Development of Klystron Modulators for High Power RF/Microwave Systems for Particle Accelerators : RRCAT Experience





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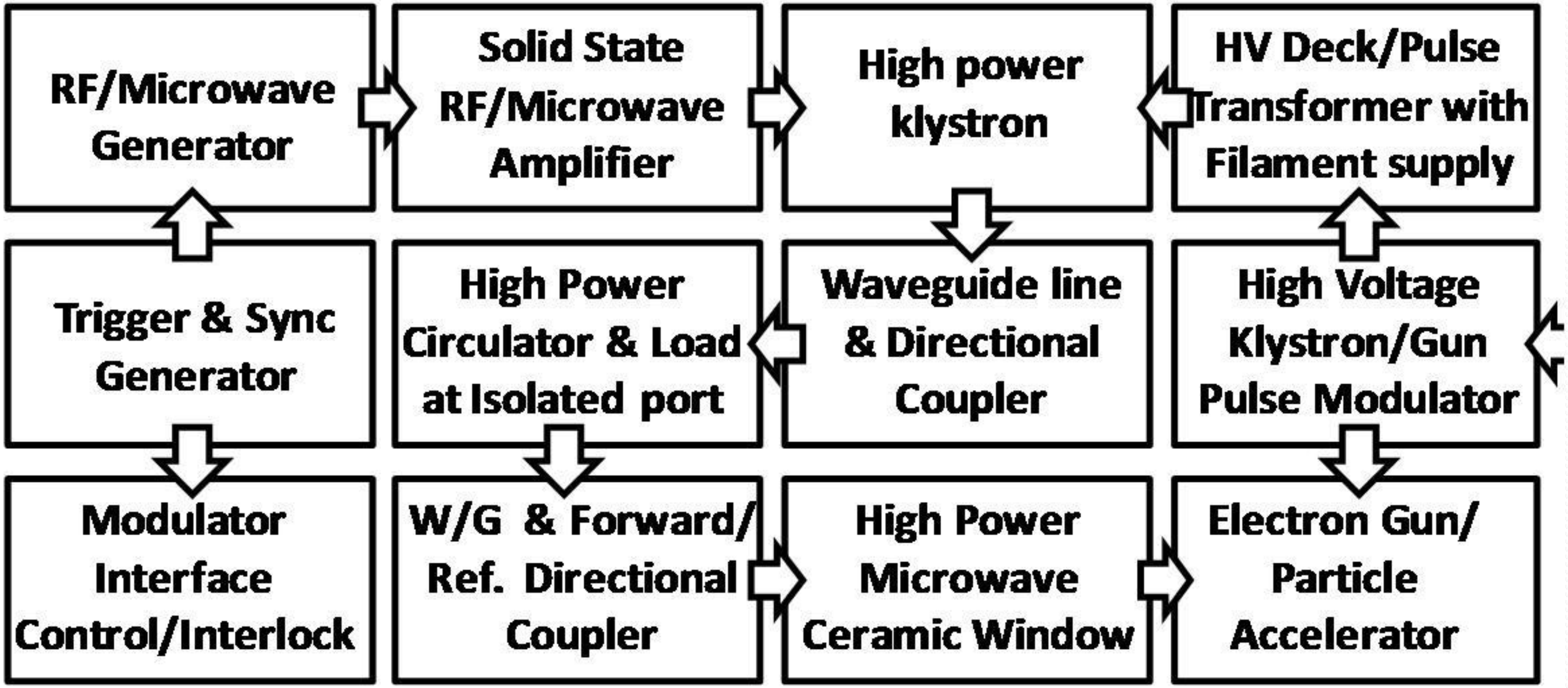
Contents

- Introduction
- Typical RF system for accelerators
- Solid state microwave amplifiers
- Pulse Modulator
    - Line type modulator
    - Solid state bouncer modulator R & D
    - Marx Modulator R & D
    - Converter Modulator R & D
    - Associated technologies development
- WR 2300 Waveguide components
- Results of systems built at RRCAT.
- Conclusion

Introduction

- The pulse modulator stores the electrical energy, and then discharges a fraction or all of this stored energy into the load.
- The microwave tube converts the electrical energy received from the modulator into the RF/Microwave .
- The pulse modulated RF/Microwave generated from microwave tube is applied to a resonant accelerating structure/cavity.
- The characteristics and quality of the beam of particle accelerator depends on the high power pulsed RF/Microwave system.
- Various considerations on the rise time/fall time, flat top, ripple on pulse top, stored energy, efficiency, reliability and safety are the key factors in designing these high power systems.
- Electrical safety, fire safety and elimination of burn out is of prime importance.
- Serious considerations for oil free construction.

