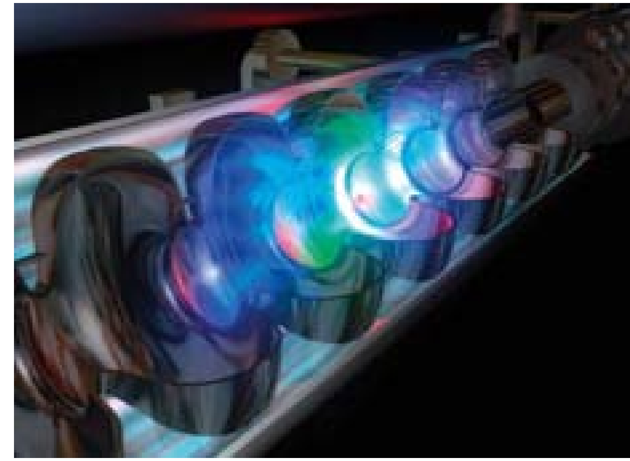


ILC Klystron Modulator Long Cable Problem

Richard Cassel SLAC

ILC Klystron modulator Requirements

Maximum distance to klystron	2.8kM
RF Pulse Length	1.37mS
Klystron Gun Voltage	120kV max
Klystron Gun Current	140A max
Modulator Pulse Length	1.7mS max
Modulator Rise/Fall Time	0.2mS max
Pulse Flatness	+/-0.5%
Total Energy per Pulse	25kJ
Repetition Rate	5Hz (10Hz for FEL)
AC Power per RF Station	~120kW
Number of modulator stations	>560
Total modulator power, site wide	75MW

Long Cable Length Between Modulator and klystron

There is no good Engineering solution to the long cables problem!

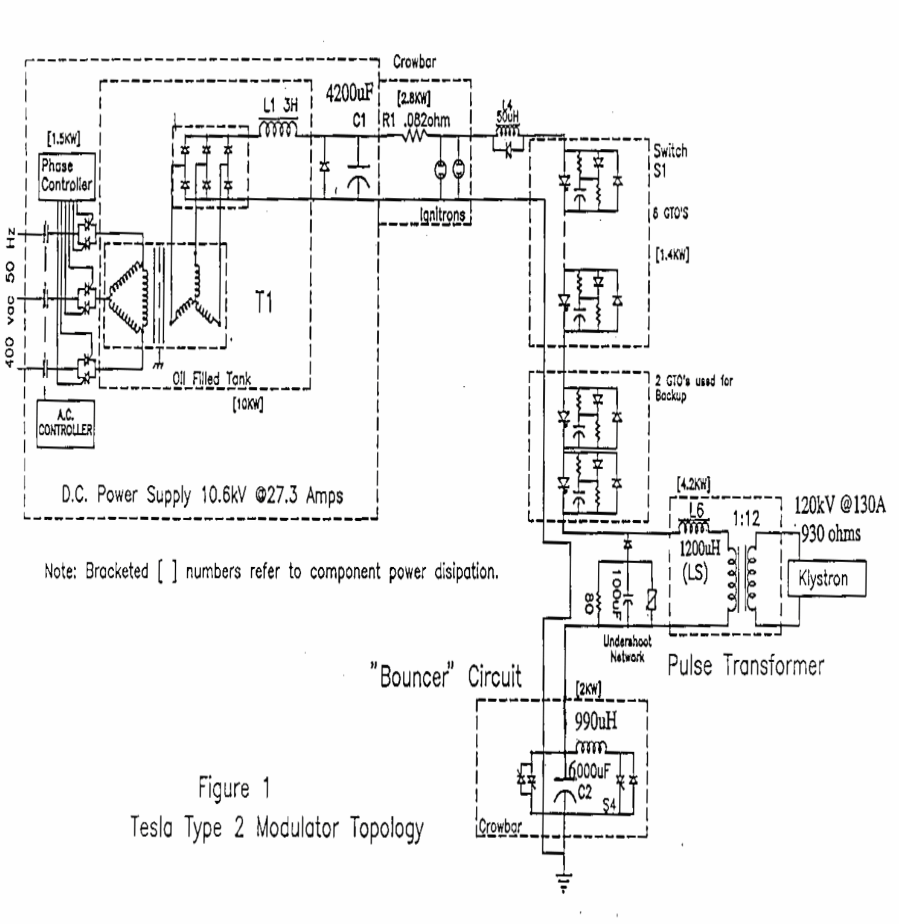
- Long cables at low voltage require large cable installations and high power loss in cable as well as unwanted reflection from pulse transformer or high snubber power loss.
- High voltage cable have reflection or high power snubber losses, high drive currents and klystron arc protection problems.
- Long cable have high installation costs

Cable Length question?

What systems can best accommodate the long cables if they are required?

