nowhere else is there adequate dispersion.

7. Traditional methods of alignment are insufficient. A steady R & D effort will be required for the next several years in order to make it possible to align the components of the next collider and keep them in alignment. The choices of site geology and operating repetition rate have bearing on the questions of vibration control.

8. The measurement of multiple bunches (at say 20 cm spacing) will entail complicated techniques, the full impact of which is not yet known. It is important to evaluate whether or not a measurement of the ensemble of sub-bunches will suffice in most cases.
9. It has been shown that particles in a bunch, of population density such as are proposed, are deflected by unacceptable amounts when these bunches pass *near* the edges of objects such as collimators. Furthermore, should such bunches *strike* materials, single bunch melting or fatigue due to repetitive stressing may result. Beam halo removal through the application of high order (i.e. non-linear fields) does not, at this moment, appear practical. These problems deserve intensive examination.
10. Overall, there was optimism that most instrumentation questions could be answered with finite amounts of work and that with some reconfiguring of accelerator parameters, the difficult instrumentation problems could probably be solved. However, it would be well to clarify the situation with respect to multibunch operation early on. Fundamental questions with respect to "collimation" remain.

List of Instrumentation Talks

1. R. Pitthan, "Optical Transition Radiation"
2. J. Seeman, "SLC Instrumentation Packages"
3. K. Bane, "Image Force Deflections from Collimators"
4. G. Fischer, "Alignment and Vibration Issues for the NLC"
5. M. Ross, "SLC Stripline BPM Studies"
6. R. Ruth, "Things to Measure"
7. C. Johnson, "A 'Machine' Luminosity Monitor"
8. A. Lumpkin, "Optics of Transition Radiation"
9. V. Parkhomchuk, "A Proton Profile Monitor and Other Devices"
10. T. Lavine, "Beam Derived Determination of Quadrupoles and BPM Offsets"
11. D. Walz, "Collimator Issues"
12. J. Seeman, "NLC Instrumentation Systems"
13. M. Lee, "Expert Systems for a Linear Collider"

Instrumentation Systems

for the next

Linear Collider

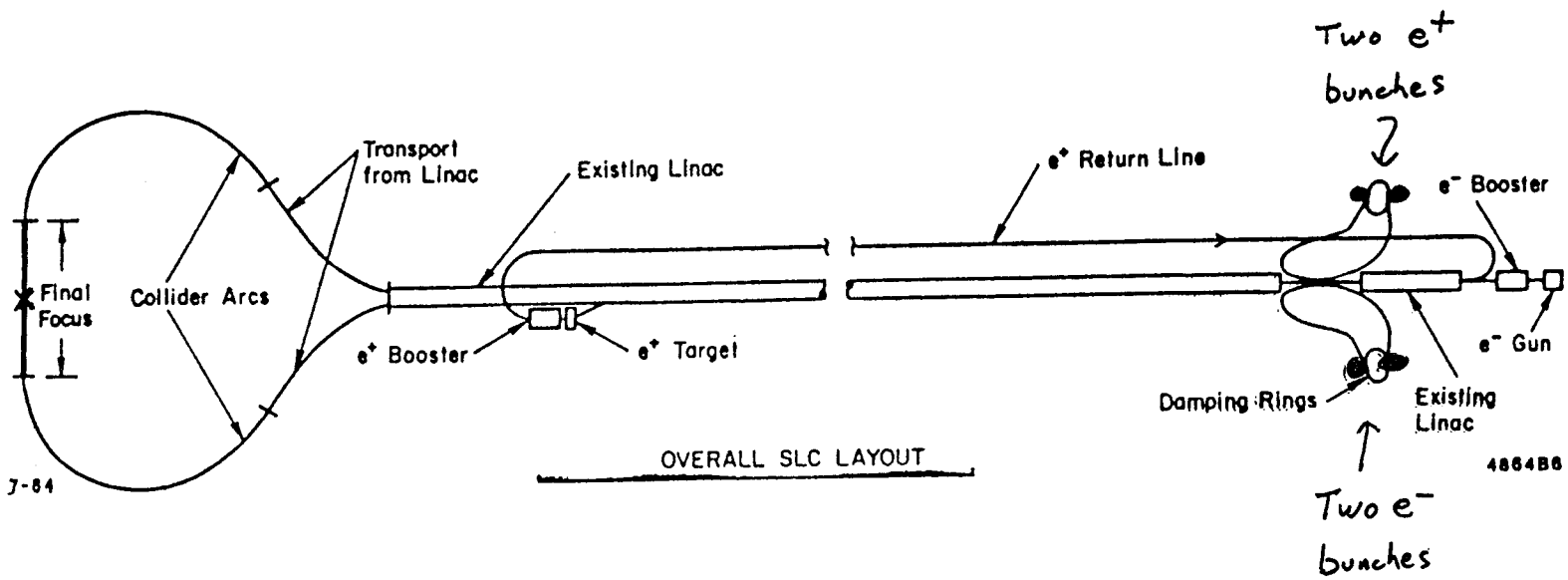
John Seeman

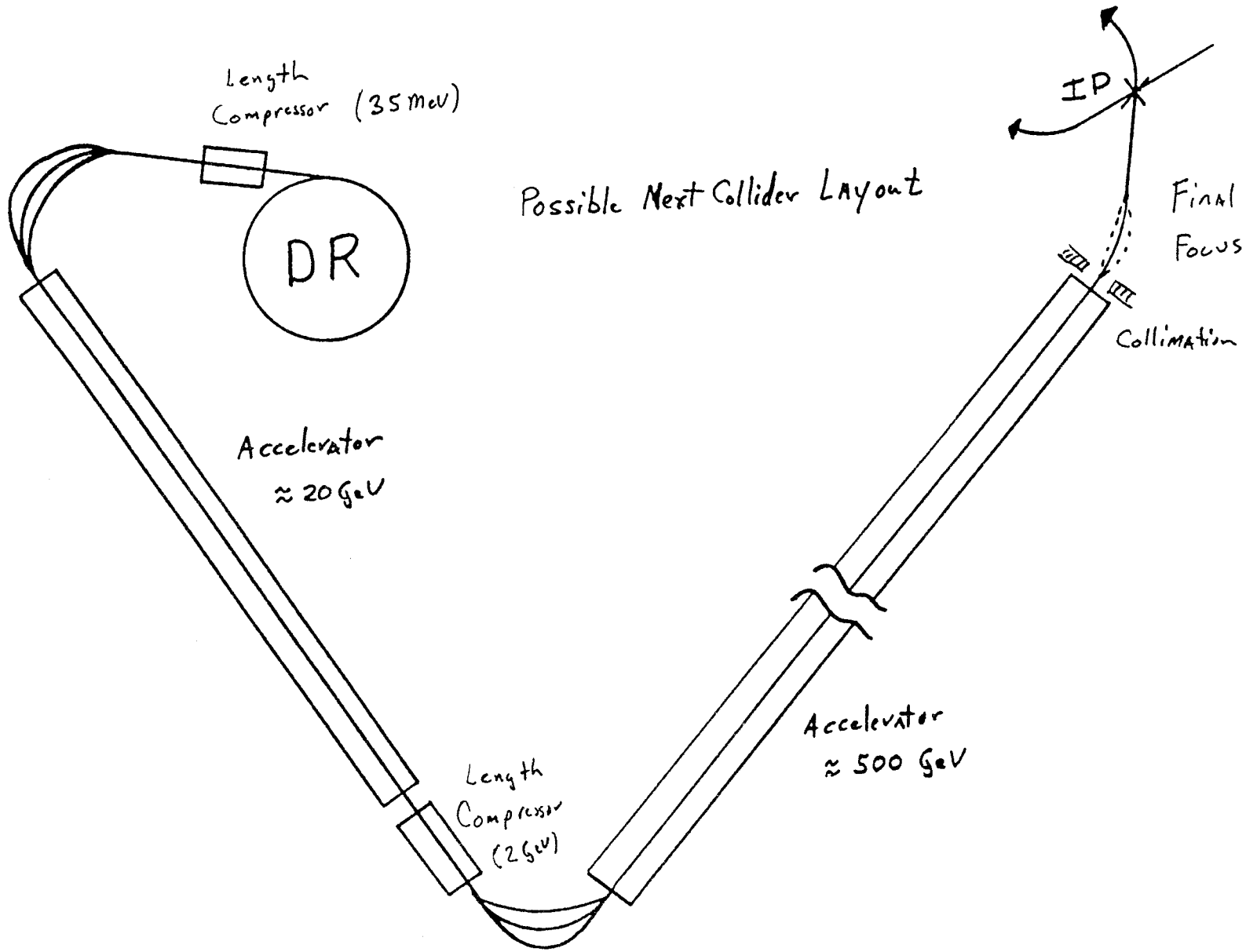
for the Working Group on Instrumentation

December 8, 1988

1) Overview
2) Alignment
3) Beam positioning
4) Beam profile measurements
5) Multiple bunches
6) Feedback
7) Crab beams

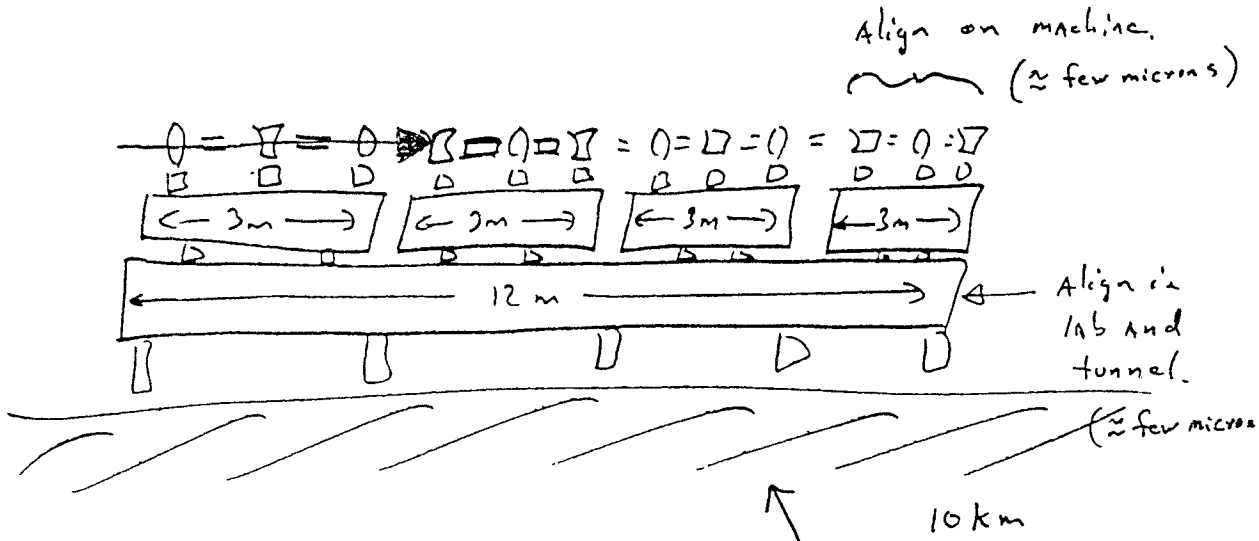
SLC Layout Overview




Length
Compressor (35 MeV)
DR
Possible Next Collider Layout
IP
Final
Focus
Collimation
Accelerator
≈ 20 GeV
Accelerator
≈ 500 GeV
Length
Compressor
(2 GeV)

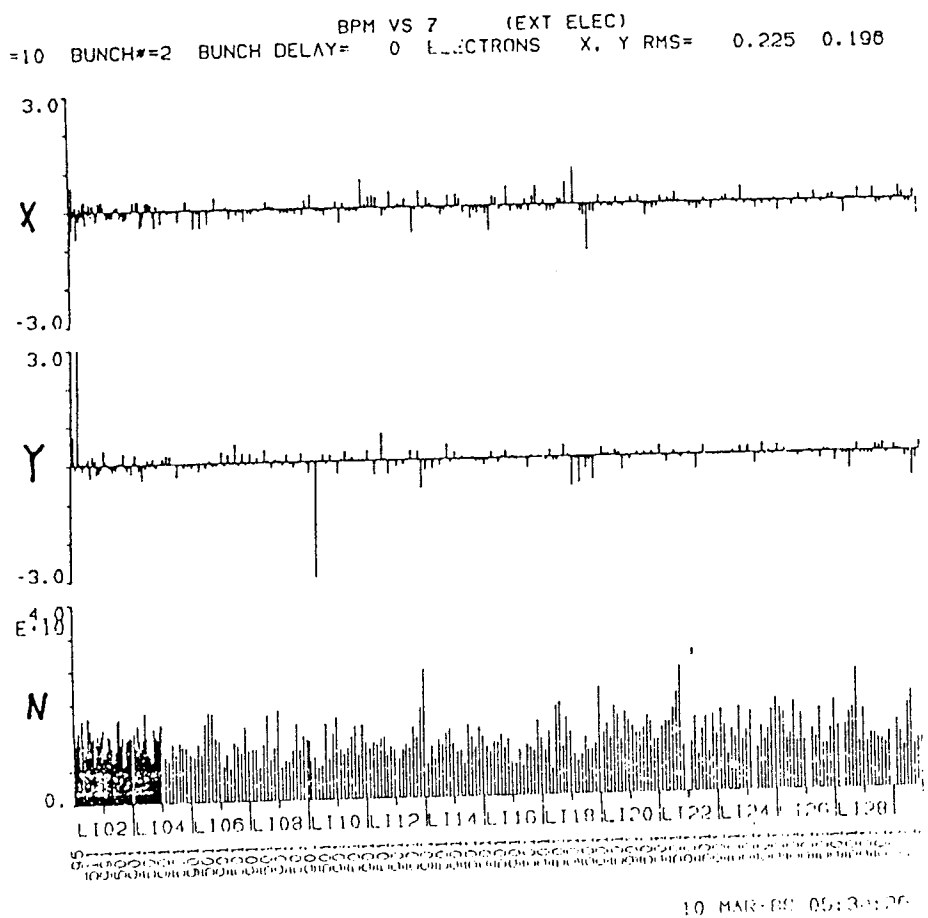
JTS

Alignment "Concept"



1. Rigid 3m sections
2. Loose 12m section
3. 12 m section aligned using "beam" in lab.
4. 3m section aligned using mechanical devices
5. 12m section aligned "straight" in lab and tunnel.
6. Laser align "Long" girders in tunnel.

SLC Beam Centering



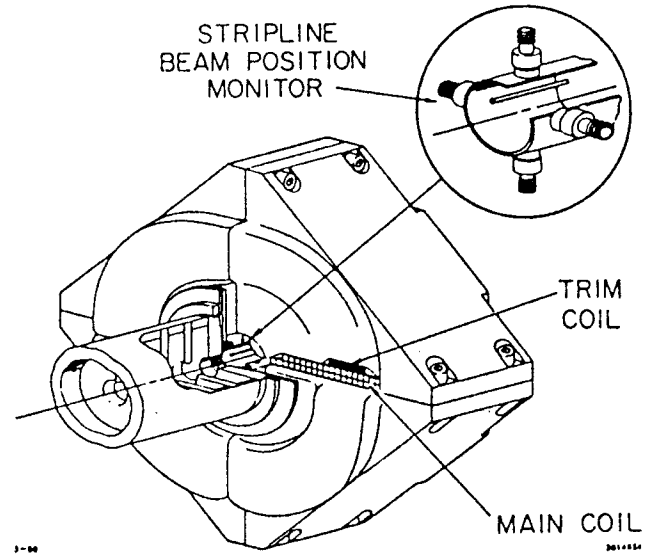
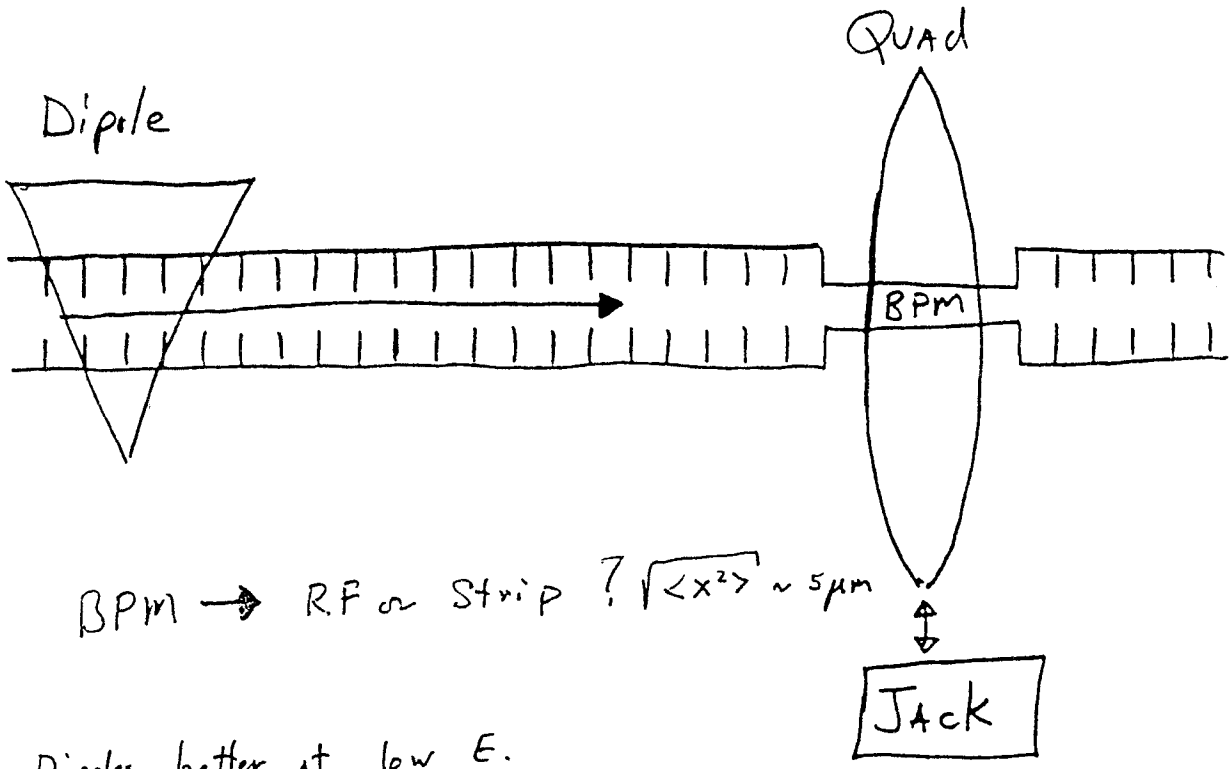


Fig. 5. Linac DC quadrupole assembly.

Beam Positioning "Concept"



BPM → RF or Strip ? $\sqrt{\langle x^2 \rangle} \sim 5\mu m$

Dipoles better at low E.

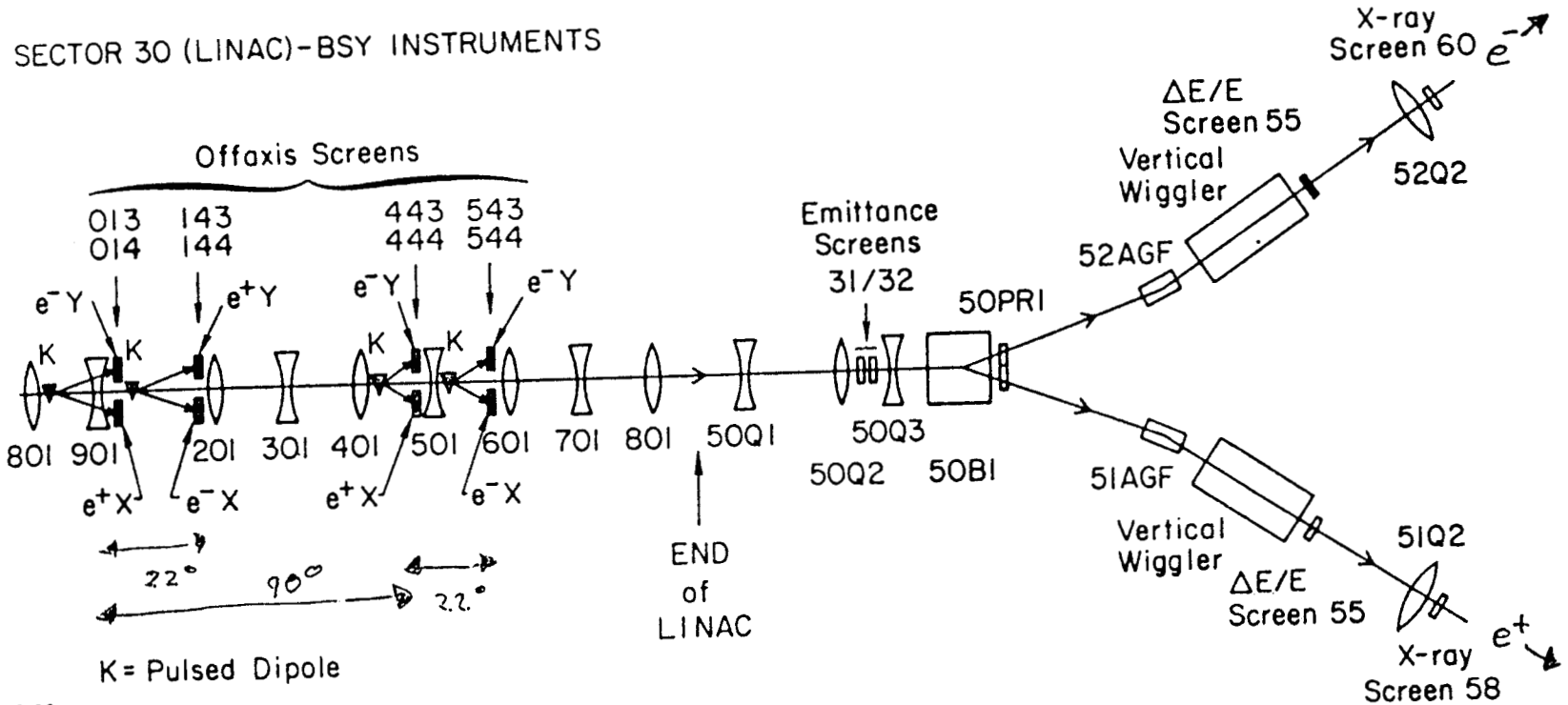
Quad jacks better at High E.

⟹ Dark Current affects RF or Strip Monitors

Must shield stray fields → (ie Earth's field)

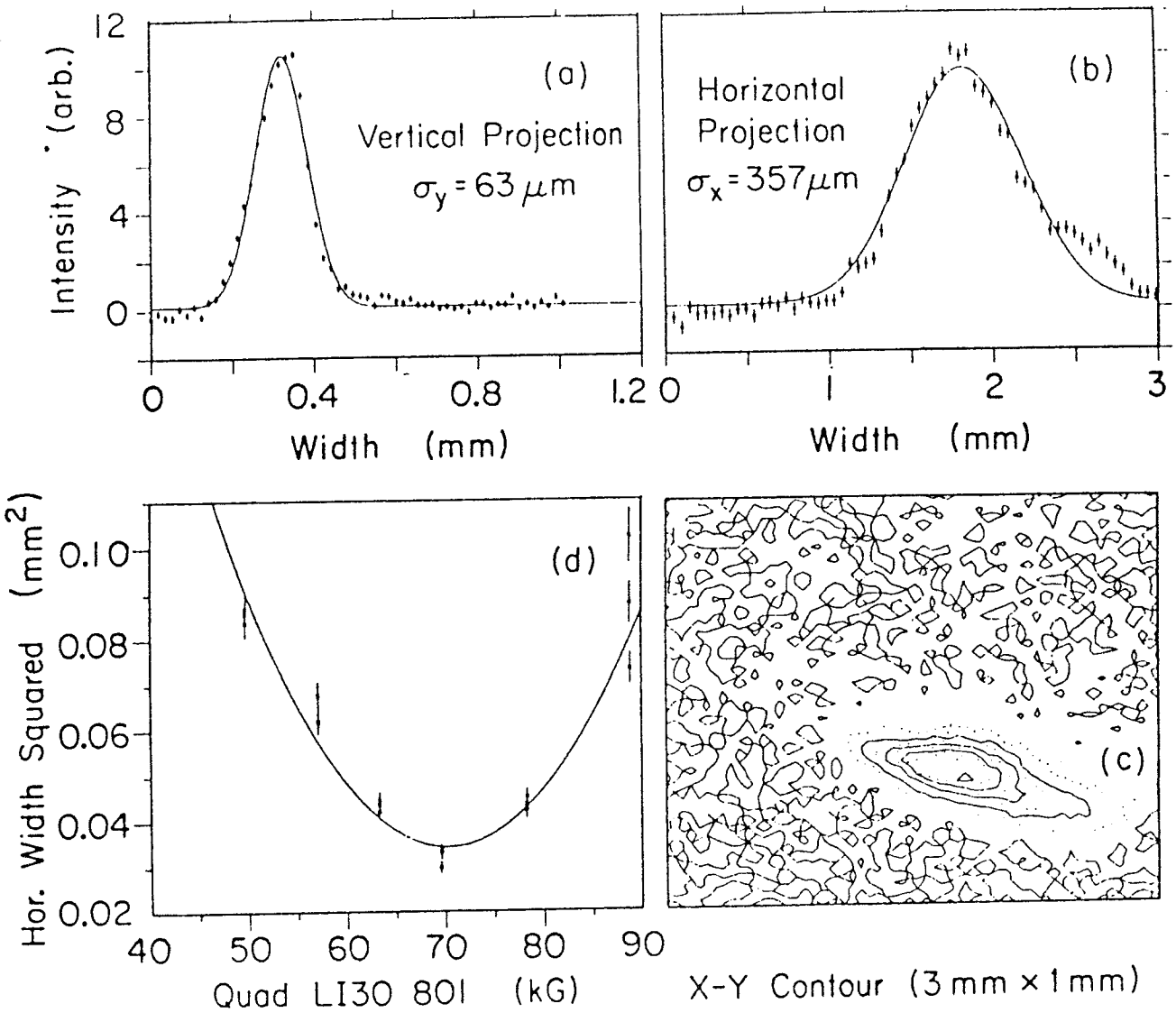
SLC Monitor Wake fields and Emittance Growth

SECTOR 30 (LINAC)-BSY INSTRUMENTS

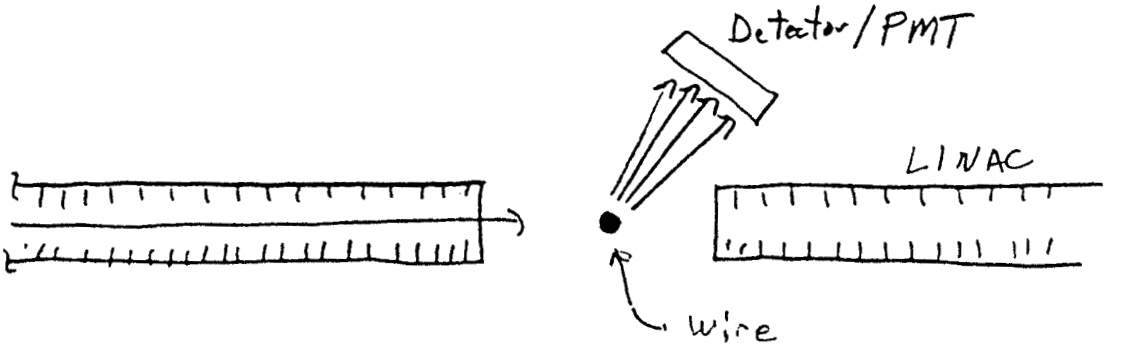


6-88
6075B1

SLC Emittance Measurements



On-Axis Profile Monitor (NLC)



$\sigma_x \sim 20\,\mu m$

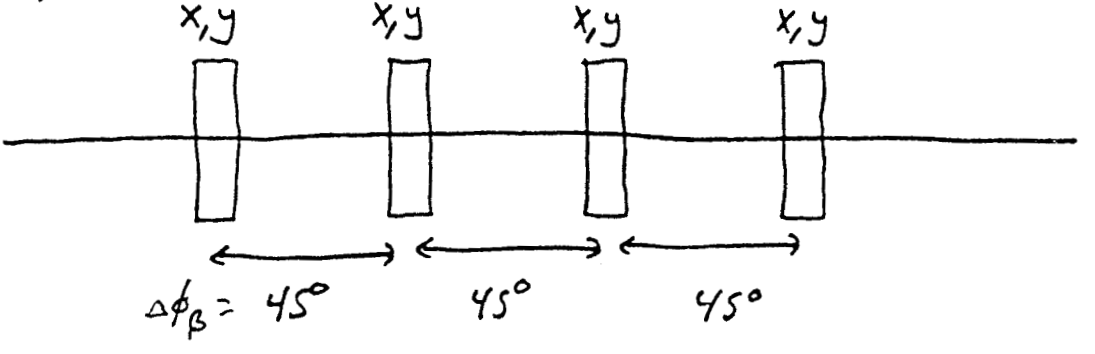
$\sigma_y \sim 2 - 10\,\mu m$

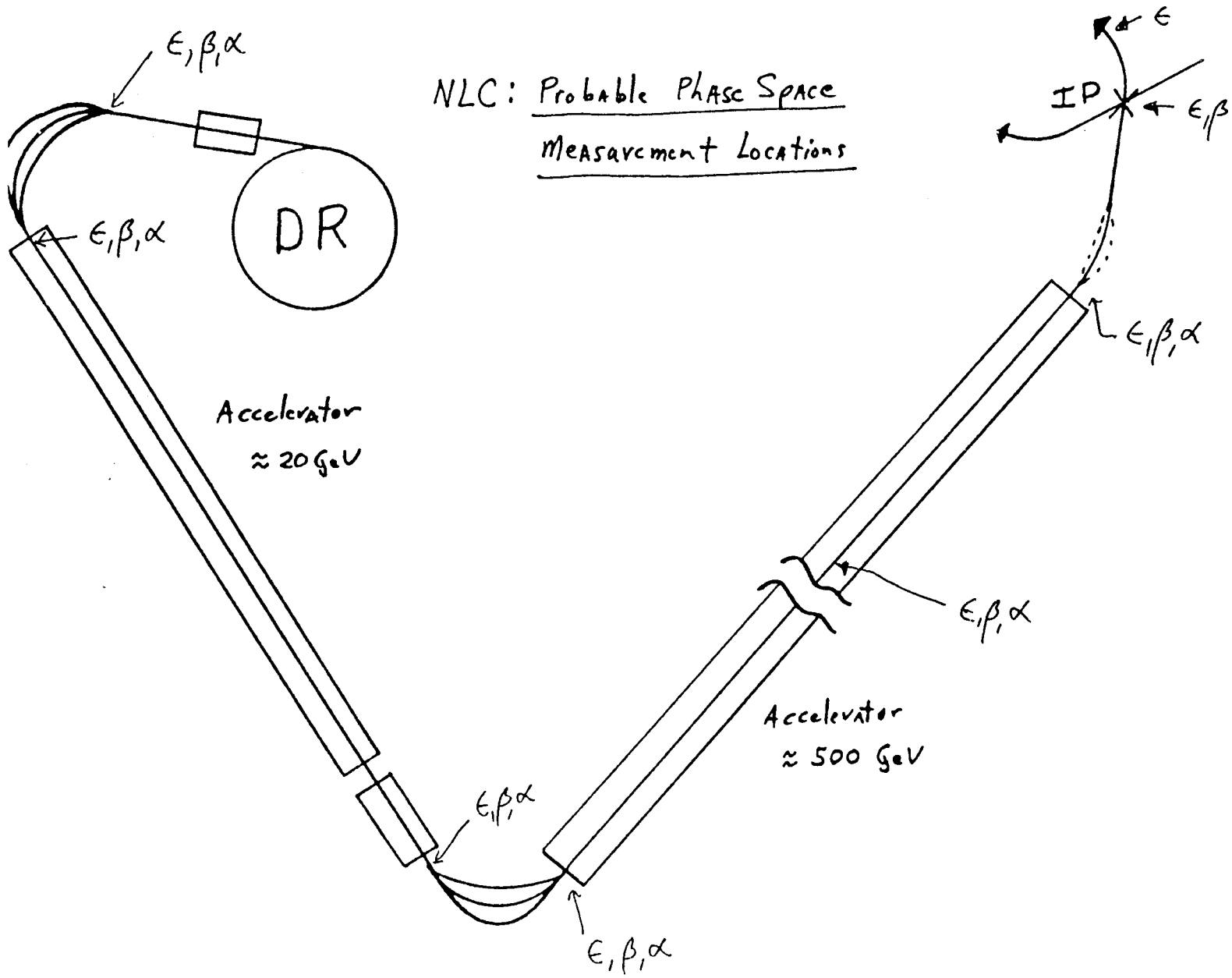
SEM signal non-linear

Scatter signal small at high E.

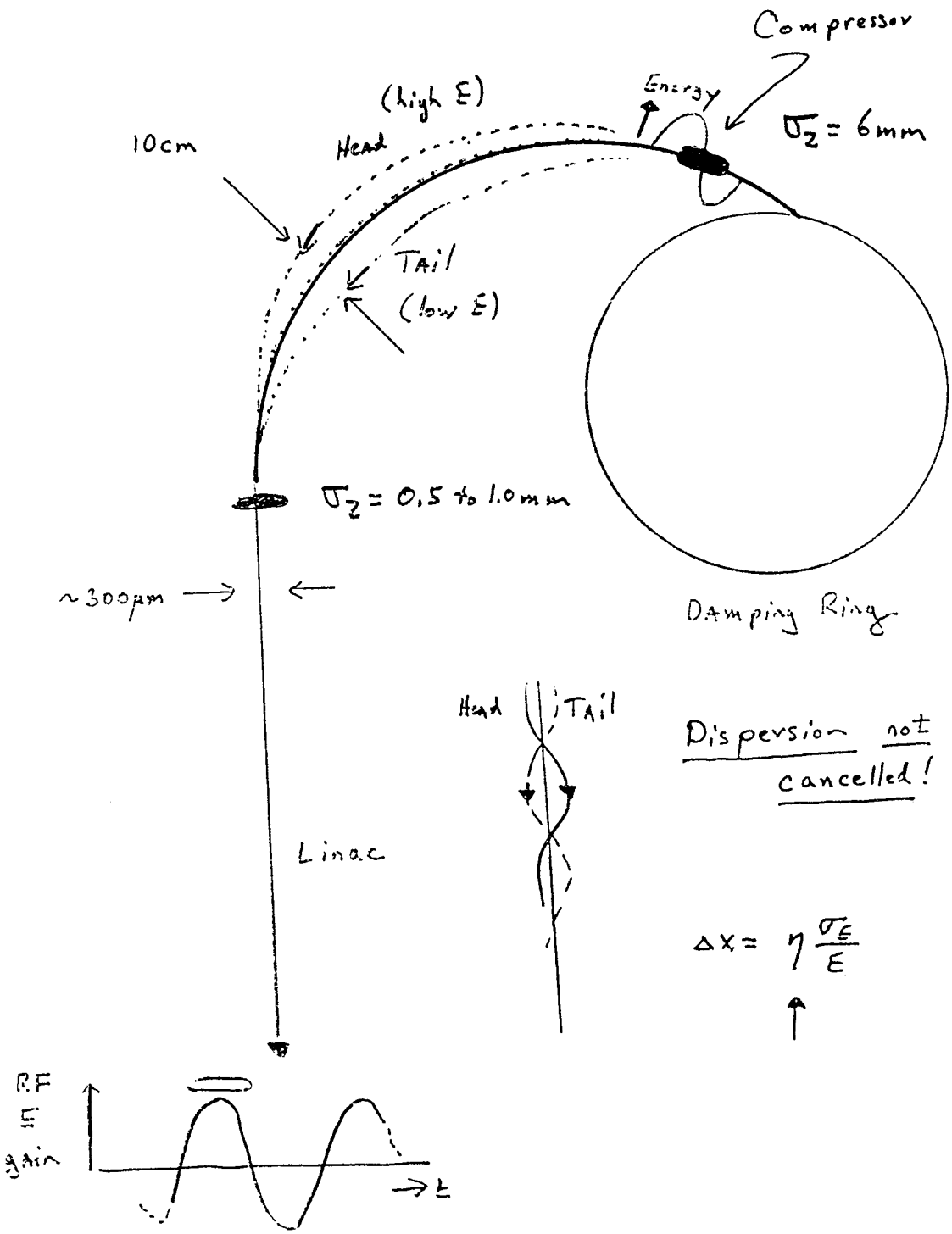
Dark current from accelerator is a concern.

System: Must measure ϵ, β, α for x, y




NLC: Probable Phase Space
Measurement Locations
ε, β, α
DR
Accelerator
≈ 20 GeV
IP
ε
ε, β
Accelerator
≈ 500 GeV

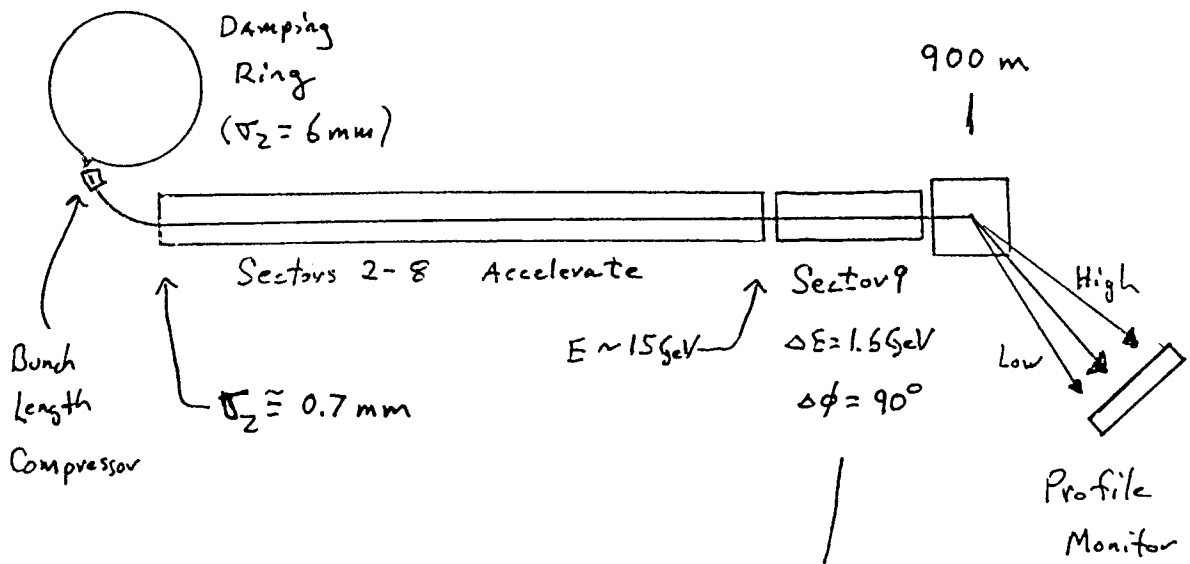
Bunch length Compression: (SLC)

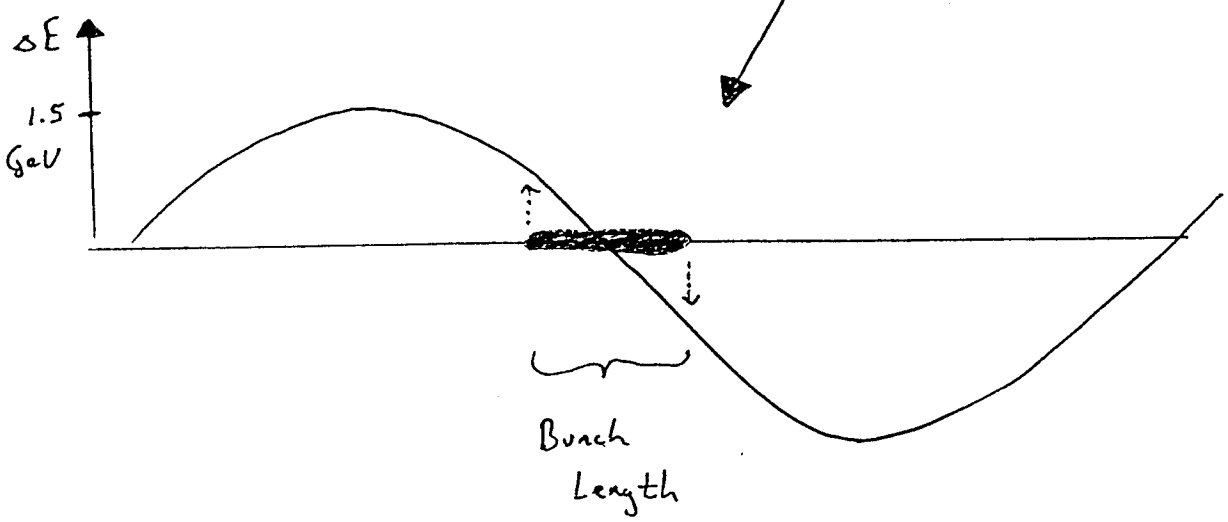


Dispersion not cancelled!