- **RRCAT has also taken up development of key technologies for advanced accelerators.**
- **A solid state bouncer modulator operating at 100kV, 20A was successfully designed, developed and supplied to CERN under Novel Accelerator Technology, (NAT) collaboration in LINAC 4 project. Further efforts on other advanced modulator design and construction are also underway.**
- **A 1.3 MW pulsed test stand at 352.2 MHz was successfully designed and developed to qualify devices, subsystems and components developed in-house for Indian as well as International collaboration projects.**
- **Development of RF systems at 1.3 GHz as well as test set ups are in progress for SCRF technology development.**

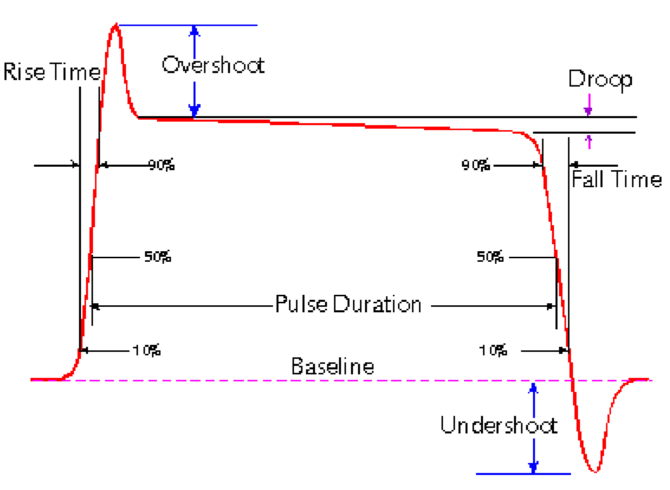


A typical klystron based microwave system

For a particular tube following considerations are important for selection/design of a modulator.

- ✓Pulse duration
- ✓Operating voltage and current
- ✓Pulse repetition rate
- ✓Pulse rise/fall times
- ✓Spurious modes
- ✓Tube protection (arcing of tube)
- ✓Pulse flatness
- ✓Efficiency
- ✓Cost, size & weight
- ✓Reliability and maintenance ease
- ✓Electrical and Fire safety

Practical pulse characteristics



Status of RF/Microwave systems developed at RRCAT

Line type thyratron switched conventional modulators

	Device	Parameters PWR/f/V/I	Machine/Use	Status
1.	Klystron	5MW, 3µsec 2856MHz 127kV,86A	20MeV SRS Injector RRCAT	Operational > 19yrs
2.	Magnetron	2MW,2998 MHz 41kV,100A,4µsec,200Hz	8/12MeV, Nuclear Physics	Operational >17 yrs Mangalore Uni.
3.	Magnetron	2MW -,,--	6/8/12MeV,	R&D
4.	Klystron	6MW,25 kW, S-Band 14µsec,300Hz	10MeV,10kW LINAC	Operational 8 yrs.
5.	Magnetron	3MW,2998 MHz 55kV,120A,200Hz	Test stand	R & D
6.	Klystron	45MW, 2856 MHz 300kV4.5µsec,10Hz	High Energy LINAC	Construction

Indigenous microwave tube development (CEERI Collaboration) and associated test stations developed by RRCAT.

1.	Klystron	5MW,2856 130kV,90A	Test station developed and supplied by RRCAT to CEERI
2.	Magnetron	2MW, 2998 42kV,110A 5microsec 250Hz	Test station developed and supplied by RRCAT to CEERI.

Long pulse solid state klystron modulator develoment

• Klystron	1.3MW, 352.2MHz 110kV/24A,800µsec	CERN LINAC4	Commissioned.
• Klystron	1 MW, 352.2MHz 100kV/20A,500µsec, 25Hz	3MeV RFQ	Under tests.

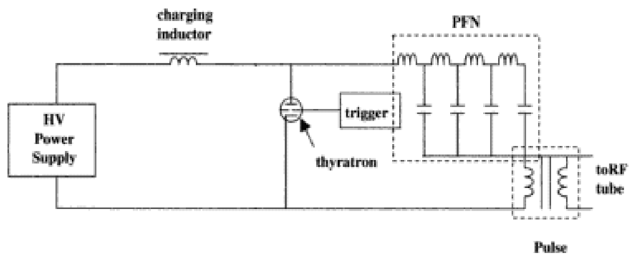
Klystron modulator R & D and in-house developments

a) 100kV, 20A, 1.6msec 10Hz Marx Modulator
b) 100kV, 20A, 3msec, 10 Hz Converter Modulator.