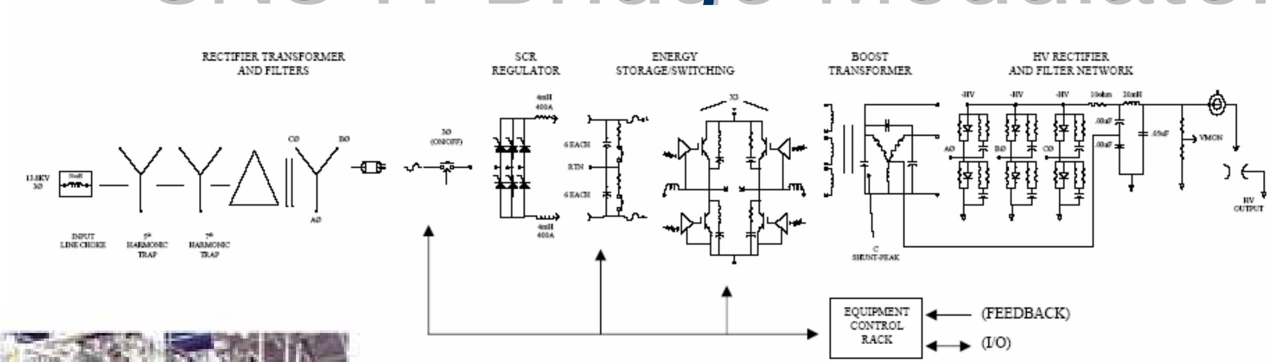
- Avoid over voltage the klystron
- Protect klystron under arc condition
- Minimize installation and cable costs
- Minimize power loss due to cables
- Insure high reliability of cables

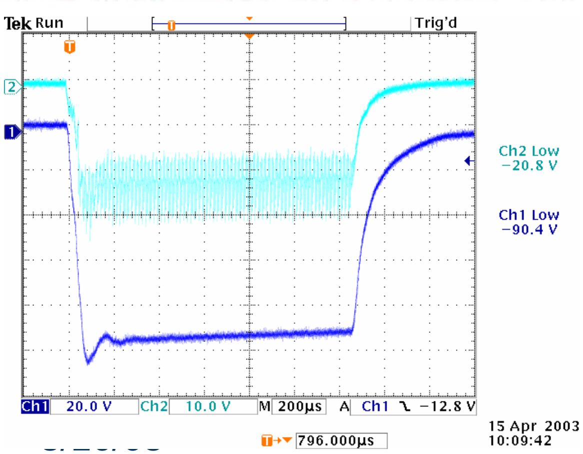
Present Fermi Pulse Transformer Modulator



- SCR controlled Power supply 10.6kV with filter and 0.004 F cap 235kJ
- Solid State Series Switch 12kV, 1680 Amps 5.1 millisecond.
- Pulse transformer 12/1 120kV/10kV 6 millisecond.
- Bouncer Circuit 2.6kV 65Hz

SNS H-Bridge Modulator





- 125kV 34A 1.5 mSec 60Hz 400kW
- Peak Power – 11 MW
- 9 Units 140 kV output
- 7 Units 80 kV

R Cassel

Series Switch 120kV Modulator

Figure 2. 140kV, 500A solid-state switch

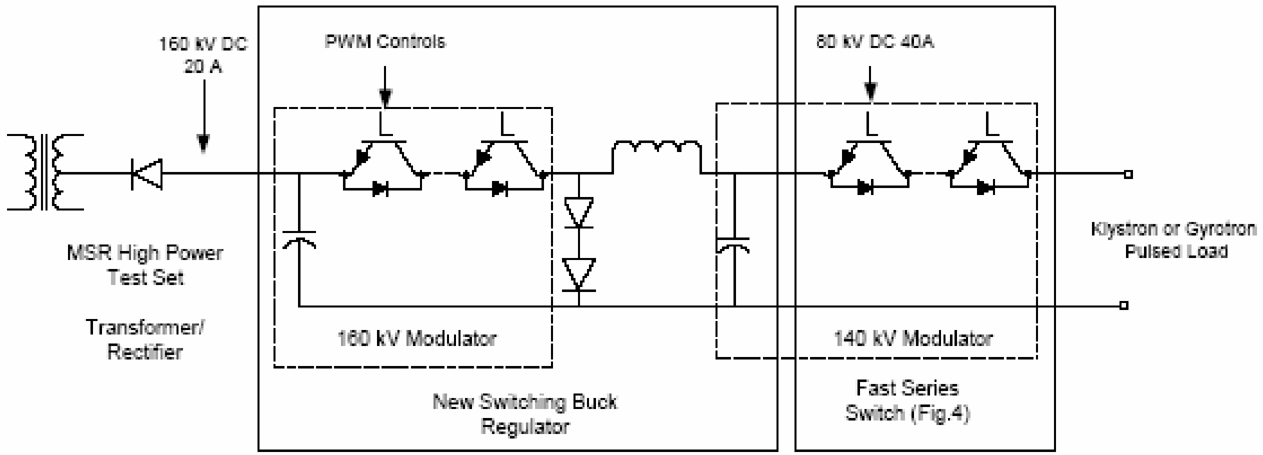


Figure 8. Modulator/Switching Buck Regulator Configuration

Diversified Technologies, Inc.