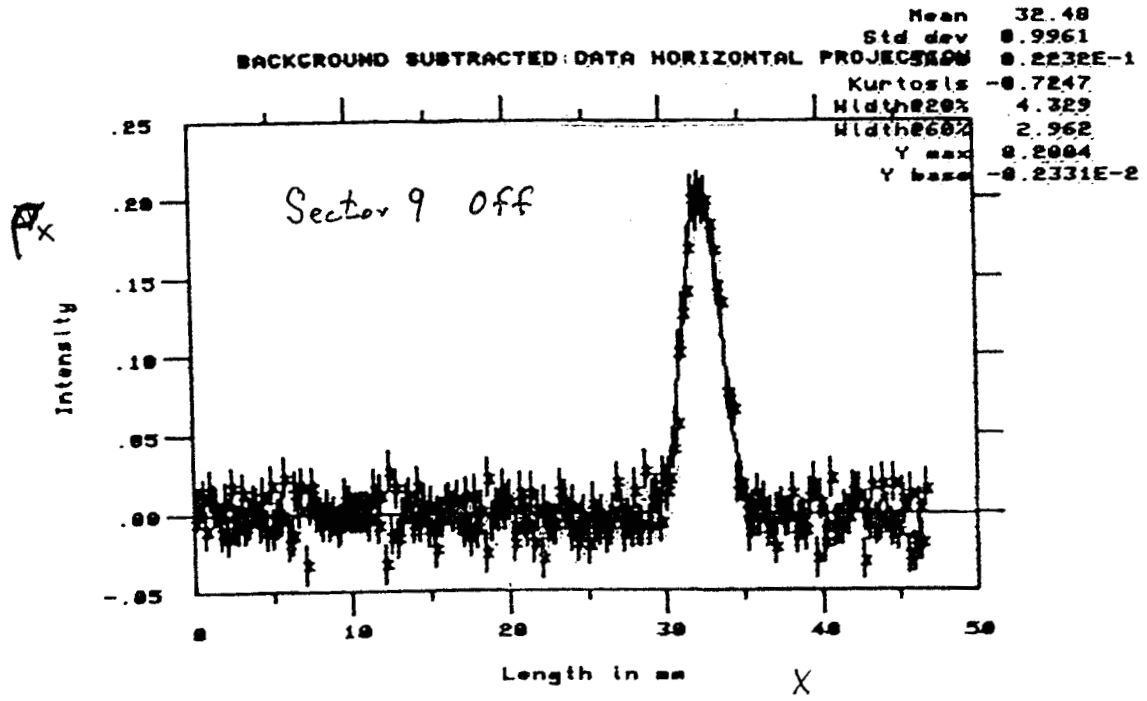
$$\Delta x = \eta \frac{\sigma_E}{E}$$

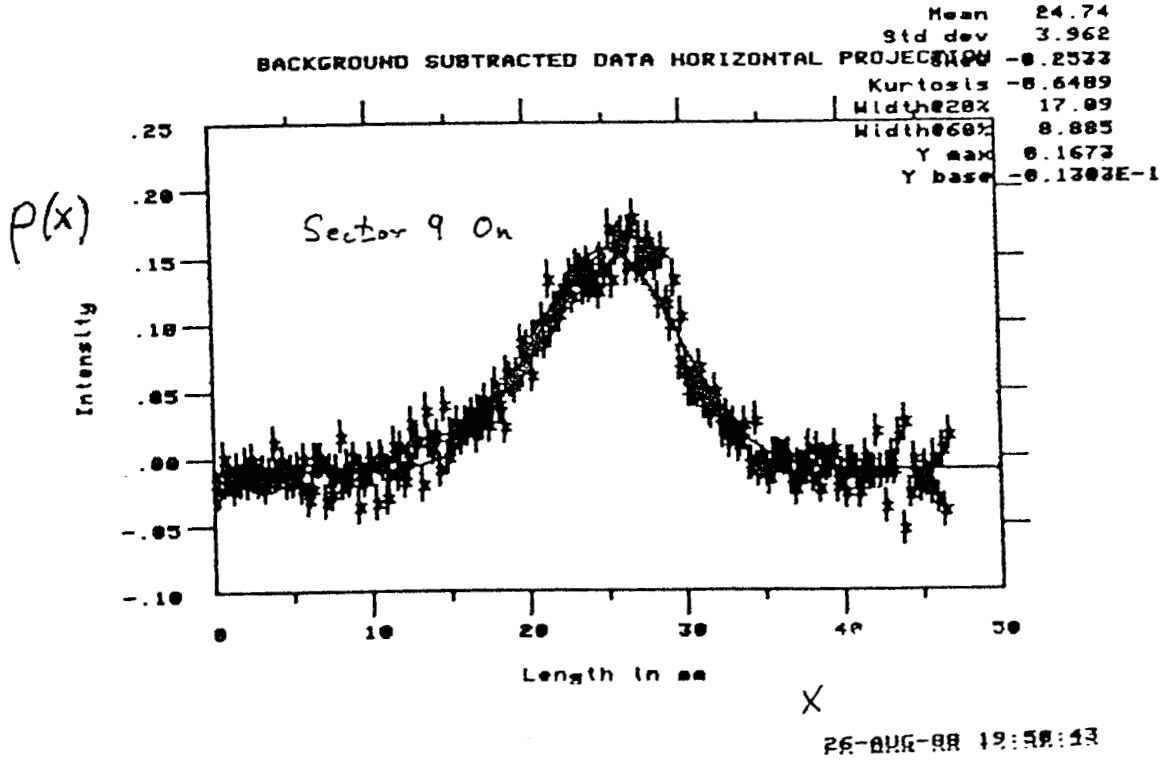
SLC Bunch Length Measurement using a Spectrometer





SLC Measurements of σ_z

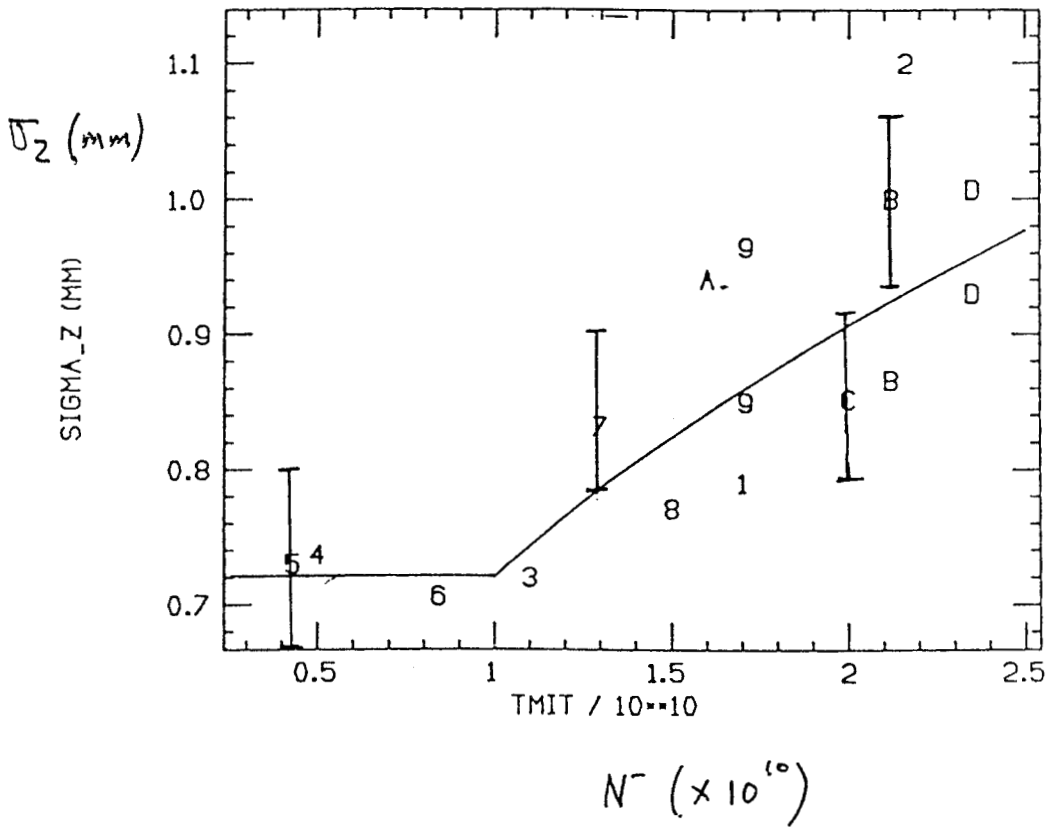




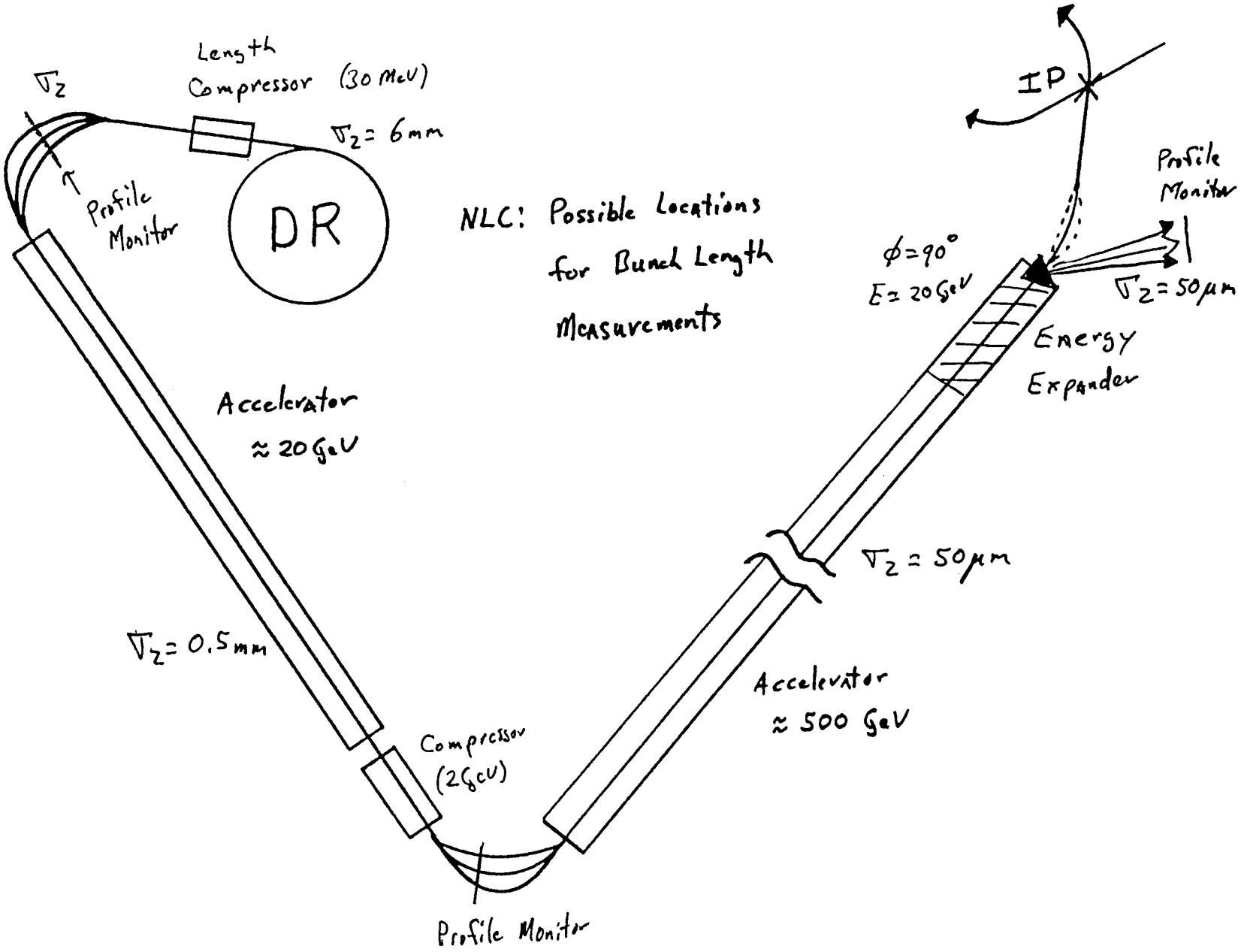
$$\sigma_z = \frac{\sigma_x \, E_0 \, \lambda_{RF}}{\eta \, E_q \, 2\pi}$$

SLC

BUNCH LENGTH AT BL10 AS FUNCTION OF CURRENT



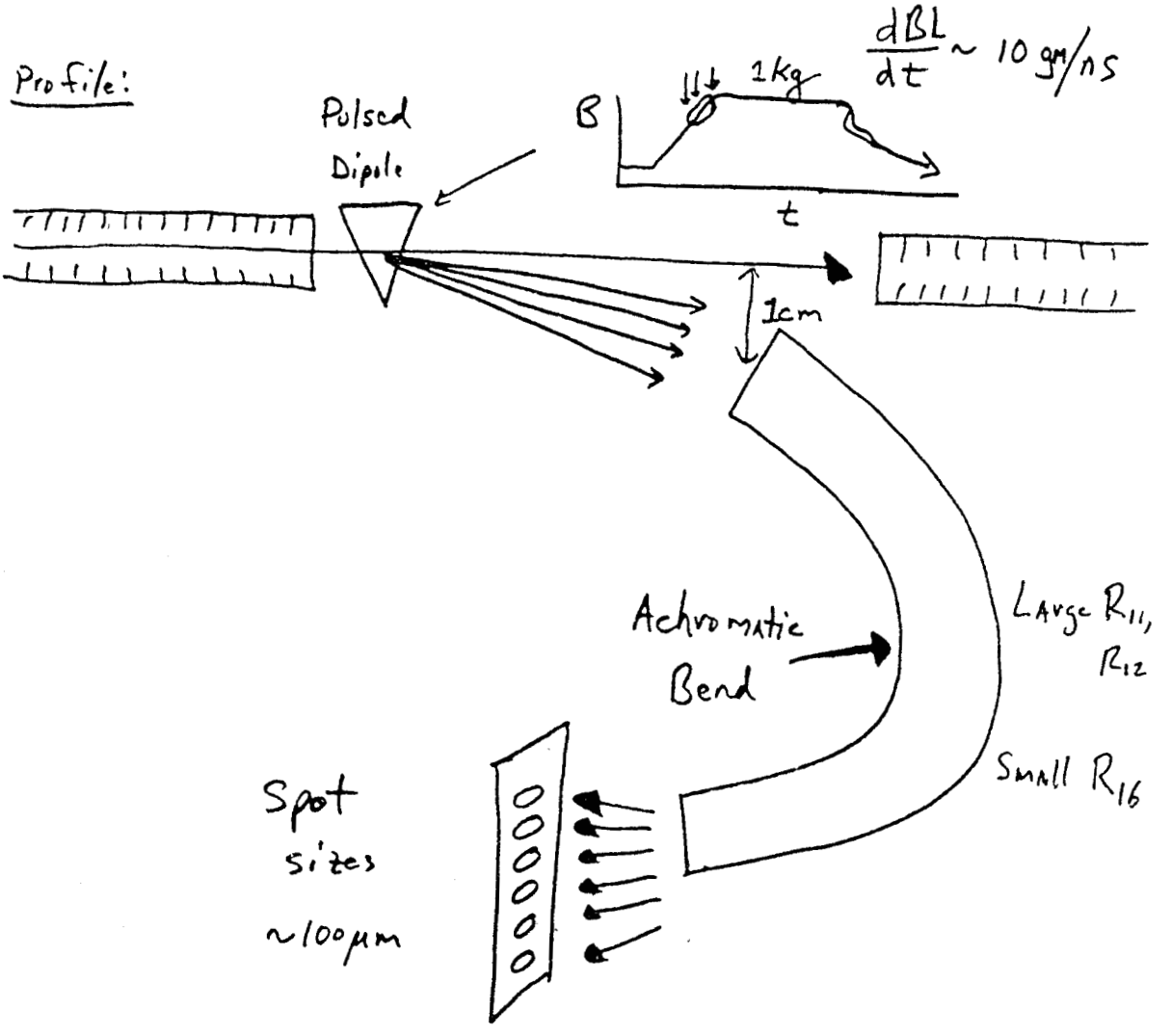
Resolution = 0.06mm ⇒ 0.2 psec !


NLC: Possible Locations for Bunch Length Measurements
Length Compressor (30 MeV)
σ_z
$\sigma_z = 6$ mm
Profile Monitor
DR
Accelerator ≈ 20 GeV
$\sigma_z = 0.5$ mm
Compressor (2 GeV)
Profile Monitor
Accelerator ≈ 500 GeV
$\sigma_z = 50\mu m$
Energy Expander
$\phi = 90°$
$E = 20$ GeV
IP
Profile Monitor
$\sigma_z = 50\mu m$

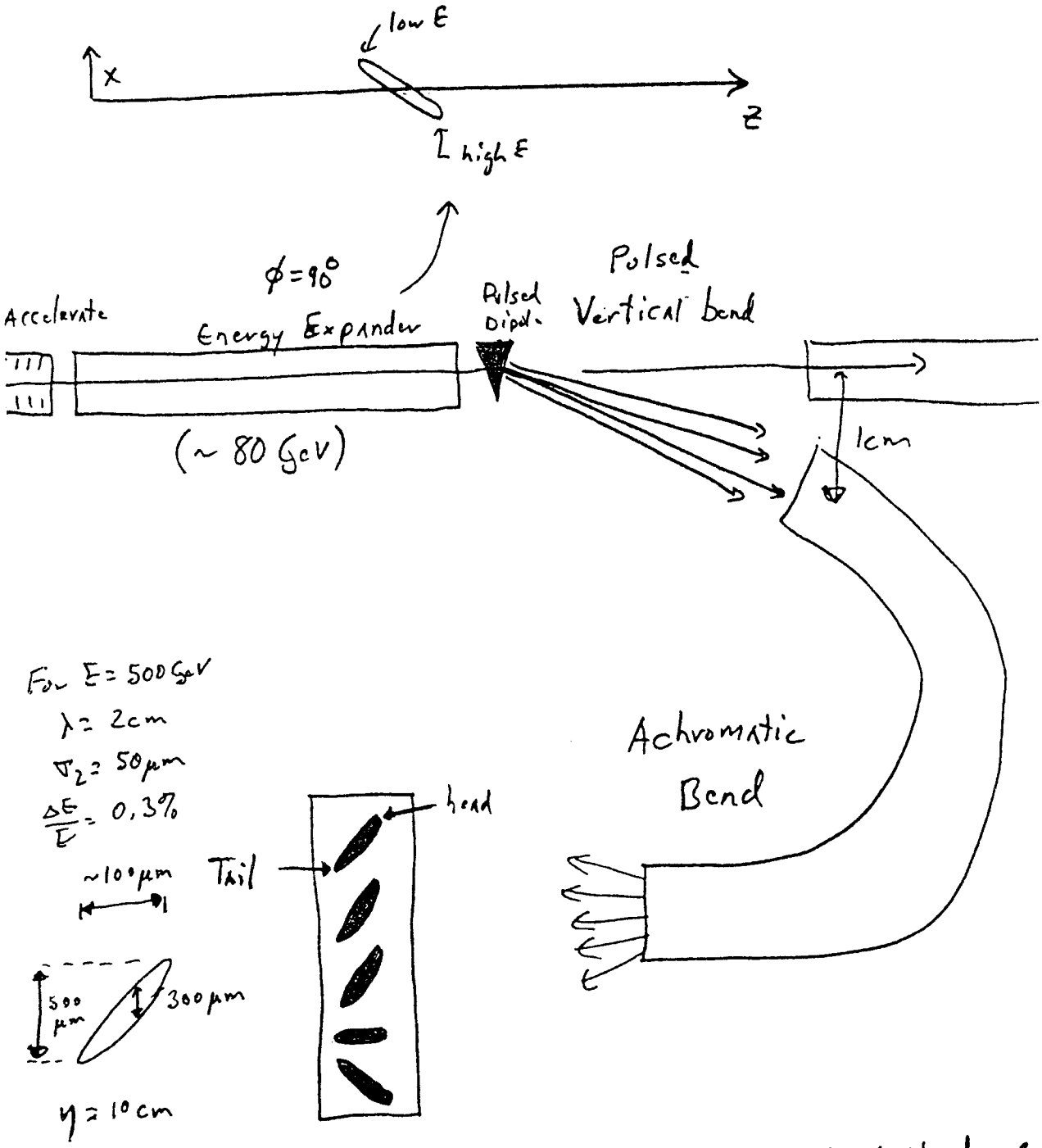
NLC Multiple Bunches (~20cm spacings)

Position: All bunches add!
or "fast" electronics

Profile:



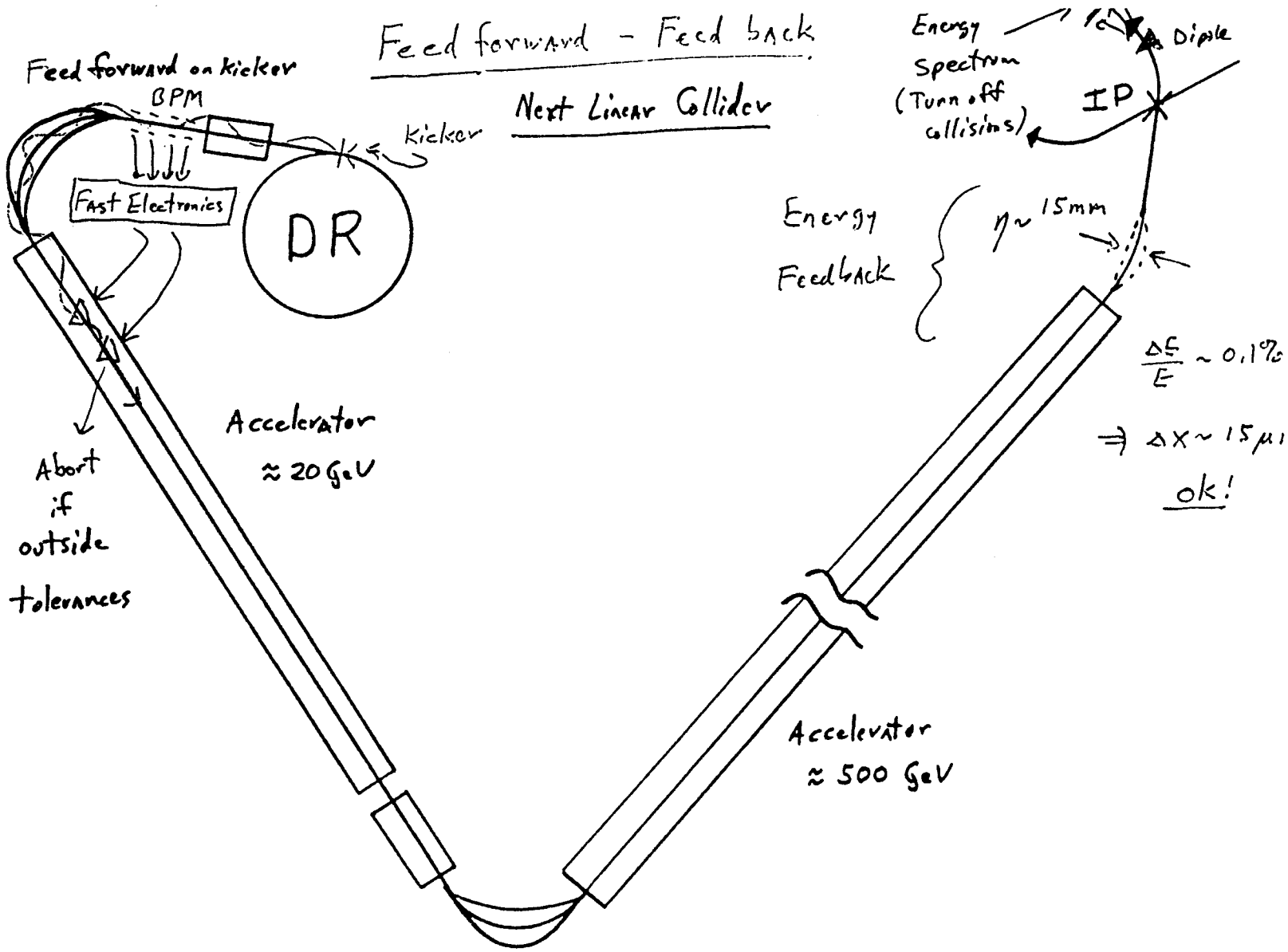
Measurement of "Crab" beams (NLC)

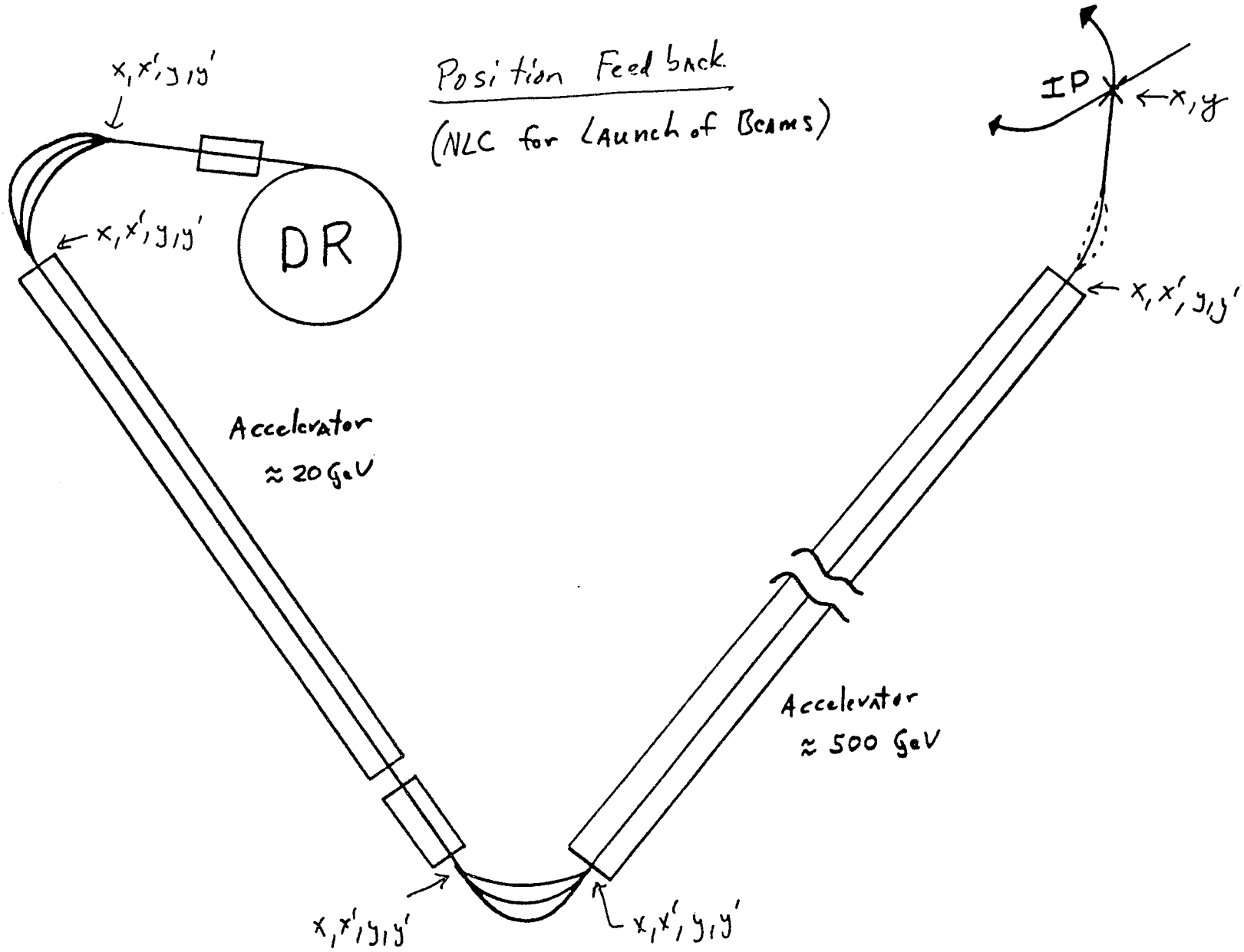


If 'Crab' is generated in the IP, must measure it at the dump.

Feed forward - Feed back

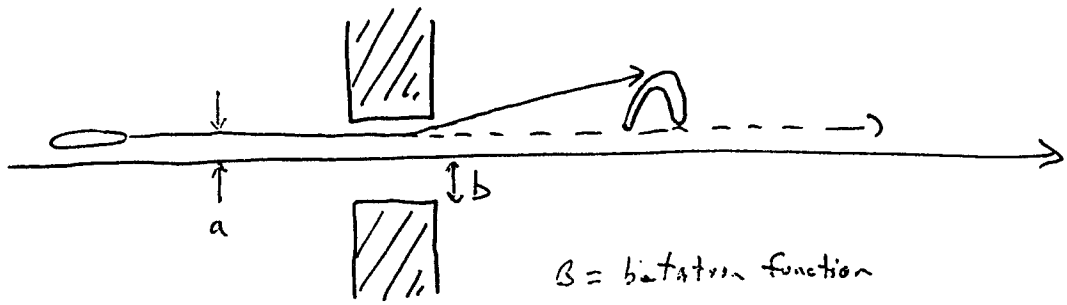
Next Linear Collider




Position Feed back
(NLC for Launch of Beams)
x, x', y, y'
x, x', y, y'
DR
Accelerator
≈ 20 GeV
IP
x, y
x, x', y, y'
Accelerator
≈ 500 GeV
x, x', y, y'
x, x', y, y'

Collimation of Beams

Bane, Morton, Roth, + others



β = betatron function

E = beam energy

$$\frac{\theta_{kick}}{\theta_{Beam}} << 1$$

$$a \propto \sqrt{\beta}$$

$$b \propto \sigma_{x,y} \propto \sqrt{\beta}$$

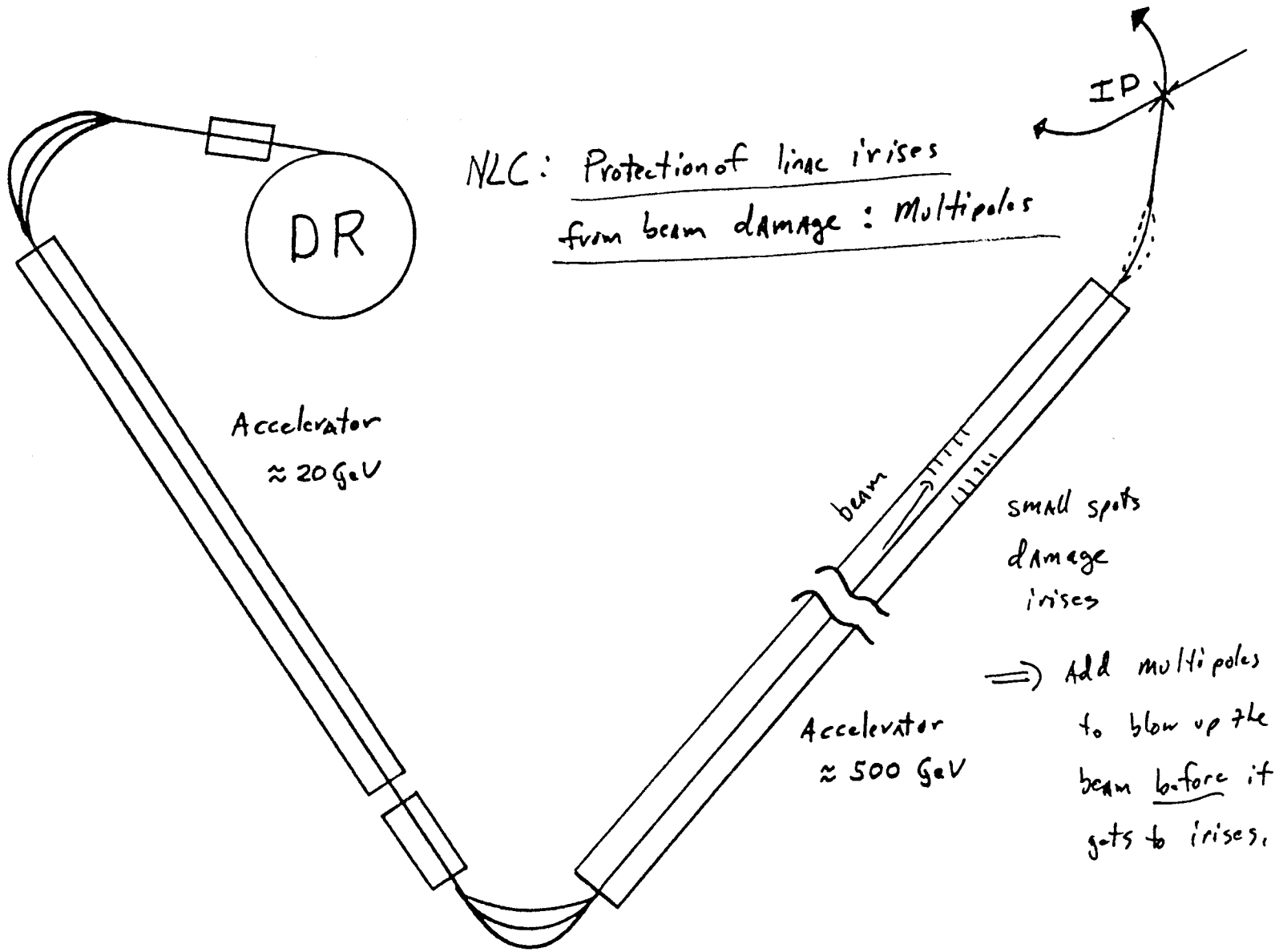
$$\theta_{kick} \propto \frac{a}{b} \quad \text{independent of } \beta$$

$$\theta_{kick} \propto \frac{1}{E}$$

$$\theta_{Beam} \propto \sqrt{\frac{1}{E\beta}}$$

$$\Rightarrow \frac{\theta_{kick}}{\theta_{Beam}} \propto \sqrt{\beta/E} \Rightarrow \text{Low } \beta \text{ and high } E$$

$\sigma_{x,y} \sim$ few microns $\rightarrow$ Big kicks
Material damage.


NLC: Protection of linac irises
from beam damage : Multipoles
DR
IP
Accelerator
≈ 20 GeV
beam
small spots
damage
irises
Accelerator
≈ 500 GeV
⟹ Add multipoles
to blow up the
beam before it
gets to irises.

Conclusions

1) System layout will require real estate

2) Design must be included early

3) Application programs needed early

4) No small beams can strike material

5) Dark current in the accelerator must be limited

6) Alignment -- Girder system needs work

7) Multibunch measurements need definition

8) 'Smart Model' of the machine is needed

9) Possible gains in Feed-Forward and Feed-Back

BEAM INSTRUMENTATION

List of participants:

Henke, H.	CERN	
Johnson, C.D.	CERN	Rapporteur
Lumpkin, A.H.	Los Alamos	
Cavallo, N.	Frascati	
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Parkhomchuk, V.	Novosibirsk	
Bane, K.L.	SLAC	
Fischer, G.E.	SLAC	Secretary
Lavine, T.L.	SLAC	
Lee, M.L.	SLAC	
Morton, P.L.	SLAC	
Pitthan, R.	SLAC	
Ross, M.L.	SLAC	
Ruth, R.R.	SLAC	
Seeman, J.T.	SLAC	Chairman/Rapporteur
Toge, N.	SLAC	
Waltz, D.R.	SLAC	
Warnock, R.	SLAC	

SUMMARIES

1.	Measurement specifications	R. Ruth
2.	Alignment	
	i) Surveying	G. Fischer
	ii) Beam alignment	T. Lavine
3.	Beam position monitoring	
	i) Electrostatic BPMs	M. Ross
	ii) Microwave position monitors	G. Fisher
	iii) Resonant microwave position monitors	
	iv) Microwave cerenkov pick-up	
4.	Beam profile monitors	
	i) Fibre scanning	V. Parhomchuk
	ii) Atomic beam profile monitor	V. Parhomchuk
	iii) Ceramic oxide fluorescent screens	C. Johnson
5.	The potential uses of Transition Radiation monitors for beam size, divergence and energy measurement	A. Lumpkin R. Pitthan
6.	Beam collimation	
	i) Steering effects of collimators	K. Bayne P. Morton
	ii) Thermal and mechanical limitations	D. Waltz
7.	Luminosity measurement for machine tuning	C. Johnson
8.	Expert System for a linear collider	M. Lee
9.	Instrumentation systems	
	i) For the SLC	J. Seeman
	ii) For the NLC	J. Seeman

Things to Measure.

R. Ruth
12/1/88

1.) Injector 200 MeV to 1.8 GeV
   a.) bunch to bunch E at 1.8 GeV
   b.) b to b position 1.8 GeV
   c.) b to b intensity 1.8 GeV
   d.) Normal BPMs, profile monitors.

2.) Damping Ring.
   1.) Beam position. ($\lesssim 50\mu m$)
   2.) Beam profile. $\gamma\epsilon_x = 3\times10^{-6}$ m, $\gamma\epsilon_y = 3\times10^{-8}$
   $\beta_x \sim 1$ m. $\sigma_\epsilon = 10^{-3}$ $\sigma_z = 5$ mm
   $\beta_y \sim 2$ m.
   $\eta_x \sim 4$ cm. $(\sigma_x, \sigma_y) \sim (30, 4)\,\mu m$.

3.) 1st Bunch Compressor
   1.) Begin: (ϵ_x, ϵ_y), $(\sigma_\epsilon, \sigma_z)$

4.) Pre accelerator (1.8 GeV to 16.5 GeV)
   1.) Matching, β, α, $\epsilon_x, \epsilon_y, \eta, \eta'$
   Beginning and end. 2.) B to B E
   3.) B to B I -B to B γ
   4.) skew
   5.) BPMs (precise one)

5.) 2nd Bunch Compressor

1.) Phase space at input. + Output.

2.) Match into Linac $\eta, \eta' \to 0$.

$\eta_x \lesssim 1\,mm$ + $\eta_y \lesssim .1\,mm$

6.) Linac

1.) BPMs $\simeq 10\,\mu m$

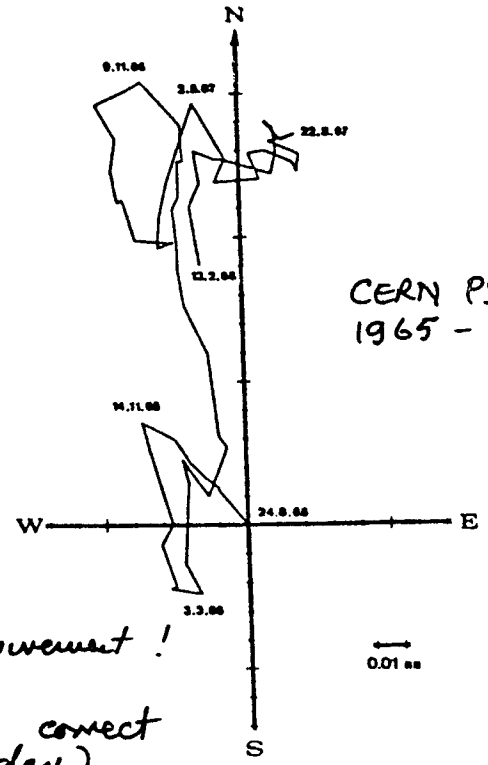
2.) Profiles $(2 \times 20\,\mu m)$

3 check
3.) B to B E
4.) B to B x

5.) $x(s)$ circulation.

ALIGNEMENT

GERRY FISCHER



Movement detected in the monument at the centre of the PS, according to measurements with horizontal pendulums over the period 24 August 1965 to 13 February 1968

CERN PS
1965 - 1968

ALIGNMENT SHEAR
~ 100μm/month

~1 month to make measurement !

∴ Measure quickly and correct
(perhaps up to 10μ/day)

Figure 6: Movement of the PS central pillar from 1965 - 68.

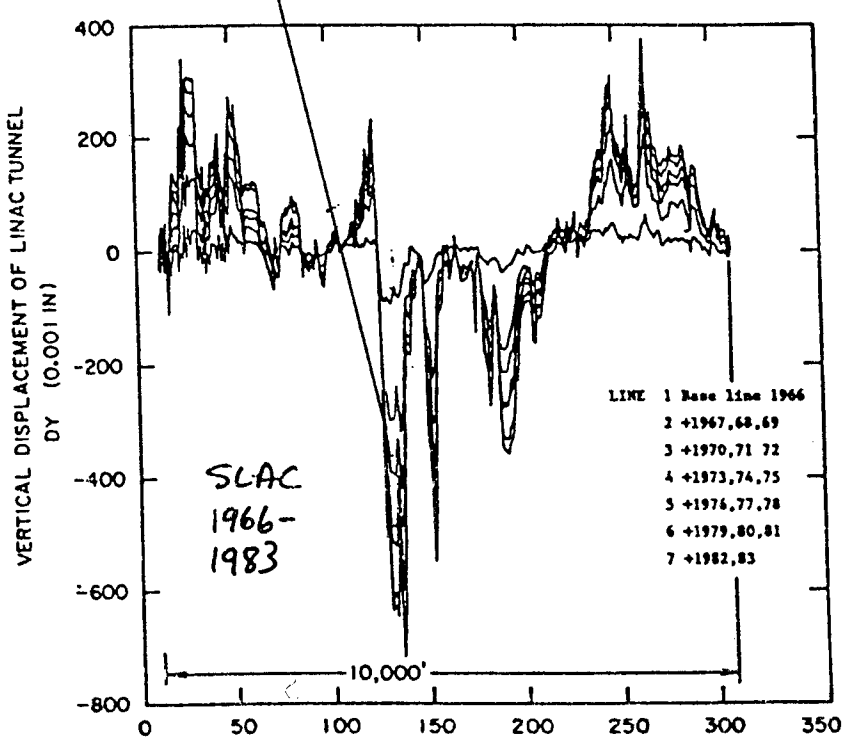


Figure 7: Displacement of the SLAC Linac Tunnel - Vertical.

CONCLUSIONS, RECOMMENDATIONS:

- Keep trying to find more 'tolerant' solutions to collider design.
- Do away with the problems of the atmosphere. (if possible)
- Take great care in engineering the support structure with respect to thermal and other stresses and avoid resonant modes.
- All collider sub-systems must be provided with mechanical reference systems independent of ground motion. (if possible)
- Alignment systems must be capable of operating and correcting continuously, also when the collider is in operation.
- Mechanical realignement should be performed, BEFORE, resorting to feedback whose error signal is 'beam derived'. (BPM)
- A vigorous R and D program in alignment techniques, engineering design and equipment development should be started now!

SLAC-PUB-4720
September 1988
(A)

Question: How do we measure ?

BEAM DETERMINATION OF QUADRUPOLE MISALIGNMENTS AND BEAM POSITION MONITOR BIASES IN THE SLC LINAC*

T. L. LAVINE, J. T. SEEMAN, W. B. ATWOOD, T. M. HIMEL, AND A. PETERSEN†

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

C. E. ADOLPHSEN

University of California at Santa Cruz, Santa Cruz, California 95064

Answer: Survey + Beam bootstrap
↳ BUT REMEMBER BEAM TIME IS THE MOST PRECIOUS COMMODITY.

ABSTRACT

Misalignments of magnetic quadrupoles and biases in beam position monitors (BPMs) in the Stanford Linear Collider (SLC) linac can lead to a situation in which the beam is off-center in the disk-loaded waveguide accelerator structure. The off-center beam produces wakefields which can limit SLC performance by causing unacceptably large emittance growth. We present a general method for determining quadrupole misalignments and BPM biases in the SLC linac by using beam trajectory measurements. The method utilizes both electron and positron beams on opposite RF cycles in the same linac lattice to determine simultaneously magnetic quadrupole misalignments and BPM biases. The two-beam trajectory data may be acquired without interrupting SLC colliding beam operations.

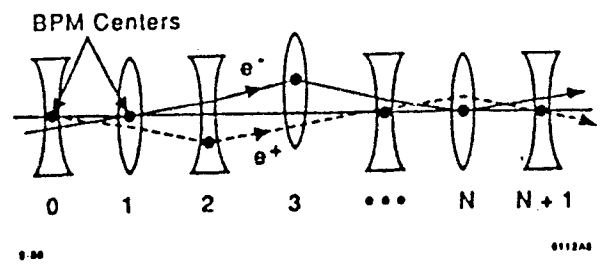


FIG. 1. Linac lattice containing a biased BPM (2) and a misaligned quadrupole (3). The electron and positron beams have been steered using correctors near each quadrupole to minimize the BPM measurements.

$$\Delta x_i = BPM_{i\,meas} + BPM_{i\,offset} + QUAD_{i\,misalignment}$$

Purposes of BPMs

M. Ross
12/5/88

Routine - continuous use
- Linac orbits
- transition launch
- Beam/Beam
- Optics

Diagnostic
- Optics
- Instability finding

<u>Requirements -</u>

Resolution - (distribution width of readings made on identical orbits)

Absolute accuracy - (placement of the beam with respect to survey monuments)

Data Acquisition - (data rate, synchronization, online analysis)

Other - Intensity dependence, single/multi bunch ..

Resolution requirement:

Instability finding - beams must fluctuate by less than $x\%$ of sigma

Optics correction - e.g. online dispersion correction using matched BPM's

Beam-beam deflection

Absolute accuracy requirement:

Linac wakefields

Transition launch

Orbit through non-linear elements (FF and compression sections)

Data acquisition requirement:

must be able to correlate BPM readings with data from pulsed devices

must be able to remove beam motion when calibrating BPM instrumentation

must have data from appropriate locations on each pulse to separate sources of instability

<u>SLC Linac BPM system uses</u>

1 in diameter stripline electrodes $2l/c$=0.3ns
30 MHz bandpass filter - (matches track and hold technology) - limits minimum $\Delta z \sim 40$ns
10bits

System performance

10-20μm resolution (r/1000)
100μm accuracy (poor performers are hard to find)
'Tagged' pulse readout necessary

New system using this design

100 MHz sampling - minimum $\Delta z \sim 13$ns
14 bits - (r/10000)
Absolute accuracy same or worse - needs improved calibration

Problems with collider BPM systems

Readings changed by small local beam losses
Can depend on higher order moments of charge distribution

Design work for future systems

Increased bandwidth -> harder to equalize cables, pickups etc.
Multi-bunch (e.g. 2GHz) must develop tuned receiver systems - single bunch absolute accuracy difficult

Some thoughts on Beam Position Monitors for TeV Linear Colliders

G.E.Fischer *

May 1988

Abstract

Current designs for future linear colliders call for position monitoring of electron or positron bunches to several orders of magnitude tighter resolution and accuracy than present practice. This note is an attempt to assess whether present technology is applicable.

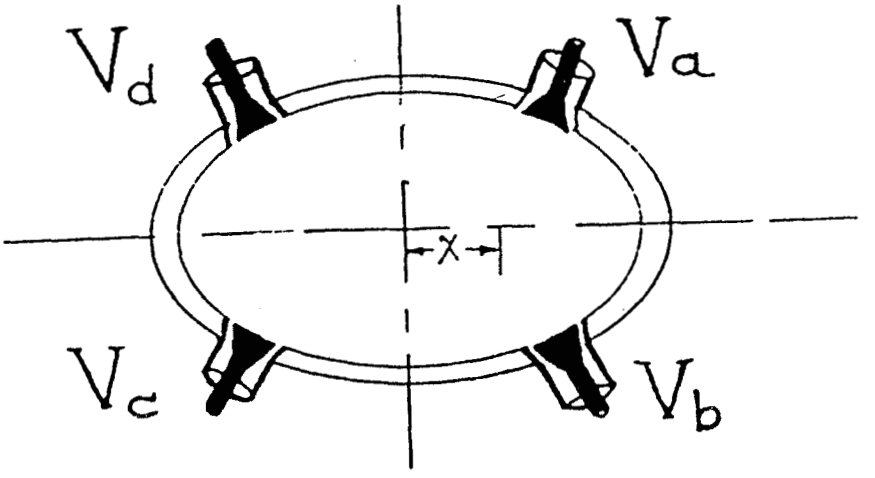


Figure 1: Cross-section of the generic monitor; the horizontal beam coordinate is given by: $X = K \times \frac{(V_a+V_b)-(V_c+V_d)}{(V_a+V_b+V_c+V_d)}$.

Requires: High precision fabrication
Impedances must be well matched

TWO ALTERNATIVE DEVICES :

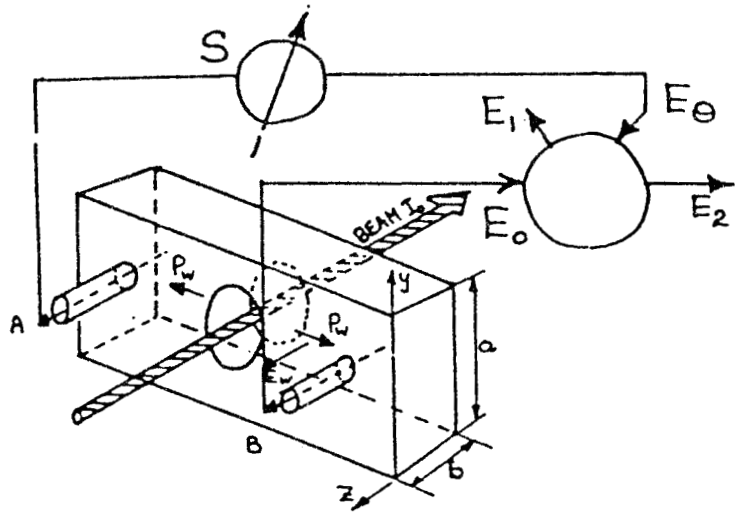


Figure 4: Schematic of the Traveling Wave Beam Position Monitor

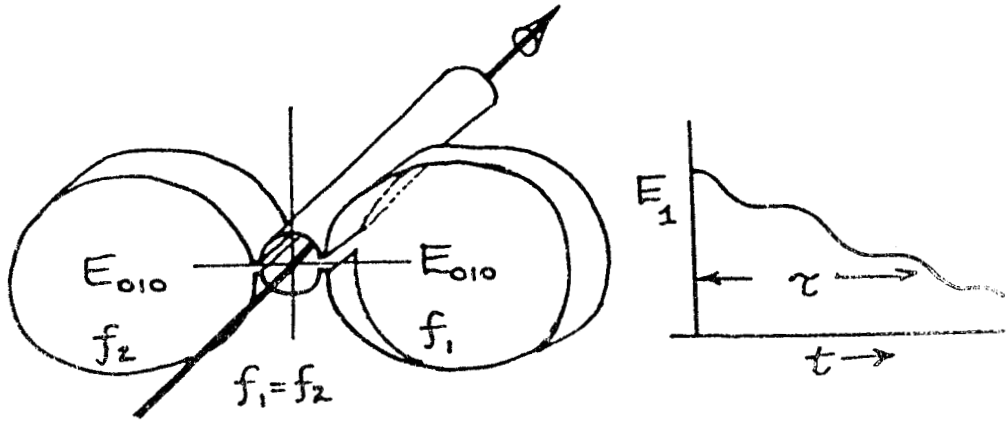
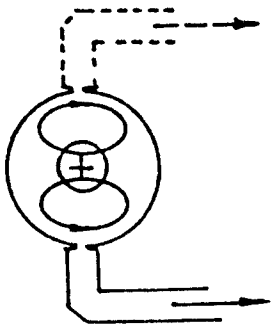
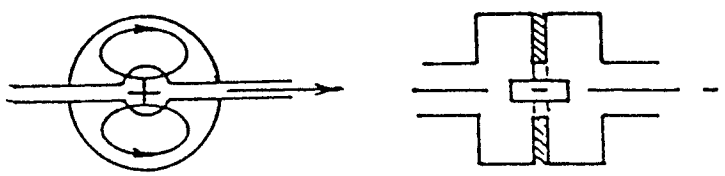


Figure 7: Conceptual scheme to measure beam position using two resonant cavities and observing the energy flow between them

W. Schnell
CLIC Note 70

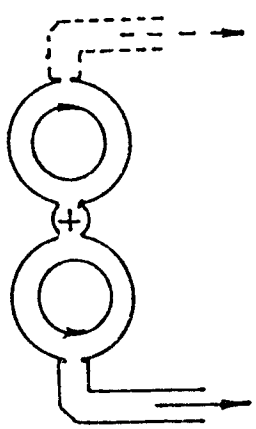


(a) high-Q, E_{11} cavity



(b) slot-damped (sliced-iris) E_{11} cavity. (Vertical and horizontal monitors may be combined in one unit.)

side view



(c) coupled zero-mode cavities

Figure 1: Three types of resonant monitor for vertical beam position. The + designates the beam seen head on, the straight arrows the signal output and the closed-loop arrows the magnetic field induced by a vertically displaced beam.

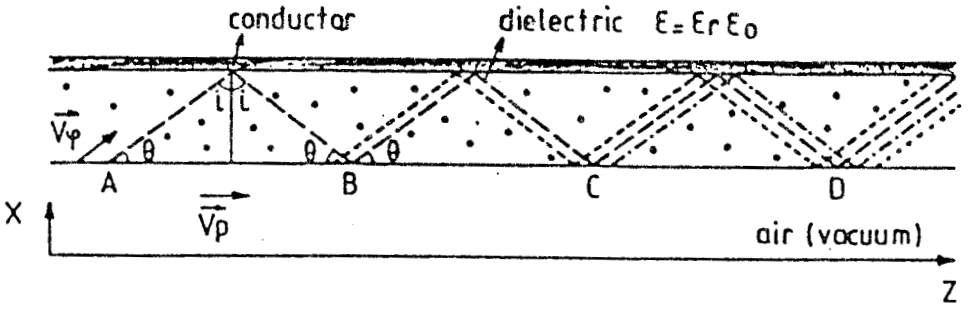


Figure 3 - Simplified view for capability to enhance Cerenkov power by a dielectrically loaded wave guide.