Component development:

- ✓ Optical drives
- ✓ Solid state high voltage switch R & D
- ✓ Pulse transformer design, development and tests.
- ✓ Fault protection systems.
- ✓ Computer control and data logging for modulator.

Line-type modulators



Simplified circuit diagram of a line-type pulse modulator.

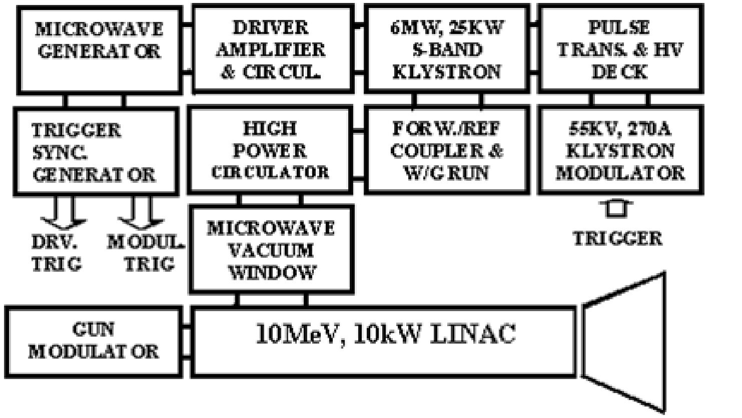
Main Parts

- Charging scheme
- Pulse forming network
- Thyratron/SCR switch
- Isolating element
- Pulse transformer
- Damping networks..

- Energy-storage device is essentially a lumped-constant transmission line so it is called line-type modulator.
- Pulse Forming Network (PFN) is charged to the required voltage.
- Switch (thyratron) is triggered and PFN delivers the all stored energy to load in the form of a rectangular pulse.
- Charging element (inductor) isolates the discharging circuit from the power supply during the pulse.

A 15 MW pulse modulator for 6 MW klystron:

10MeV, 10kW LINAC at RRCAT



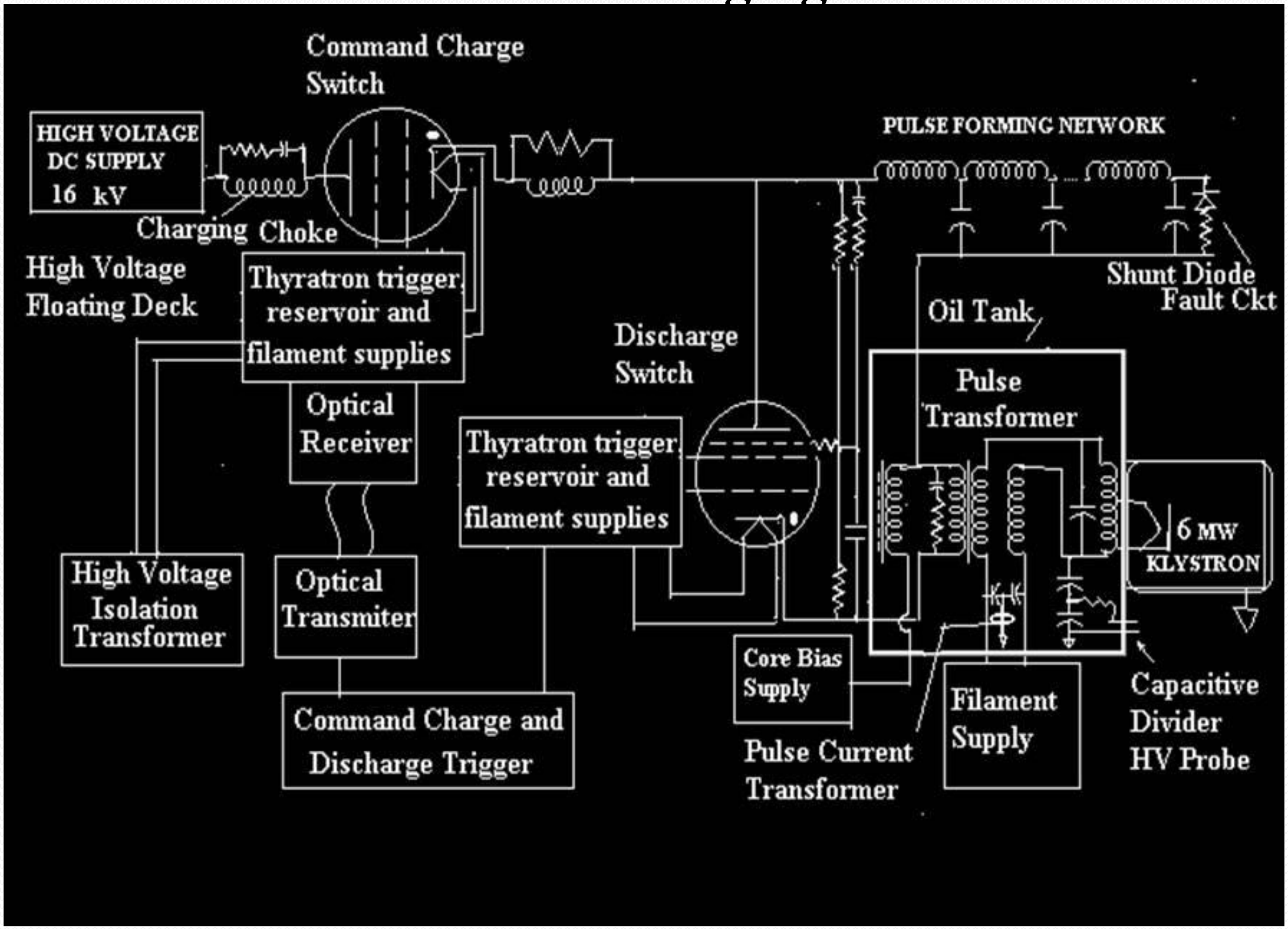
SCHEMATIC OF 6MW S-BAND MICROWAVE SYSTEM