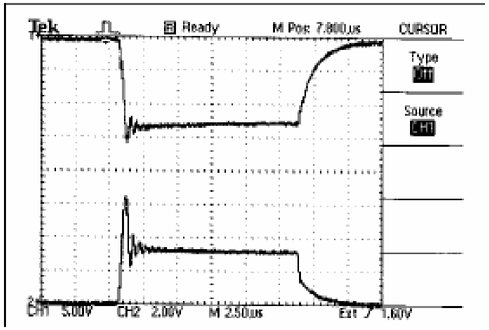
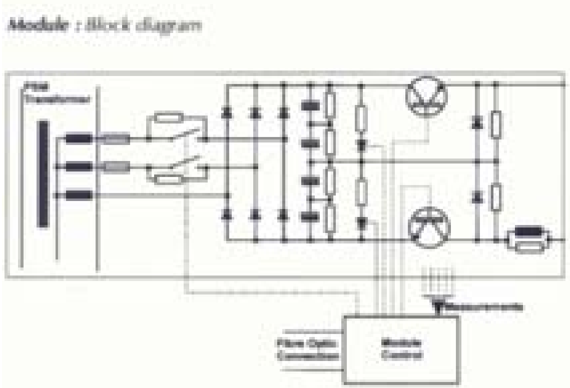
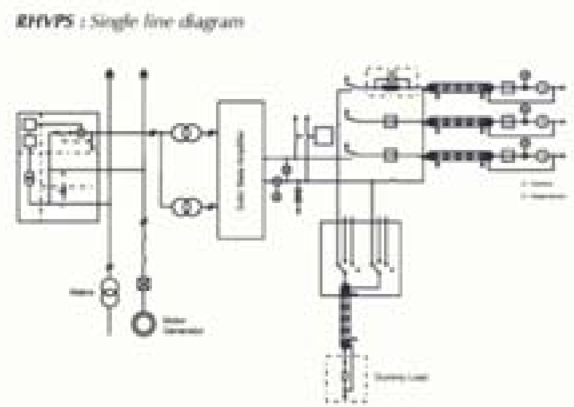


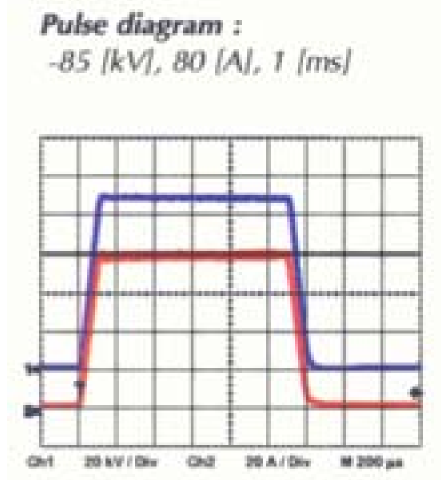
Figure 3: Test pulse (140 kV, 160 A, 13 µsec) of solid-state modulator. Upper trace is voltage at 63 kV/division. Lower trace is current at 100 A/division