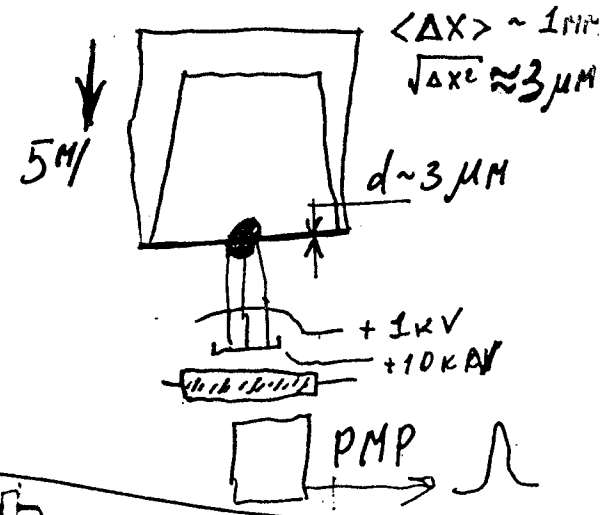
E. Brambilla - Innocenti CERN / Napoli

Cerenkov μ-wave pick-up*

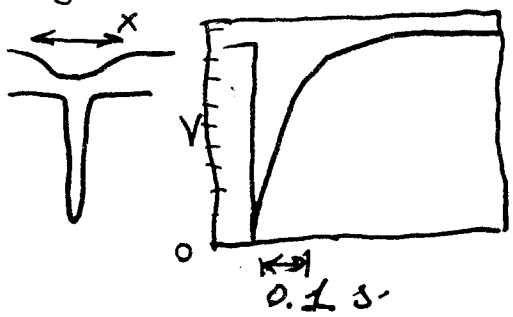
May be useful in situations having high background of low β radiation.

* proposed by Ginzburg in 1947

International Workshop on
Next Generation linear colliders
V. Parfomchuk



Magnesium atomic beam



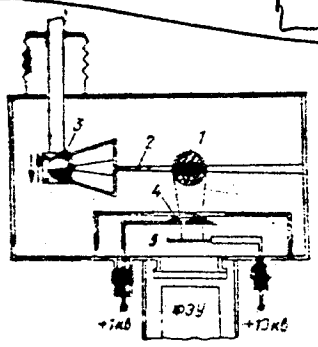


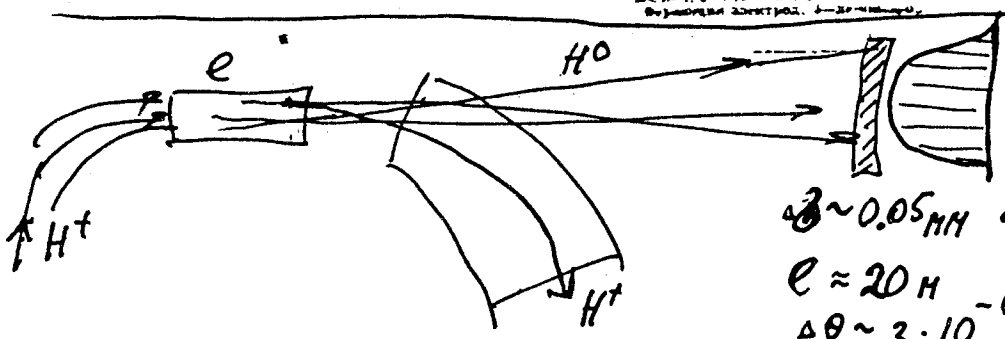
Рис. 1. Изотопный атомный пучок:

$\langle \Delta X \rangle = \pm 0.05$ мм

$\sqrt{\langle \Delta X^2 \rangle} = 0.5$ мм

$P_{jet} \approx 10^{-6}$ torr

$P_{cham} = 10^{-10}$ torr



$\Delta X^2 \approx \Delta X_0^2 + (\ell \cdot \Delta\theta)^2$

$\ell >> \beta^*$

$\Delta X_0 \sim 0.05$ мм $\quad \Delta X \approx \ell^2 \Delta\theta^2$

$\ell \approx 20$ м

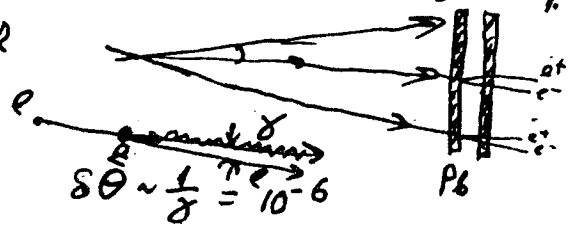
$\Delta\theta \sim 3 \cdot 10^{-6}$ rad

e^+e^- collider

$\Delta\theta \approx 10^{-3}$

$\Delta X \sim 1$ μм

$\beta \approx 1$ мм



$\delta\theta \sim \frac{1}{\gamma} = 10^{-6}$

FLUORESCENT SCREENS

C. D. Johnson

Fig. 1a

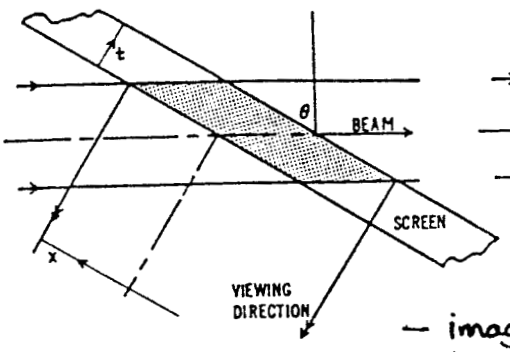
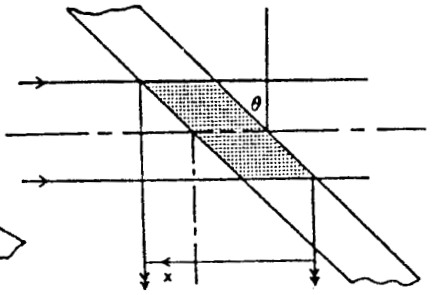


Fig. 1b



— image broadening due to screen thickness.

Scintillator may be polycrystalline or single crystal Al_2O_3. Cr watch out for thermal quenching of fluorescence!

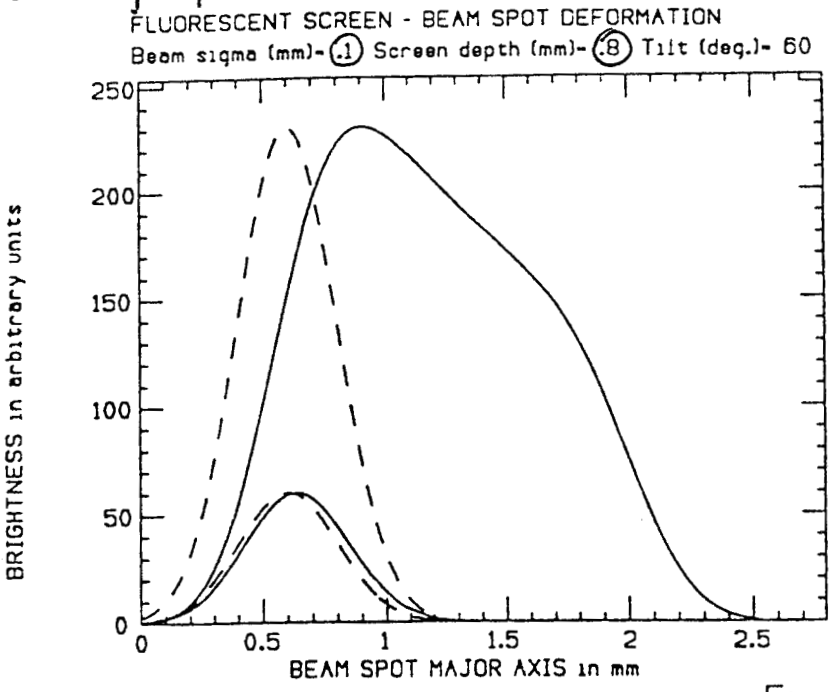
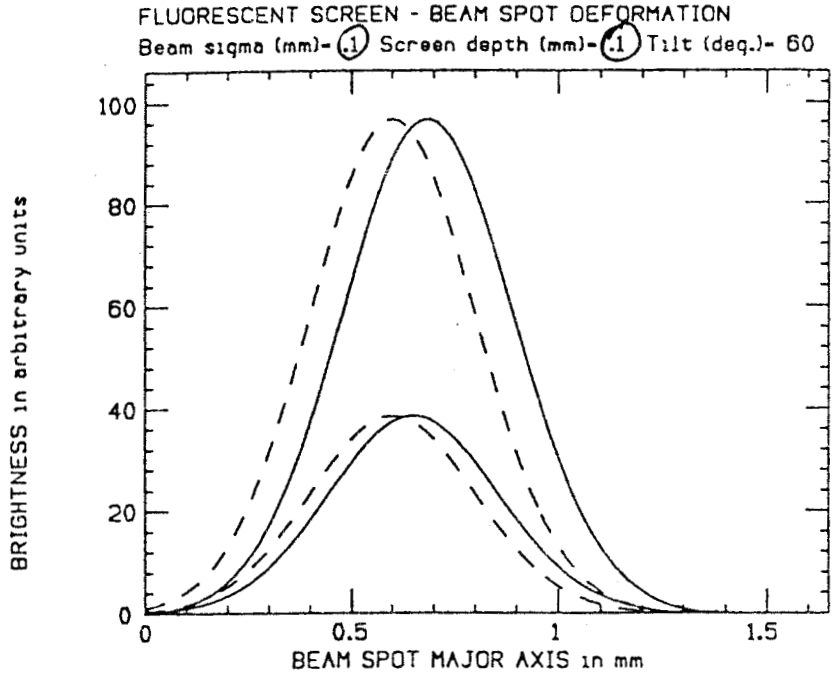
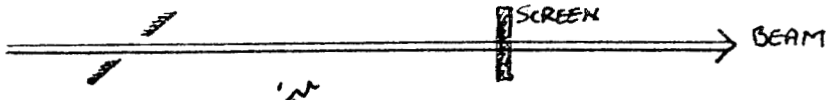
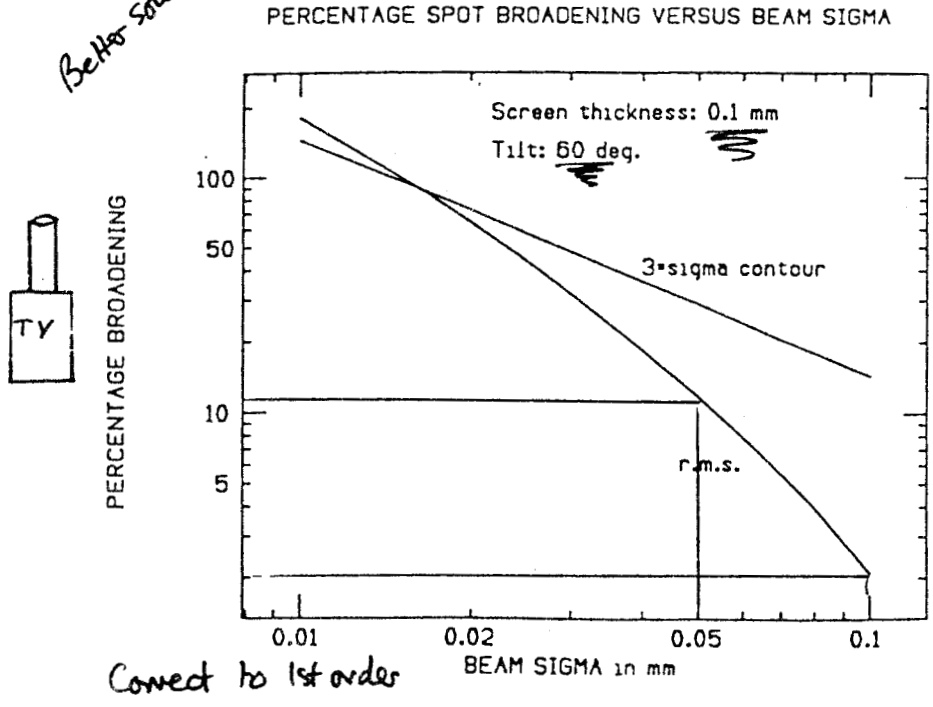


Fig. 2



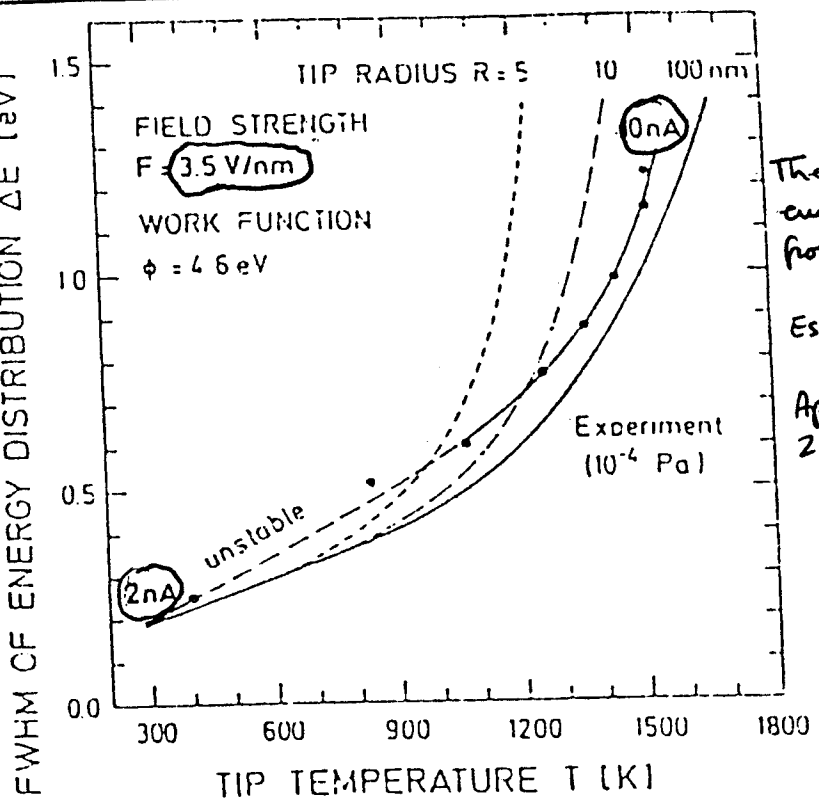


Better solution



Correct to 1st order

CARBON FIBRE PROFILE MONITORS - PROBLEMS



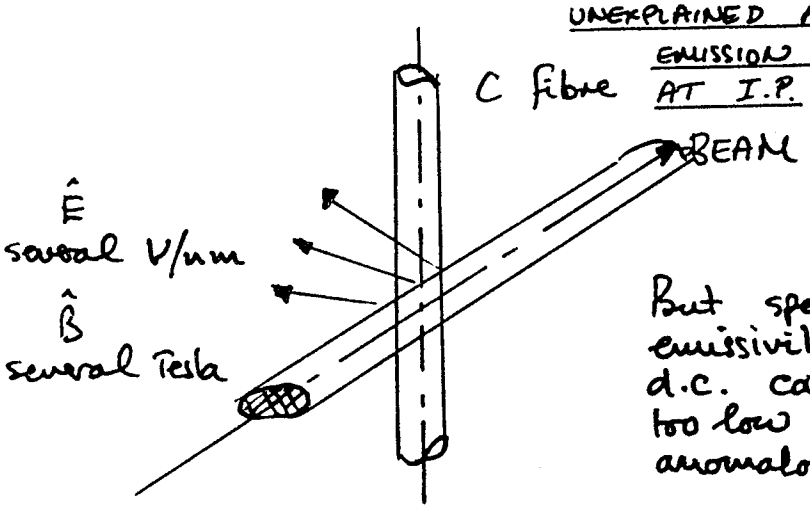
Thermally field emitted electrons from carbon fibres

Essig & Geiger

Applied Physics 25, p115, 1981

Fig. 2. Experimental and theoretical full width at half maximum values ΔE as function of the tip temperature T for low current densities. Theoretical curves are given for the tip radii $R = 5$, 10, and 100 nm, the latter is nearly identical with the curve for the plane emitter. Final electron energy 25 keV

UNEXPLAINED ANOMALOUS e^- EMISSION FROM C FIBRE. AT I.P.

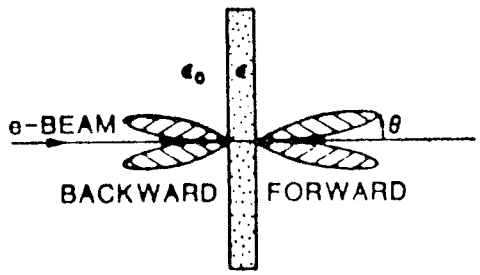


C. Field

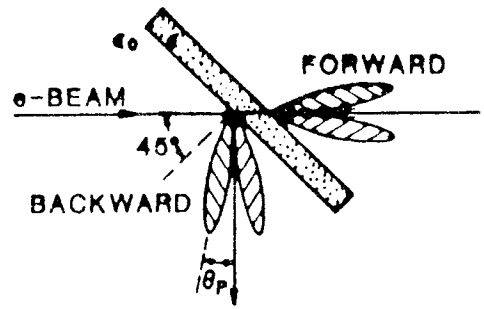
But specific field emissivity for d.c. case is far too low to explain anomalous signals

Alex Lumpkin
Los Alamos - Physics Div.

OPTICAL TRANSITION RADIATION PATTERNS

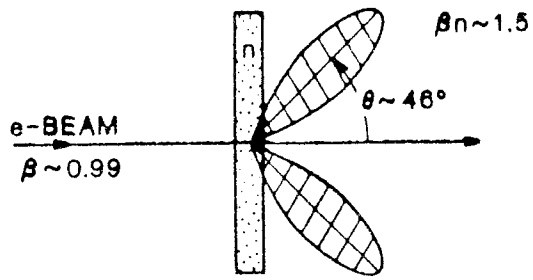


a.) NORMAL INCIDENCE



b.) OBLIQUE INCIDENCE
($\phi = 45°$)

CHERENKOV RADIATION PATTERN ($\theta \sim 46°$)



$$Z_v \simeq \frac{\lambda\gamma^2}{2\pi} \quad \text{and} \quad r_f = \frac{\lambda\gamma}{2\pi}$$

J. Bosser, J. Haan
G. Ferioli, L. Wartski
CERN - ORSAY

2.5) Results from the previous formulae

Table I gives the photon yield N in the wavelength range : 0.35 to 0.8μm (the mean wavelength is 0.5μm), the depth of field and resolution for different incident particles expected to be used in the SPS.

OPTICAL TRANSITION RADIATION - Conventional wisdom

Particle	γ	N photons/particle	Z_v	r_f
p or pbar	27.7	12.10^{-3}	60μm	4.3μm
	500	20.10^{-3}	20mm	80μm
$16_0{}^{8+}$	10	0.5	8μm	1.6μm
	200	1	3mm	32μm
e^- or e^+	7000	29.10^{-3}	3.9m	1.1mm
	40000	35.10^{-3}	127m	6.3mm
	10^6		3km	!

LIMITATIONS : at high energies small beams can not be resolved, the opening angle of the cone becomes aperture limit. Energy and divergence information might still be extracted.

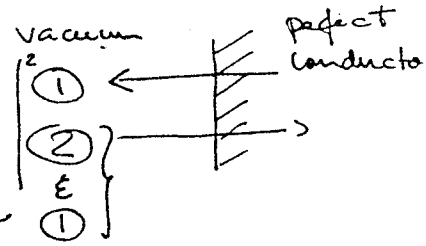
Foilless OPTICAL DIFFRACTIVE TRANSITION RADIATION

Produced by particle passing through hole in a conductor (Iris). At 500 GeV 5mm Iris will produce visible light. Dense beam will radiate coherently with high power. Needs more study, also for beam dynamics, but in general same equations as foil produced OTR

WRP 12/7/88

Collapsing dipole radiation of light of frequency ω into the solid angle $d\Omega$ around Θ (which is the angle of observation measured from the normal to the surface).

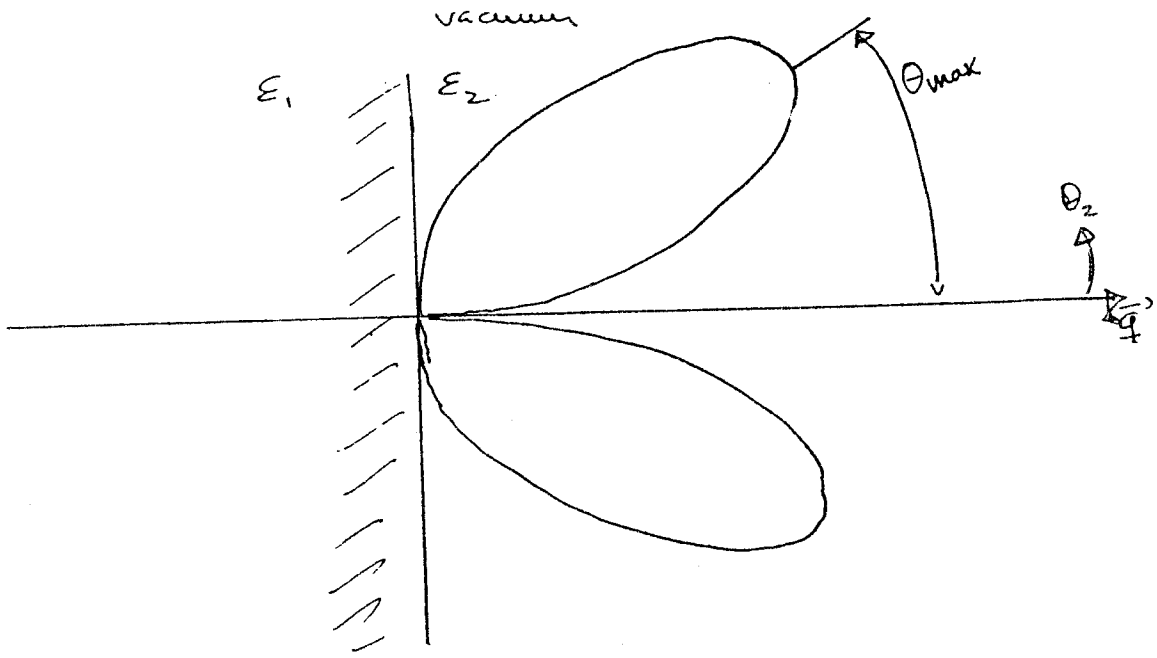
$$\frac{dI}{d\omega\, d\Omega} = \underbrace{\frac{e^2 \beta^2 \sin^2\Theta}{\pi^2 c\,[1-\beta^2\cos^2\Theta]^2}}_{①} \underbrace{\left|\frac{\sqrt{\varepsilon}-1}{\sqrt{\varepsilon}+1}\right|^2}_{②}$$

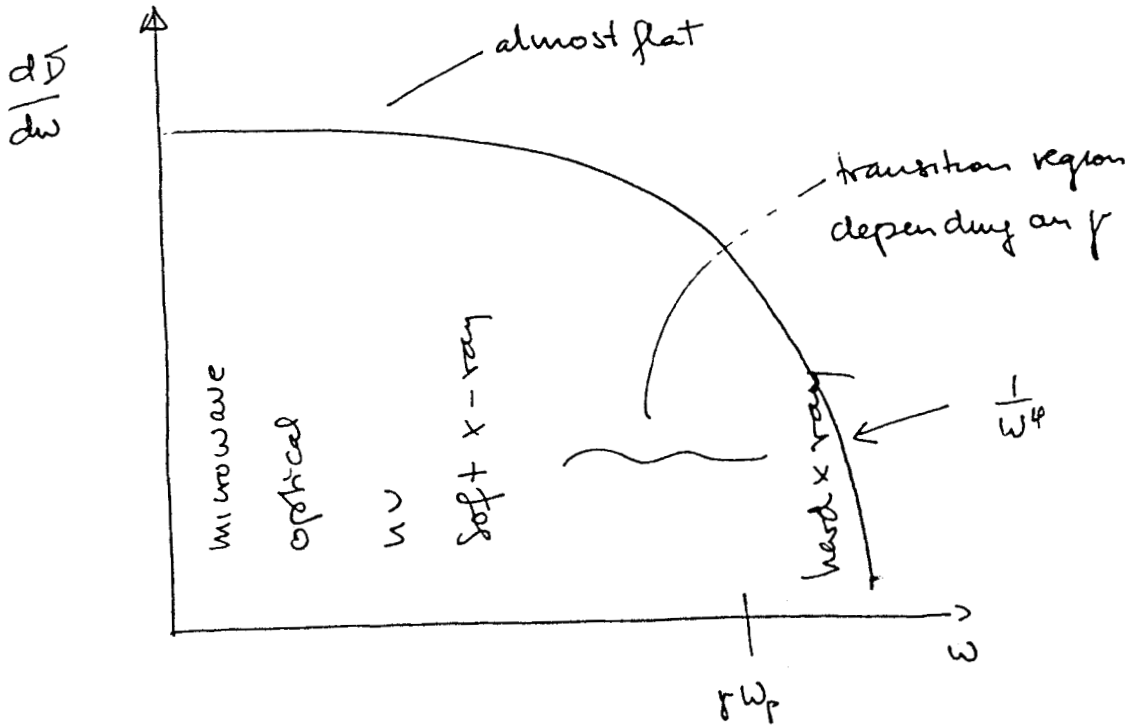


Maximum intensity at

$$\Theta_{max} \approx \gamma^{-1}$$

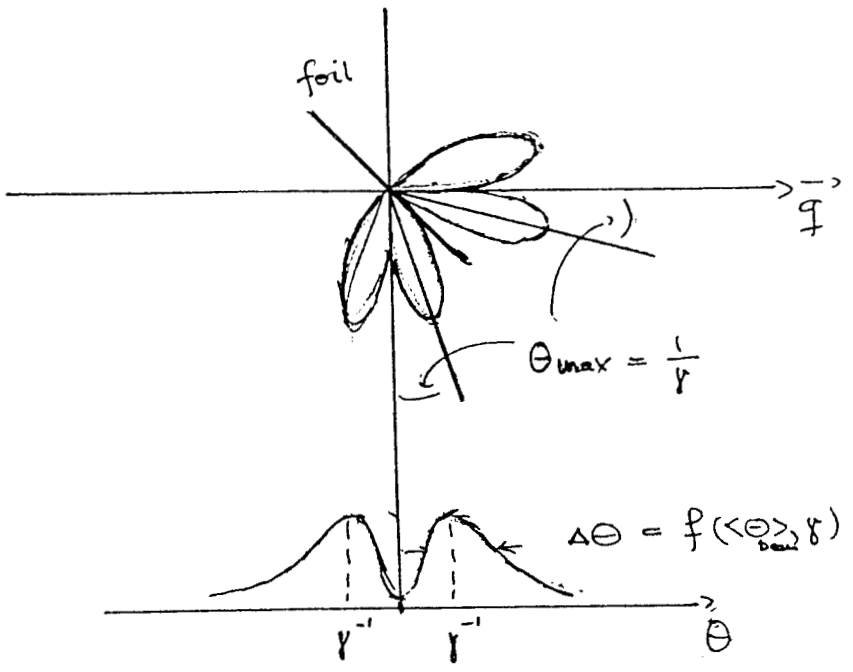
100 MeV	5 mrad
1 GeV	0.5 mrad
50 GeV	10 μrad

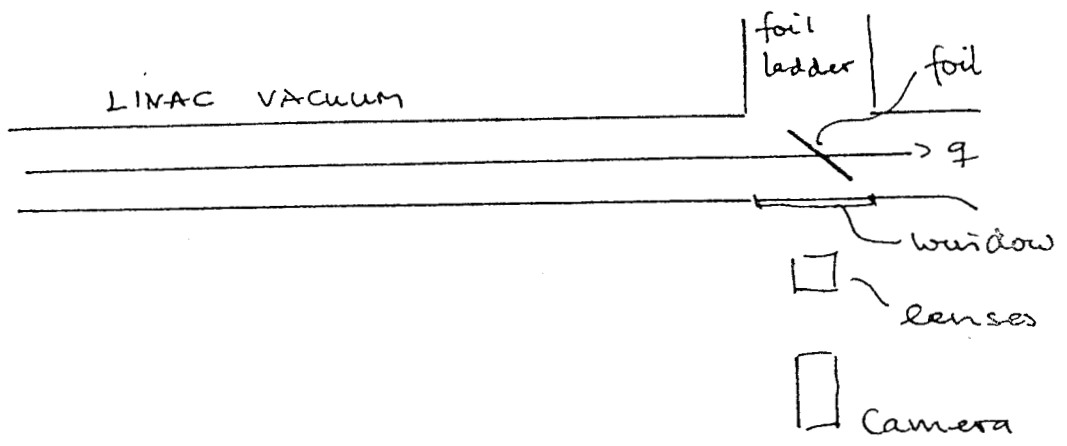



$\frac{dD}{d\omega}$
almost flat
transition region
depending on γ
microwave
optical
UV
soft x-ray
hard x-ray
$\frac{1}{\omega^4}$
ω
$\gamma\omega_p$

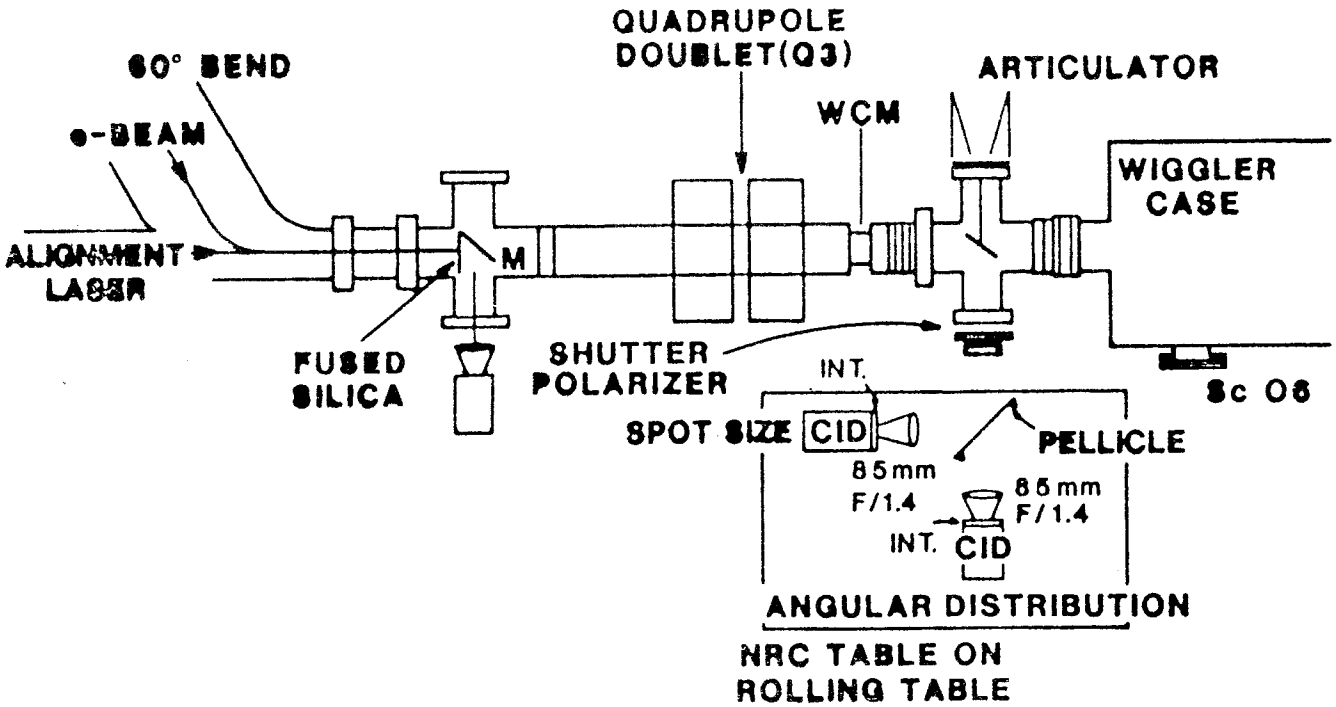
What can one diagnose in the beam?
First one modification: oblique incident angles

↳ Backward OTR comes out to be symetric (for $\gamma \gtrsim 100$) around angle of secular reflection

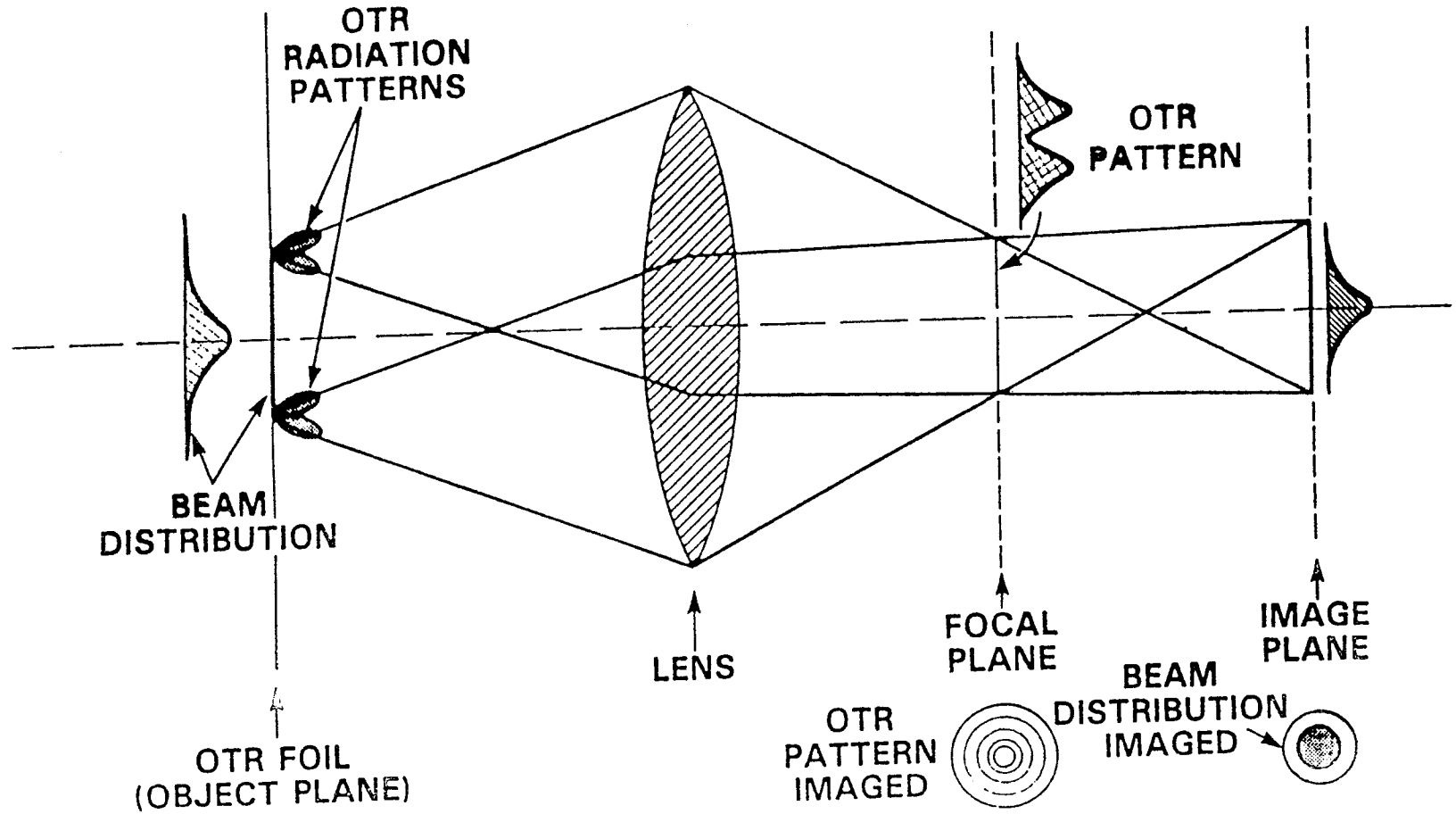


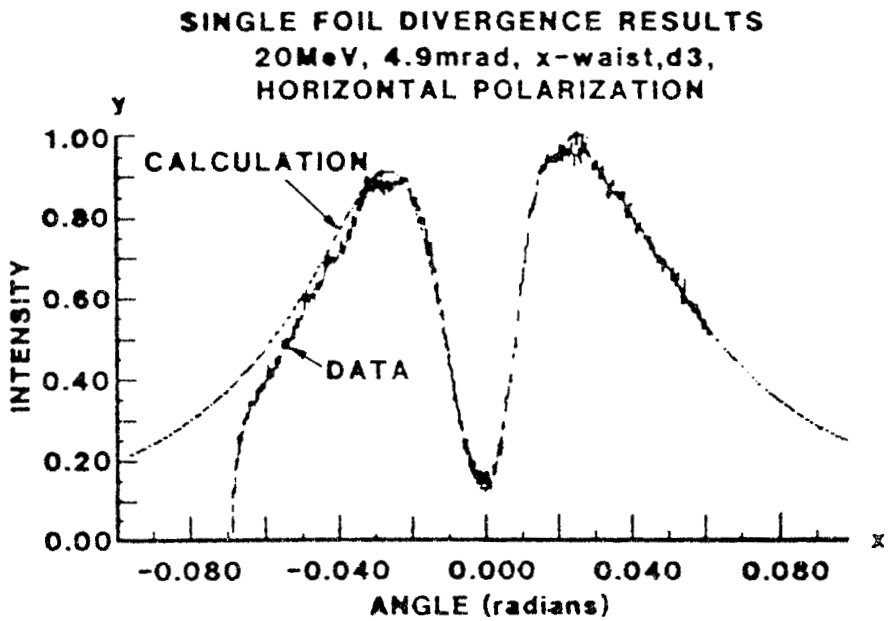


Schematic of OTR Experiment
(Los Alamos)

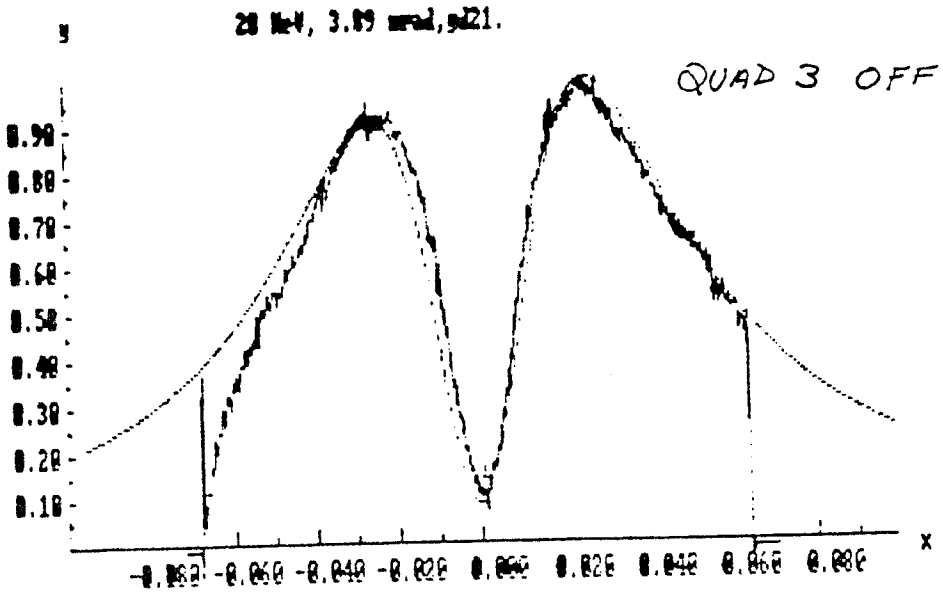


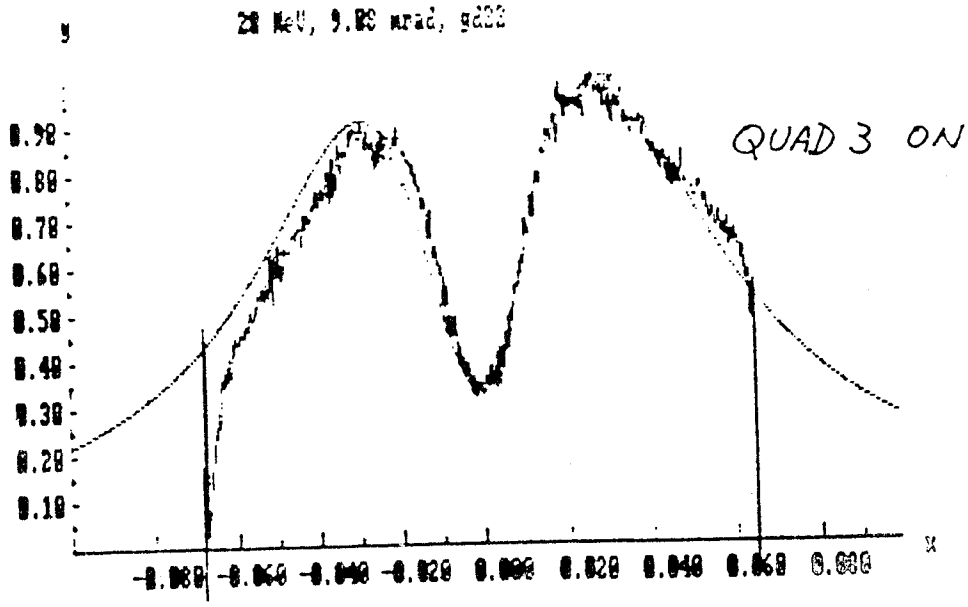
OPTICAL RAY DIAGRAM FOR OTR IMAGING



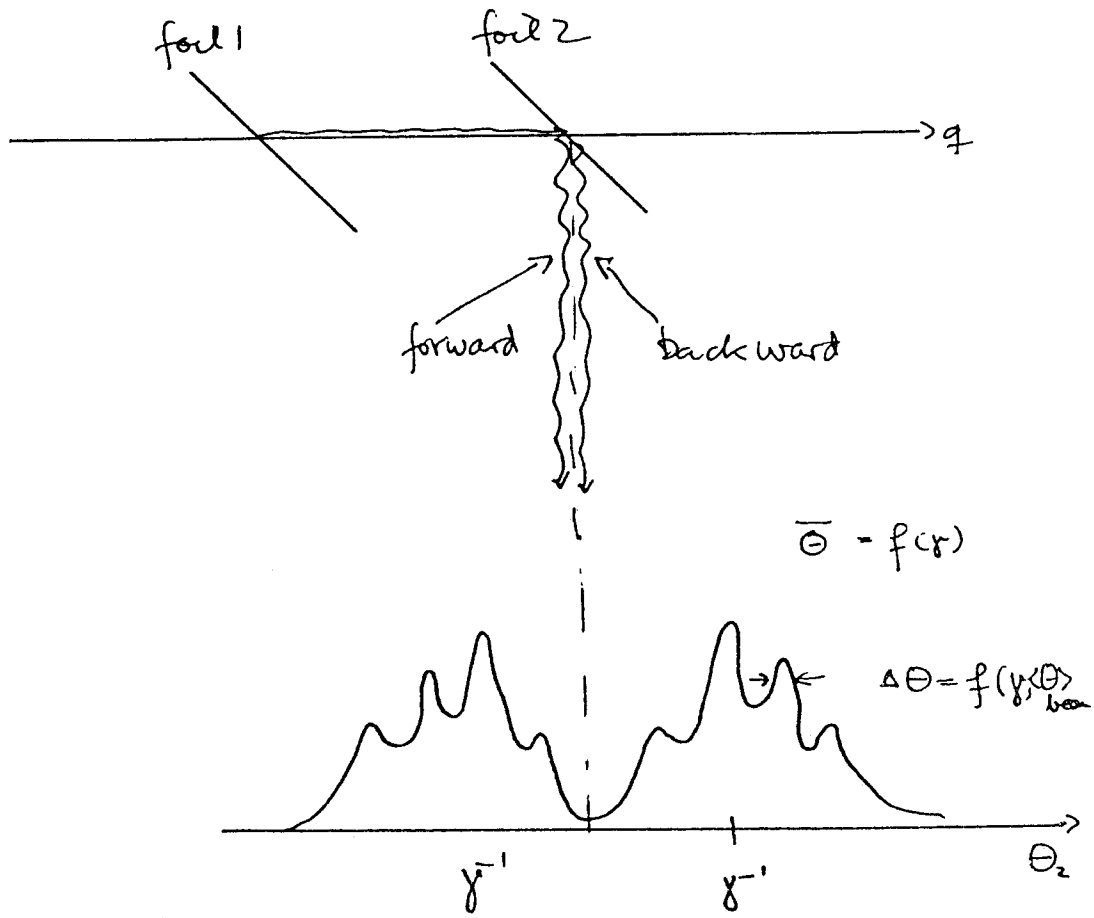

SINGLE FOIL DIVERGENCE RESULTS
20MeV, 4.9mrad, x-waist,d3,
HORIZONTAL POLARIZATION
Y
1.00
0.80
0.60
0.40
0.20
0.00
INTENSITY
CALCULATION
DATA
-0.080
-0.040
0.000
0.040
0.080
ANGLE (radians)
X