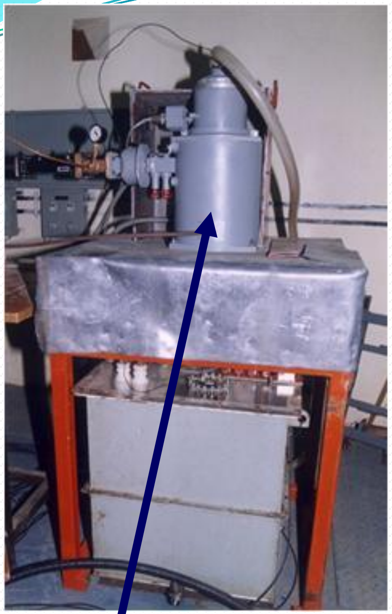
Modulator Specifications		
Pulse output power	MW	15
Pulse voltage output	kV	55
Output impedance	Ω	200
Pulse duration	µS	15
Rise time	µS	<1
Fall time	µS	<2
Flat top variation	%	< ±1
Mean output power	kW	90

Microwave system specs.		
Peak o/p power	MW	6
Average o/p power	kW	25
Operating frequency	MHz	2856
Pulse duration	µS	12.5/6.8
Pulse repetition rate	Hz	300/800
Pulse top variation	%	±1
Pulse rise time	µS	<1
Pulse-pulse stability	%	<1
Frequency stability	/day / °C	$1x10^{-8}$ $1x10^{-8}$

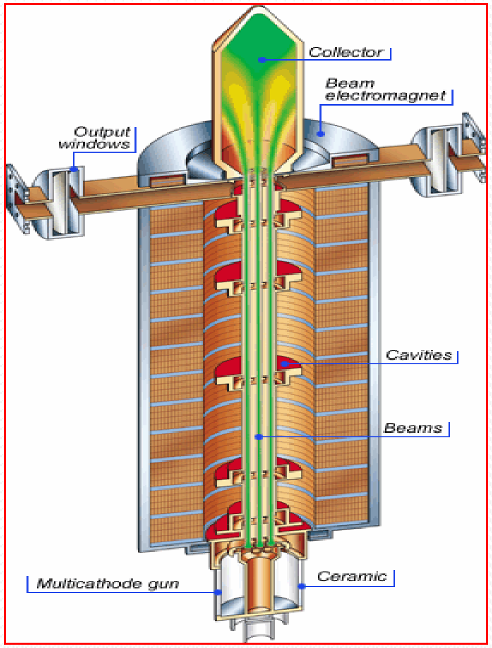
Klystron specifications		
O/p power peak	MW	6
O/p average	kW	25
Frequency	MHz	2856+/-5
Pulse duration	µS	16
Gain	dB	55
Beam voltage	kV	55
Beam current	Amp	280
Output	W/G	WR 284
Input	Coax.	N type