- IGBT Series Switch
- 140kV 500A Switch
- Diversified Technologies

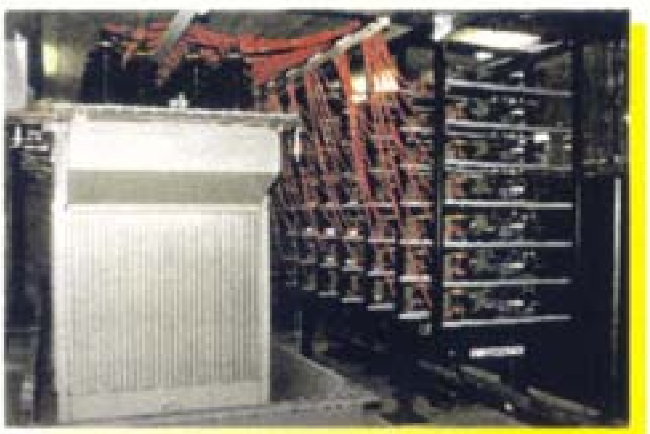
Stacked Switching Supplies







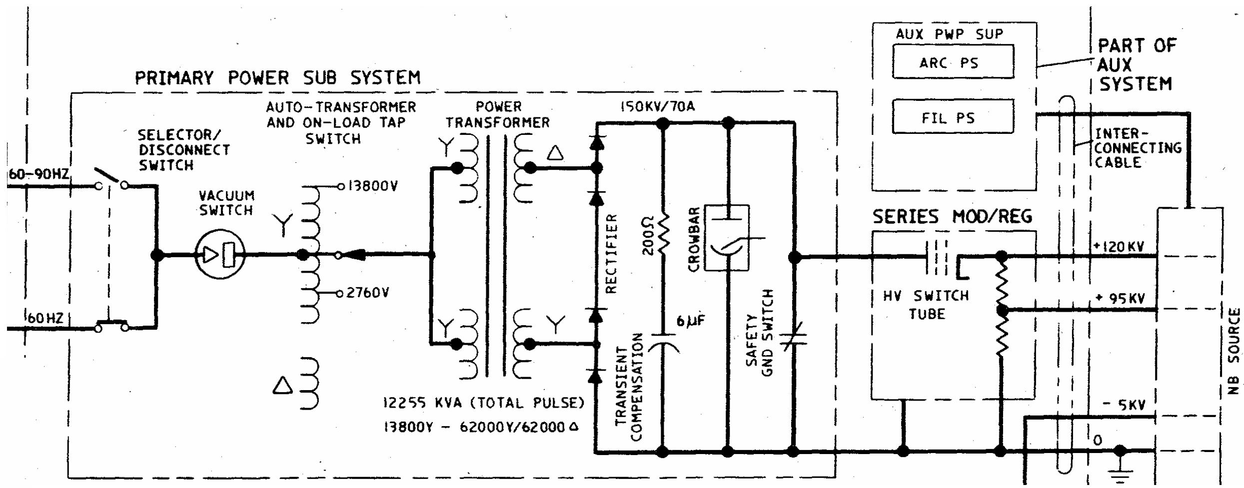
RHVPS I in Lausanne (CH)
room size : 11 [m] x 4.5[m] x 3.5[m]

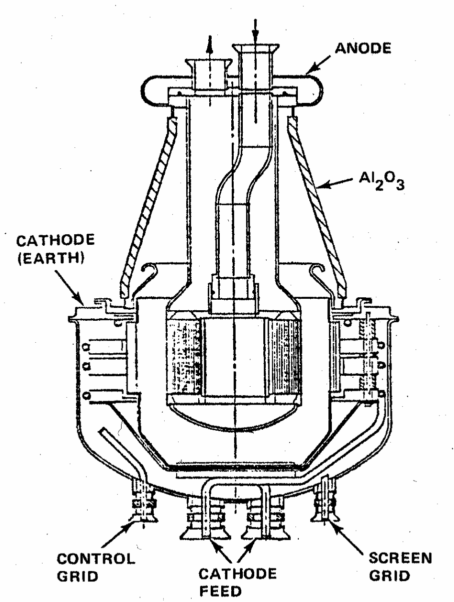


J. Alex, Dr. W. Schminke
THOMCAST AG, Turgi, Switzerland

- 80kV 80A 1 mSec 10Hz
- Thomson-CSF

Hard Tube Modulator TFTR

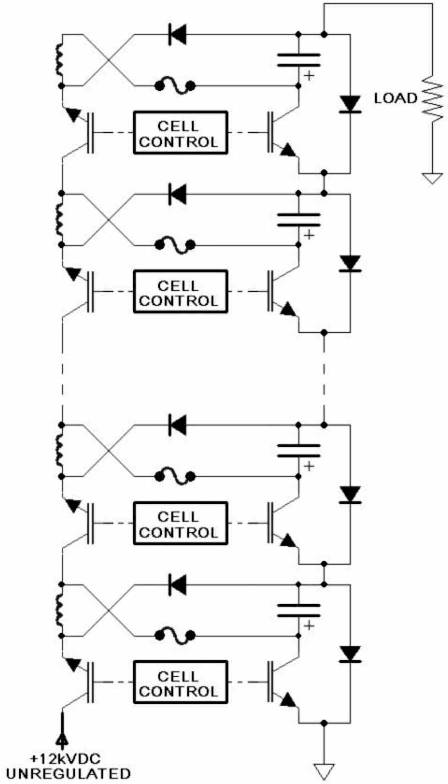




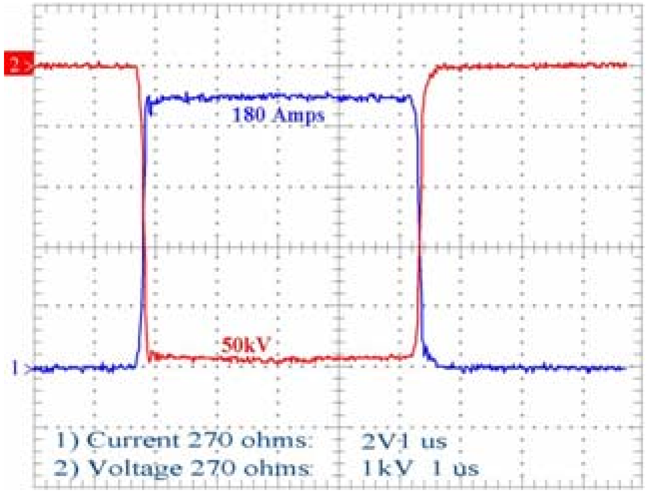
RCA SWITCH TUBE

- 120kV 65 A 0.5 sec.
- Duty factor 0.033 500kw average
- Hard Tube 200kV @ 125A 5 Sec
- 30kV on voltage
- Other tubes could be made

Solid State Marx Modulator



Existing Solid State Marx



Stangenes Ind.