EXAMPLES

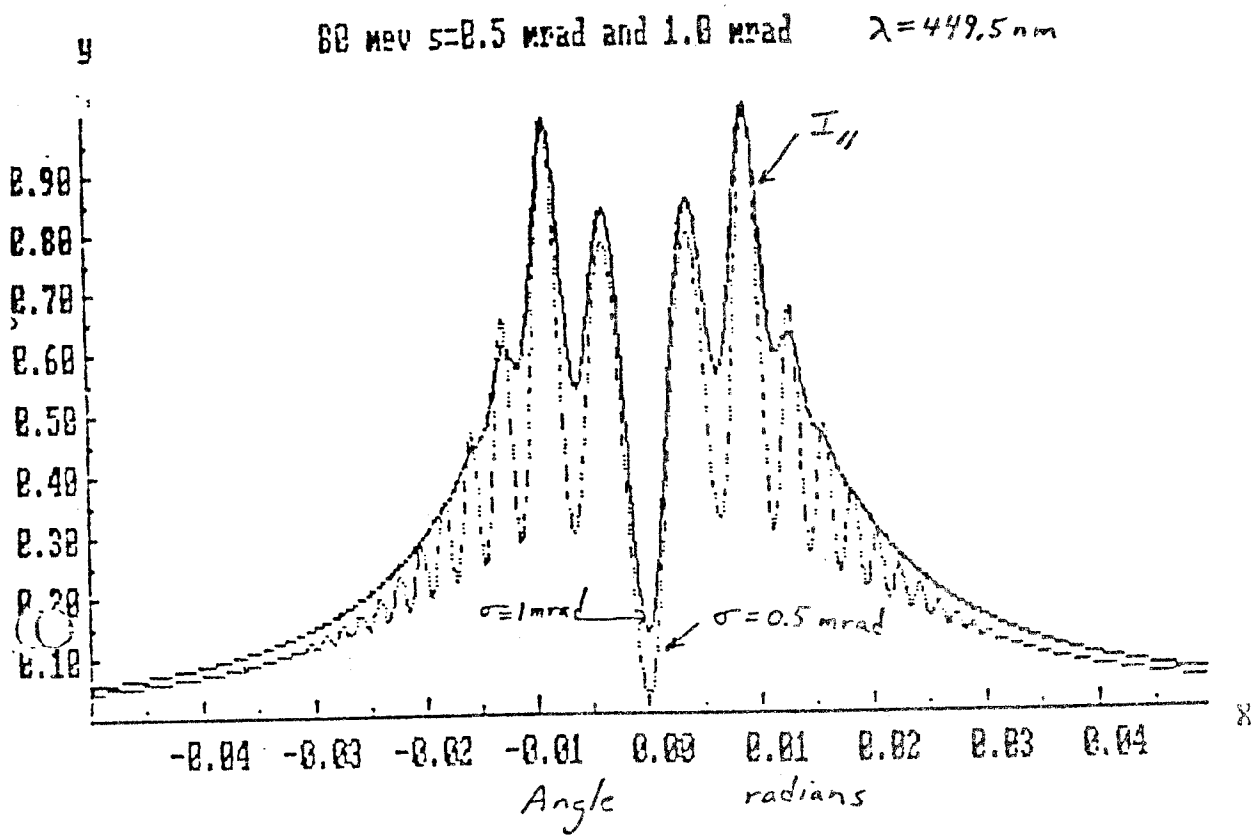


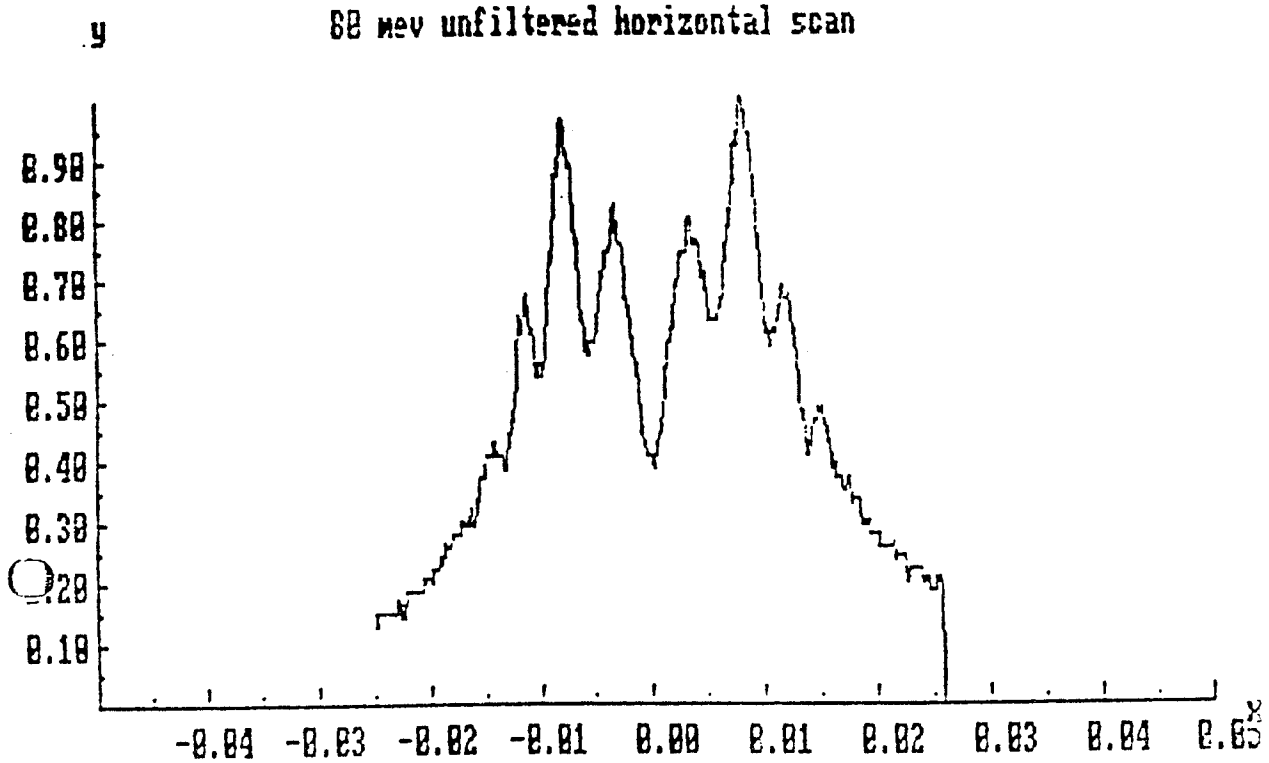


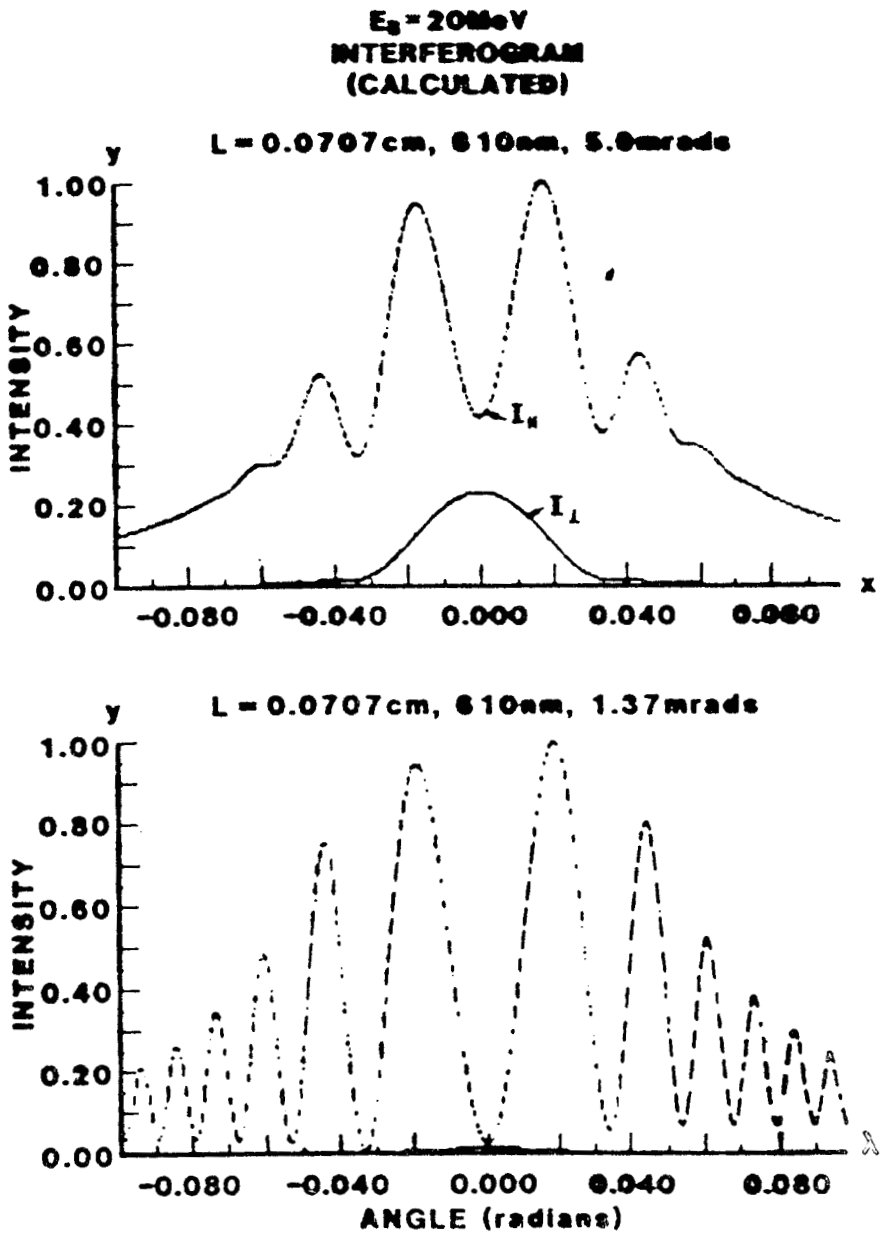
Wartski - Interferometer



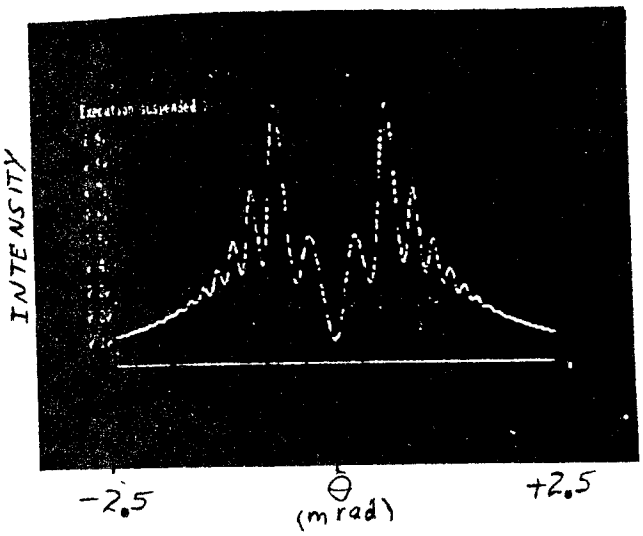
Interference pattern


80 mev s=0.5 mrad and 1.0 mrad
λ=449.5nm
y
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
$I_{//}$
σ=1mrad
σ=0.5 mrad
-0.04 -0.03 -0.02 -0.01 0.00 0.01 0.02 0.03 0.04
x
Angle radians

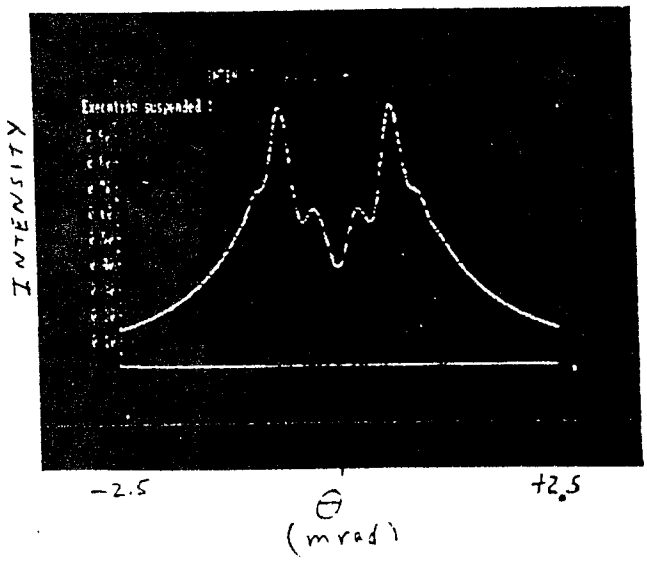

68 mev unfiltered horizontal scan
y
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
-0.04
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
0.04
0.05
x


INTERFEROGRAM
(CALCULATED)
L = 0.0707cm, 610nm, 5.0mrads
y
1.00
0.80
0.60
0.40
0.20
0.00
INTENSITY
$I_{\parallel}$
$I_{\perp}$
x
-0.080
-0.040
0.000
0.040
0.080
L = 0.0707cm, 610nm, 1.37mrads
y
1.00
0.80
0.60
0.40
0.20
0.00
INTENSITY
-0.080
-0.040
0.000
0.040
0.080
ANGLE (radians)

CALCULATED INTERFEROGRAM
E = 1 GeV, ΔL ~ 200cm
(PRELIMINARY)



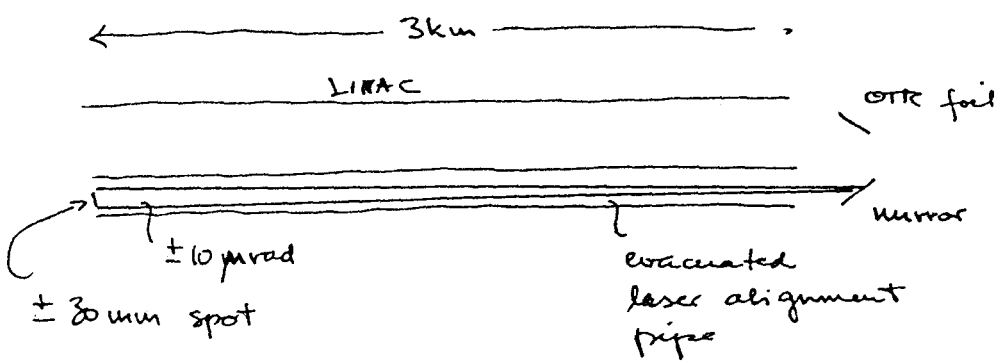
$\sigma = 0.05$



$\sigma = 0.10$

Example for present LINAC:

50 GeV beam at end of LINAC produces OTR cone of ± 10 mrad.



At 1 TeV and 6 km a system would result in ± 3 mm spot which can easily be digitized.

Try to stabilize beam energy at 50 GeV
Assume 10^{-3} photons/e^- in $\theta < \theta_{max}$ where single foil OTR varies like γ^4.

Goal 50 MeV : 1‰ requires 10^6 photons
current to $\lesssim$ 1‰

Available $5 \cdot 10^7$ photons ($10^{-3} \cdot 5 \cdot 10^{10}$),
so we could do better, conceivably down to $\approx$ 10 MeV.

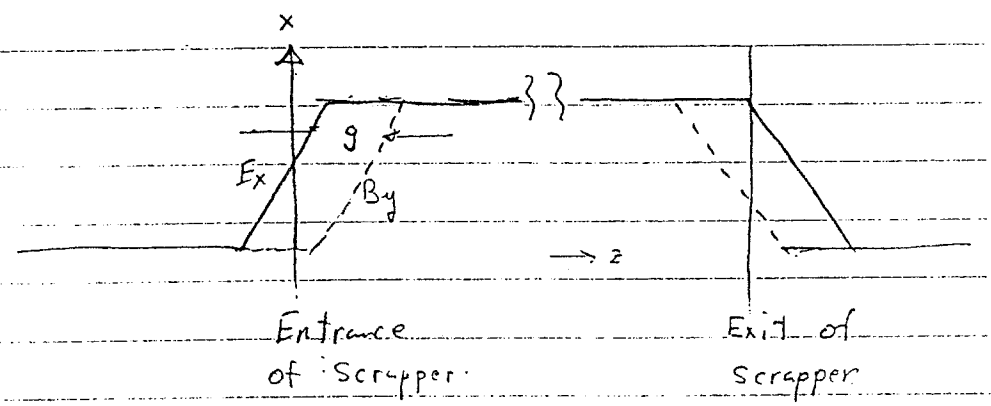
SCRAPERS

Karl Bane, Phil Morton

Long Bunch approaching edge of scrapper

image charges increase at scrapper edge

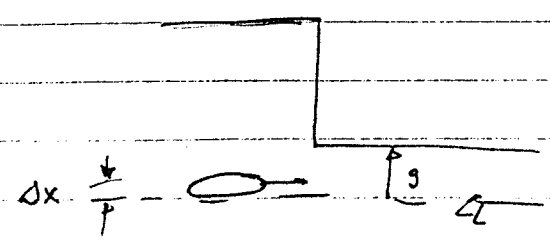
image currents decrease at scrapper edge.



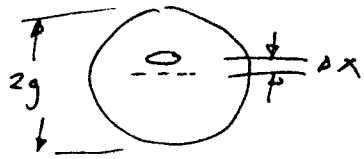
g is ½ gap or radius of pipe

$$c\,\Delta P_x = e\int_{-\infty}^{\infty} dz\,[E_x - \beta B_y] \approx e\,g\,\Delta E_x$$

$$\Delta\theta = \frac{\Delta P_x}{m\gamma c} = \frac{e\,g\,\Delta E_x}{\gamma\, m c^2}$$



For round beam in round pipe displaced by Δx



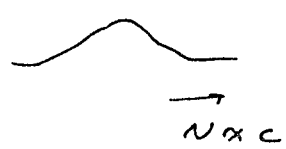
$$\Delta E_x = \frac{2e\lambda\Delta x}{g^2}$$

λ = longitudinal charge density

$\therefore$ $\Delta\theta$ for each edge

$$\Delta\theta = \frac{2\lambda r_e}{\gamma}\left(\frac{\Delta x}{g}\right)$$

where gaussian bunch varies from zero at ends to $\Delta\theta_{max}$ in middle



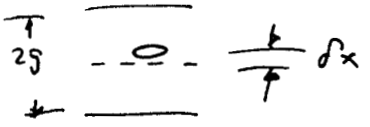
$$\Delta\theta_{max} = \frac{2Nr_e}{\sqrt{2\pi}\,\gamma\,\sigma_z}\left(\frac{\Delta x}{g}\right)$$

$$= (.3\,\mu r)\left(\frac{\Delta x}{g}\right)$$

with $r_e = 2.8\times10^{-13}$ cm
$\gamma = 2\times10^6$
$N = 10^{10}$ $\sigma_z = 40\,\mu m$

b) <u>round beam in straight edged scraper displaced by δx</u>

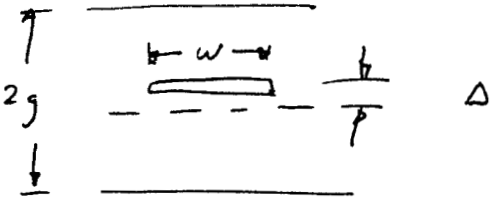
J. Laslett



$$\Delta E_x = \left(\frac{\pi^2}{4}\right) \frac{e\lambda \Delta x}{g^2}$$

multiple image charges

c) <u>flat beam between parallel scraper</u>



From first 2 image charges get

$$\Delta E_x = \frac{2e\lambda}{w}\left[\tan^{-1}\frac{w}{2(g-\Delta)} - \tan^{-1}\frac{w}{2(g+\Delta)}\right]$$

$$\simeq 2e\lambda \frac{\Delta}{g^2}\left(\frac{1}{1+\left(\frac{w}{2g}\right)^2}\right)$$

$\frac{\Delta}{g}$ small

s — shielding factor

Dependence of Scraper Kick on Angle

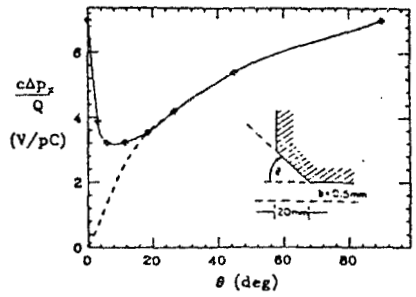


Fig. 5. Peak kick of 1/2 scraper as a function of scraper angle θ, when $\xi/b = 1.0$ mm and $\sigma = 1.0$ mm.

Discussion

We have shown that scrapers that pass close by high peak current beams can significantly degrade the beam emittance. A circular scraper was chosen for this study since, at the moment, it is the only one that we can compute. But it can be expected that these results give a reasonably good approximation for a normal rectangular window scraper, with b representing the half width of the window. Whenever wakefield effects can be important scrapers that only have one side should be avoided since they will give larger kicks than computed here. Furthermore, they have no ideal trajectory along which there is no kick, as the symmetric scrapers have.

References

[1] T. Weiland, DESY 82-015 (1982) and NIM 212, 13 (1983).

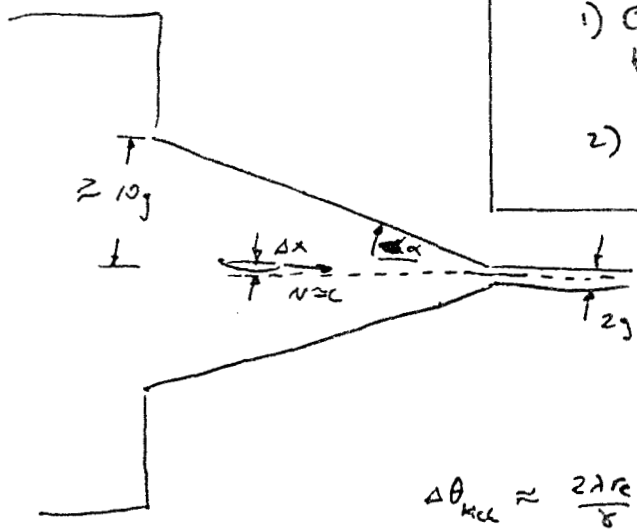
[2] K. Bane and P. Wilson, Procedings of the 11th Int. Conf. on High-Energy Accelerators, CERN (Birkhäuser Verlag, Basel, 1980), p. 592.

[3] T. Weiland, DESY M83-02 (1983) and NIM 216, 31 (1983).

Questions:

1) Can we use low-angle taper?

2) What is the effect of ceramic scrapers?



$$\Delta\theta_{kick} \approx \frac{2\lambda r_e}{\gamma}\left(\frac{\Delta x}{g}\right)\left(\frac{2\alpha}{\pi}\right)^{1/2} \qquad \frac{\sigma_z}{g} \gtrsim 1$$

with $\gamma = 10^6$

$N = 10^{10}$

$\sigma_z = 40\mu m$

$$\Rightarrow \Delta\theta_{kick} = (.6\mu r)\left(\frac{\Delta x}{g}\right)\left(\frac{2\alpha}{\pi}\right)^{1/2}$$

So if $\alpha = 10°$ kick is reduced by $\frac{2}{3}$ if taper length $\gtrsim 60g$

COLLIMATORS

Dieter Walz

$$T_{max}^{(e^-)} = \phi(E_0, Z) \quad (\text{in } X_0)$$

E_0	Be	C	H_2O	Al	Ti	Fe	Cu	W	Pb
1.2 GeV	1.4	1.7	1.8	2.4	2.9	3.1	3.2	4.0	4.1
20 GeV	4.2	4.6	4.7	5.3	5.8	5.9	6.1	6.9	7.0
50 GeV	5.2	5.5	5.6	6.2	6.7	6.8	6.9	7.8	7.9
500 GeV	7.5	7.8	7.9	8.5	9.0	9.2	9.3	10.1	10.2

$$\Pi_{max}^{(e^-)} = \phi(E_0, Z)$$

1.2 GeV	~3	~3	~3	5	8	9	10	21	23
20 GeV	26	35	37	64	103	118	131	280	305
50 GeV	60	80	86	150	240	276	300	660	720
500 GeV	497	678	732	1287	2087	2413	2631	5793	6390

Can approximately calculate energy loss due to ionization and thus power deposition

$$P' \sim \Pi \left(-\rho \frac{dE}{dx}\right) N \times PRR \quad (W/cm)$$

Temperature Rise per Bunch

radial interval	0 – 100 μm	$\Delta T \sim 13\ ^\circ C$
	100 – 200 μm	$\sim 10\ ^\circ C$
	200 – 400 μm	$\sim 5\ ^\circ C$

Scaled to $\underline{1.5 \times 10^{11}}$ per 10 bunch train
(Note, this is independent of energy)

0 – 100 μm	$\Delta T \sim 39\ ^\circ C$
100 – 200 μm	$\sim 30\ ^\circ C$
200 – 400 μm	$\sim 15\ ^\circ C$

Local Temperature Spike in Microvolume

will give rise to

Instantaneous Compressive Thermal Stresses
and after some time lapse, Strains

Remember Hooke's Law

$\sigma_{th} \propto E \alpha \Delta T$ for elastic system

In the example above of a 1mm thick — say iris-in a waveguide structure we had $\Delta T \sim 40°C$ per bunch train and 1.5×10^{11}

In a fully-restrained body Hooke's law would result in a thermal stress rise of $\sigma_{th} \sim 12{,}000$ psi

∴ The iris would clearly not fail in one exposure, but repeated impingement of the beam onto the same location would cause surface deterioration from formation of washboard configuration, perhaps laced with microcracks.

∴ Buckling of the iris should not be a problem at this temperature in such a small volume

∴ The steady state power deposition @ 360Hz is only 3.6 W and should present no problems

Question:

What transverse beam size would it take to melt the copper iris in one bunch train?

For $\sigma_x = \sigma_y = 30\,\mu m$* and $P' = 1.02 \times 10^{-2}$ W/mm (for SLC $N = 5 \times 10^{10}$)

& assumed uniform power dissipation (no gaussian)

$$\Delta T = \frac{1.02 \times 10^{-2}}{3.45 \times .003^2 \pi} \approx \underline{1050\,°C}$$

The melting point of Cu is ~ 1080 °C and allowing for Gaussian distribution we have reached the melting point for $\sigma = 30\,\mu m$

For a TLC pulse or bunch train with 1.5×10^{10} we reach the same $\Delta T \sim 1050\,°C$ for $\sigma \sim 52\,\mu m$.

What about the nth iris where the peak volumetric heating occurs?

But what is "thermal range"?

For the same 50 GeV, 200 μm*, 5×10^{10} beam as used above a Monte Carlo Calculation using a semi-infinite medium gave peak temperature rises per bunch of ~ 375 °C.

Scaled to 1.5×10^{11}/bunch train one obtains

$\Delta T \sim 1100$ °C/bunch train @ 50 GeV

Scaled to 500 GeV the temperature rise is of the order of 10,000 °C

(This is just a rough, ball park estimate)

A corresponding value for sometimes used collimator materials such as W, W-25Re or Ta-10W is $\Delta T \sim 2500$ °C/bunch at 50 GeV, 5×10^{10} and $\sigma = 200$ μm. Scaling like above to 500 GeV and one bunch train would give

$\Delta T \sim 22{,}500$ °C

∴ Not the Way to Go !

* probably about = to "Thermal range"

Mitigating Factors

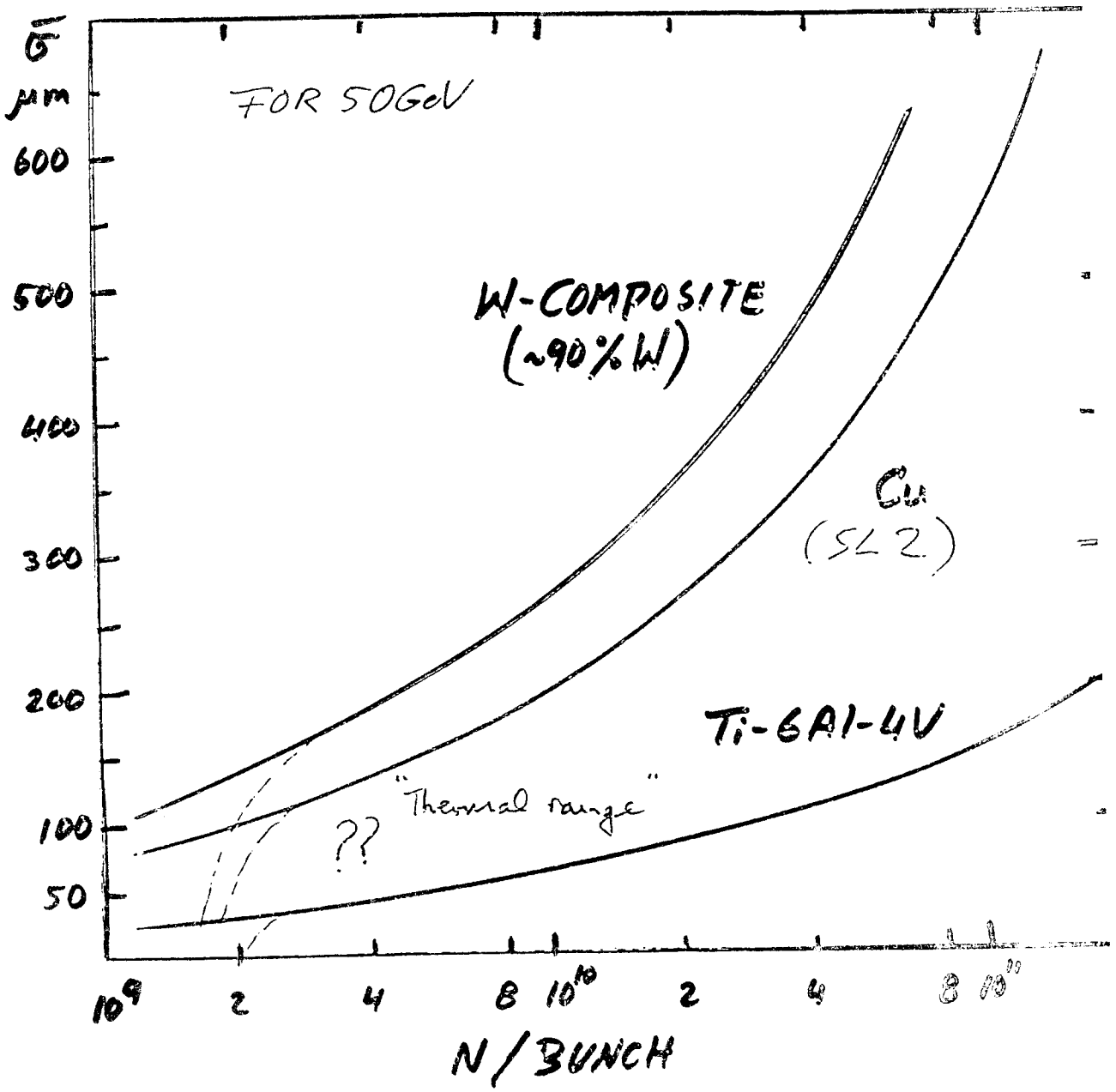
Irises in Accelerator Structure are separated from each other by vacuum space of thickness mm. Each iris or disc will act as a spoiler and helps to blowup the beam.

Effect not too pronounced in the early part of the shower, but significant after several X_0.

∴ This will significantly lower peak temperatures, but probably not enough to save the day.

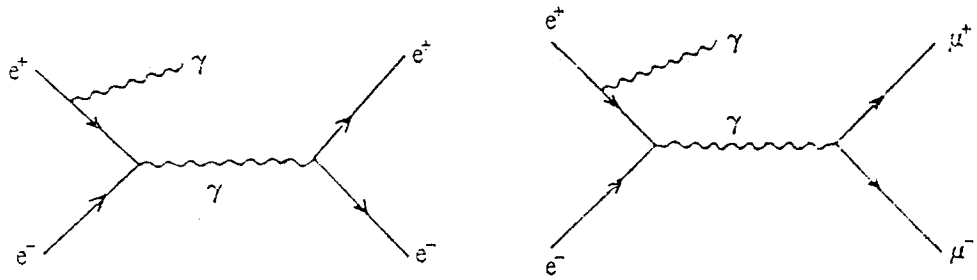
The average power in the beam for 500 GeV, 10 bunches of 1.5×10^{10} in one train and 360 Hz is $\{P_{av} \sim 4{,}300\,kW\}$ 4.3 MW

This is manageable provided the beam can be blown up to a size appropriate for the material



MOMENTUM SLIT OR COLLIMATOR
SINGLE BUNCH LIMITS

MACHINE LUMINOSITY



"Machine" Luminosity for tuning - must have a rate > few events/hour at $10^{28}\ cm^{-2}s^{-1}$

1) Non Radiative Bhabha scattering at lab. scattering angles from 2 to 4 mrad

At SLC S.R. background from final triplet is too high (E_c SLC = 2.4 × E_c LEP)

2) At higher energies non-radiative Bhabha $\sigma \sim \frac{1}{s}$, but $e^+e^- \to e^+e^-\gamma$, $\sigma \sim \ln s$
So we should detect γ's (or μ's) P.G-W, CDJ

Or the scattered e^-s H. Steiner et. al. LBL

Hard Photon Luminosity Monitor for Linear e^+e^- Collider

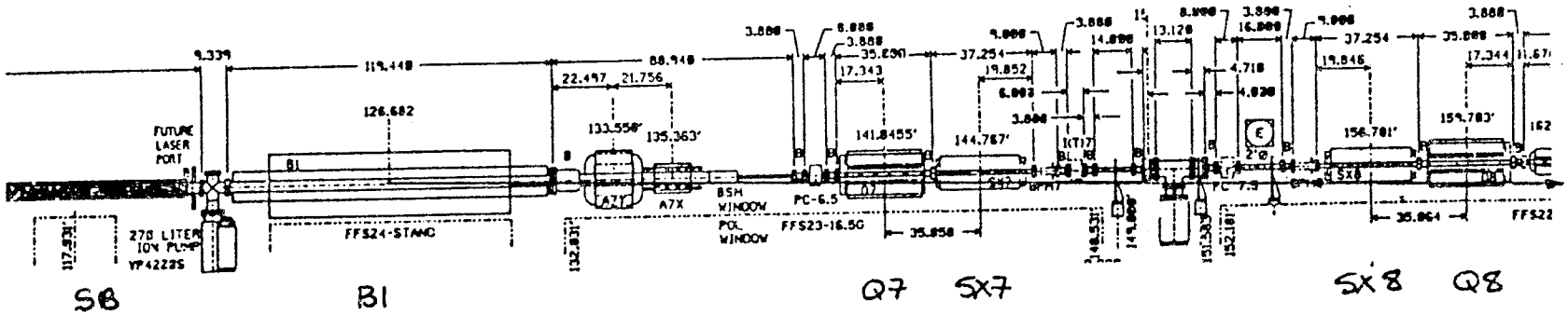
P. Grosse-Wiesmann and C.D. Johnson, SLAC, CA 94305

ABSTRACT, 1989 Accelerator Conference, Chicago.

The ultimate performance characteristic of particle beam colliders is the integrated luminosity. Insofar as the beam parameters: position, size and particle distribution functions, are known the luminosity, and hence the interaction rates, can be calculated, and these derived values may be summed over time to obtain the integrated luminosity. However, in practice it is far from simple to reliably extract these beam parameters. It is therefore desirable to have direct fast on-line luminosity monitoring. Traditionally elastic Bhabha Scattering ($e^+e^- \rightarrow e^+e^-$) above a scattering angle of a few degrees is used. Unfortunately elastic Bhabha Scattering into a fixed angular acceptance decreases $\sim \frac{1}{s}$ and leads to a rather small cross section at high collision energies. In contrast the radiative Bhabha process ($e^+e^- \rightarrow e^+e^-\gamma$) has a very high cross section which increase logarithmically with energy $\sim ln\ s$. The feasibility of such a Bhabha monitor is determined by the possibility of extracting the hard photons from backgrounds and will depend upon: the lattice and mechanical implementation of the Final Focus, and the ability of the detector to discriminate between the hard photons and the softer background of synchrotron radiation and beamstrahlung. Some design examples and background numbers are presented for the SLC.

SLC case

SFF SB TO Q8



CLEAR ± 1.2 mrad for ν beam

SOLUTION 1.

ENLARGE Q7 SX7, MODIFY BACKLEGS OF SX8, Q8 – GOOD FOR ± 0.5 mrad

SOLUTION 2:

HALF QUADS IN PLACE OF Q7, Q8, COMBINED DIPOLE + SEXTUPOLE TO REPLACE SX7 AND SX8 – GOOD FOR > 1.2 mrad. but steering a nightmare.

Martin Lee

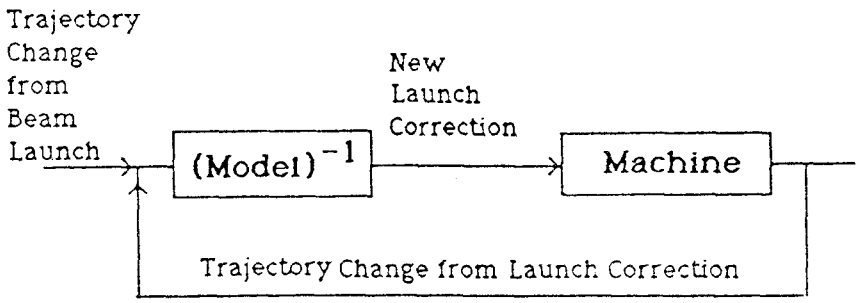


Fig. 1 A block diagram of a conventional launch feedback control.

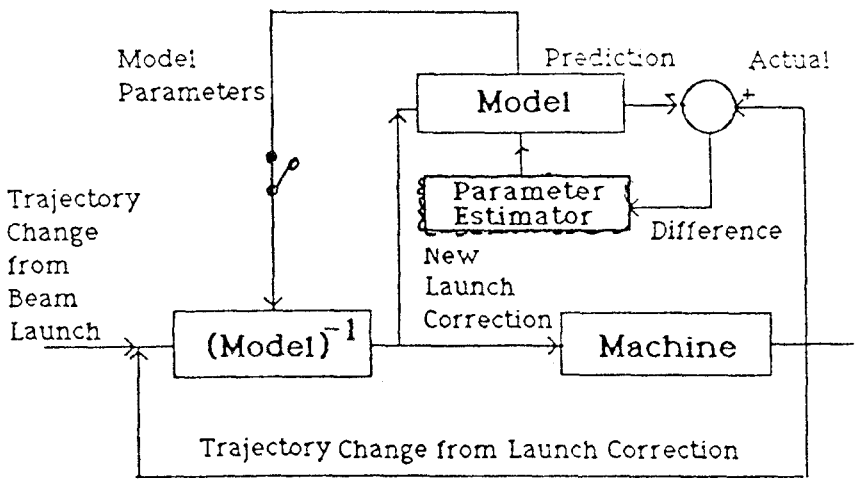


Fig. 2 A block diagram of a Model-Reference Adaptive System for the launch control.

A WORLD-WIDE COLLABORATION ON MACHINE CONTROL HAS BEEN SET UP IN THE FORM OF REGULAR WORKSHOPS.

BUT WHAT ABOUT 'BEAM CONTROL'? — STUDY AT SLAC.

FINAL FOCUS WORKING GROUP

Chairman: D. Burke SLAC

Secretary: T. Fieguth SLAC

Members and Contributors

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T. Taylor	CERN
B. Zotter	CERN
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J. Perez	Orsay (LAL)
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Summary of Final Focus Group Discussions

David L. Burke, Theodore H. Fieguth

The Final Focus Working Group included a total of 26 physicists representing all participating institutions. Each morning the group as a whole heard and discussed reports of ongoing work. The afternoon sessions found the group divided into smaller working groups. A total of 23 oral presentations were delivered in seven days. The topics discussed fell mainly into the following catagories: a) final focus optics, b) beam-beam interactions, c) magnet design and measurement techniques, d) special small-beam instrumentation, e) tolerance to errors, f) backgrounds and g) exotic ideas. Two additional topics were the commissioning experience with the SLC final focus and the prospects of a Final Focus Test Beam at SLAC. Parameters for final focus systems for TLC, CLIC, JLC and VLEPP were compared where possible and were found to be similar. All have unequal emittances for the horizontal and vertical planes and unequal values for the betatron functions and spot sizes at the interaction point. These parameters differ in detail usually only by an order of magnitude or less. Topology of the interaction regions do vary greatly and this is still a matter of great interest. An important result of the workshop was the finding that it would be necessary to increase the crossing angle for the TLC from the original design value of 3 milliradians to 60 milliradians in order to minimize the background from the pair production background discussed below. This result has generated a new interest in the "crab crossing" technique to correct for the loss of luminosity due to the large crossing angle.

The topic of chromatic corrections is still of great interest and the question of which is most desirable, "correction in one plane only, or two?", is still being debated. There was some work on optical scaling laws which prove to be helpful in gaining insights to design. Minimum achievable spot sizes are limited no matter how well the optics is designed due to the chromatic dilution induced by the synchrotron radiation in the final quadrupoles. This synchrotron radiation limit (Oide Limit) was examined and has yet to present a serious problem.

Beam-beam interactions were examined and a process that had not been previously investigated was found to have serious implications. This effect is the coherent production of electron-positron pairs by the interaction between the beamstrahlung photons from one beam and the collective electromagnetic fields of the opposing bunch. For large beam-beam disruption, the number of high energy beamstrahlung photons is approximately equal to the number of incident electrons or positrons, and the interaction of these photons with the coherent electromagnetic field of the opposing bunch create secondary electron-positron pairs. For bunches containing a large number of particles this process can generate intolerable backgrounds. The production rate is controlled by limiting the collective magnetic field of the beam (measured by a parameter called upsilon)

which can only be reduced by lowering the charge per bunch. This solution in turn requires increasing the number of bunches or the frequency of crossings in order to retain luminosity.

This closer look at pair production led to the conclusion that much more detailed work will be required to find the optimum paradigm for the interaction region that will control this source of background. Most of the secondary electron-positron pairs are produced at small angles with respect to the incident beams, so one scheme to reduce this background is to simply increase the crossing angle to allow for larger exhaust beam ports. To do so and still not lose luminosity would require crab crossing. This scheme uses an RF deflector of the type used for RF separators to induce a correlation between the longitudinal position of the particles in the bunch and their transverse momentum. As seen in the center of mass of the two beams the effect of the crossing angle is removed. In other words those particles at the head of one bunch will interact with all of those in the opposing bunch and likewise so will those at the tail. Of course, there are other ways of inducing such a correlation but this method appears easiest to control.

There were several suggestions for measuring small spot sizes and controlling their positions. Among these were the use of ante-beams, bremsstrahlung from foils and/or saturated plasmas in foils.

The requirements imposed on the properties of the final quadrupole lenses by various optical designs were examined, and it was concluded that conventional technology, perhaps using permanent magnets, will be able to meet them.

There were discussions of the purposes and design for a proposed Final Focus Test Beam at SLAC. Such an experimental area would take advantage of the small emittances obtainable at SLC and provide an appropriate beam for the development of hardware and techniques for generating, measuring and maintaining sub-micron size beams. A preliminary optics and layout has been developed for this beamline. As proposed it would be an extention almost coaxial with the linac into the existing C-beam channel. A small bend of approximately one degree needed for chromatic correction would be the only deviation from the direction of the linac. The total length would be between 125 and 250 meters. The beam would operate at 10^{10} electrons or positrons per pulse at the full SLC energy of 50 GeV. The beam power would be 1kW at the operating frequency of 10 Hz. There is an attempt underway to provide flexible optics that can be tailored to best suit the proposed experiments. To test future chromatic correction schemes in one plane only, a flat beam is desired. A design for such a beam has been completed with a beam size of about 50 nanometers in the vertical plane and 3 microns in the horizontal plane. Some possible experiments such as those dealing with plasma lenses will usually require rounder beams. An effort is being made now to elicit suggestions and requirements from future experimenters and collaborators to include in the design of this facility.

List of Final Focus Talks

1. W. Kozanecki, "SLC Commissioning Experience"
2. K. Oide, "Final Focus Test Beam Optics Design"
3. T. Fieguth, "Proposed SLAC Final Focus Test Beam"
4. J. Norem, "High Resolution Beam Monitor"
5. J. Spencer, "Some First Principles of FFS Design"
6. K. Brown, "Scaling Laws for SLC-Type Final Focus Optics"
7. J. Rosenzweig, "Perspectives on the Plasma Lens"
8. P. Chen, "Beamstrahlung Pair Creation"
9. V. Parkhomchuk, "Beam Density Monitor"
10. M. Hildreth, "Beamstrahlung Profile Monitor"
11. V. Telnov, "Gamma-Gamma and Gamma-Electron Colliding Beams"
12. K. Oide, "Synchrotron Radiation Limit on Focusing"
13. T. Taylor, "Final Focus Quadrupole Design"
14. B. Zotter, "CLIC-TLC Comparison," and "Tolerance to Error"
15. J. Buon, "Synchrotron Radiation Limit for Two Dimensions"
16. K. Oide, "Wire Resonance; Measurement of Magnetic Gradients"
17. P. Chen, "Beam-Beam Pair Production"
18. S. Drell, "Beam-Beam Pair Production"
19. B. Richter, "Beam-Beam Pair Production"
20. R. Palmer, "Crab Crossing"
21. W. Kozanecki, "Constraints on Final Focus Designs"
22. S. Yu, "Plasma Focusing"
23. F. Couchot, "Ante-Beams"

REVIEW OF THE FINAL FOCUS SYSTEM

BRUNO AUTIN

CERN - LBL

1. Introduction
2. Topology of the interaction region
3. Matching procedures
4. Synchrotron radiation in quadrupoles (Oide's limit)
5. Tolerances
6. Magnet technology
7. SLAC Beam Test Facility
8. Beam monitoring
9. γ-γ collisions
10. Final remarks

Purpose of the final focus system

To focus a beam coming from a conventional beam transport channel down to TINY SPOT SIZES σ measured in nano-meters:

$$\sigma = \sqrt{\epsilon \beta}$$

The real emittance ϵ depends on the particle energy and on the normalized emittance determined by the damping rings:

$$\epsilon = \frac{\epsilon_n}{\gamma}$$

ϵ_n is small ($< 2 \cdot 10^{-6}$ m . rad),

γ is high ($> 7 \cdot 10^6$),

nevertheless $\underline{\beta}$ has still to be made very small.

(a fraction of mm or less !). It is therefore

of interest to consider the converse aspect

of the focussing, namely:

the collection of a large divergence beam

emitted at the interaction point. The

strength of the final lens and the focussing

aberrations, especially the chromatic aberrations,

are uniquely determined by the topology of

the interaction region.

Bruno Autin

FINAL FOCUS PARAMETERS

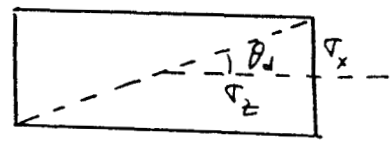
	SLC	TLC	CLIC	JLC	e^+e^- VLEPP	Beam Test Facility	VLEPP $\gamma\gamma$
Beam Energy [GeV]	50	500	1000	500	500/1000	50	1000
Normalized Emittance [$10^{-6}\pi$ mrad]							
ϵ_H	30	2.5	3		6	30	1
ϵ_V	30	.025	1		.06	.3–3	~ 0.1
β Function at IP [mm]							
β_H	7.5	30	22		100	34	0.8
β_V	7.5	.040	0.4		1	.1	.5
Momentum Bandwidth [10^{-3}]		± 3	± 3		± 5	± 3	± 3
Spot Size [nm]							
σ_H	2000	260	180	300	1000	3000	~ 20
σ_V	2000	1	20	3	10	17–55	~ 20
Bunch Length [mm]							
σ_z	1	.079	0.2	0.079	0.5	1	0.75
Beam Disruption							
D_H	<.8	.03			0.1		-
D_V	<.8	6	3		10		-
Υ		0.3	0.5				<0.5
Poletip Field [T]	1.1	1.4	1.4			1.4	~ 1
Final Lens Radius [mm]	20	.5	1–2.5			5	0.5
Final Straight Section Length [m]	2.8	.4	< 2.5			.4	~ 1

Topology of the interaction region

1. Background

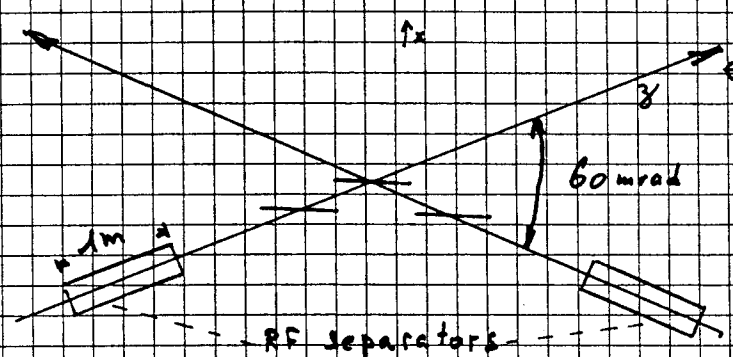
As it has been shown by P. Chen, the collision between e^+ and e^- bunches produces "debris" (photons, $e^+(e^-)$ in the tail of the distributions, e^+-e^- pairs) which must not hit the final quadrupoles. The direct consequence is an INCREASE of the CROSSING ANGLE accompanied by CRAB CROSSING (R. Palmer) to avoid a degradation of the luminosity.