Schematic of the high power long pulse klystron modulator with command charging at RRCAT





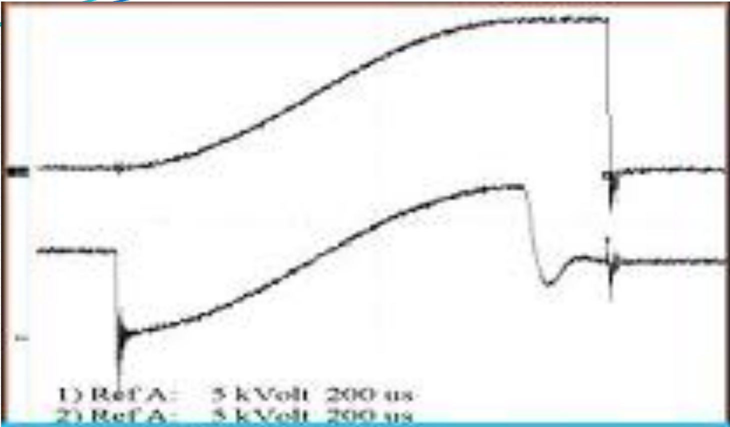
6MW Peak power S-Band Multi Beam klystron (MBK) without shield

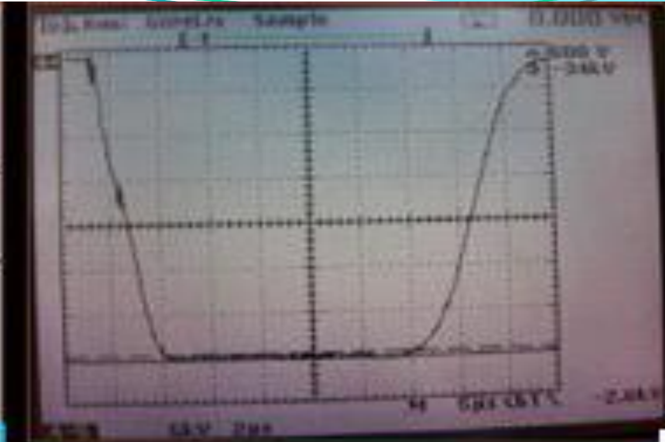


An MBK schematic

6MW Klystron with X ray shield connected to waveguide line to LINAC

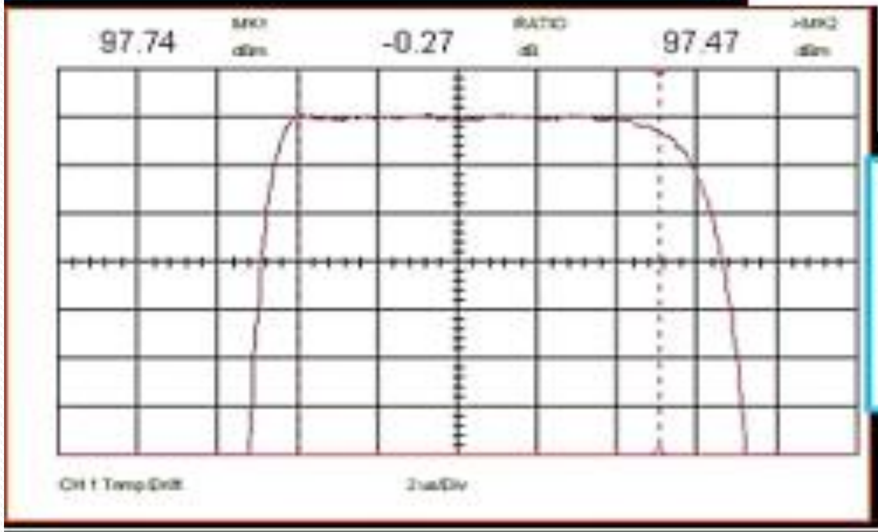
6MW Klystron based microwave system with modulator and microwave drive chassis for 10MeV LINAC





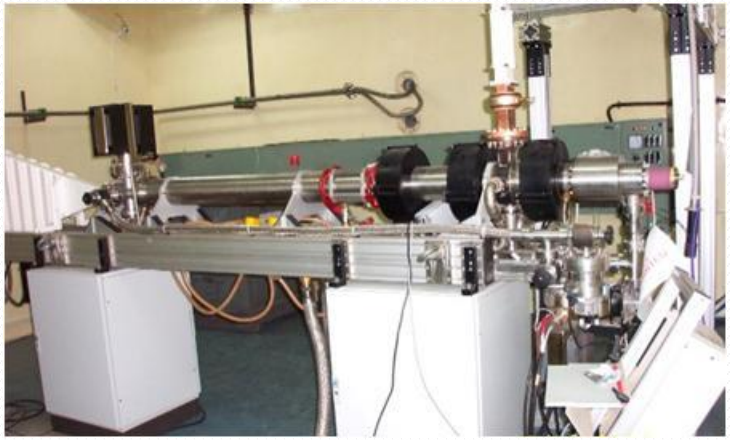
PFN charging voltage after the thyratron and lower trace is before thyratron @200 µsec/ div horizontal scale.