Under development at SLAC
120kV 150 A 0.13 sec.
12kV per stage solid state Marx

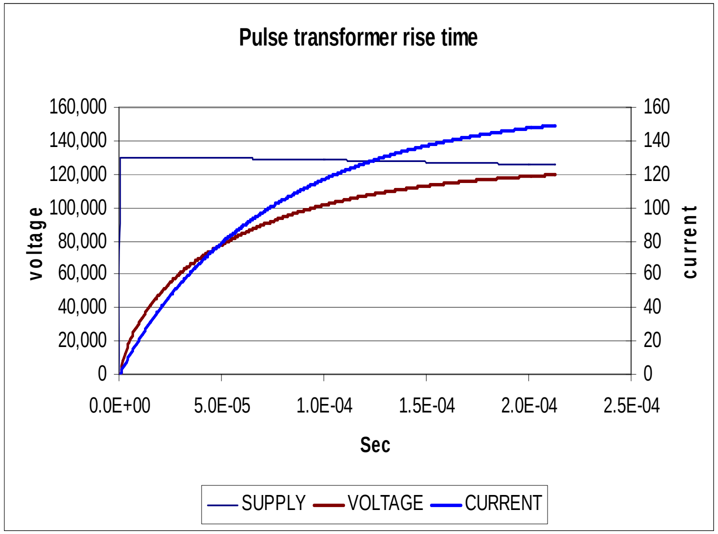
20 stage Marx modulator
50 kV pulse 180 A
Pulse width **5μSec**
Magnetron Load

Cable Length question?

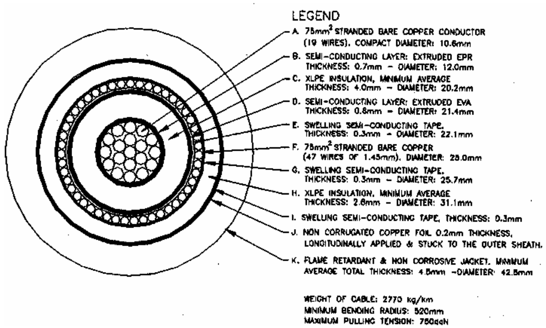
Present Fermi with low voltage Cables

Klystron impedance	850 Ohms
Transformer turns ratio	12/1
Transformer Leakage inductance	>0.05 Hy
Pulse transformer stored energy	~580 Joules
Total stored energy cable and transformer	~820 Joules
Snubber losses TBD	>400 Joules

There will be some reflections due to transformer leakage inductance. Which could be reduced by use of snubber resistor/capacitor at an energy loss of several times the cable stored energy (RF on at 80% voltage)



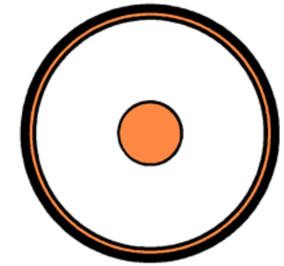
Cable Length question?
Present design



4 each Cable resistance total	~0.16 Ohms
4 each Cable Inductance total	~57 µHy
4 each Cable Capacitance total	~1.5 µFd
4 each Cable Impedance total	~6.1 ohms
Cable matched only at full klystron load	
4 each 25 ohm cables 10kV, 1800A total	242 Joules
Delay time	~15 µsec
Cable size	1.75" OD
RMS Current in Cables	145 amps
Power Loss 4 cables	~3,400 W

Cable Length question?