Early crossing angle with no "crab":

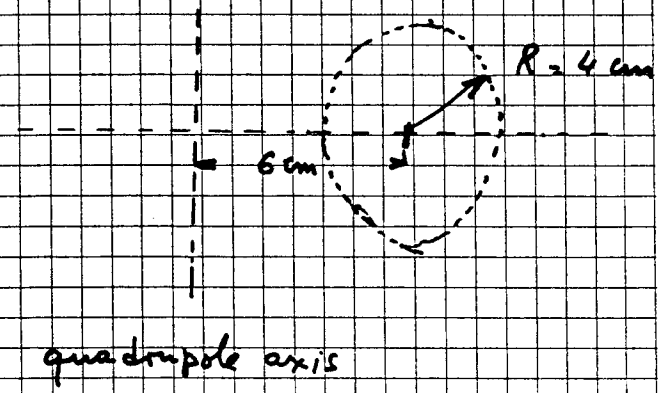


$$\theta_\perp \sim \frac{\sigma_x}{\sigma_z} \simeq 3\,\text{mrad}$$

To-day: $\theta_c \sim 60$ mrad



$\ell = 1$m from IP



Electric field gradient in RF separators: 20 MeV/m

Tolerance on RF wave amplitude: $\frac{dA}{A} = \frac{\theta_d}{\theta_c} = 7\%$

Timing error: $\Delta z = \frac{2\sigma_x}{\theta_c} \sim 25\mu$

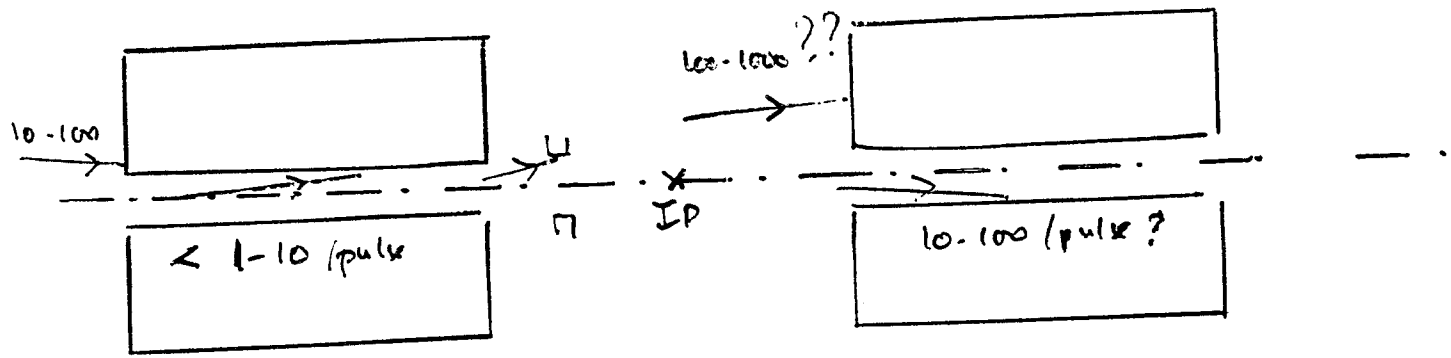
W. Kozanecki

ROUGH LIMITS on ALLOWABLE

$e^{\pm}$ (x GeV) per pulse

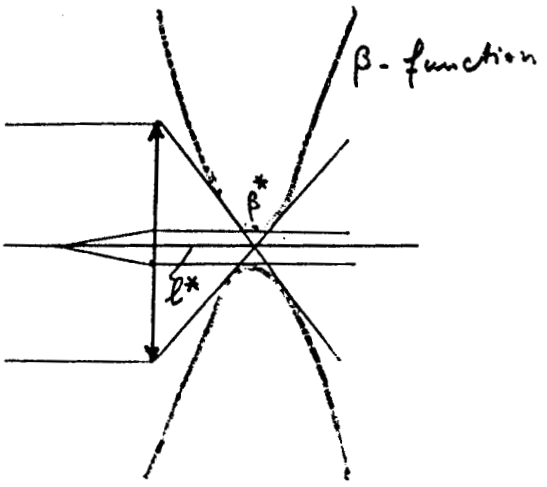
near IP

clearly different if E ~ 250 MeV



Limits on the number of beam particles that could be allowed to strike machine elements near the interaction point before backgrounds become severe in the detector.

Topology of the interaction region : OPTICS

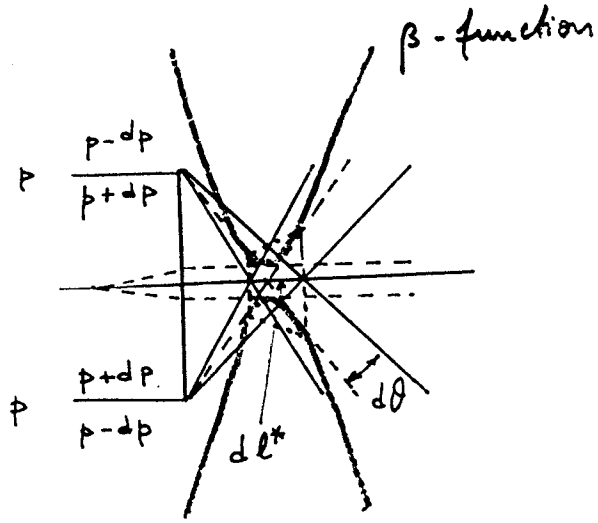


1. ℓ^* is the focal length ; it determines the focusing strength of the lens :

$$k = \frac{1}{\ell^*}$$

CLIC : $\ell^* = 2.5\,m$, $k \sim .3\,m^{-1}$

TLC : $\ell^* = .4\,m$, $k \sim 2\,m^{-1}$



2. The chromatic aberration is a

depth of focus

problem. The scaling parameter is

$$l^* / \beta^*$$

From this point of view: the final lens has to be <u>close</u> to the interaction point.

The same argument is true for the tolerance on the focussing strength.

Matching procedures

2 functions have to be fulfilled:

i) To match the characteristic functions (β, α) of the interaction region to those of the upstream transport channel.

ii) To correct the chromatic aberrations with sextupole (s) and may be with higher order multipoles in a region where a finite orbit distortion is created by dipoles: the Chromaticity Correction Section.

The CCS can be <u>distinct</u> from the final transformer in the case of <u>oval</u> beams or

merged in the case of flat beams (TLC).

In both cases, the matching process is severely constrained by the chromaticity errors generated in the final lenses. All these errors are driven by terms of the form

$$K \beta l \frac{\Delta p / p}{1 + \Delta p / p}$$

a. In the final lens:

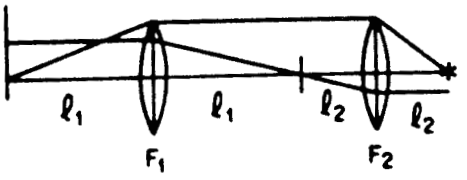
$$K \beta l \sim \Delta \alpha \sim \alpha = \frac{l^*}{\beta^*}$$

The propagation of the chromaticity errors is not linear: there is a cross-talk between quadrupoles due to the distortion of the $(\beta - \alpha)$ functions and the series expansion of $f(\frac{\Delta p}{p})$ is controlled up to 6th order

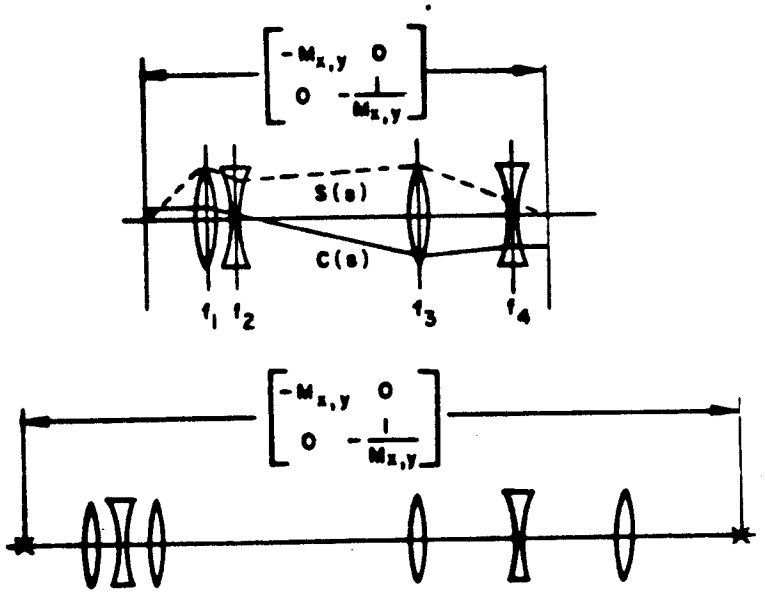
b. In the <u>CCS</u>, the sextupole strengths must be limited to avoid excessive <u>geometric aberrations</u>. The focussing correction in a sextupole is:

$$K' \eta \frac{\Delta p}{p}$$

The orbit dispersion η depends upon the strength of the dipoles and the distance between dipoles and sextupoles. The deflection angle in the dipoles is adjusted so that the emittance blow-up due to synchrotron radiation is maintained within tolerance.



A Thin Lens Telescopic Transformer.

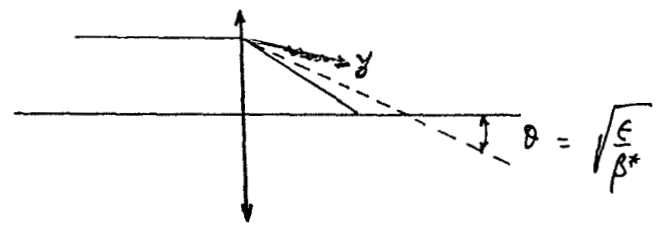


Telescopic Transformers using Doublets and Triplets.

Synchrotron Radiation in the Quadrupoles
(Oide's limit)

A second origin of chromatic aberration is due to the emission of photons by the electrons when they are bent by the magnetic field of conventional quadrupoles.

The effect is the same as for ordinary aberrations:



$$\sigma_y^{*2} = \beta_y^* \epsilon_y + C \gamma^5 F(\sqrt{K} L, \sqrt{K} \ell^*) \left(\frac{\epsilon_y}{\beta_y^*}\right)^{5/2}$$

σ_y^* is minimum for

$$\beta_{y\,min}^* = \left[\frac{275}{3\sqrt{6\pi}} r_e \lambda\!\!\!^{-}_e F\right]^{2/7} \gamma\, \epsilon_{ny}^{3/7}$$

$$\sigma_{y\,min}^* = \sqrt{\frac{7}{5}} \left[\frac{275}{3\sqrt{6\pi}} r_e \lambda\!\!\!^{-}_e F\right]^{1/7} \epsilon_{ny}^{5/7}$$

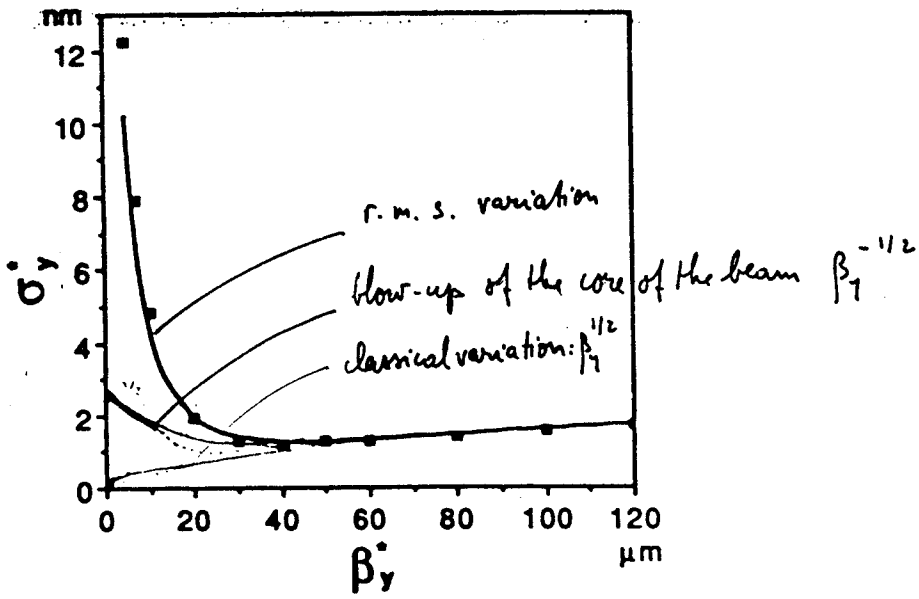


Fig. 2

The calculation has been generalized by J. Buon to a full telescope. It turns out that the <u>last two quadrupoles</u> give roughly the same amount of synchrotron radiation.

The <u>2-D</u> calculation shows an increase of σ_y^* by a factor <u>1.3</u>.

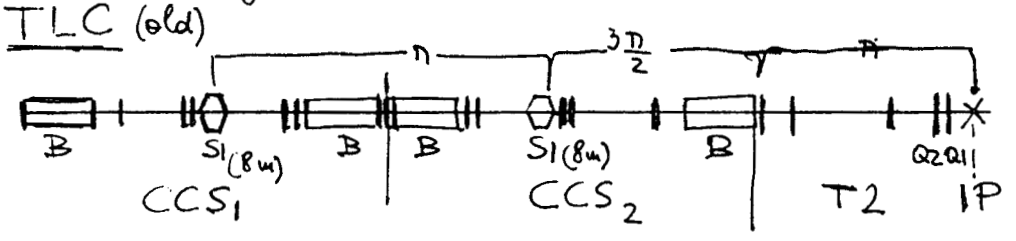
T. Fieguth – K. Oide – B. Zotter
6.12.88

1) Comparison TLC – CLIC

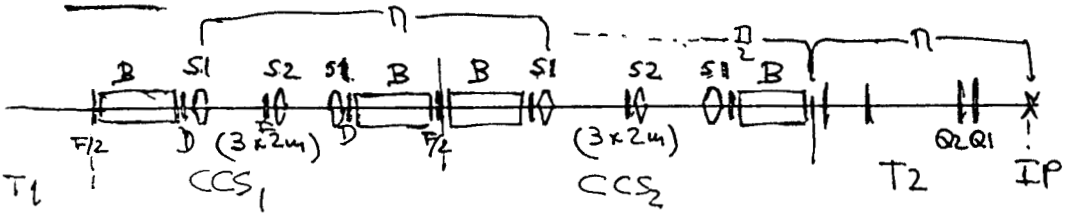
a) similarities

basic geometry

TLC (old)



CLIC



b) differences "Choices + prejudices"

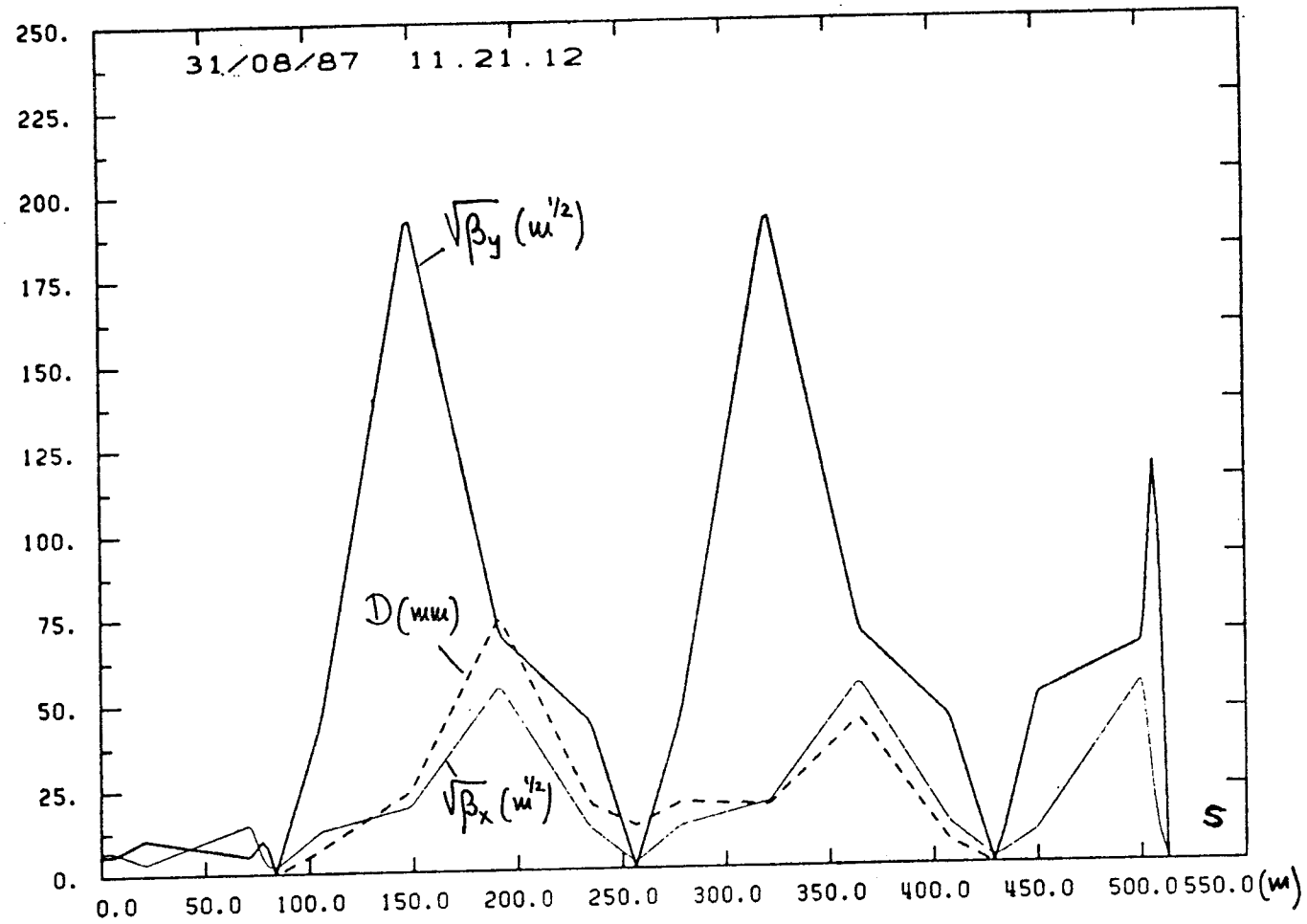
1) energy: TLC 0.5 / CLIC 1 TeV emittance growth $\sim E^5$ – 32!

2) vertical emittance/horizontal 100 / 3 larger emittance increases 'Oide' limit $\sim \epsilon^{5/7}$

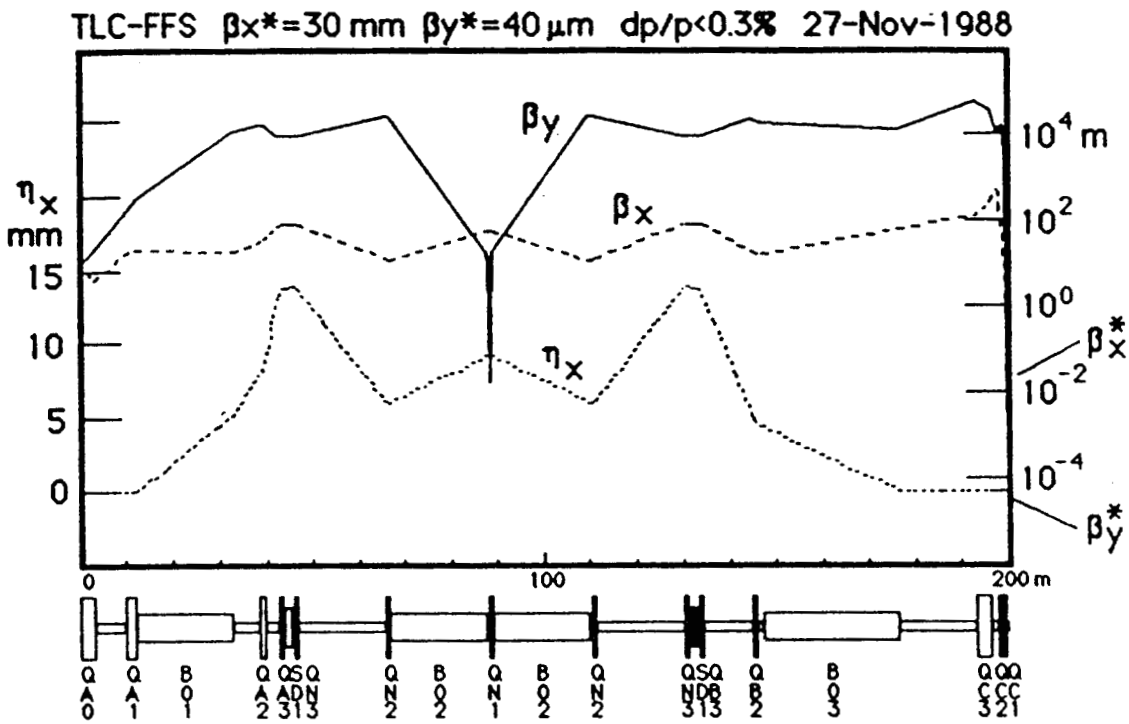
3) quad aperture 0.1 / 1 mm longer focal length – larger l^* 0.4 – 2.5 m

new TLC – 0.5 mm : converging

new CLIC – unequal telescopes, T2 stronger – reduces l^*



CLIC Final Focus machine functions



TLC Final Focus machine functions

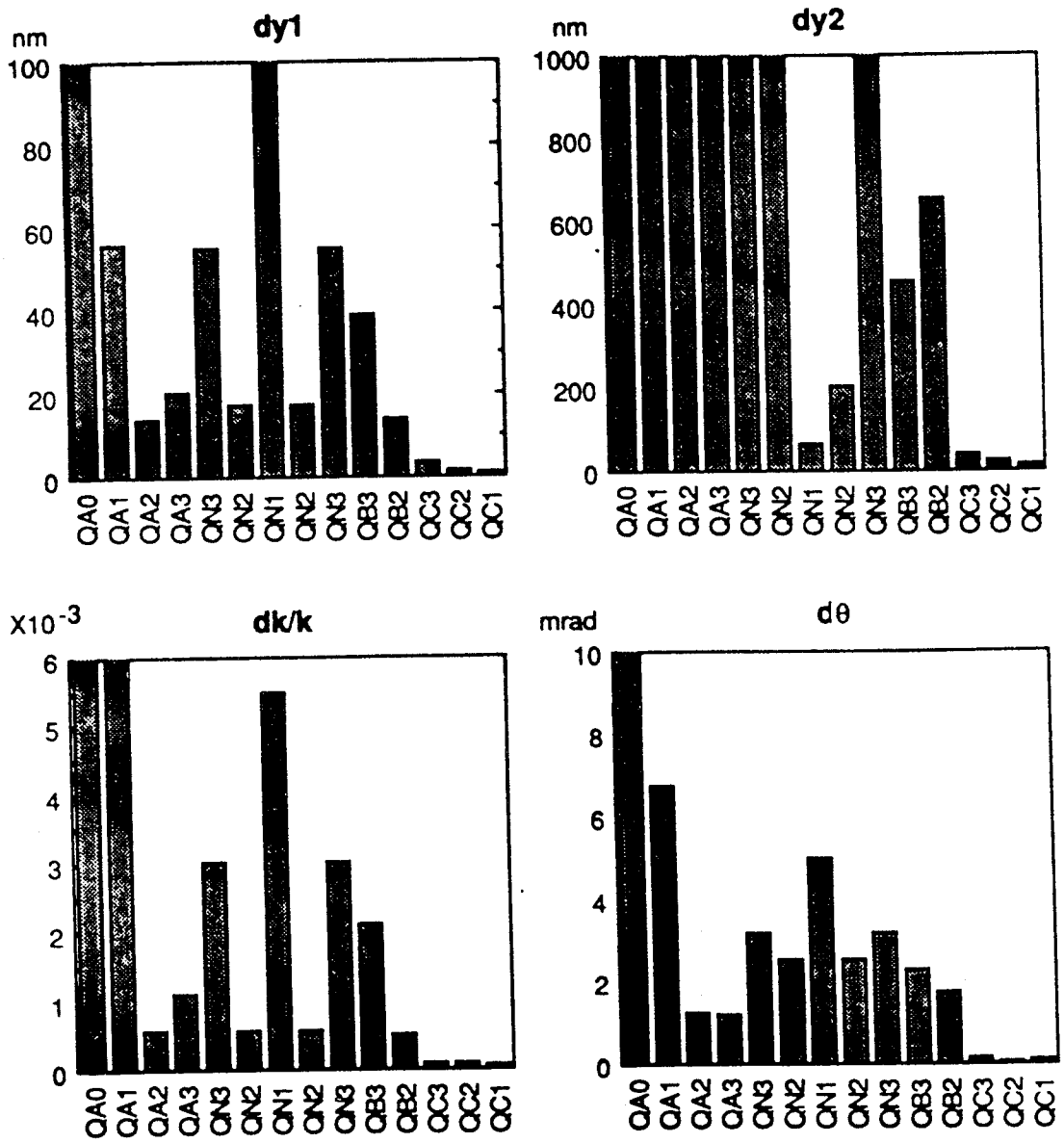
Tolerances

The smallest tolerances concern the reproducibility of the beam in position and shape from pulse to pulse, this is the jitter problem which has been analyzed for quadrupoles and sextupoles.

Important issues have still to be addressed:

Static alignment tolerance

Correction schemes



Size of error which will displace beam by one σ or increase beam size by a factor of $\sqrt{2}$

a. dy 1 = offset of quad which displaces beam.
b. dy 2 = offset of quad which increases size (dispersion).
c. dk/k = relative field error; increases beam size.
c. dθ = roll of magnet; increases vertical beam size.

MAGNET TECHNOLOGY

DIFFERENT APPROACHES WHICH CAN BE APPLIED TO THE QUEST FOR HIGHER GRADIENTS

① EXTEND THE COILS ALONG THE AXES (D. WALZ / A. BARON) AS SHOWN BY K. OIDE
→ SHOULD WORK FOR SMALL (< 5mm) APERTURES

② GO SUPERCONDUCTING SLC/SLD
LIMITED TO ~0.75 Tm^{-1} (IN APERTURE ϕ15 mm)
ENVIRONMENTAL PROBLEMS? SEVERE TOLERANCE PB.

③ PERMANENT MAGNETS !
(PURE 'HALBACH'-TYPE) AS SHOWN BY J. SPENCER
→ GOOD SOLUTION FOR APERTURES DOWN TO ϕ5 mm

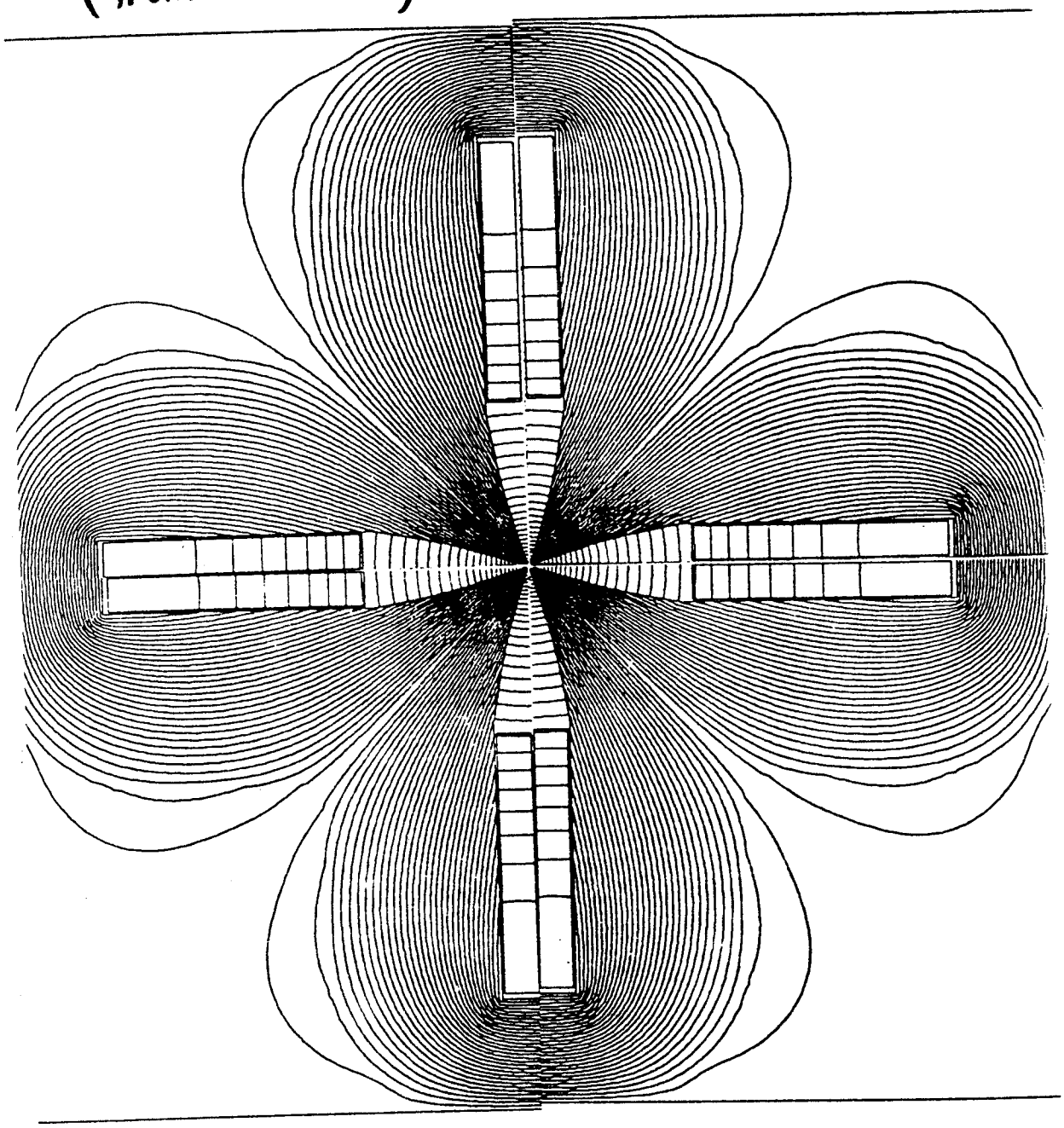
④ PERMANENT MAGNETS 2 T. TAYLOR
(HYBRID, WITH SOFT FERROMAGNETIC POLES)
→ AS ①, WITH MMF FROM PM BLOCKS

⑤ PULSED IRONFREE MAGNET
PROBABLY THE ONLY WAY TO GET MORE THAN 10^4 Tm^{-1} ...

TO WATCH

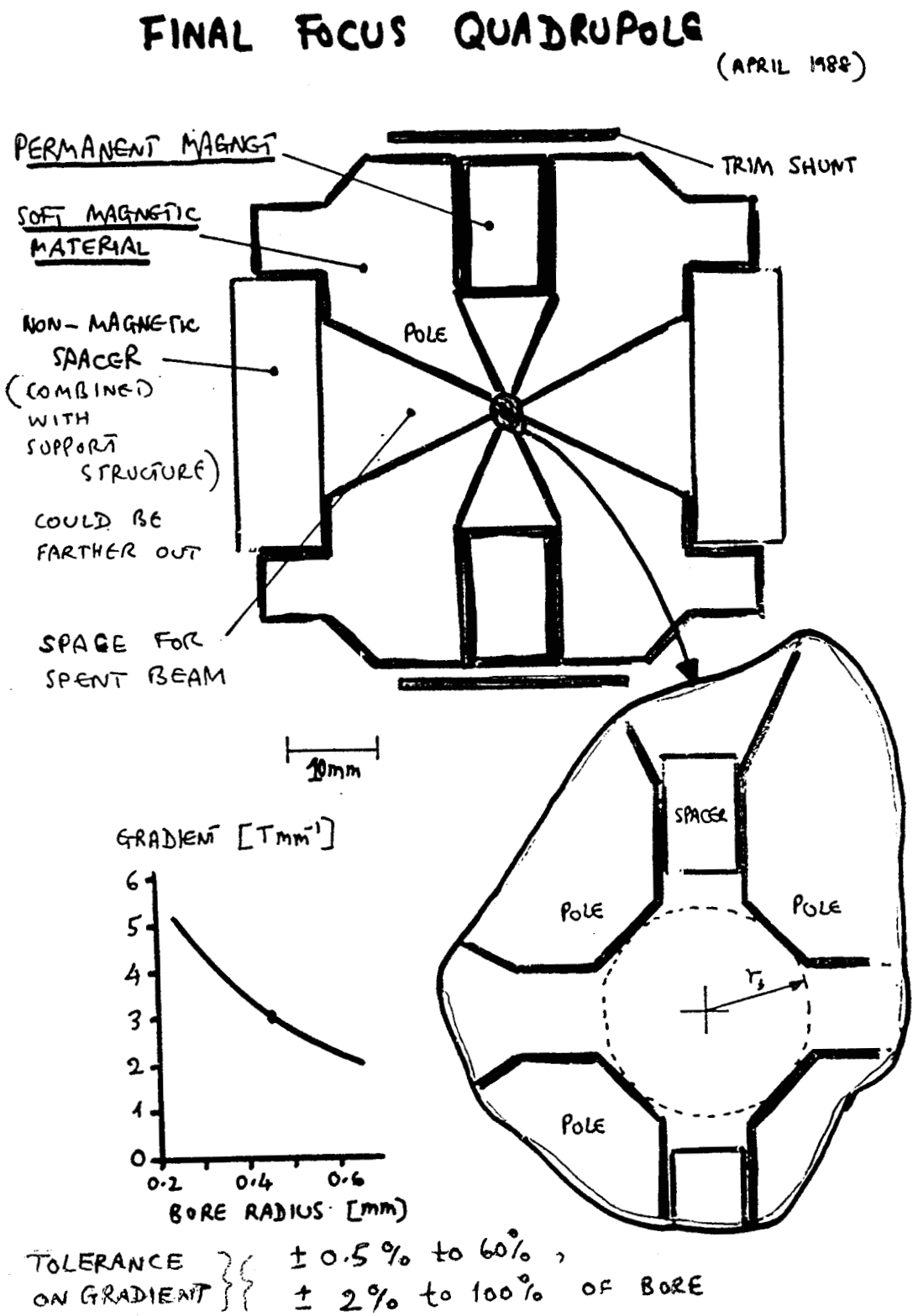
- HOW TOLERANCES ARE HANDLED
- IMPLICATIONS OF MAGNETIC DOMAIN SIZE

(from K. Oide)

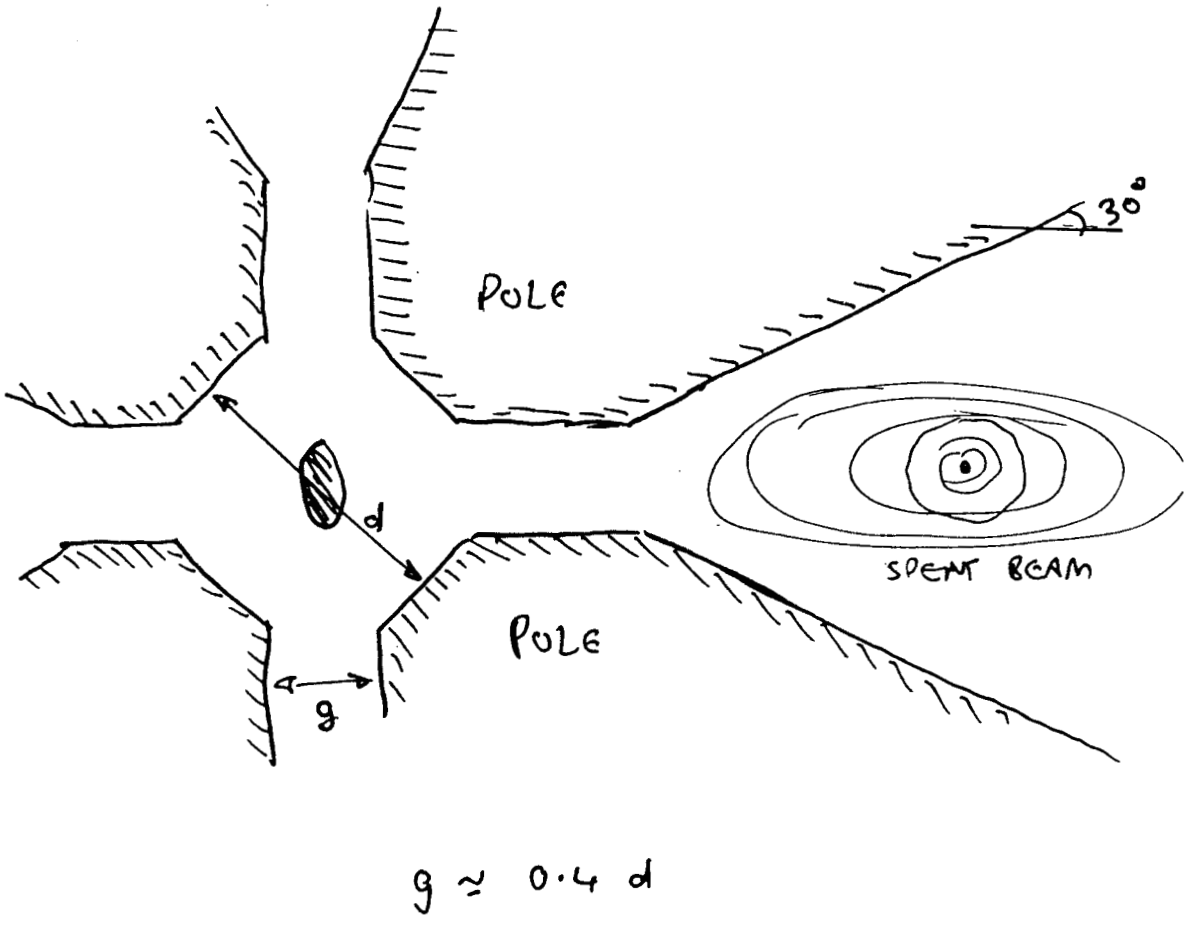


A. Baron

Conventional high gradient quadrupole design with aperture 0.5 mm.



Hybrid high gradient quadrupole design with permanent magnets and soft iron pole tips.



Expanded view of hybrid magnet aperture showing incoming beam at the center of the four pole tips and the outgoing spent beam passing between two of the tips.

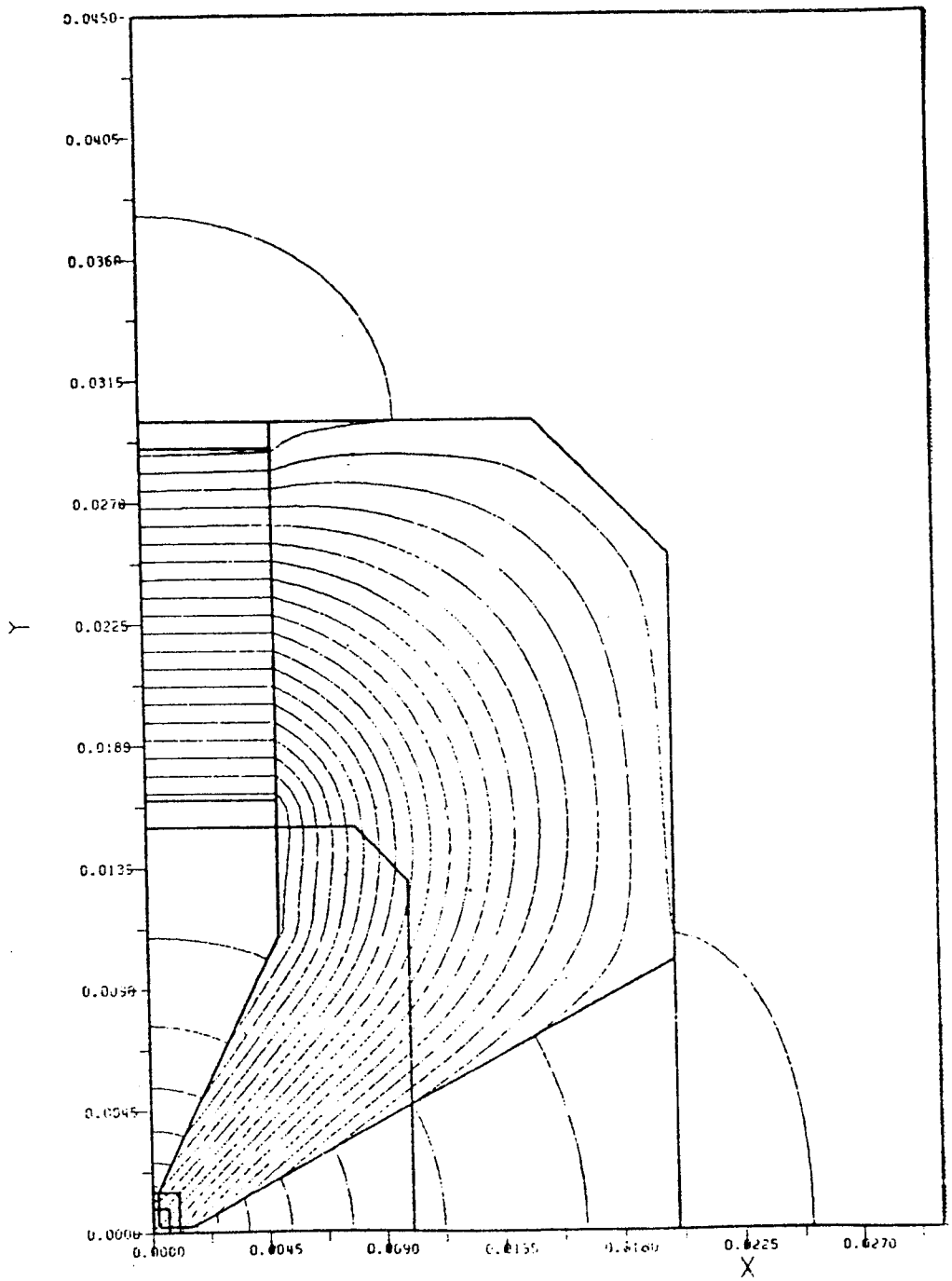
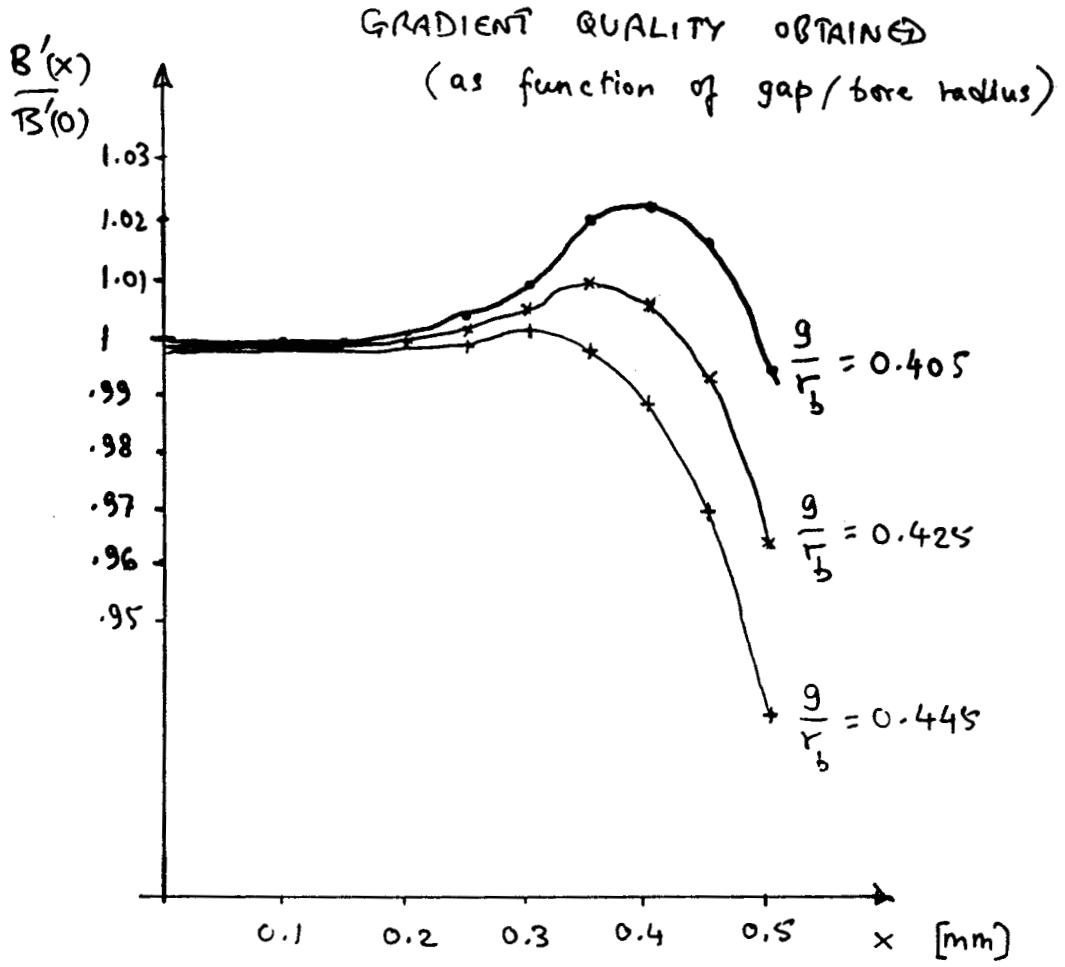


FIG 11

PARAMETER STUDY USING POISSON BY K.EGAWA



- FIELD QUALITY NOT SIGNIFICANTLY AFFECTED BY LEVEL CHANGE USING SHUNT
- BORE RADIUS = 0.495 mm FOR COMPUTATION
- GEOMETRIC TOLERANCES ~ 1 μm
- LITTLE TO BE GAINED BY GOING ASYMMETRIC (+ TOLERANCES GET TIGHTER)

Gradient quality expected to be obtainable in hybrid magnet designs.