Klystron beam voltage @2µsec /div. Variations < ± 1%. With Divider ratio1:1.47 peak voltage is 50kV.



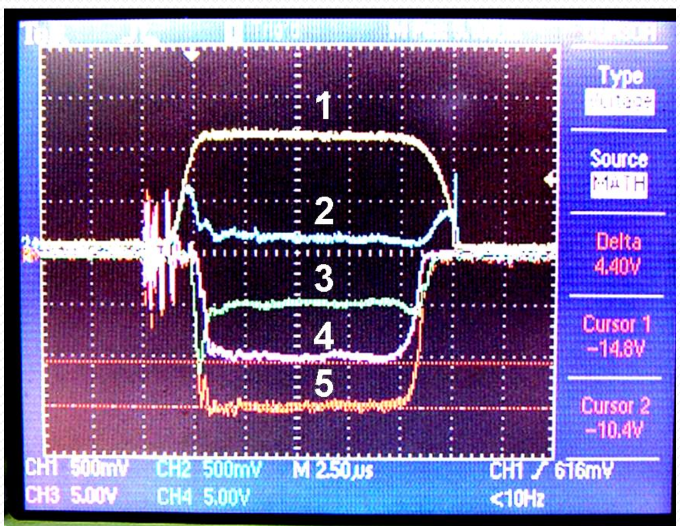
6.4MW output from the klystron the flat top variations are within 0.1dB. Horizontal @2µsec /div.

Microwave system for 10MeV LINAC



10MeV Electron LINAC RRCAT

Electron beam on target

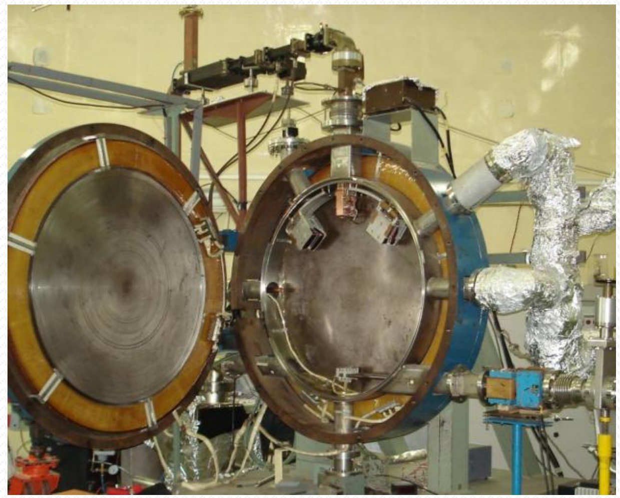


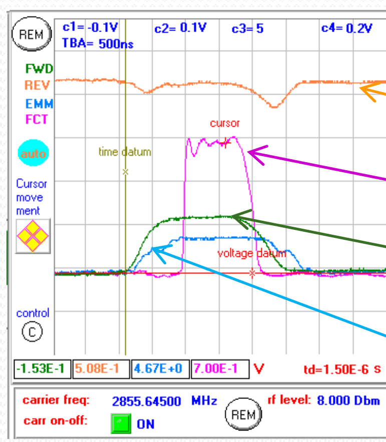
1.	FORWARD POWER	6MW
2.	REFLECTED POWER	100kW
3.	FIRST TARGET PEAK BEAM CURRENT	100mA
4.	SECOND TARGET BEAM CURRENT	200mA
5.	TOTAL PEAK BEAM CURRENT	300mA

@ 10 MeV BEAM ENERGY

MICROWAVE SYSTEMS DEVELOPED BY RRCAT

5MW peak power S Band pulsed klystron based microwave system for 20MeV Microtron pre-injector for Booster Synchrotron of Indus 2