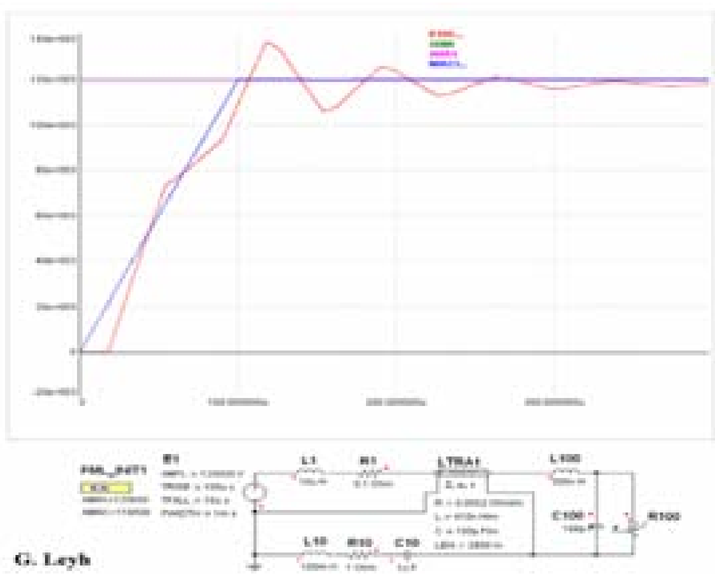
Pulsed High voltage cable

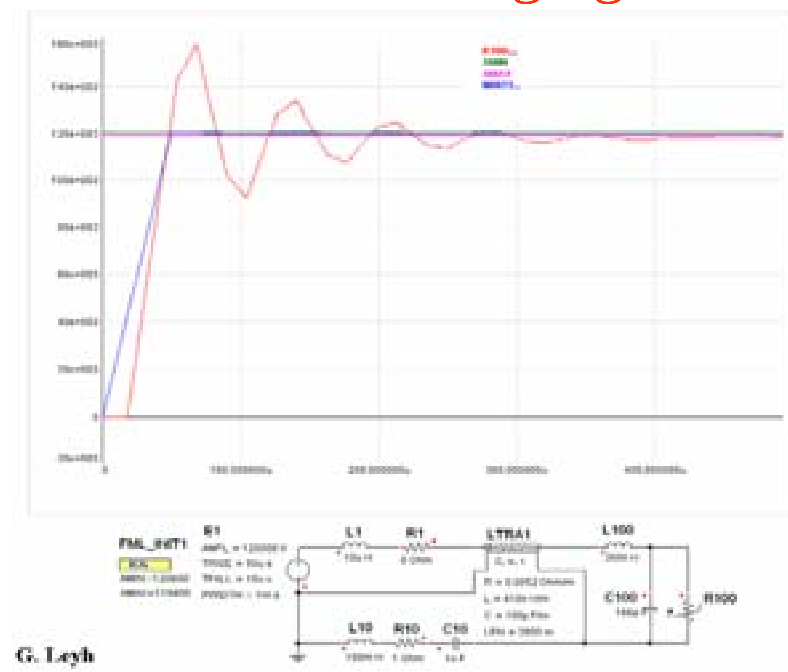


120kV Cable	50 Ω
Stored energy	1.3kJ
Delay time	~15 μsec
RMS Current	12 amps

Slowing down the rise time is not enough, high loss snubber would be needed to correct ringing

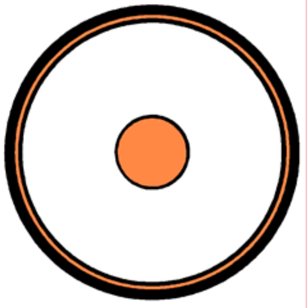
Note most high voltage cables are <50 ohms





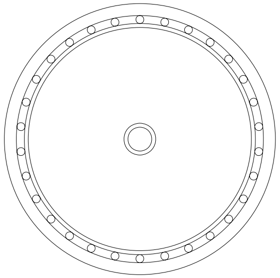
Cable Length question?

High voltage cable 50 Ω



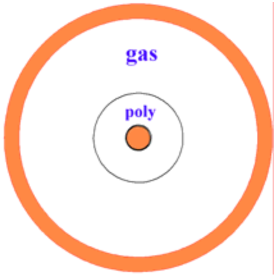
RG-220 CABLE rated at 120kV DC	2800M
Cable Impedance total	50 ohms
cables 120kV, 140A total	1344 Joules
Cable resistance	1.5 Ohms
Cable Inductance total	~470 uHy
Cable Capacitance total	~.19 uFd
Delay time	~15 μsec
Cable size	~1” OD
RMS Current in Cables	12.5 amps
Power Loss	220W

International Linear Collider
at Stanford Linear Accelerator Center



Cable Length question?
High voltage cable 90 Ω

RG-220 with double thickness of insulation	2800M
Cable resistance	1.5 Ohms
Cable Inductance total	~770 uHy
Cable Capacitance total	~.1 uFd
Cable Impedance total	90 ohms
cables 120kV, 140A total	754 Joules
Delay time	~15 µsec
Cable size	2.0” OD
RMS Current in Cables	12.5 amps
Power Loss	220W



Cable Length question?

High voltage cable 130 Ω

Needs Development

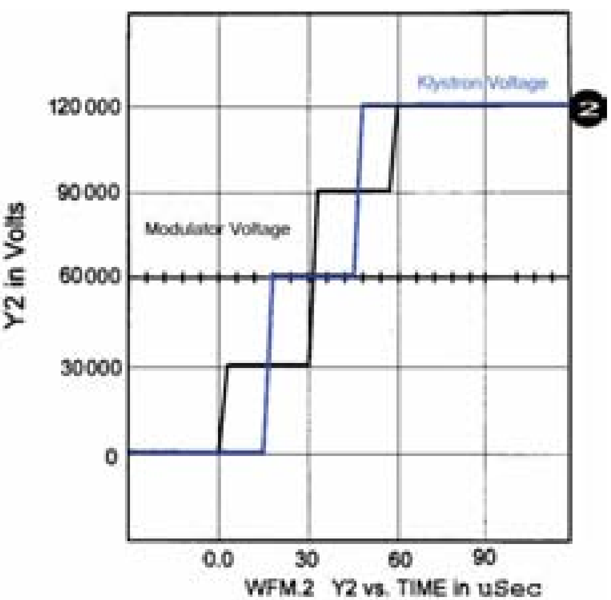
Andrew Nitrogen/SF6 & RG-220	2800M
Cable resistance	1.5 Ohms
Cable Inductance total	~1.2 mHy
Cable Capacitance total	~.067 uFd
Cable Impedance total	130 ohms
cables 120kV, 140A total	480 Joules
Delay time	~10 µsec
Cable size	3.0” OD
RMS Current in Cables	12.5 amps
Power Loss	220W

Note: Cable are have been made at above 100 ohms but not at this voltage

Cable Length question?