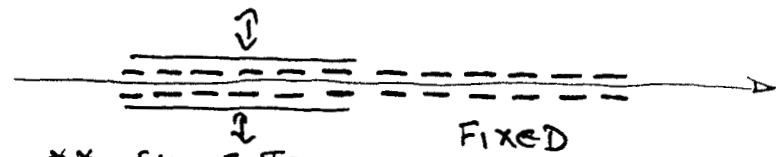
INDIVIDUALLY TUNED MODULES
EACH ABOUT 5 cm LONG

ASSEMBLED INTO TUBULAR SUPPORT *

⇒ SUB-UNIT (~ 30 cm LONG)

SUB-UNITS
- FIXED FIELD 1 or more
- VARIABLE FIELD ** 1

AS MACHINE ENERGY INCREASES
ADD ON FIXED SUB-UNITS

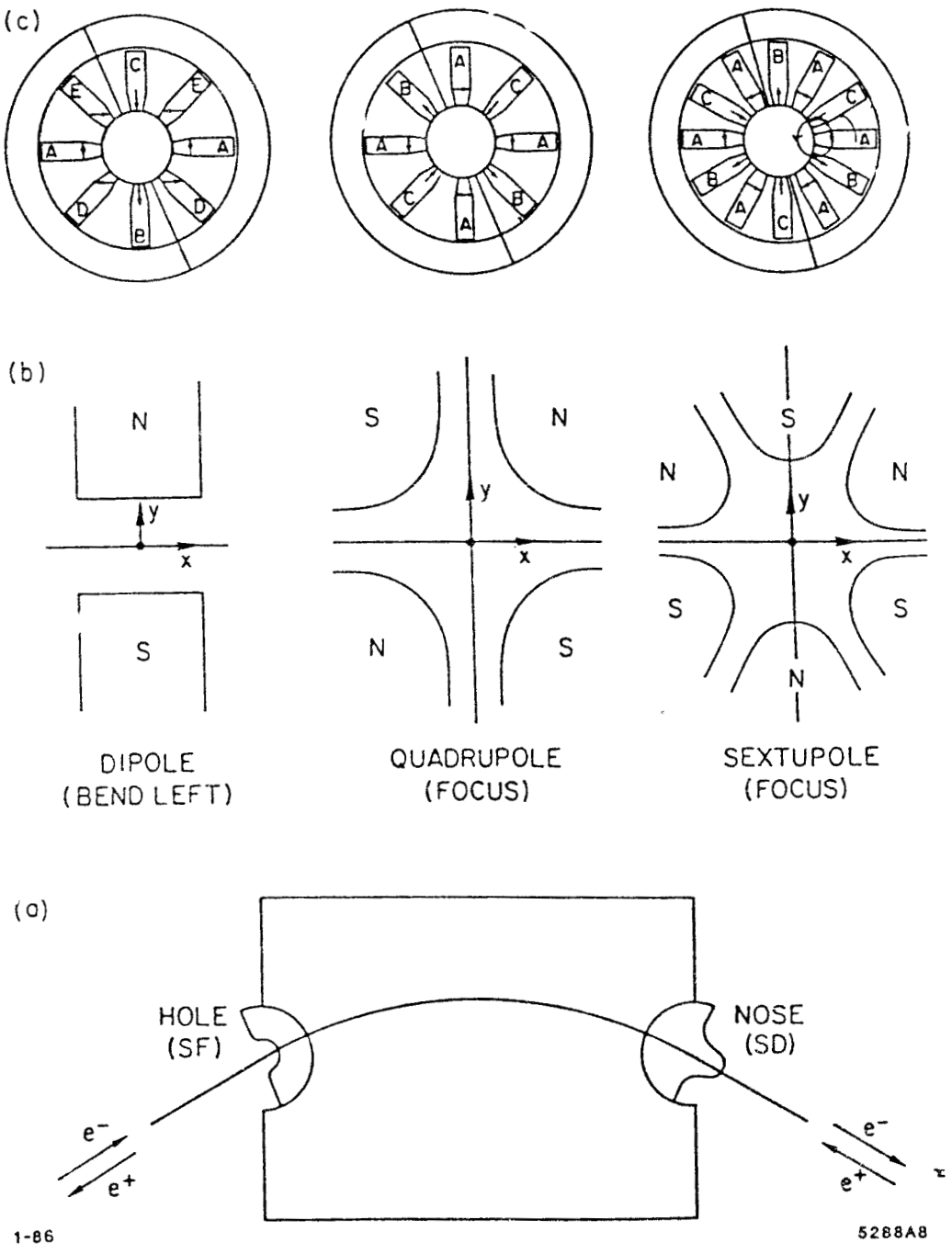


** SHUNT TO VARY GRADIENT

* IF SPECTROMETER USES SOLENOID STRUCTURE MUST INCORPORATE SHIELD AND/OR BUCKING FIELD

Topology of hybrid magnets that could be used to form a variable strength final lens.

(from J. Spencer) $\vec{J}_N = J_r e^{i[\pi/2 + (N+1)\theta]}$



Permanent magnet designs for various order multipoles.

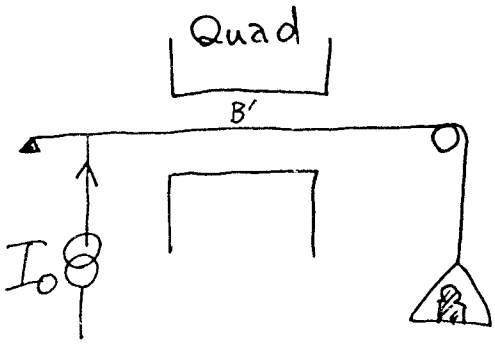
1 to 1·2 T poletip field

1 part in 1000 gradient quality

Wire Resonance Method for Measurements of B'

K. OIDE

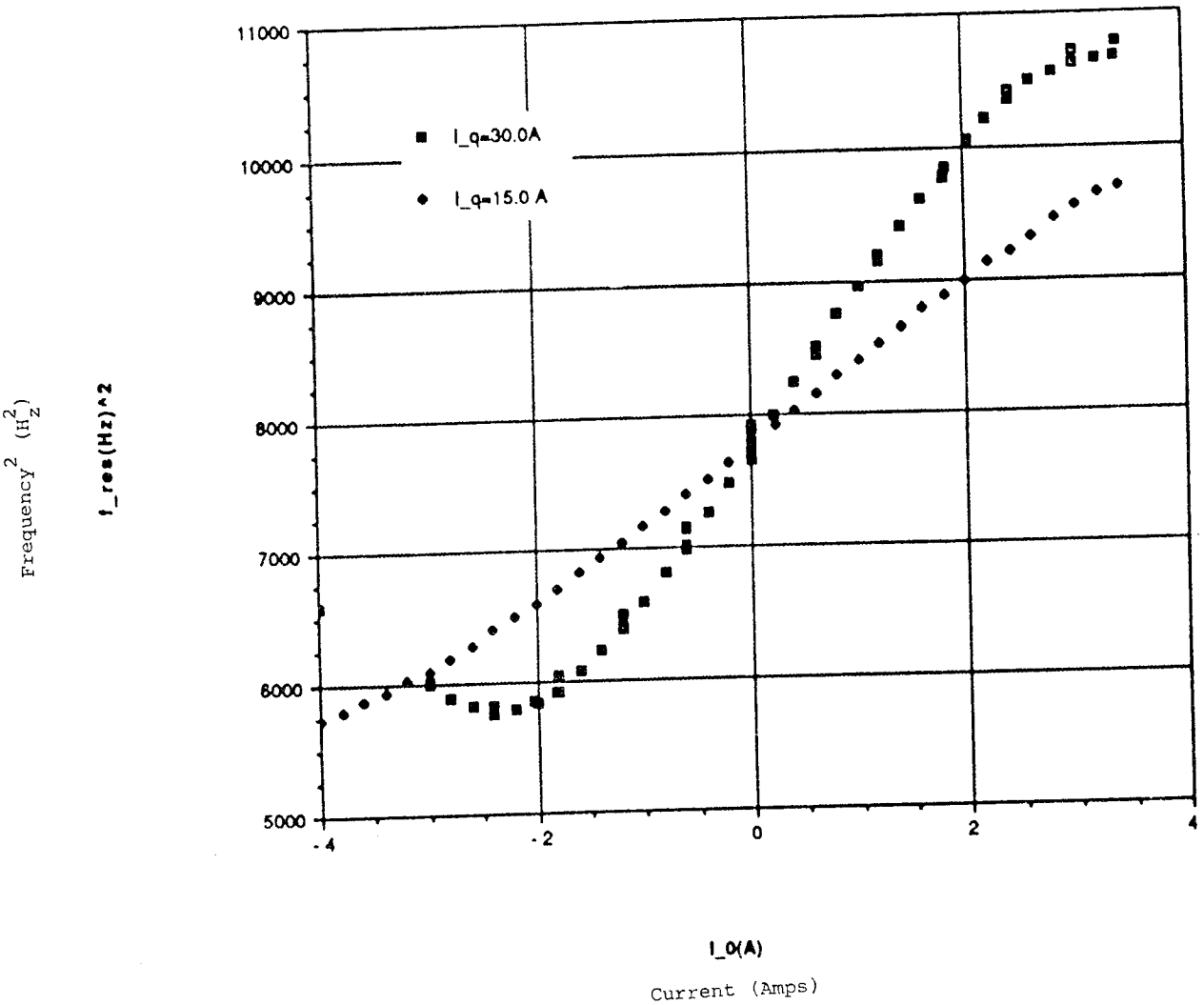
KEK N. Yamamoto, K. Oide et al



$$\rho \frac{\partial^2 y}{\partial t^2} + T \frac{\partial^2 y}{\partial s^2} \pm I_0 B' y = 0$$

$$\omega^2 \sim \omega_0^2 \pm I_0 B'$$

- measure the resonant frequency of the wire as the function of the applied DC current I_0.


11000
10000
9000
8000
7000
6000
5000
-4
-2
0
2
4
I_q=30.0A
I_q=15.0 A
f_res(Hz)^2
Frequency^2 (H_z^2)
I_0(A)
Current (Amps)

CONCLUSIONS

- CAUTIOUS OPTIMISM

  CLIC
  TLC' FFS magnets should be possible
  VLEPP

  TLC° aperture ϕ 0.2 mm may also be feasible

  next generation (2-10 TeV) PULSED MAGNETS

- MUCH TECHNICAL WORK TO BE DONE
  - MEASUREMENTS
  - SUPPORT STRUCTURES
  - → ALIGNMENT ⟺ Magnetic axis
  - MATERIALS ...

SLAC Final Focus Beam Test Facility

Issues:

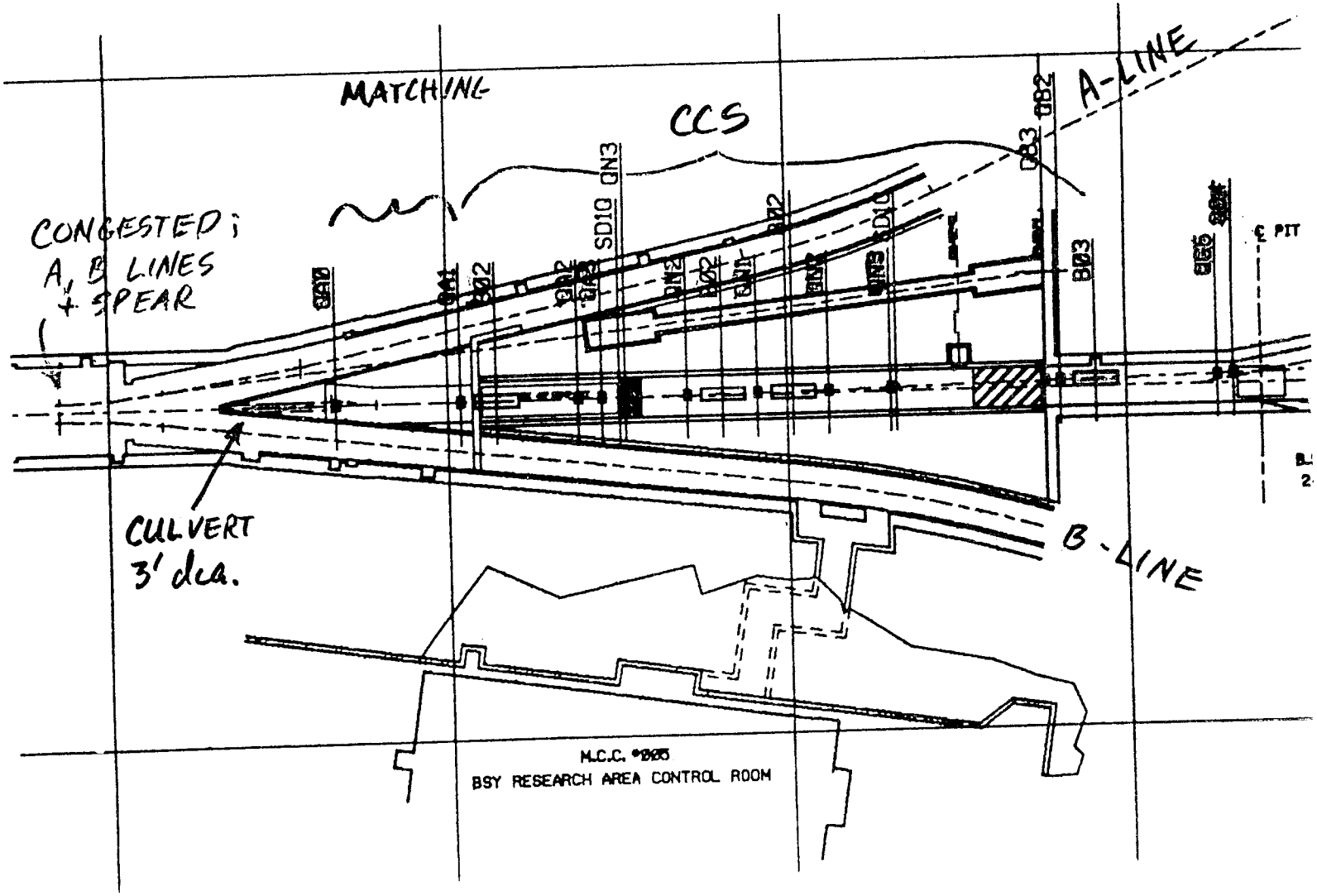
1. Level of radiation coming from final lens area ⇒ Beam size monitors

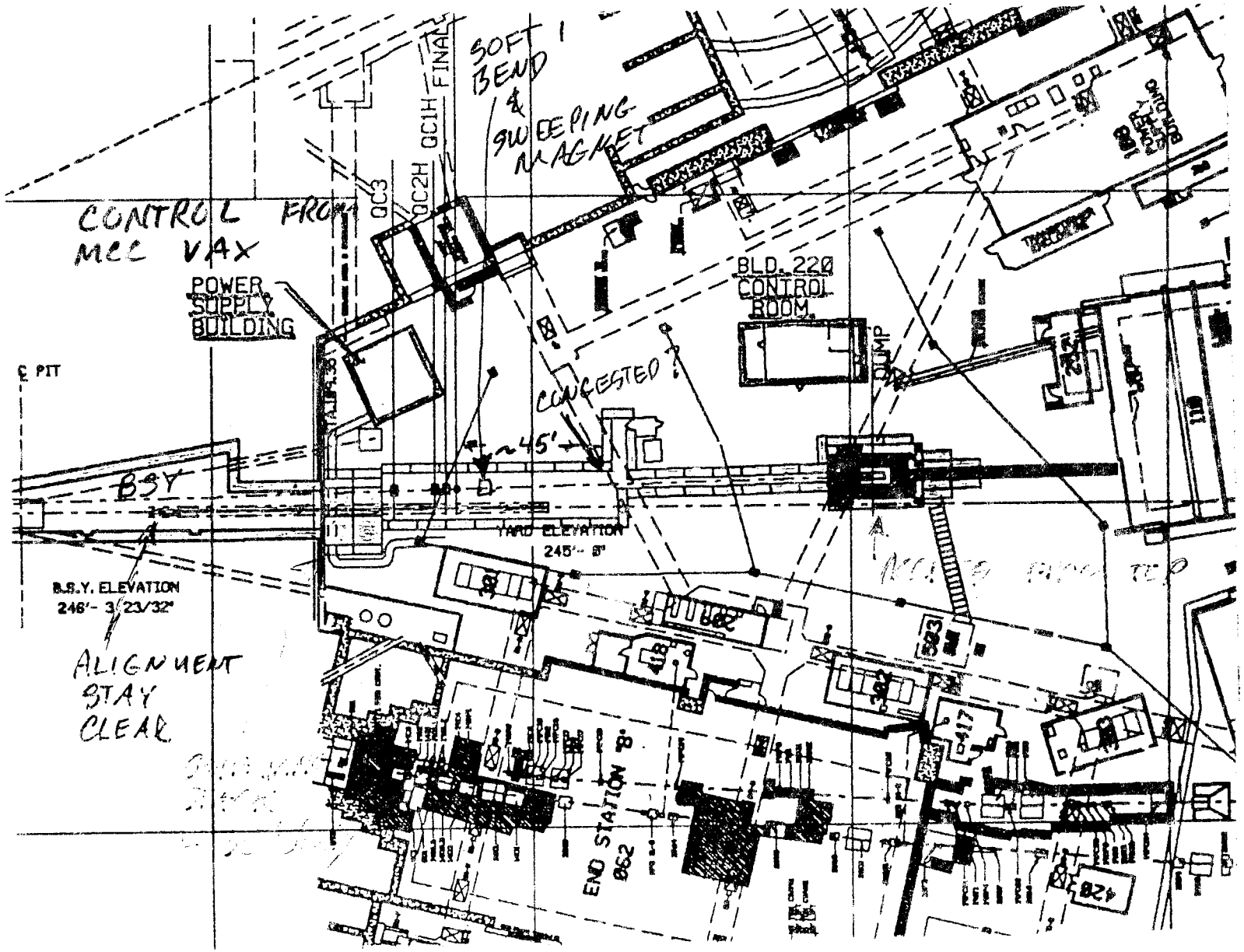
2. How "round" or how "flat" can the spot be made ⇒ Plasma lens
   ⇒ CLIC vs TLC optics

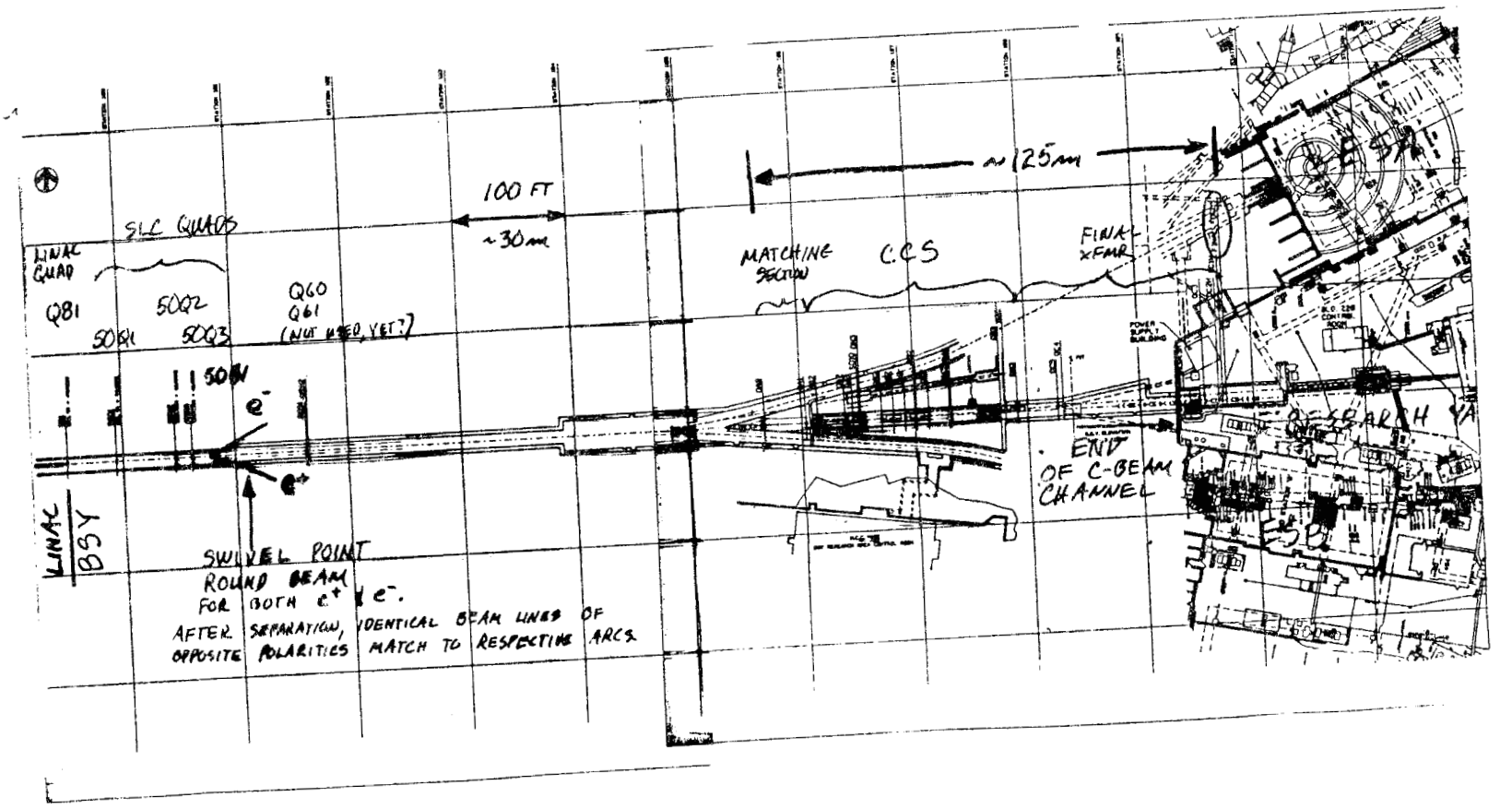
3. Time for use of the beam after 1991?

4. Jitter and alignment tolerances

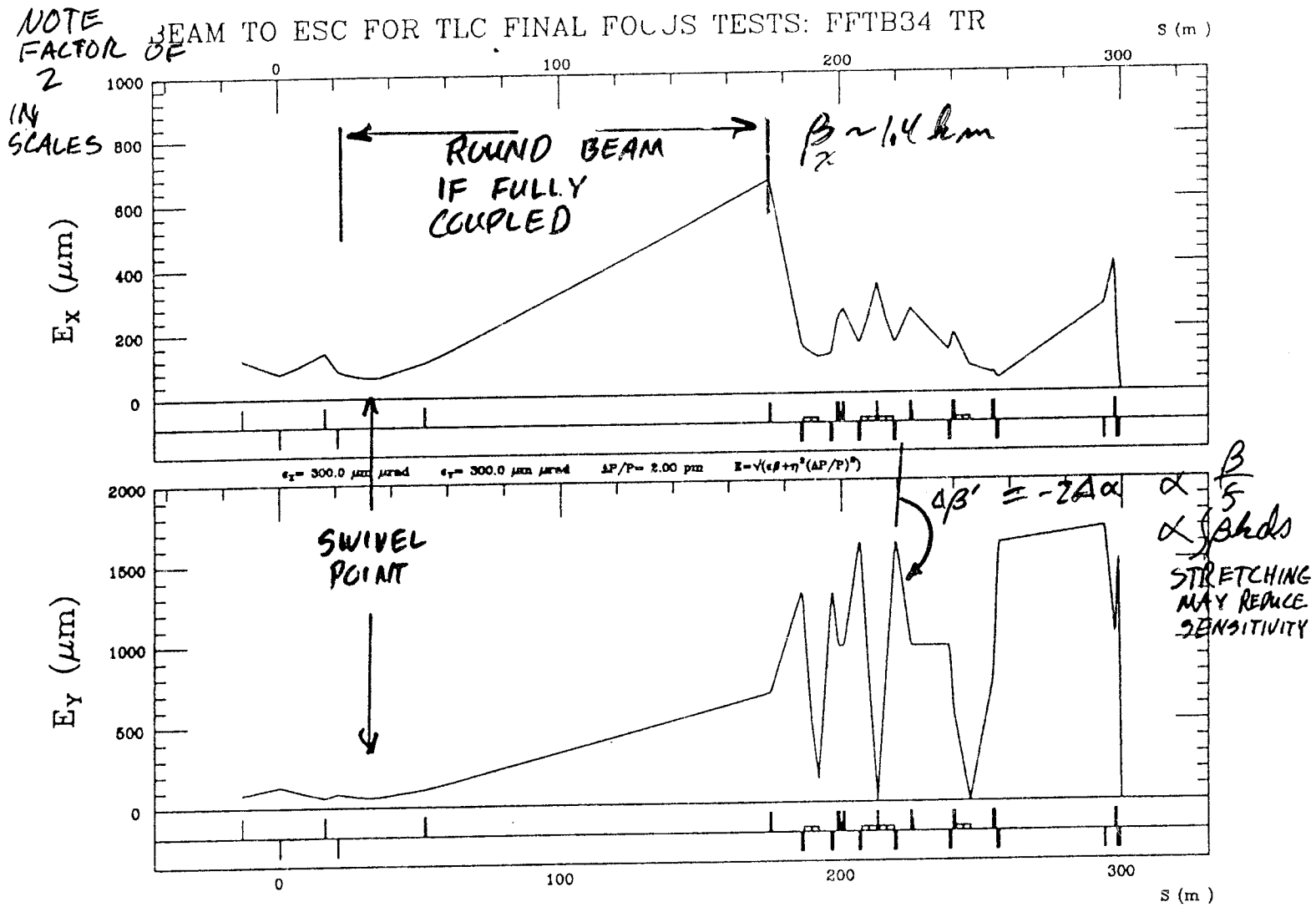
5. Space for beam diagnostics


MATCHING
CCS
A-LINE
B-LINE
CONGESTED;
A, B LINES
+ SPEAR
CULVERT
3' dia.
SD10
DN3
DB2
DB3
BD3
BE6
℄ PIT
M.C.C. #005
BSY RESEARCH AREA CONTROL ROOM


CONTROL FROM
MCC VAX
POWER SUPPLY BUILDING
QC3
QC2H
QC1H
FINAL
SOFT BEND & SWEEPING MAGNET
BLD. 220 CONTROL ROOM
PUMP
CONGESTED
~45'
℄ PIT
BSY
YARD ELEVATION
245'- 8"
B.S.Y. ELEVATION
246'- 3/23/32"
ALIGNMENT STAY CLEAR
END STATION "B"
862
863
417
420

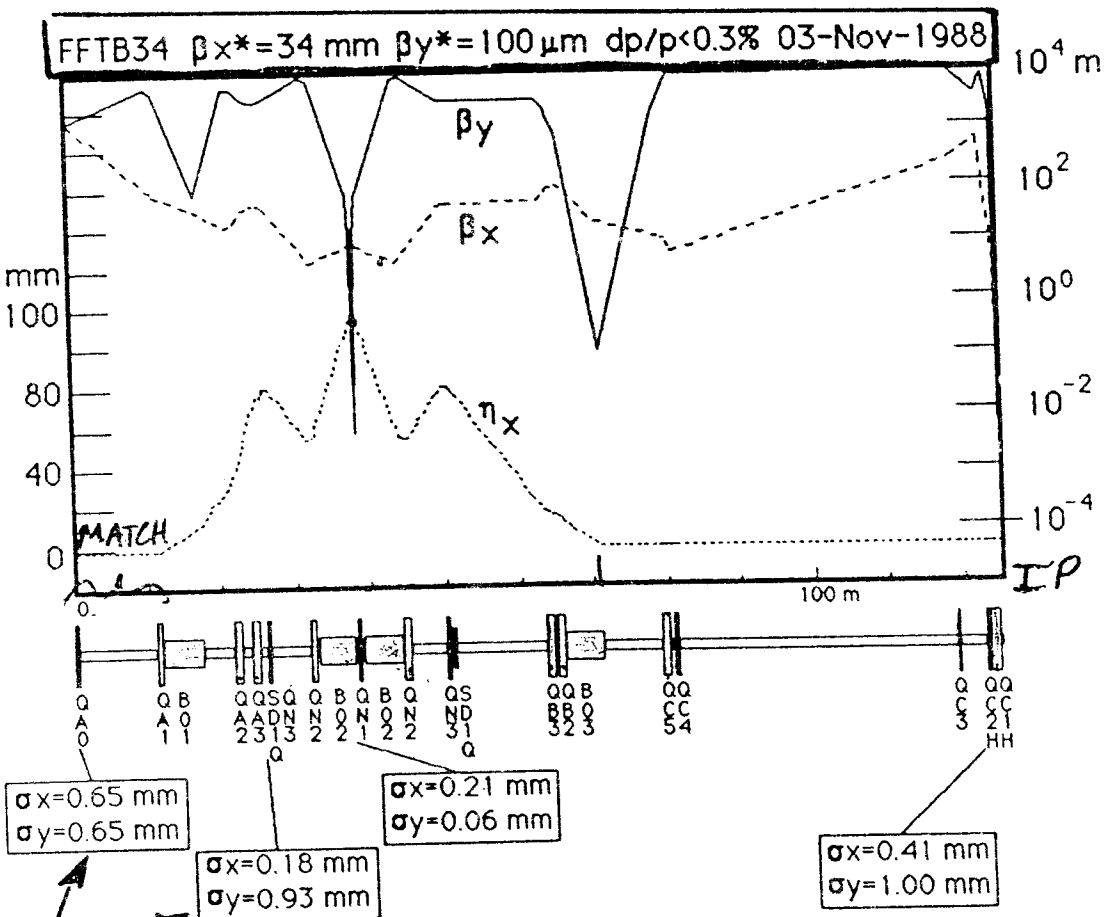


Proposed layout of SLAC Final Focus Test Beam


NOTE FACTOR OF 2 IN SCALES
BEAM TO ESC FOR TLC FINAL FOCUS TESTS: FFTB34 TR
S (m)
E_X (μm)
ROUND BEAM IF FULLY COUPLED
$\beta_x \sim 1.4$ km
ϵ_x= 300.0 μm μrad
ϵ_y= 300.0 μm μrad
$\Delta P/P$= 2.00 pm
$E=\sqrt{(\epsilon\beta+\eta^2(\Delta P/P)^2)}$
E_Y (μm)
SWIVEL POINT
$\Delta\beta' \simeq -2\Delta\alpha$
$\alpha \sim \frac{\beta}{s}$
$\alpha \sim \int \beta k ds$
STRETCHING MAY REDUCE SENSITIVITY
S (m)

K. OIDE'S TEST BEAM DESIGN

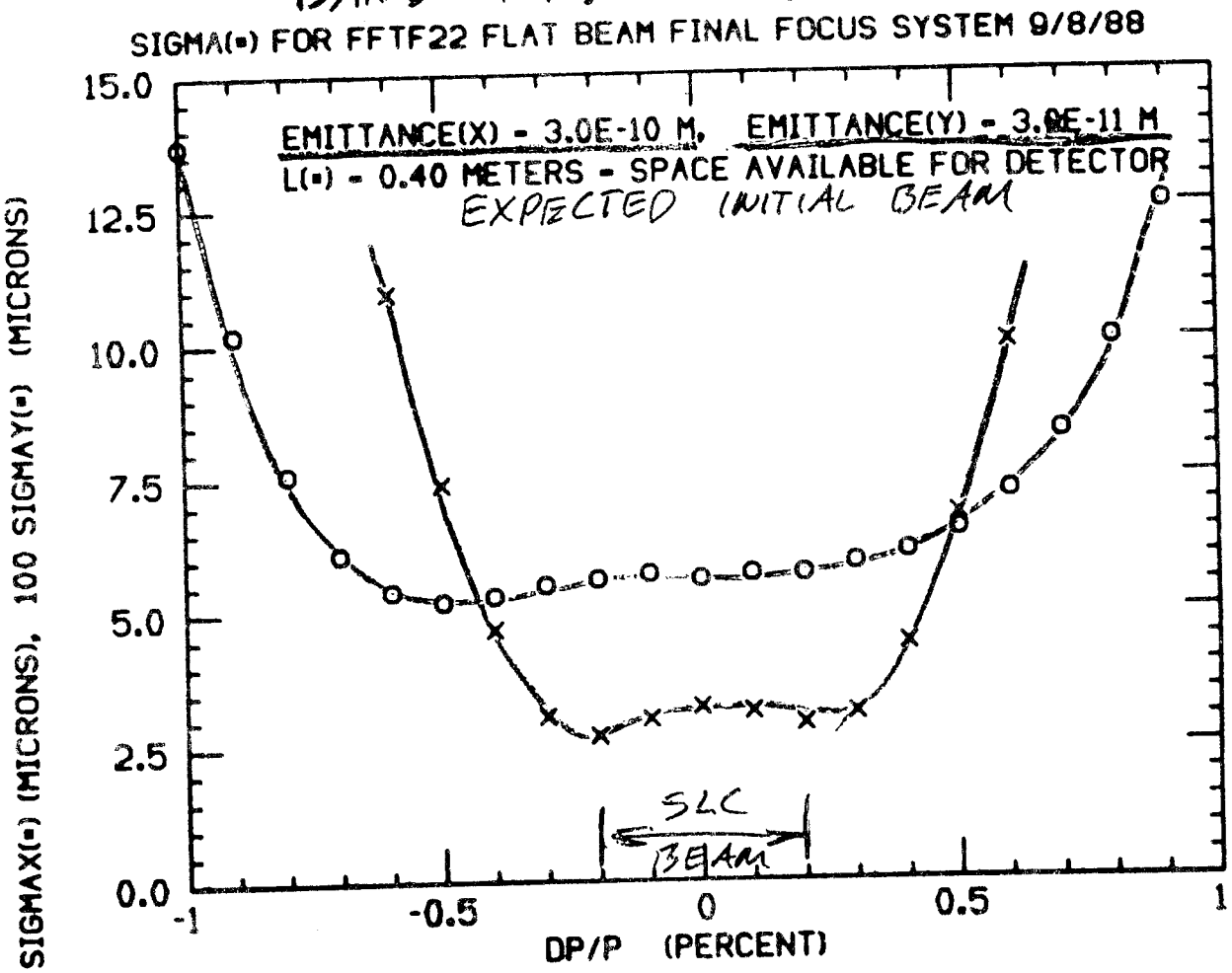
NOTE LOG SCALE

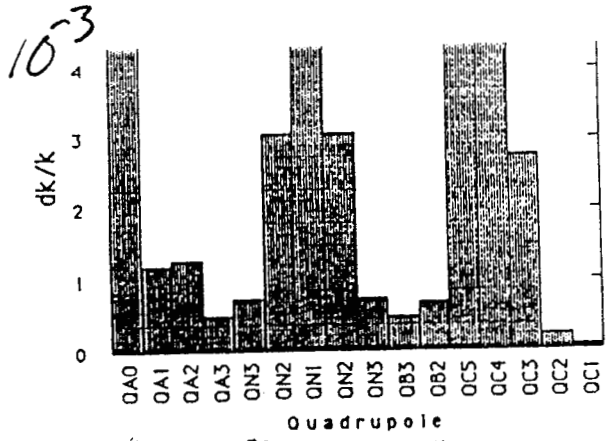


Beam sizes indicated are for fully coupled beam

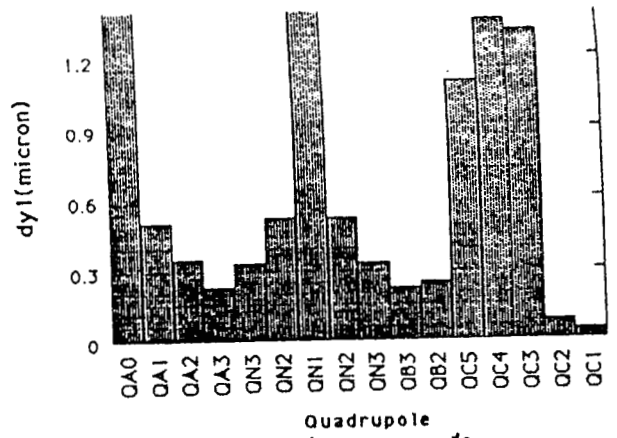
$\epsilon_x = \epsilon_y = 3 \times 10^{-10}$ m-rad

BAND PASS CHECK BY K. BROWN

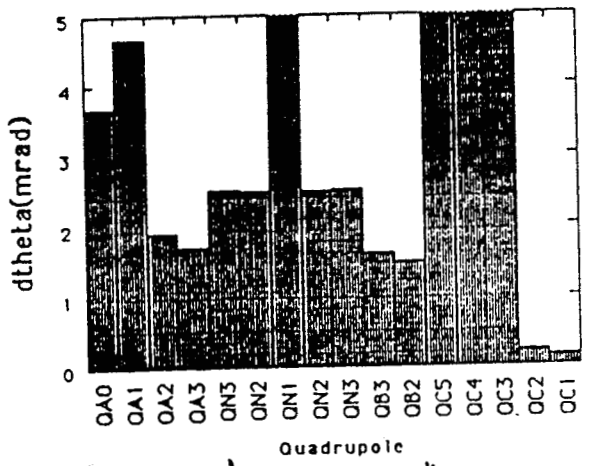




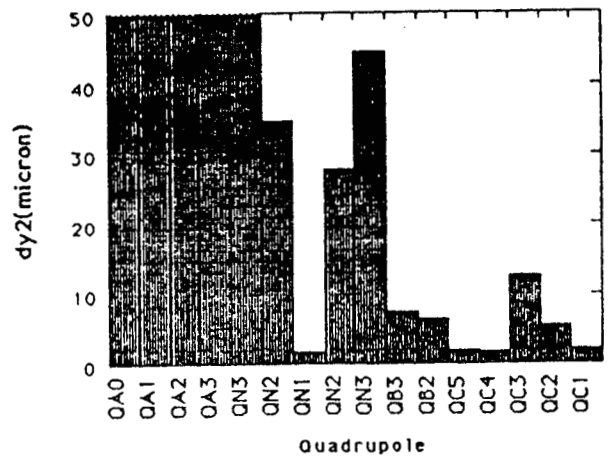
for $\sigma_y^* = \sqrt{2}\,\sigma_{y0}^*$



for $\Delta y^* = \sigma_y^*$
systematics & vibration



for $\sigma_y^* = \sqrt{2}\,\sigma_{y0}^*$



for $\sigma^* = \sqrt{2}\,\sigma_{y0}^*$
dispersion

B. Zotter

b) Sextupole errors

much larger tolerances : ~ 1 μm displacement (trans)
> 3% strength

longit. displacement : ±10 cm negligible
(phase shift small since β large)

phase error between S1 and IP due to quad
strength → ~10^{-3} yields 10% growth
avoid w permanent magnets

3) FF Test beam

presently squeezed into "available" space ~125 m

a) sensitivity to errors ± 10 μ (J. Murray)
seems too tight – could be relieved by longer
beam line (at least factor 2)

b) flexibility to make flat beam –
round beam (plasma lens test)
needs 2 sextupole families + more space

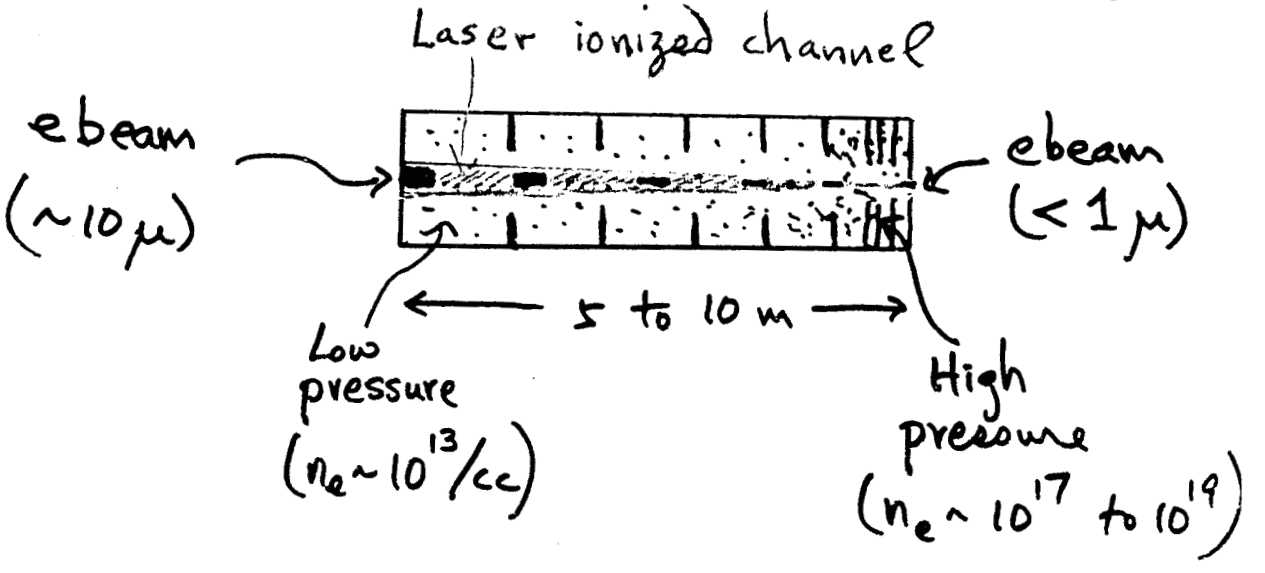
c) space for diagnostics
Test beam up to existing road : ~250 m !

Comments on proposed Final Focus Test Beam

SCHEME OF ADIABATIC FOCUSING

S. YU

Adiabatic increase in focusing strength



Basic elements:

1. Chamber with varying gas density $\sim 10^{13}$/cc at entrance; 10^{17} to 10^{19} at exit
2. Laser ionization to form plasma channel

EXAMPLE "SLC"

at entrance : $(n_{i0} = 10^{13})$

$$\lambda_{\beta 0} = 6.7\,\mathrm{m} \left(\frac{\gamma}{10^5}\right)^{1/2} \left(\frac{10^{13}/\mathrm{cc}}{n_i}\right)^{1/2}$$

$$a_0 = 18\mu \left(\frac{\epsilon_N}{.003\ \mathrm{cm\text{-}rad}}\right)^{1/2} \left(\frac{10^5}{\gamma}\right)^{1/2} \left(\frac{\lambda_\beta}{6.7\mathrm{m}}\right)^{1/2}$$

at exit :

$$n_{if} = 10^{19}/\mathrm{cc}$$

$$\lambda_{\beta f} = 6.7\ \mathrm{mm}$$

$$a_f = 0.56\ \mu$$

Length of experiment

$$L \sim \lambda_{\beta 0} \lesssim 10\ \mathrm{m}$$

Plasma lens J. Rosenzweig

- Cannot replace a conventional magnetic system.
- Can IMPROVE LUMINOSITY of the colliders in the following conditions:

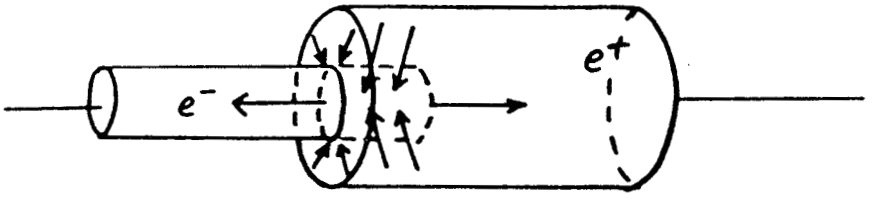
  i) Under-dense regime $\Rightarrow$ tolerable background

  $$N_{plasma} < N_{e^-}$$

  ii) Electron focusing only

  iii) Luminosity enhancement through "bootstrap disruption"

III. BOOTSTRAP DISRUPTION



If one only reduces the spot size for one of the two colliding beams, then the luminosity enhancement due to the lens, but excluding depth of focus and beam-beam disruption effects, is

$$H_\ell = \frac{2\sigma_>^2}{\sigma_<^2+\sigma_>^2} = \frac{2\beta_>}{\beta_< + \beta_>} \lesssim 2 .$$

Example: Reduction of β^* by a factor 5; i.e. $\beta^*/\beta_0^* = 1/5$,

$\Rightarrow H_\ell = 1.66$.

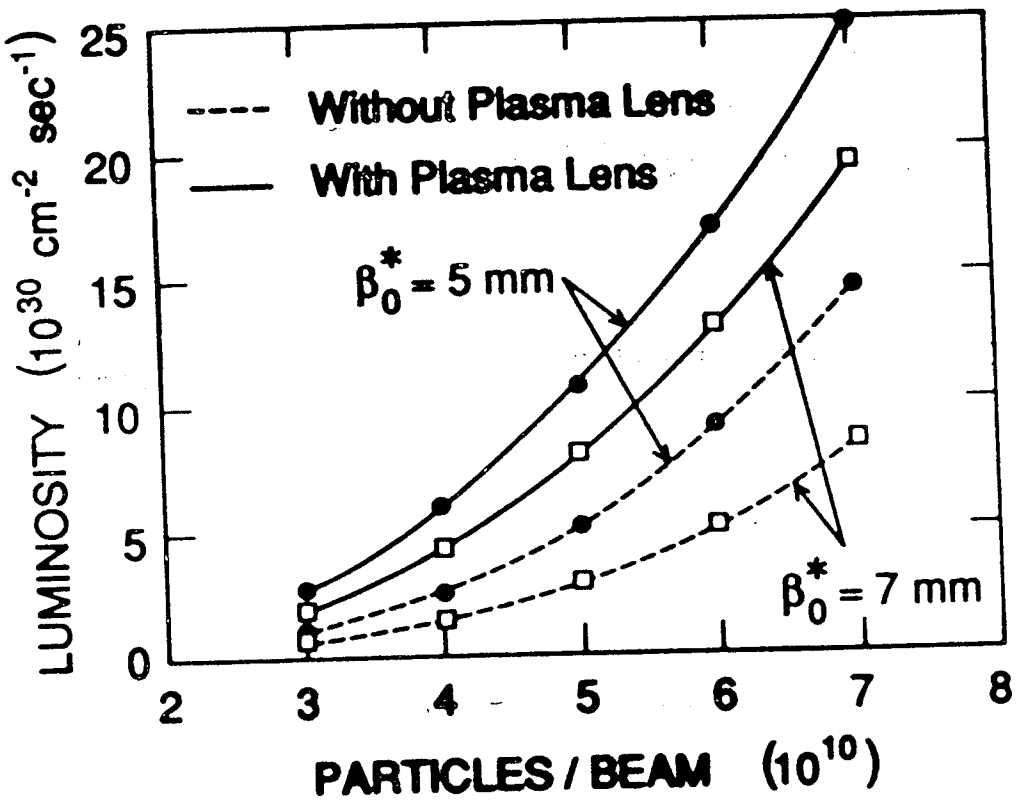
With beam-beam disruption turned-on, we further gain by factors $H_{D>}$ for e^+ beam and $H_{D<}$ for e^- beam. So,

$$H_T = \frac{H_\ell \cdot H_{D>} \cdot H_{D<}}{H_{D0}}$$

Example: For SLC design $H_{D0} = 1.38$, and $H_{D>}$ can be calculated (assuming ξ fixed) to be $H_{D>} = 1.95$ for $\beta^*/\beta_0^* = 1/5$. Assuming that $H_{D<} \simeq H_{D0}$, then

$H_T \simeq 3 - 3.5$.