Reflected power

Beam current

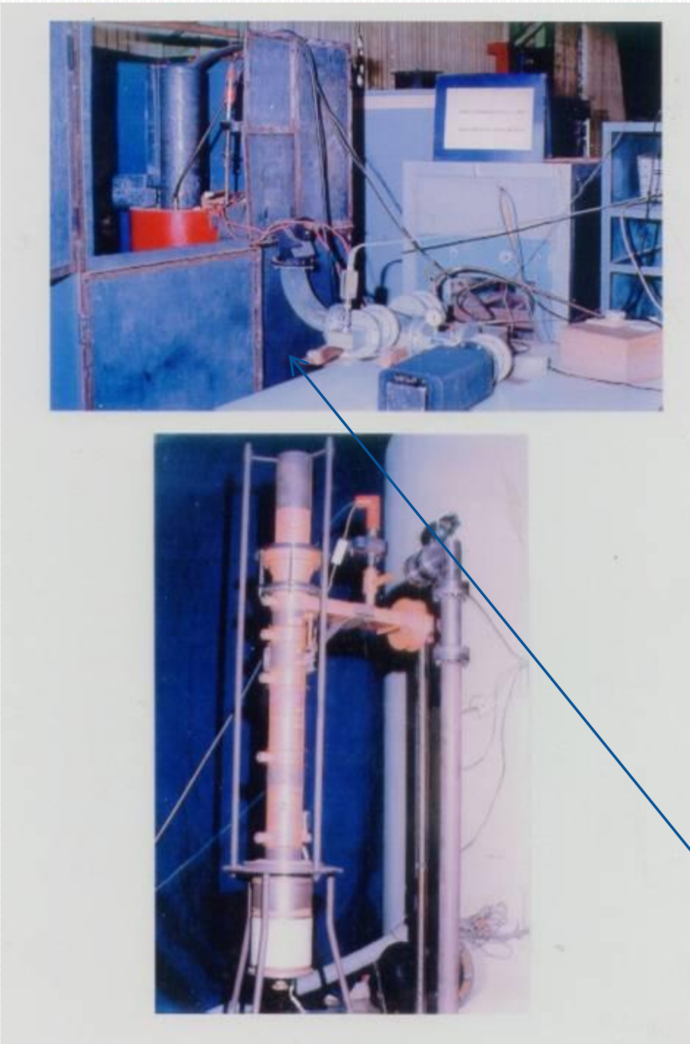
Power fed to cavity

Emission current

20MeV Microtron results

2MW Pulsed Magnetron based microwave system for 8MeV Microtron delivered to Mangalore University

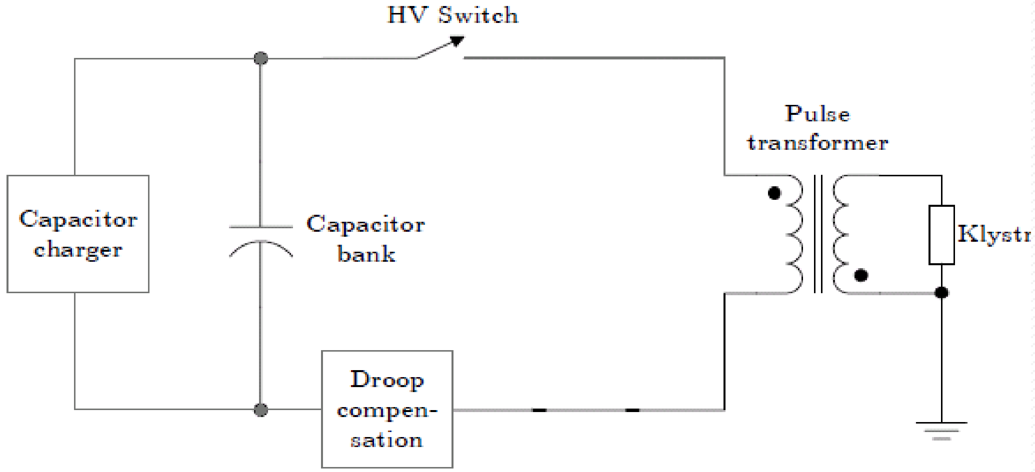
MICROWAVE TEST STANDS FOR INDIGENOUS TUBE DEVELOPMENT