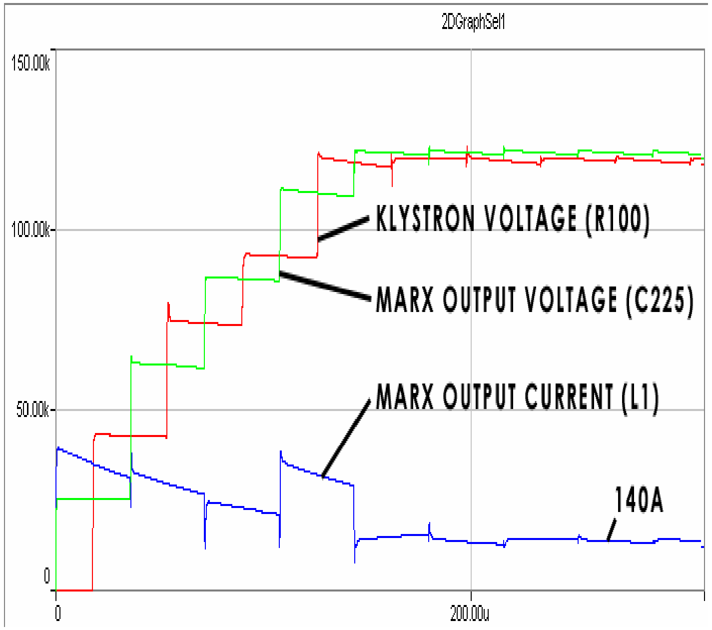
Step Ramp of High Voltage Cable

120kV Cable	50 Ω -130 Ω
Cable stored energy	1.5kJ to 480 joules
Cable size	1 each 2”-3” OD
Delay time	<15 µsec



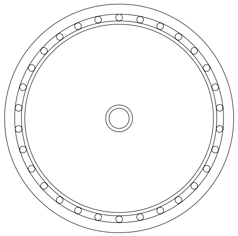
3 step ramp

A modulator can step ramp the voltage up in less than 80 usec the reflections can be corrected by timing.



Simulation 5 step ramp 50 Ω

Down side modulator must pulse higher current during step ramp to match cable impedance



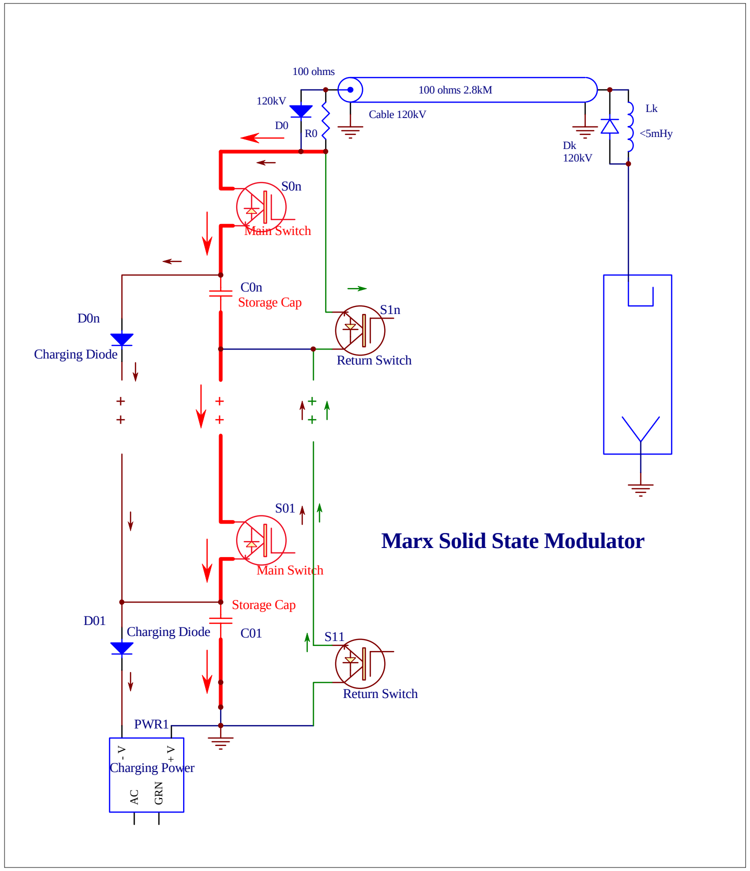
Cable Length question?

Arc Protection of Klystron with High voltage cable

An inductor of ~0.005Hy L/R>50uS with bypass diode & crowbar at the modulator with terminating resistor would protect klystron arcs.