Bootstrap for SLC parameters



from
Chen, Rajagopalan & Rosenzweig

Beam monitoring

1. Plasma beam size monitor

   1.1 Beamstrahlung

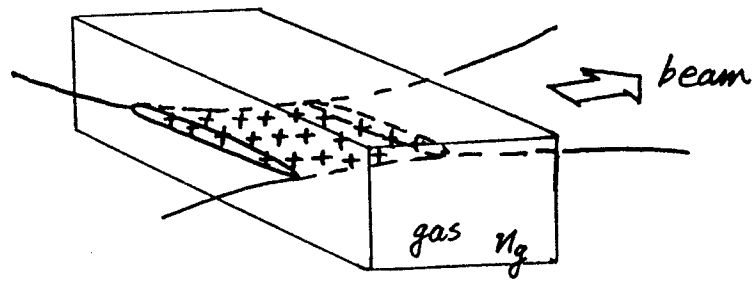
   1.2 Bremstrahlung and "pinhole" optics

2. Beam density monitor

11-30-88

PLASMA BEAM SIZE MONITOR

P. Chen, D. Burke, M. Hildreth, R. Ruth



1. Assume that the gas within the beam channel is fully ionized
2. The gas density is lower than the beam density.

$\Rightarrow$

1. Number of e^--ion pairs is proportional to beam cross-section.

$$N_p = 4\pi\sigma_x\sigma_y l n_g = N_g$$

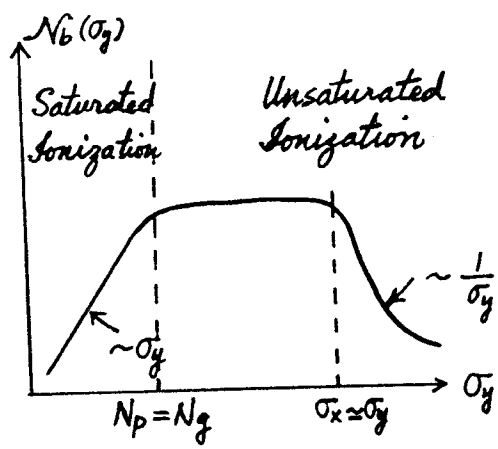
2. All plasma e^- are expelled out of the channel.

$\therefore$ The beamstrahlung signal is proportional to beam height σ_y:

$$\eta = 2\sqrt{3}\,\pi\,\frac{r_e \lambda\!\!\!^{-}_c \sigma_x n_g \gamma}{1+R}.$$

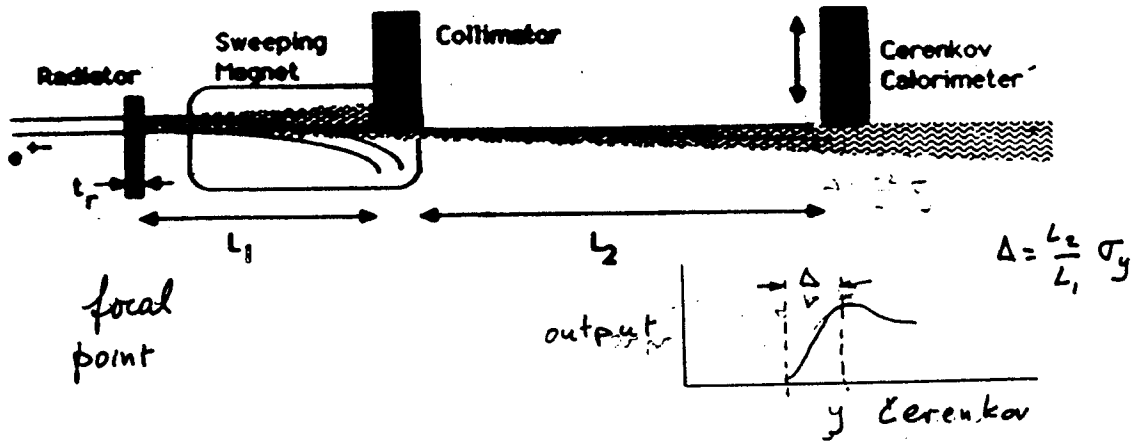
$$= (2\sqrt{3}\,\pi\, r_e \lambda\!\!\!^{-}_c n_g \gamma)\,\sigma_y.$$

$$R = \frac{\sigma_x}{\sigma_y}$$



Pinhole Optics

J. Norem



Parameters

	SLC	TLC	SPS	
electron energy	50	1000	20	GeV
particles/pulse	$3.0 \cdot 10^{10}$	$0.8 \cdot 10^{10}$	$0.8 \cdot 10^{10}$	
ϵ	$0.3 \cdot 10^{-9}$	$1.2 \cdot 10^{-14}$	$0.5 \cdot 10^{-7}$	m
β_x^*	7.	0.043	25,000.	mm
σ_x	1400.nm	0.001	1,000	μ
$\sigma_{x'}$	0.2	0.016	0.05	mr
radiator thickness	0.6	0.030	0.6	mm
θ_{ms}	0.09	0.001	0.24	mr
B	0.5	0.5	1.0	T
E_γ on coll	12.	2.1	1.3	J/pulse
E_c (synch)	0.8	300.	0.2	MeV
L1	1.0	1.0	1.0	m
L2	10.	100.	10.	m
M	10.	100.	10.	
Synch/Brems Energy	10^{-4}	10^{-1}	10^{-4}	
σ_x at det	2.0	1.6	2.3	mm

Density Monitor
Pazhomchuk V. (Novosibirsk)

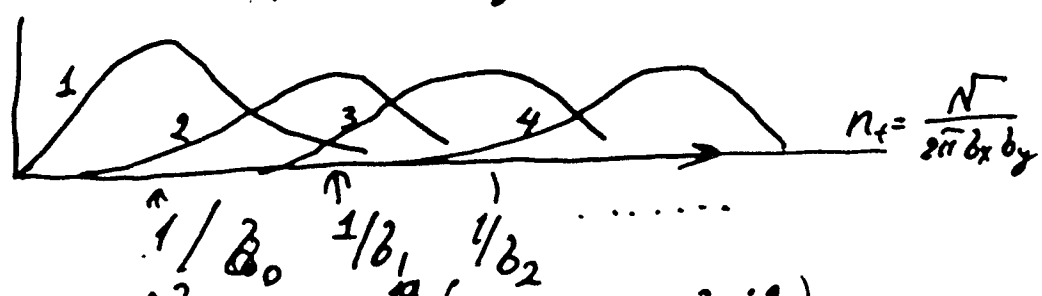
Multy charge ions $\quad Z \quad 0 \to 1 \to 2 - 3 \cdots \quad Z_{max}$

$$\frac{dN_i}{dt} = N_{i-1} n_e \sigma_{i-1} c - N_i \sigma_i n_e c$$

↑ electron beam density

N_i - density ions with charge i

N_0 - density of gas

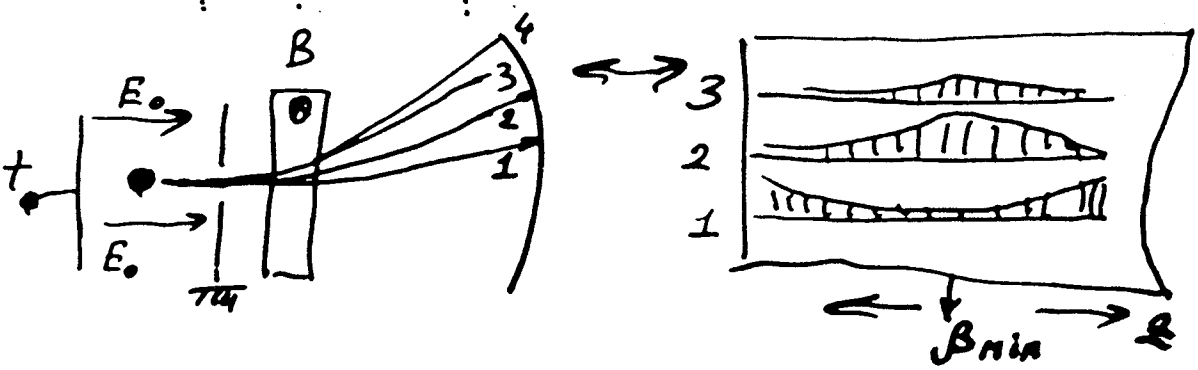


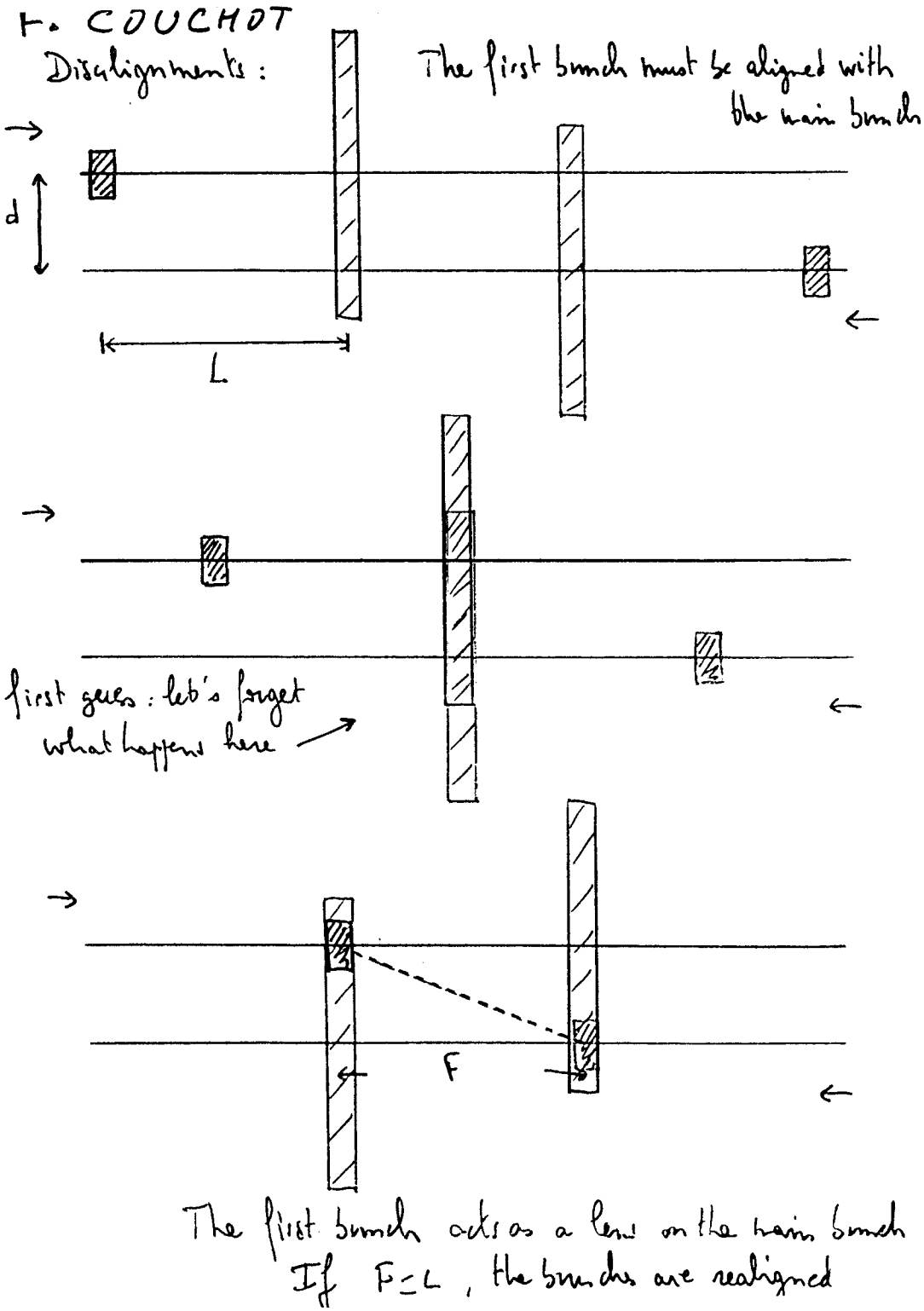
$$\sigma_i = A \frac{2e^2}{(E_i/mc^2)} \approx \frac{10^{-19}}{i^2} \quad (E_i \approx mc^2 \alpha^2 i^2)$$

$n_e \approx 4\,10^{20} \frac{1}{cm^3}$ {CLIC, VLEP}

$\sigma_2 = 0.075\,cm$

i	σ_i (cm)	$n_e \sigma_i \sigma_2$
1	10^{-19}	3
2	$2.5\,10^{-20}$	0.75
3	10^{-20}	0.3
⋮	⋮	⋮

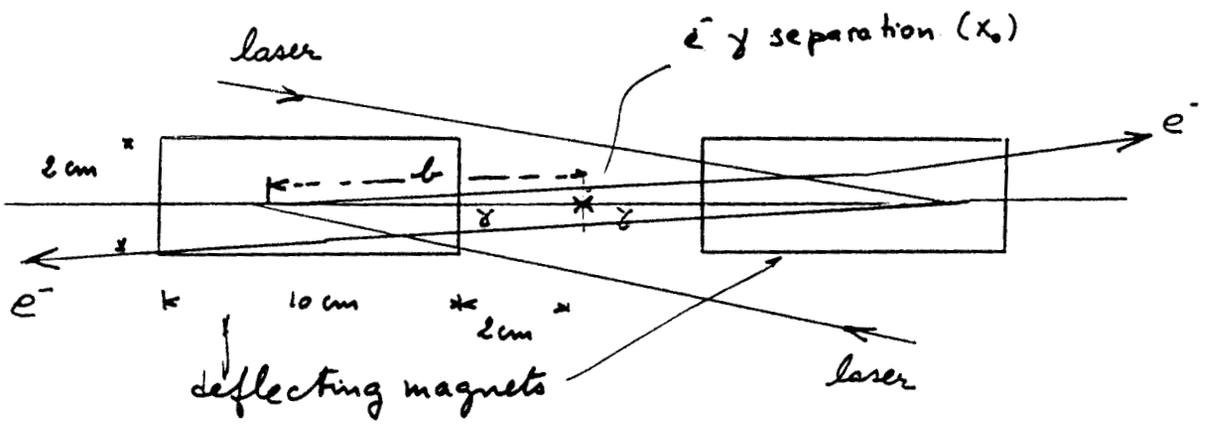




Concept of beam focusing by precursor bunches.

γ-γ collider

V. Telnov



1. $e^-\gamma$ separation is determined by e^+e^- pair production : γ must decrease from 100 to .5

   $x_0 \propto \gamma$; $x_0 \simeq 1\mu$

2. b = distance from conversion point to interaction point : $b \propto \gamma$

3. a_γ = spot size = $\frac{b}{\gamma}$ is independent of γ

4. Laser parameters: 2 J / flash

$\lambda [\mu] \simeq 4 E_{e^-} [\mathrm{TeV}]$

$K =$ Conversion efficiency : 50%

$\Rightarrow N_\gamma = \frac{1}{2} N_{e^-}$

5. Superconducting deflecting magnets:

$B \sim 5T$, $\ell \simeq$ several centimeters

6. Luminosity:

$$L_{\gamma\gamma}^{max} = \frac{N_{e^-}^2 f K^2}{\ell \pi a_\gamma^2}$$

For VLEPP parameters:

$$L_{\gamma\gamma} \sim 5 . 10^{33}$$

Final Remarks

1. More thorough understanding of background problems and tolerable beam losses.

$\Downarrow$

i) Large crossing angle + crab-crossing

ii) Influence of an enlarged hole on the magnet design.

2. Basic focussing problems are understood and solved with conventional magnets at least up to 500 GeV.

Very important questions have still to be addressed ... and answered :

i) definition of l^*

ii) to what extent can a beam be FLAT?

iii) Correction schemes

iv) Alignment tolerances

v) Polarisation schemes

3. Basic design for a Final Focus Test Beam Facility at SLAC:

i) feasibility of critical components

ii) Plasma focusing experiments

iii) Beam monitoring

4. $\gamma\gamma$ colliders: a new avenue in particle physics?

Dec. 8, 1988

REVIEW OF BEAM-BEAM INTERACTION

Pisin Chen
SLAC

PART 1. DISRUPTION EFFECTS

I. Luminosity Enhancement

II. Disruption Angles

III. Kink Instability

PART 2. BEAMSTRAHLUNG PAIR CREATION

I. Incoherent Pair Creation

II. Coherent Pair Creation

III. Probability of Pair Creation

IV. Incoherent Pair Creation Spectrum

V. Deflection Angle

PART 1. with K. Yokoya

PART 2. with V. Telnov, K. Yokoya, K. Oide, N. Kroll, S. Drell, R. Blankenbecler, B. Richter, R. Palmer, etc..

PART 1.
DISRUPTION EFFECTS

I. LUMINOSITY ENHANCEMENT

* Disruption Parameter D:

$$\boxed{D_{x,y} = \frac{2Nr_e\sigma_z}{\gamma\sigma_{x,y}(\sigma_x+\sigma_y)}.}$$

for flat beams ($\sigma_x > \sigma_y$). For round beams, i.e., $\sigma_x = \sigma_y \equiv \sigma_0$, we have

$$D = \frac{Nr_e\sigma_z}{\gamma\sigma_0^2} \qquad \text{(R. Hollebeek)}$$

D measures the strength of mutual pinching of e^+e^- beams. For example, for $D \ll 1$,

$$D = \frac{\sigma_z}{f}, \qquad f = \text{focal length}.$$

* We found it necessary to introduce another paramete A:

$$\boxed{A_{x,y} = \frac{\sigma_z}{\beta^*_{x,y}}}$$

A measures the inherent divergence, or the Twiss effect.

* Note: $$\frac{A}{D} = \frac{\epsilon_n}{r_e N},$$

A/D measures the initial phase space area per particle in units of r_e.

Ignoring disruption effects, the luminosity is defined as

$$\mathcal{L}_0 = \frac{fN^2}{4\pi\sigma_x\sigma_y}$$

When the Twiss effect is included, the nominal luminosity reduced slightly to

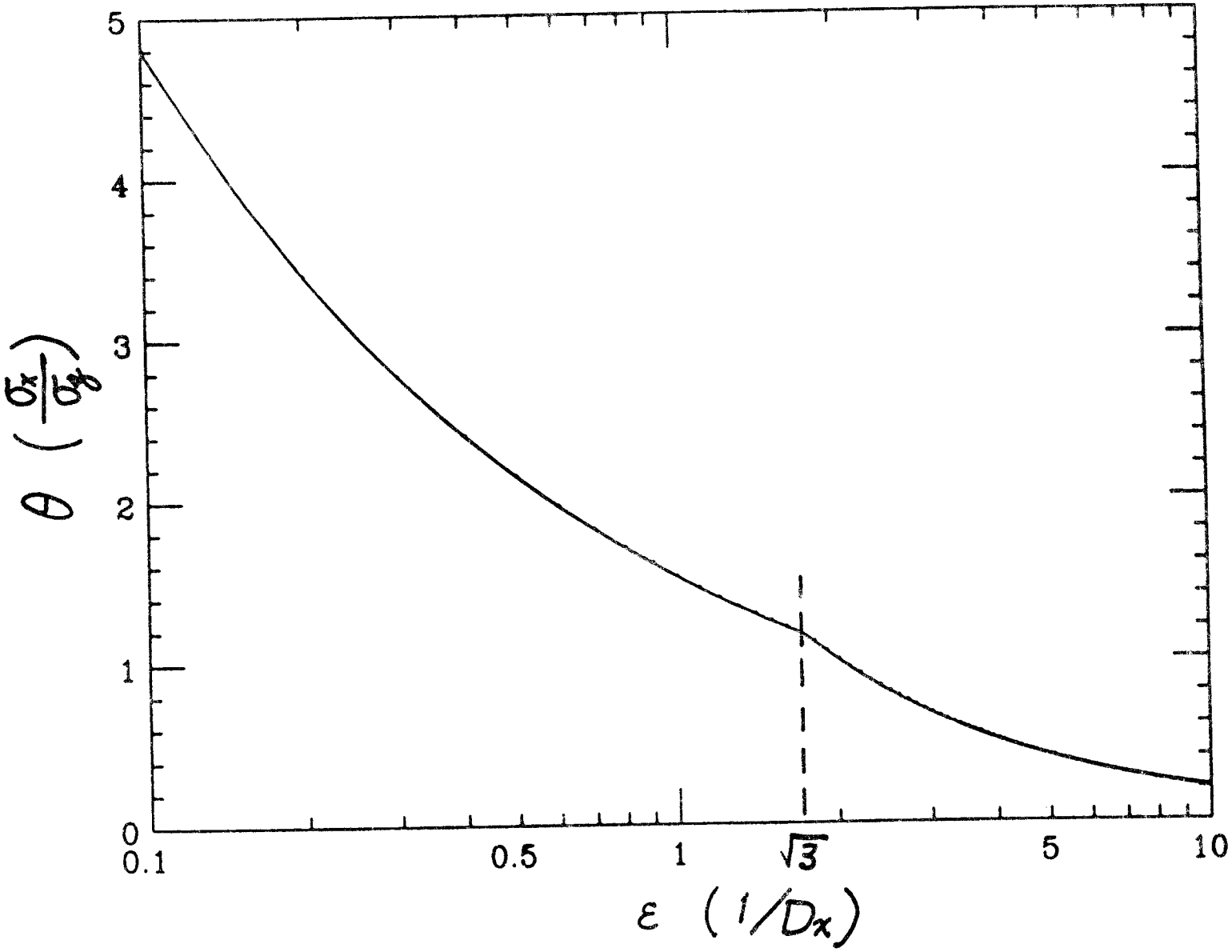
$$\mathcal{L}_A \equiv \eta_A \mathcal{L}_0 = \left[\frac{2}{\sqrt{\pi}\sigma_z}\int_0^\infty \frac{e^{-z^2/\sigma_z^2}}{1+z^2/\beta^{*2}}\,dz\right]\cdot\mathcal{L}_0$$

* Luminosity Enhancement Factor:

$$\boxed{H_D \equiv \frac{\mathcal{L}}{\mathcal{L}_0}}$$

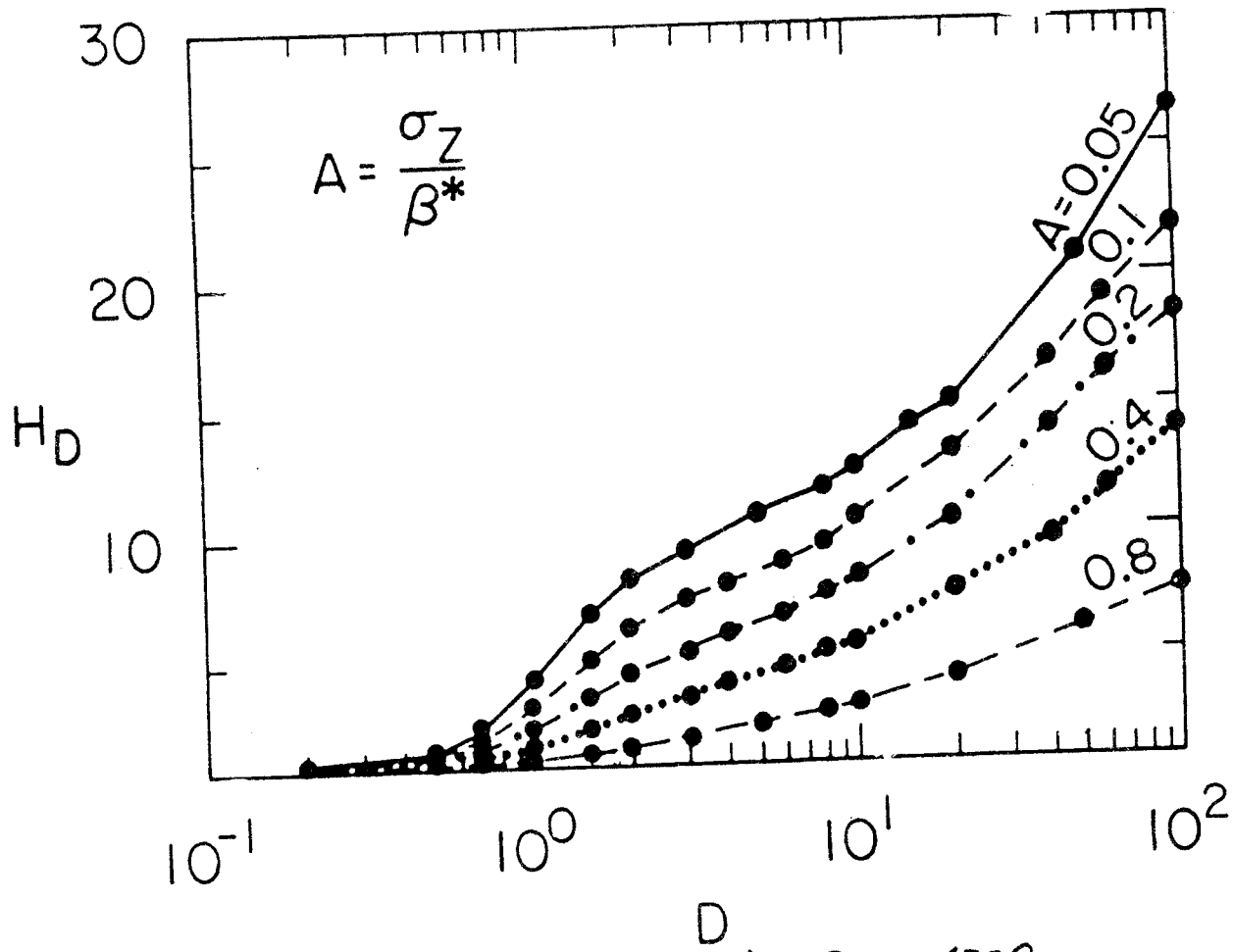
$\mathcal{L}$ = effective luminosity

DEFLECTION ANGLE AS A FUNCTION OF POSITRON ENERGY

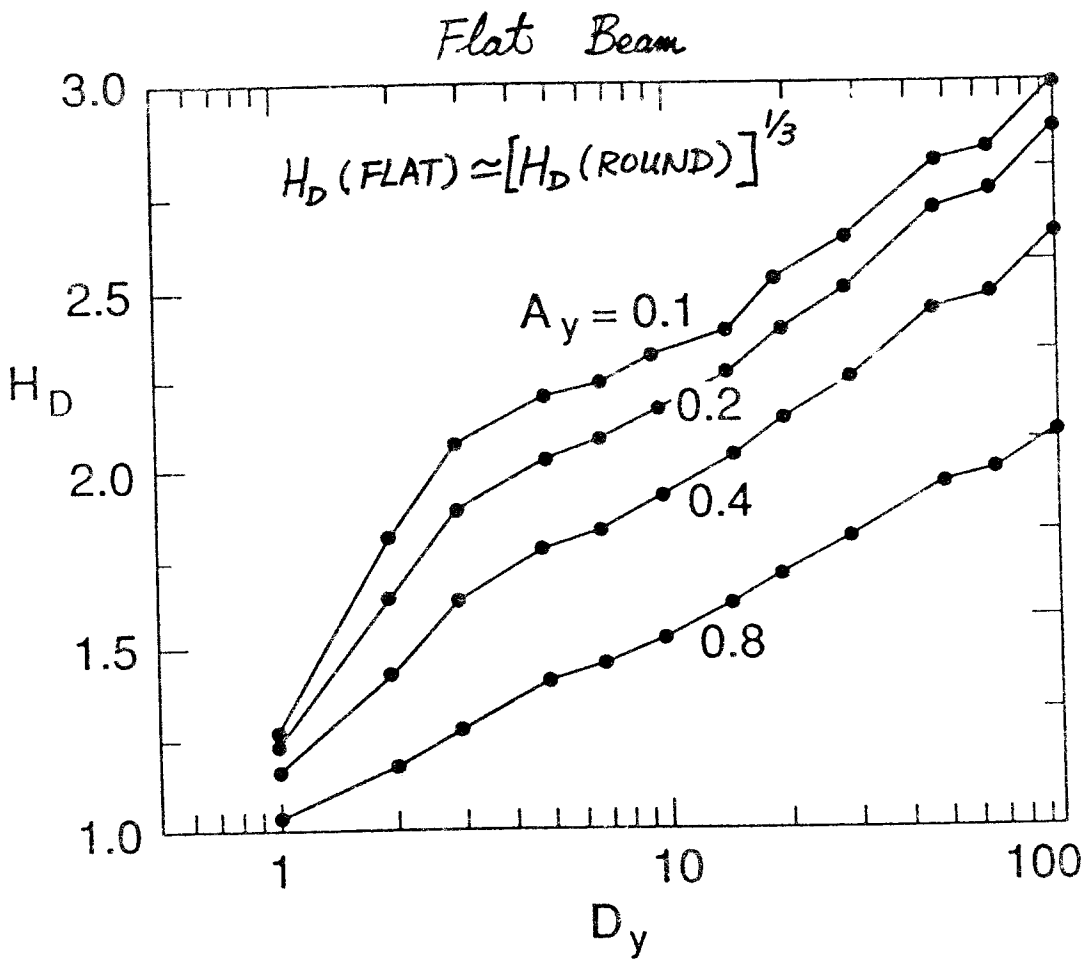


Empirically, we find the following scaling law that fits all the data within ±10%:

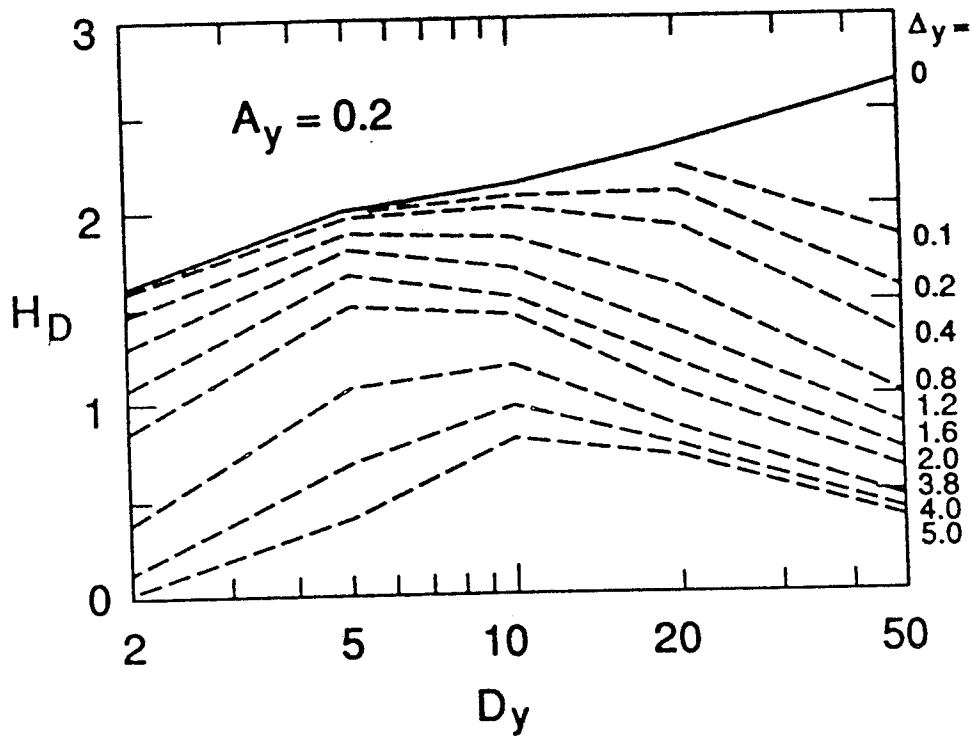
$$H_D = 1 + D^{1/4}\left(\frac{D^3}{1+D^3}\right)\left[\ln(\sqrt{D}+1) + \ln\left(\frac{0.8}{A}\right)\right]$$



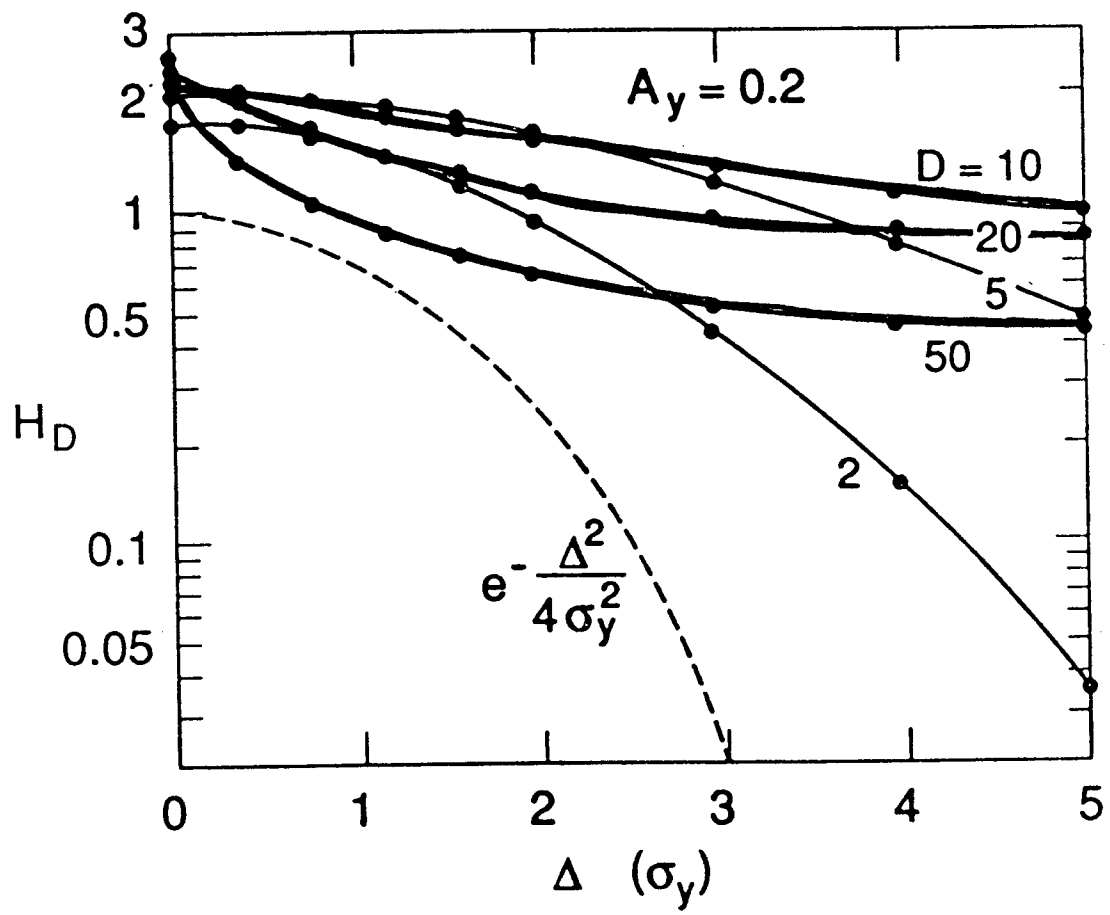
P. Chen and K. Yokoya, SLAC-PUB-4339
(Phys. Rev. D, Aug. 1, 1988)


Flat Beam
H_D (FLAT) $\simeq [H_D$ (ROUND)$]^{1/3}$
$A_y = 0.1$
0.2
0.4
0.8
3.0
2.5
2.0
1.5
1.0
H_D
1
10
100
D_y

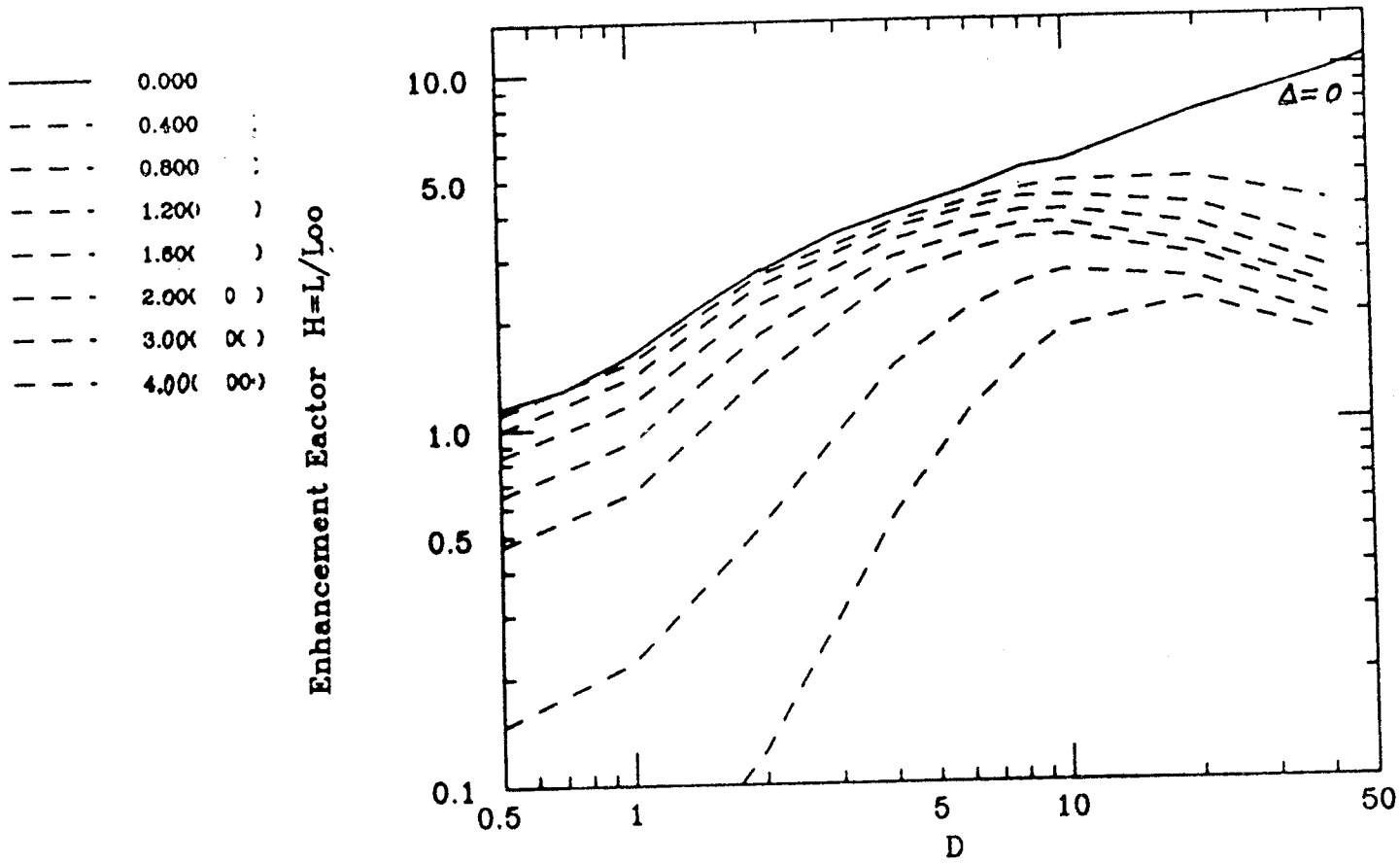
Flat Beam H_D with Vertical Offset



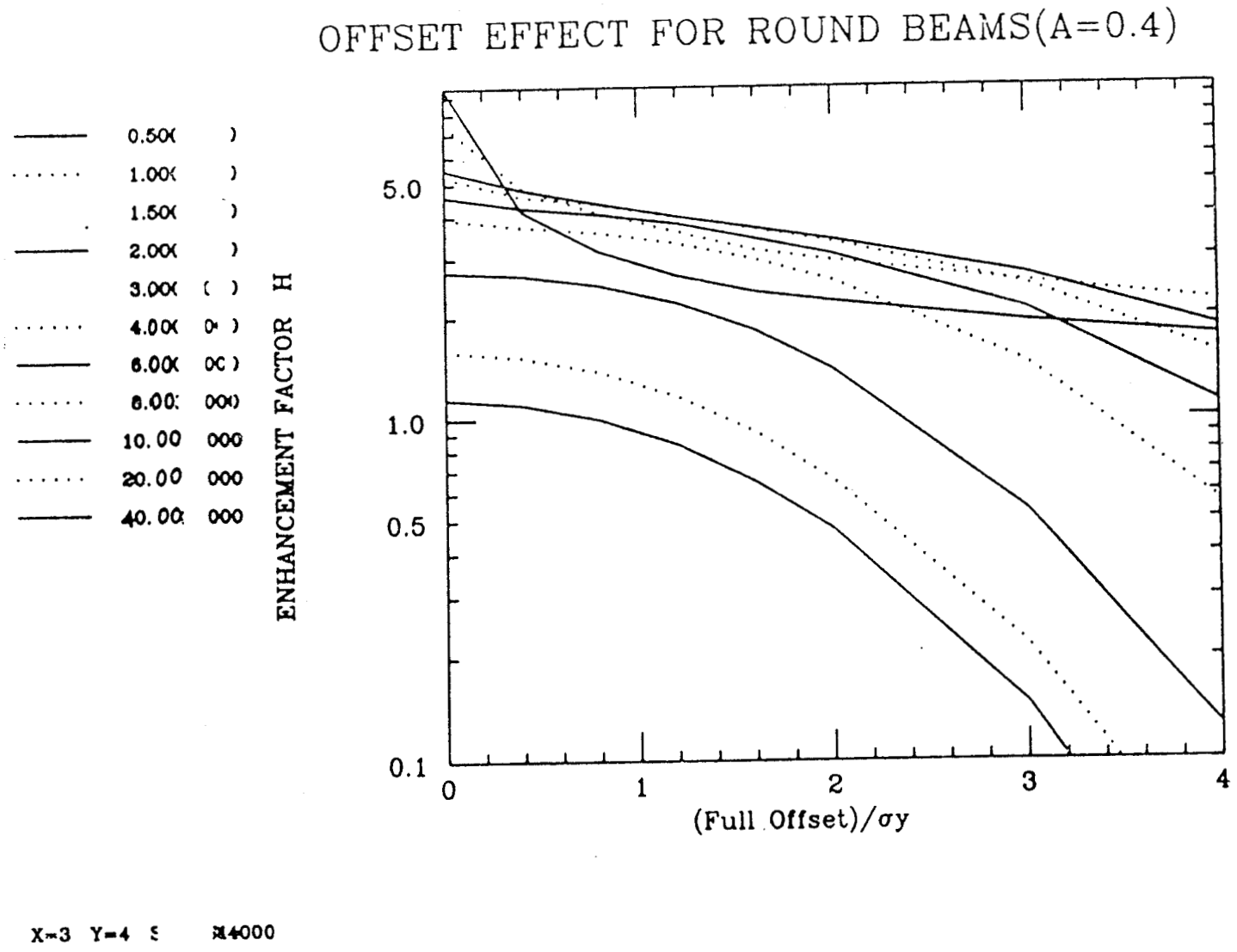
Flat Beam H_D as a function of Offset



OFFSET EFFECT FOR ROUND BEAMS (A=0.4)



X=1 Y=4 S : 01400


OFFSET EFFECT FOR ROUND BEAMS(A=0.4)
0.50
1.00
1.50
2.00
3.00
4.00
6.00
8.00
10.00
20.00
40.00
ENHANCEMENT FACTOR H
5.0
1.0
0.5
0.1
0
1
2
3
4
(Full Offset)/σy
X=3 Y=4

II. DISRUPTION ANGLES

* When beamstrahlung is "turned off", the maximum disruption angle can be easily estimated.

The equation of motion of a test particle is

$$y'' + \frac{D_y}{\sigma_z^2} y = 0.$$

The solution is

$$y = y_0 \cos\left(\sqrt{D_y}\,\frac{s}{\sigma_z}\right).$$

$$\rightarrow \quad y' = \theta = \sigma_y \cdot \frac{\sqrt{D}}{\sigma_z} \sin\left(\frac{\sqrt{D_y}}{\sigma_z} s\right).$$

So we expect

$$\theta \propto \begin{cases} D_y \dfrac{\sigma_y}{\sigma_z} & , \quad D \ll 1 \\ \sqrt{D_y}\,\dfrac{\sigma_y}{\sigma_z} & , \quad D \gg 1. \end{cases}$$

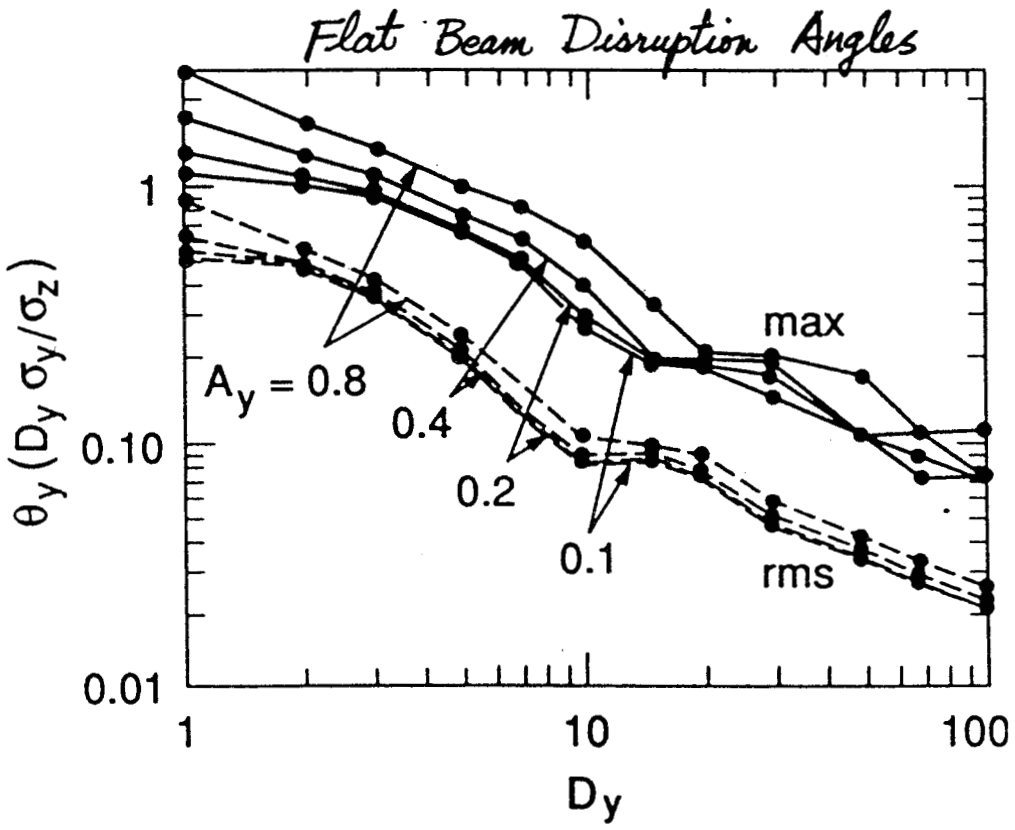
The same is true for the x-dimension.