PEP-II klystrons are protected using this method. A similar system was used at TFTR for neutral beam arc protection.

Stored energy of inductor ~55 Joules

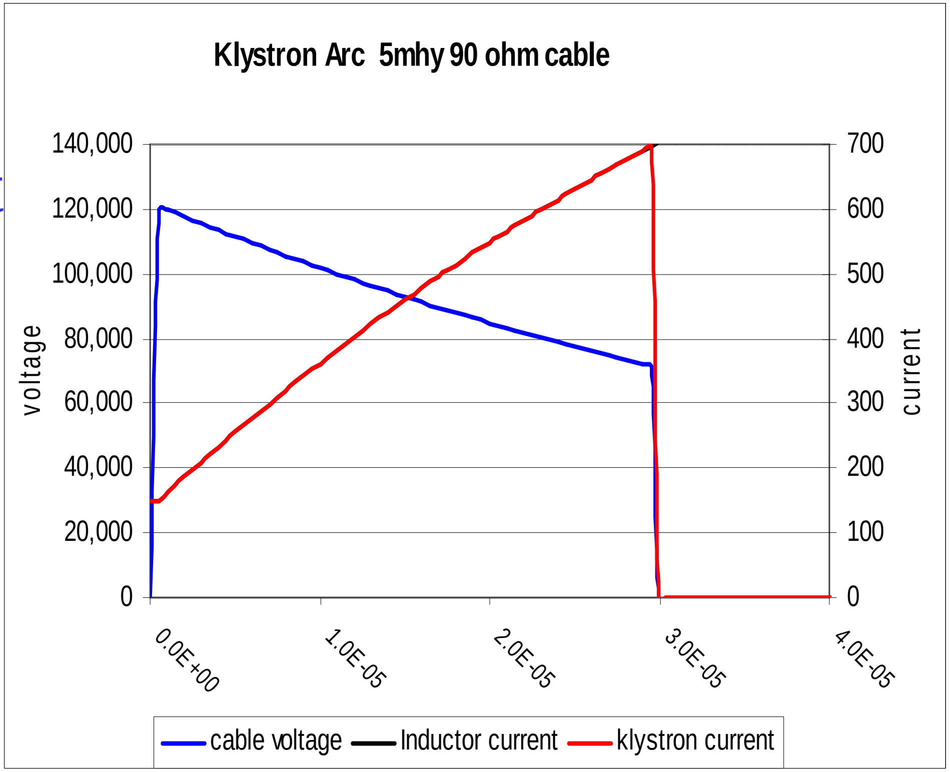


Cable Length question?

Arc Protection of Klystron with High voltage cable

Series inductor with bypass Diode & a resistor crowbar at the modulator the klystron arc current would be limited to would protect klystron from klystron arcs.

Less than 3 Joules and I*I*t<10 in klystron arc



Reliability of High voltage cable

1) Over 1,500 KM of High voltage 120-300kV AC extruded cables have been installed in the last 10 years by just one cable manufacture.
2) 177 KM of 150kV DC cable was installed in France in 2002 for power distribution
3) Duty factor if ILC cable is1.7mSec at 5 Hz or ~0.042 compared to 60 Hz operation.
4) MTTF of the 2.8kM cable is ~1500 year at 60 Hz or 35,000 year with duty factor added.
5) MTTF of any cable failure is 5.3 year to 127 years depending if you use the duty factor.

Reliability of High voltage cable

3 LITERATURE FROM JICABLE 2003

The first paper with interesting information is from ABB [7]. ABB takes the present experience with their cables and accessories operating at stress levels of 12 to 14 kV/mm as an expectation for other operating systems that could work on the actual EHV voltage class range at a similar electric field stress of 12 to 14 kV/mm due to other dimensioning of the cable. Although this extrapolation has some drawbacks, it is a reasonable approach. ABB assumes that based on this approach, for EHV cable this would lead to 0.024 failures per 100 km per year (or 0.038 failures per 100 miles per year).and for the EHV accessories about 0,01 failures per 100 accessories per year. In reference [1], an XLPE double circuit of 15.5 miles with 48 accessories per circuit phase (= 288 accessories in total) has been chosen for comparison with a HPFF cable. For such an XLPE cable double circuit, the ABB figures in this reference would lead to a total number of faults in 40 years of 1.4 failures for the cable and 1.2 failures for the accessories, making in total about 3 failures for this 15.5 miles double circuit per 40 years. This is an excellent reliability indeed (if ABB's assumptions are correct).

Conclusions

Long cables between Klystron and Modulator

1) Over voltage can be avoided with low power snubber loss by Step Pulsing the cable.
2) The klystron can be protected by the addition of a inductor with bypass diode and terminating the cable at the modulator end.
3) A single cable per klystron would reduces the installation costs and improve reliability.
4) Using a high impedance cable would reduce the peak pulsed current and reduce the power loss due to cabling.
5) Modern extruded cables have the reliability needed for ILC.

The Only modulator that can perform all of these requirements is the solid state Marx design