From simulations, we find it scales more like

$$\theta \propto D_y^{1/3} \cdot \frac{\sigma_y}{\sigma_z}.$$

Example: For $D_y = 5$, $\sigma_y = 1\,nm$, $\sigma_z = 50\,\mu m$,

$$\theta_{max} \simeq 0.1 \text{ mrad}.$$

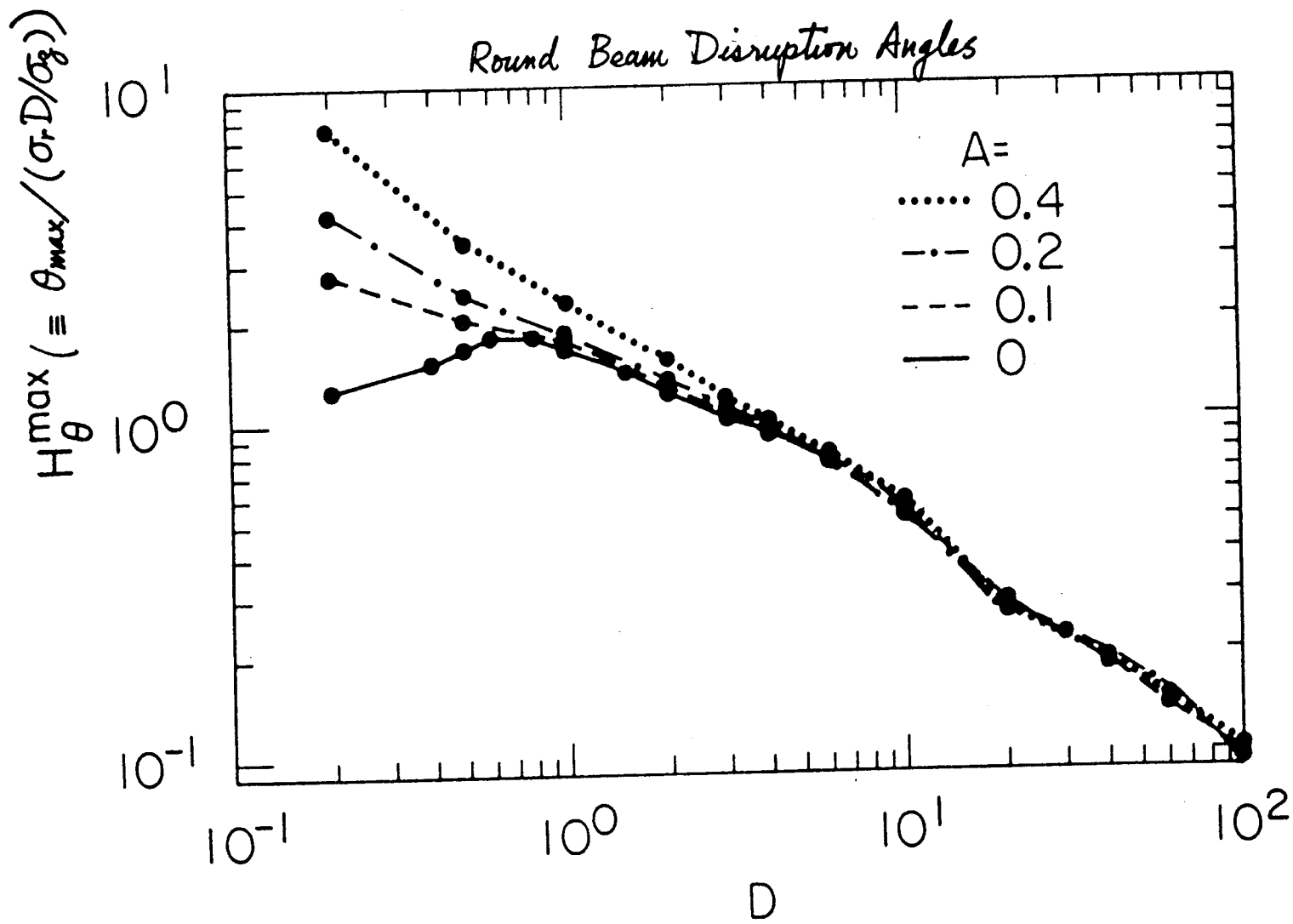


From the figure,

$$\theta_{y,rms} \sim \sqrt{\frac{\pi}{6\sqrt{3}}} \cdot \frac{\sigma_y}{\sigma_z} \frac{D_y}{[1+(D_y/2)^5]^{1/6}},$$

and

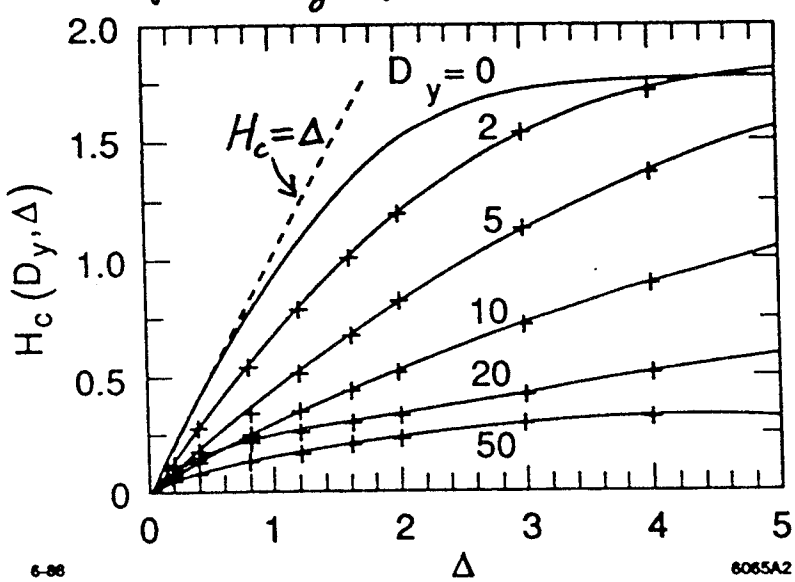
$$\theta_{y,max} \sim 2.5\, \theta_{y,rms}.$$


Round Beam Disruption Angles
$H_\theta^{max} (\equiv \theta_{max}/(\sigma_r D/\sigma_g))$
10^1
10^0
10^{-1}
A=
0.4
0.2
0.1
0
10^{-1}
10^0
10^1
10^2
D

For flat beams, the disruption angle in the presence of vertical offset is also important. The deflection angle of the center-of-mass of the bunch can be written in the form:

$$\Theta_y = \frac{1}{2}\frac{\sigma_y}{\sigma_z} D_y \cdot H_c(D_y, \Delta).$$

(Δ = vertical offset in units of σ_y)



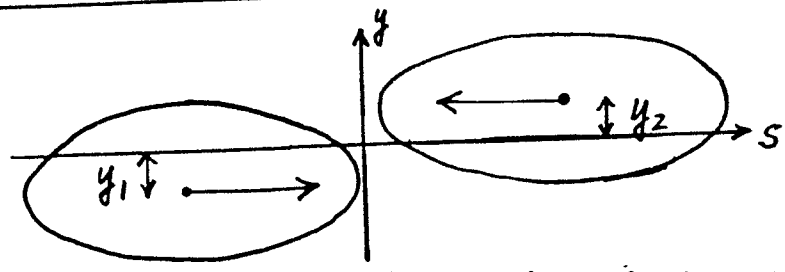
In the limit of small D_y and Δ,

$$\lim_{D_y, \Delta \to 0} H_c(D_y, \Delta) = \Delta.$$

On the other hand, for $D_y = 0$, and arbitrary Δ,

$$H_c(0, \Delta_y) = \int_0^{\Delta_y} e^{-y^2/4}\, dy.$$

III. KINK INSTABILITY



* SINGLE BUNCH INSTABILITY. Fawley-Lee, Y.H. Chin

From fluid model,

$$\begin{cases} \left(\frac{\partial}{\partial t}+\frac{\partial}{\partial s}\right)^2 y_1 = -\kappa(y_1-y_2) \\ \left(\frac{\partial}{\partial t}+\frac{\partial}{\partial s}\right)^2 y_2 = -\kappa(y_2-y_1), \end{cases} \qquad \kappa \equiv \frac{\sqrt{2\pi}}{6}\frac{D_y}{\sigma_z^2}$$

The solution for the largest growth rate is

$$y_{1,2} = e^{\pm i\left(\frac{\sqrt{3}}{2}\sqrt{\kappa}\, s - \frac{\pi}{6}\right) + \frac{1}{2}\sqrt{\kappa}\, t}$$

From this we deduce the following:

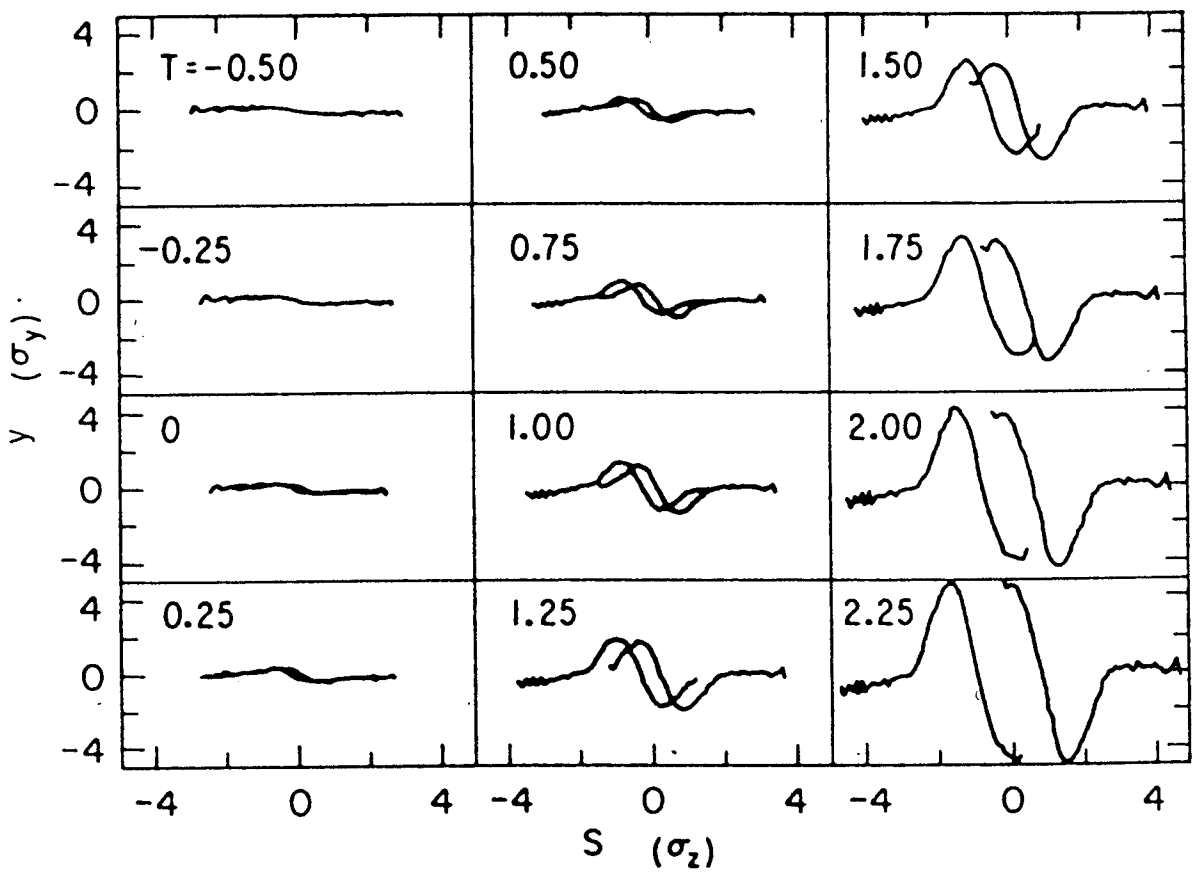
* Wavelength: $4\pi\sqrt{\frac{2}{\sqrt{2\pi}\, D_y}}\,\sigma_z \simeq \frac{11}{\sqrt{D_y}}\,\sigma_z$

* Phase difference between e^+e^- bunches: 60°

* Growth rate: $\frac{1}{2}\sqrt{\frac{\sqrt{2\pi}\, D_y}{6}}\,\frac{1}{\sigma_z} \simeq \frac{\sqrt{D_y}}{3}\cdot\frac{1}{\sigma_z}$

* Blow-up factor: $\sim e^{\sqrt{\frac{\sqrt{2\pi}}{8}D_y}} \sim e^{0.56\sqrt{D_y}}$

Evolution of Single Bunch Kink Instability



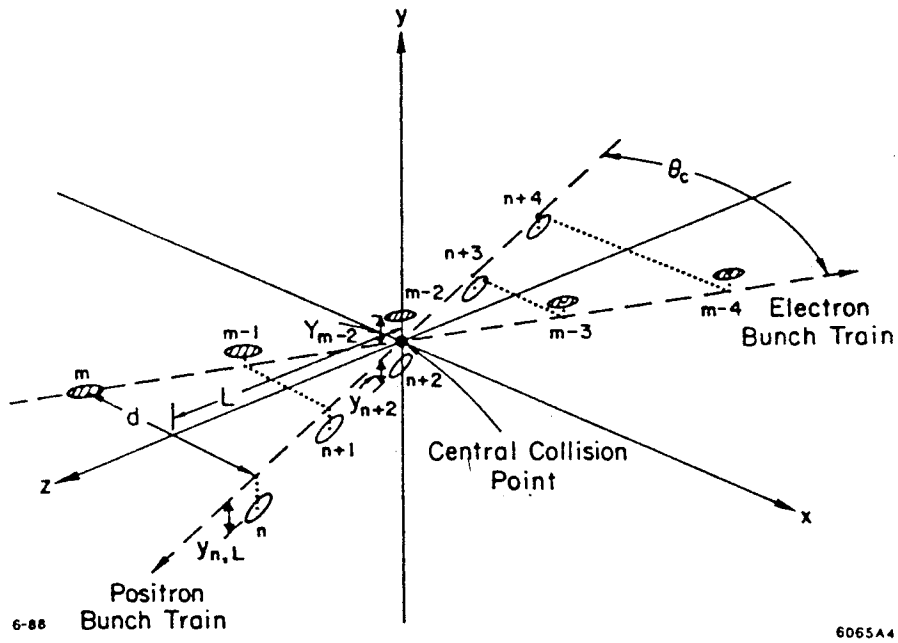


Fig. 1

Schematic diagram of multi-bunch collision with crossing angle θ_c. $n+2 = m-2$ in this particular "snap-shot".

* Effective Cumulative Offset

$$\Delta_m = C \sum_{n<m} H_c(D_y, \Delta_n) + \delta_m .$$

The stability constraint is therefore relaxed to

$$\boxed{(N_B - 1) D_x D_y \lesssim 2}$$

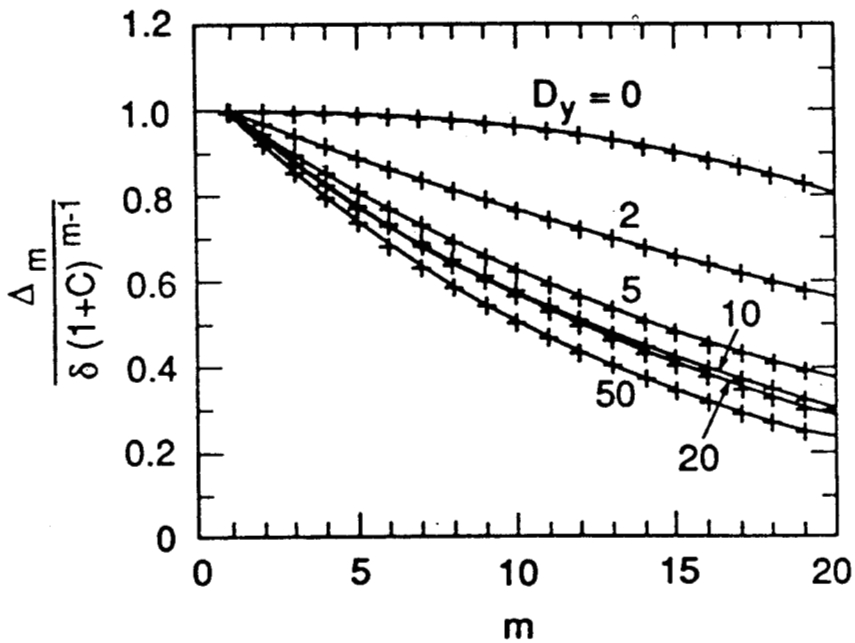


Fig. 3

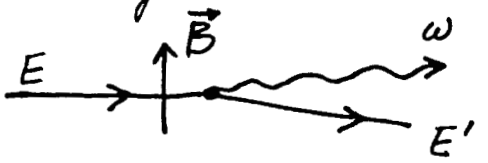
The cumulative offset Δ_m in units of the theoretical offset, $\delta(1+C)^{m-1}$, as a function of the number of bunches.

* One possible cure to the multi-bunch crossing instability is to partition the two bunch trains by a septum.

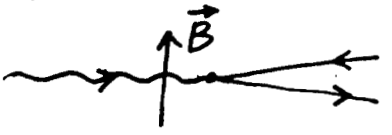
(R. Palmer)

PART 2.
BEAMSTRAHLUNG PAIR CREATION

In beamstrahlung, we have



Analogously, the photon can also pair-create:



Like in the case of radiation in a collection of particles, where there can be two processes:

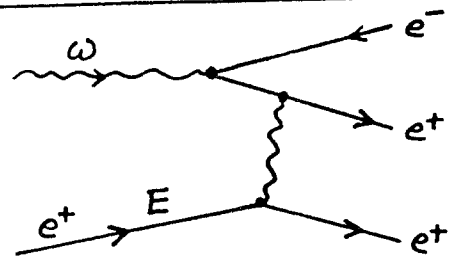
1. Incoherent Scattering (Bremstrahlung),
2. Coherent Scattering (Synchrotron Radiation, or Beamstrahlung).

Similarly, for pair creation, we have both contributions.

At high energy and high fields, <u>beam</u>strahlung dominates over <u>brem</u>strahlung. Likewise, for pair creation, the <u>coherent</u> effect dominates over <u>incoherent</u> effect.

I. INCOHERENT PAIR CREATION

V. Telnov



The cross-section is

$$\sigma_{e^+e^-} \sim \frac{28}{9}\alpha r_e^2 \log\frac{2\omega E}{m^2}.$$

This is a very slowly varying function of photon energy ω.

For TLC, $\gamma = 1\times10^6$, the cross-section <u>per beam</u> is

$$\sigma_{e^+e^-} \sim 5\times10^{-26}\ \mathrm{cm}^{-2}, \quad \text{for} \quad \omega \sim E = 500\ \mathrm{GeV},$$
$$\sim 4\times10^{-26}\ \mathrm{cm}^{-2}, \quad \omega \sim 0.1E.$$

Take beam parameters $N = 8\times10^9$, $\sigma_x = 190\ \mathrm{nm}$, $\sigma_y = 1\ \mathrm{nm}$, and $\sigma_z = 26\ \mu\mathrm{m}$, the attenuation coefficient is

$$\mathcal{A}_i = \sigma_{e^+e^-}\cdot n_b = \sigma_{e^+e^-}\cdot \underbrace{\frac{N}{12\sqrt{2}\,\pi\sigma_x\sigma_y\sigma_z}}_{\sim 3\times10^{22}\ \mathrm{cm}^{-3}}$$
$$\sim 1.2\times10^{-3}\ \mathrm{cm}^{-1}.$$

and the number of e^+e^- pair per bunch crossing is

$$N_{e^+e^-} = \sigma_{e^+e^-}\cdot \mathcal{L}/f_{rep} \sim 5\times10^6.$$

II. COHERENT PAIR CREATION

The rate of pair creation in an external magnetic field is

$$\frac{dw}{dt} = \begin{cases} \frac{3\sqrt{3}}{16\sqrt{2}} \frac{\alpha \eta}{\lambda\!\!\!^{-}_c \gamma} \cdot e^{-8/3\chi}, & \chi \ll 1. \\ \frac{15}{7}\left(\frac{2}{3}\right)^{1/3} \frac{\Gamma(5/6)}{\Gamma(1/6)} \frac{\alpha \eta}{\lambda\!\!\!^{-}_c \gamma} \cdot \chi^{-1/3}, & \chi \gg 1. \end{cases}$$

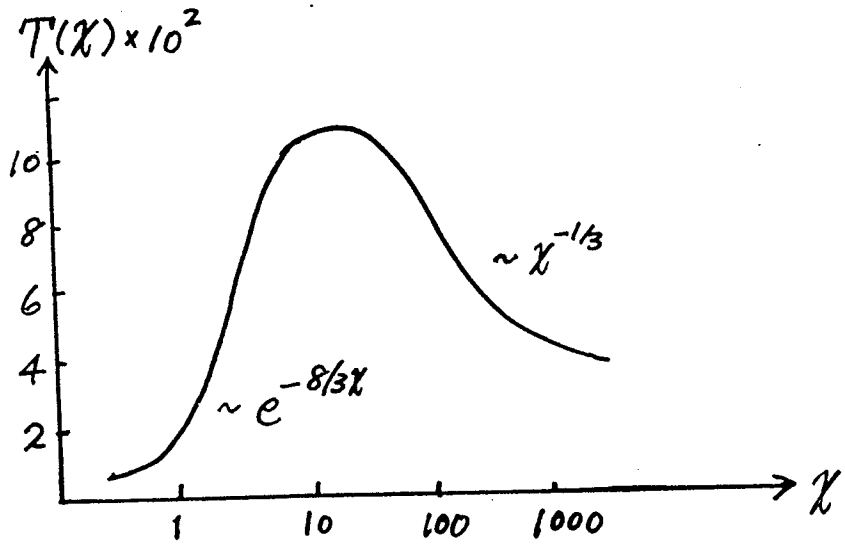
where $\boxed{\chi \equiv \frac{\hbar\omega}{E} \cdot \eta}$, and $\eta \equiv \gamma \cdot \frac{B}{B_c}$, $B_c = \frac{m^2c^3}{e\hbar} \simeq 4.4 \times 10^{13}$ G

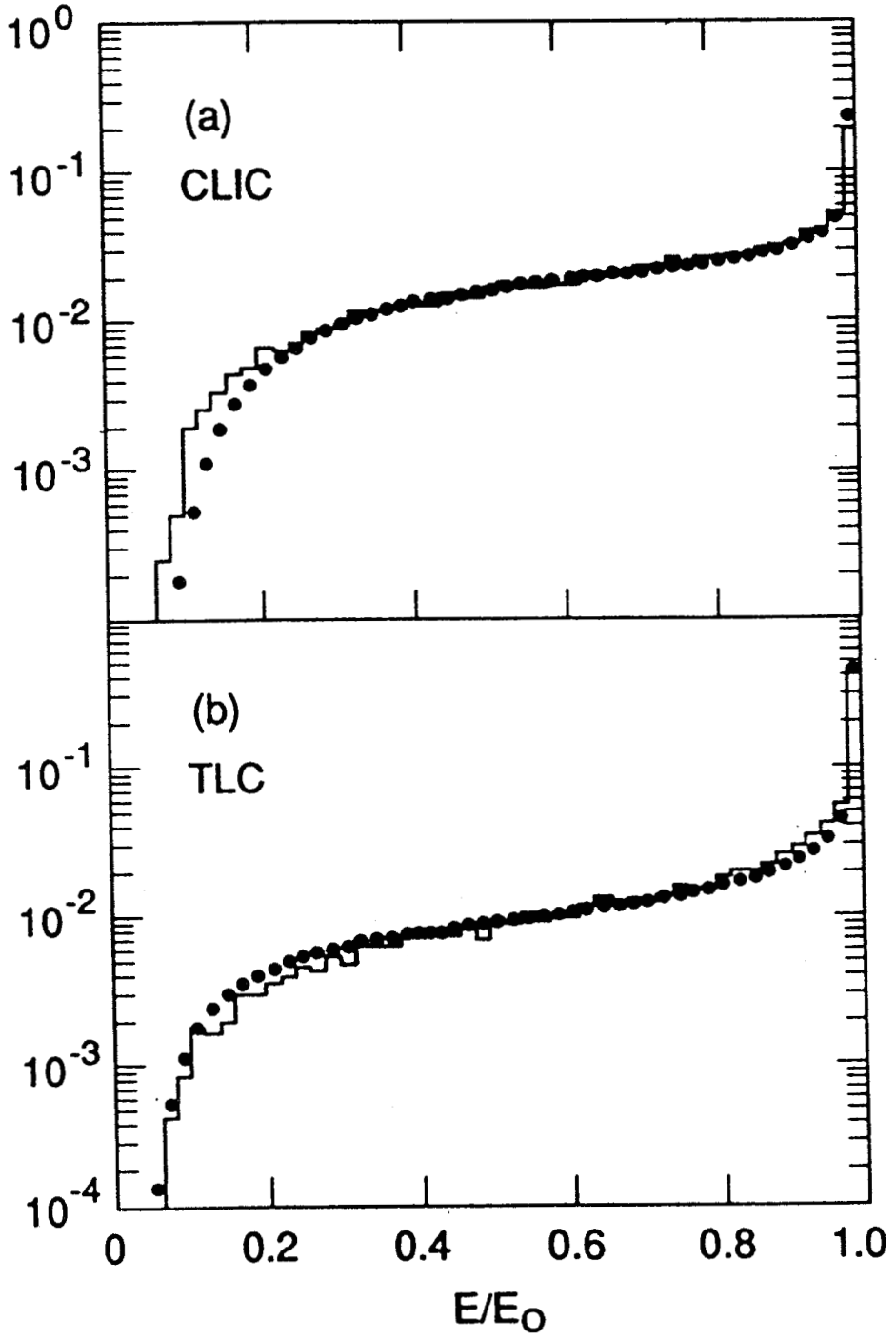
Let $\frac{dw}{dt} \equiv \frac{\alpha \eta}{\lambda\!\!\!^{-}_c \gamma} T(\chi)$.

To a very good approximation,

$$T(\chi) = 0.16\, \chi^{-1} \cdot K^2_{1/3}\left(\frac{4}{3\chi}\right).$$

T. Erber.




(a)
CLIC
(b)
TLC
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.2
0.4
0.6
0.8
1.0
E/E_O

The attenuation coefficient in this case is

$$\mathcal{A}_c(\chi) = \frac{\alpha \Upsilon}{\lambda_c \gamma} \cdot T(\chi) .$$

For TLC again, $\Upsilon \sim 2.3$

N_γ	$\hbar\omega/E$	χ	$T(\chi)$	$\mathcal{A}_c(\chi)$ [cm^{-1}]
$\ll 10^7$	1.0	2.3	0.055	24.
4×10^8	0.8	1.8	0.05	22
6×10^8	0.6	1.4	0.03	13.2
8×10^8	0.4	0.9	0.02	8.8
$\sim 10^9$	0.2	0.5	1×10^{-4}	0.04

This is much stronger than the contribution from the individual pair creation.

Number of e^+e^- pairs expected: $N_{e^+e^-} = \mathcal{A}_c \sigma_z \cdot N_\gamma$

$\hbar\omega/E$	$N_{e^+e^-}$
1.0	$\ll 6.2\times10^5$
0.8	2.3×10^7
0.6	2.0×10^7
0.4	1.8×10^7
0.2	1.0×10^5

The total e^+e^- pairs is

$$\underline{N_{e^+e^-} \sim 10^8}$$

III. PROBABILITY OF PAIR CREATION (Chen/Yokoya,

Recall that the rate of pair creation in an external field B is

$$\frac{dW}{dt} = \frac{\alpha \Upsilon}{\lambda_c \gamma} T(\chi).$$

It is easy to show that through out the collision time

$$W = \sqrt{3}\,\sigma_z \cdot \frac{\alpha \Upsilon}{\lambda_c \gamma} T(\chi) = \sqrt{3}\,\sigma_z \cdot \frac{dn_{ce}}{dt} T(\chi) \equiv n_{ce} \cdot T(\chi)$$

where dn_{ce}/dt is the rate of photons radiated based on <u>classical</u> theory of synchrotron radiation.

To evaluate the probability of finding a e^+e^- pair per incoming e^- we notice that the synchrotron radiation spectral function a la Sokolov + Ternov is

$$\frac{dn_b}{d\omega} = \frac{1}{\pi} \frac{\alpha \sigma_z}{\gamma^2} \left\{ \int_y^\infty K_{5/3}(x)\,dx + \frac{\xi^2 y^2}{1+\xi y} K_{2/3}(y) \right\}$$

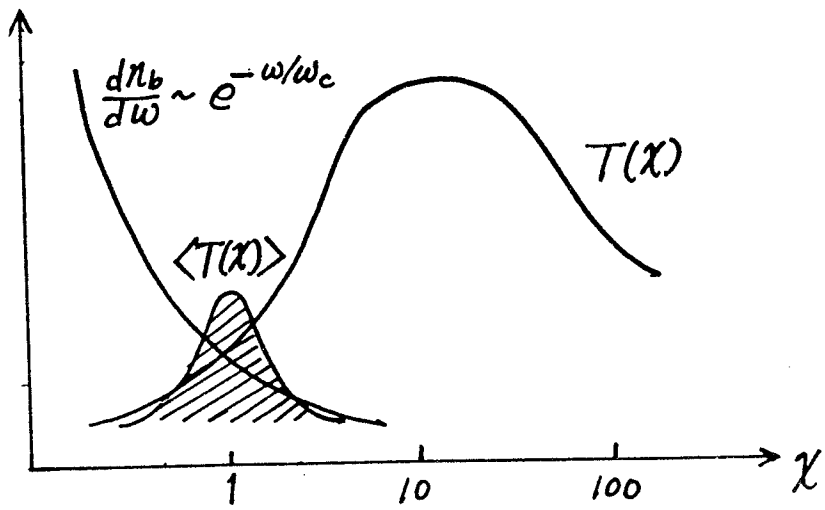
where

$$\xi = \frac{3}{2}\Upsilon \quad \text{and} \quad y = \frac{1}{\xi} \frac{\omega}{E_0 - \omega}.$$

$$= \frac{\omega_c}{E_0}$$

Thus for a fix value of Υ, the average probability of pair creation per photon is

$$\langle W \rangle = n_{ce} \langle T(\chi) \rangle$$
$$= n_{ce} \cdot \left\{ \int_0^{E_0} T(\chi) \frac{dn_b}{d\omega} d\omega \Big/ \int_0^{E_0} \frac{dn_b}{d\omega} d\omega \right\}$$



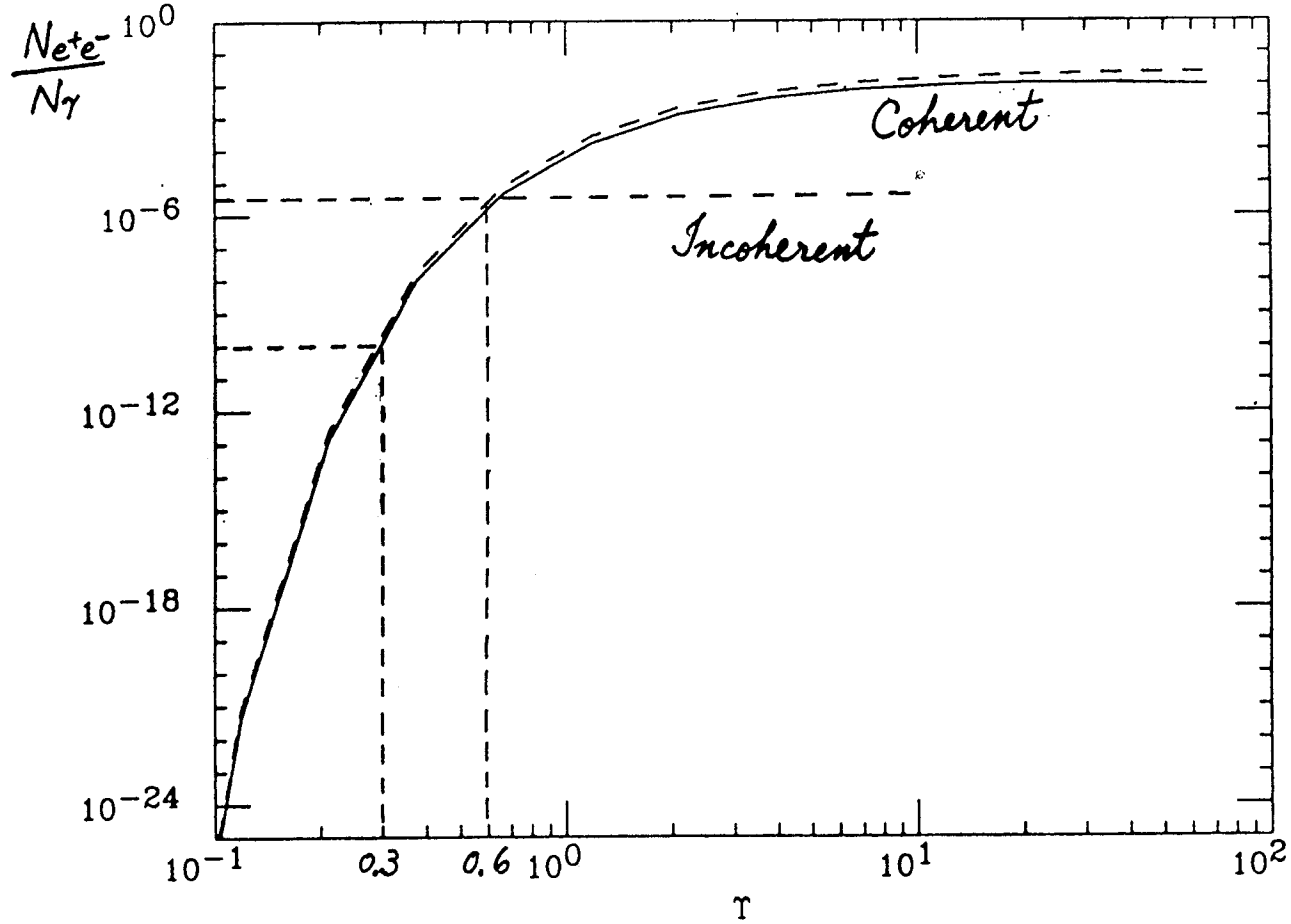
So the total number of e^+e^- pairs in a given field is

$$N_{e^+e^-} = \langle W \rangle \cdot N_\gamma$$
$$= N_\gamma n_{ce} \langle T(\chi) \rangle .$$

In beamstrahlung n_{ce} is of order unity. Thus to suppress e^+e^- pairs, one needs to find a Υ such that

$$\langle T(\chi) \rangle \sim \frac{1}{N_\gamma} .$$

PROBABILITY OF BEAMSTRAHLUNG PAIR CREATION

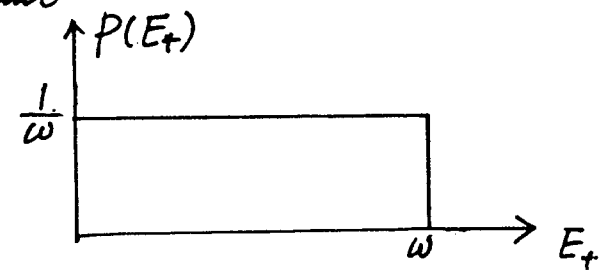


IV INCOHERNT PAIR CREATION SPECTRUM

Approximate the photon spectral function by

$$\frac{dn_b}{d\omega} = \frac{1}{\pi}\frac{\alpha\sigma_z}{\gamma^2}\left\{\frac{1}{\Gamma(1/3)}(1+\xi y)\, y^{-2/3} e^{-y}\right\}.$$

Furthermore, assume the e^+e^- energy spectrum to be constant:



So the probability of finding a pair-created positron at energy $E_+ < \omega$ is

$$P(E_+) = \frac{1}{\omega}$$

The "differential luminosity" for photons at ω is

$$\frac{d\mathcal{L}}{d\omega} = \frac{N^2}{4\pi\sigma_x\sigma_y}\frac{dn_b}{d\omega}$$

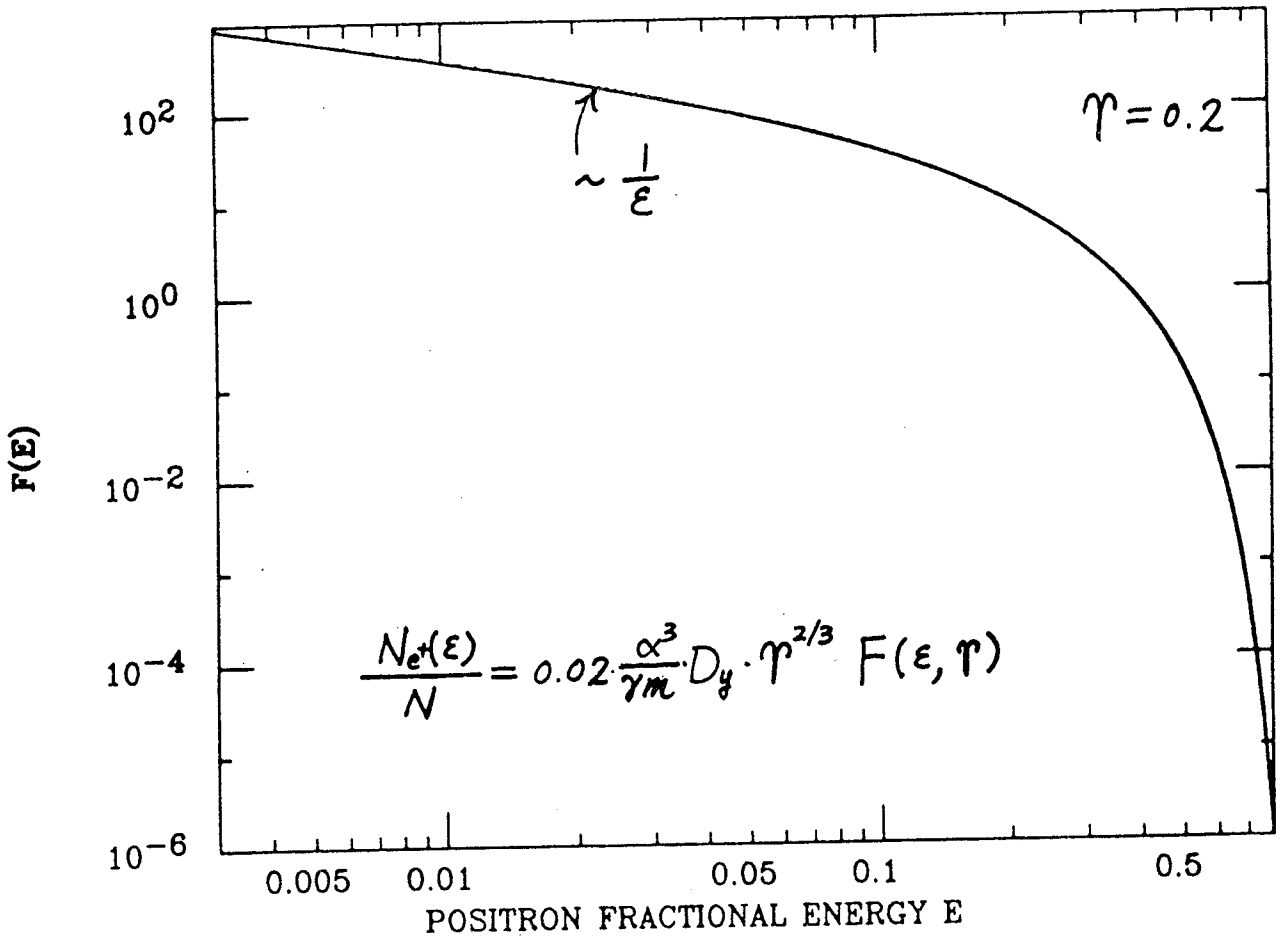
So the number of e^+e^- pairs created by photons with energy ω is

$$N_{e^+e^-}(\omega) = \sigma_{e^+e^-}\cdot\frac{d\mathcal{L}}{d\omega}$$

and the spectrum is therefore

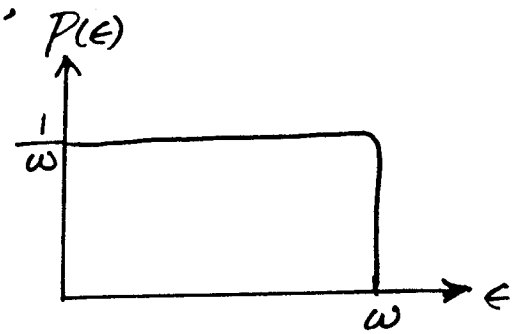
$$\boxed{N_{e^+}(\varepsilon) = \int_\varepsilon^{E_0} N_{e^+e^-}(\omega)\frac{1}{\omega}d\omega = \overbrace{\left[\frac{7(3/2)^{2/3}}{18\pi^2\cdot\Gamma(1/3)}\right]}^{0.02}\frac{\alpha^3}{\gamma m}\overset{\text{number of beam particle}}{N}D_z\Upsilon^{2/3}\cdot F(\varepsilon)}$$

POSITRON SPECTRUM FROM INCOHERENT PAIR CREATION

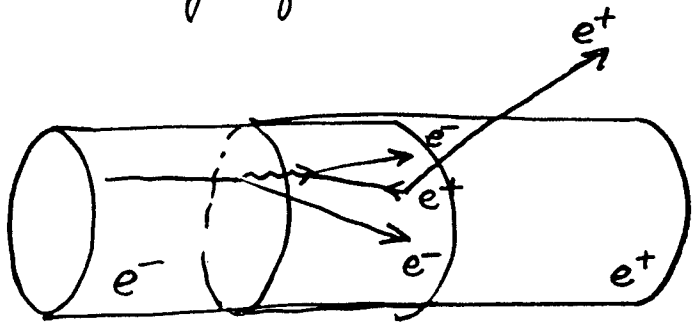


V. DEFLECTION ANGLE (Chen/Telnov)

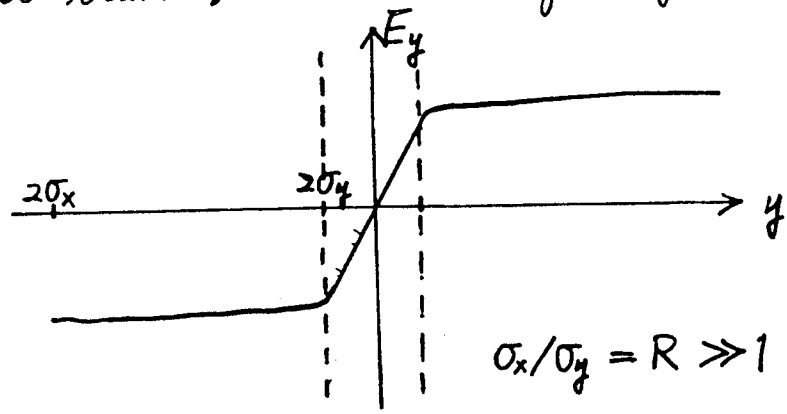
Since the energy spectrum of e^+e^- is almost constant,



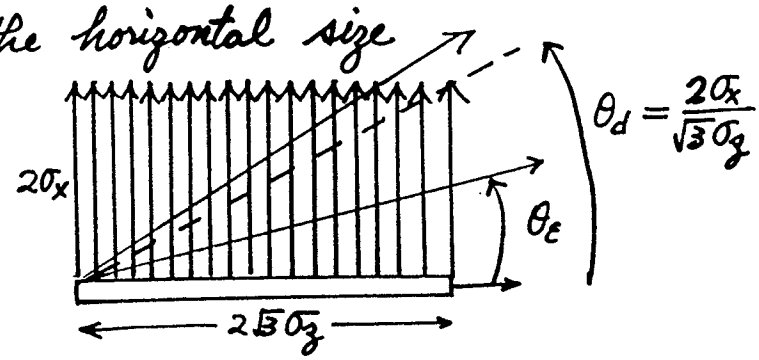
the energy of e^+e^- spreads through out the entire range of beam initial energy.



For flat beams, the vertical field goes like



To evaluate deflection angle, we assume that the y-field is constant outside the beam to a distance equals to the horizontal size



For deflecting angle $\theta_\varepsilon > \theta_d$,

$$\theta_\varepsilon = \frac{2}{3^{1/4}} \frac{\sigma_x}{\sigma_z} \sqrt{\frac{D_x}{\varepsilon}}, \qquad \theta_\varepsilon > \theta_d$$

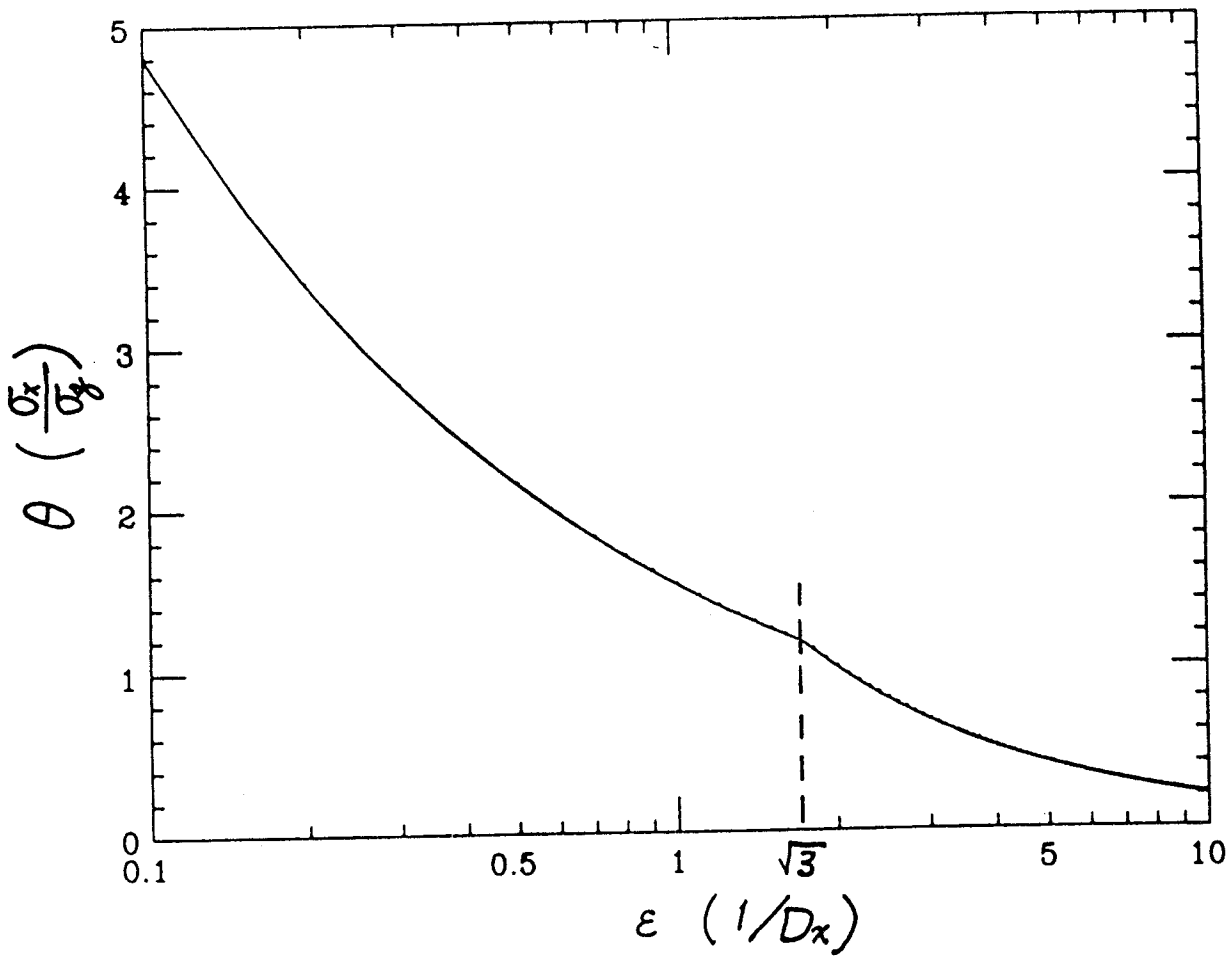
and

$$\theta_\varepsilon = 2 \frac{\sigma_x}{\sigma_z} \frac{D_x}{\varepsilon}, \qquad \theta_\varepsilon \le \theta_d$$

At θ_d, $\varepsilon_d = \sqrt{3}\, D_x$.

The spectrum for transverse momentum $P_\perp$ is easy to deduce, just $P_\perp = \varepsilon \cdot \theta_\varepsilon$.

DEFLECTION ANGLE AS A FUNCTION OF POSITRON ENERGY



International Workshop on
Next-Generation Linear Colliders

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