2MW MAGNETRON HIGH POWER TEST STATION DEVELOPED BY (RR)CAT

HIGH POWER TEST STATION DEVELOPED BY (RR)CAT, LOWER PHOTO IS THE FIRST 5MW INDIAN KLYSTRON

Solid state hard switched modulator development



Main parts

HV switch and optical drive

Storage capacitors

Bouncer droop compensation

Pulse transformer

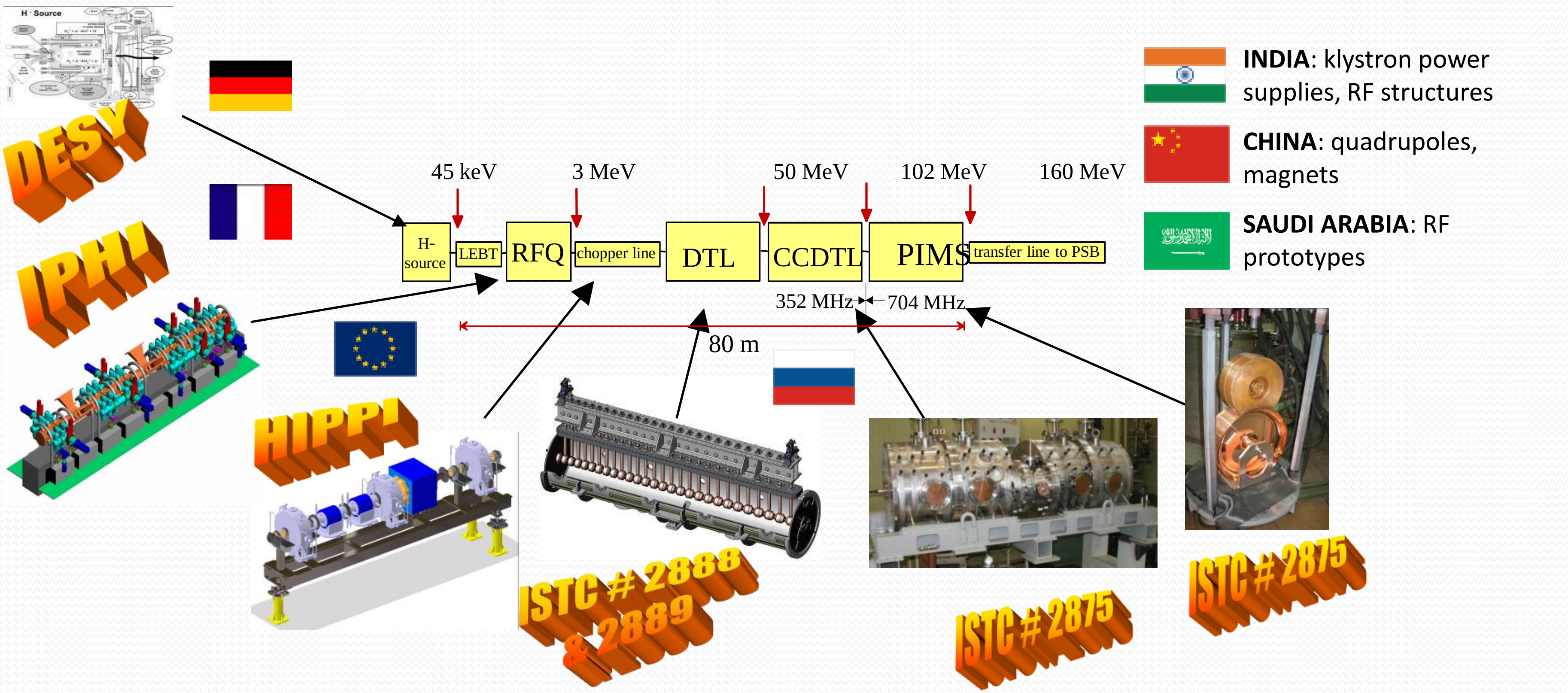
Damping circuits

- The capacitor bank is charged to the required output voltage.
- HV switch is turned on and capacitor is discharged for required pulse duration and then turned off.
- A pulse appears at load during the discharge period.
- A bouncer circuit compensates the droop during discharge period. RRCAT proposed active compensation.

1MW CW Klystrons for proton LINAC at RRCAT

Parameter	Unit	TH2098
Output power	MW CW	1
Operating Frequency	MHz	352.2
-1dB Elct. BW	MHz +/-	0.8
Gain	dB	40
Driver power max.	W	200
Efficiency	%	70
Beam Voltage	kV	90
Beam Current	A	20
Length	m max	4.8.
Height	m	1.85
Width	m	1.0
Weight with magnet	kg	2250
Output waveguide	WR 2300	FH

Collaboration with CERN :R&D on Linac4



Network of collaborations for the R&D phase, with the support of the EU-FP6 and ISTC, or in the frame of CERN-CEA/IN2P3 and CERN-India agreements.

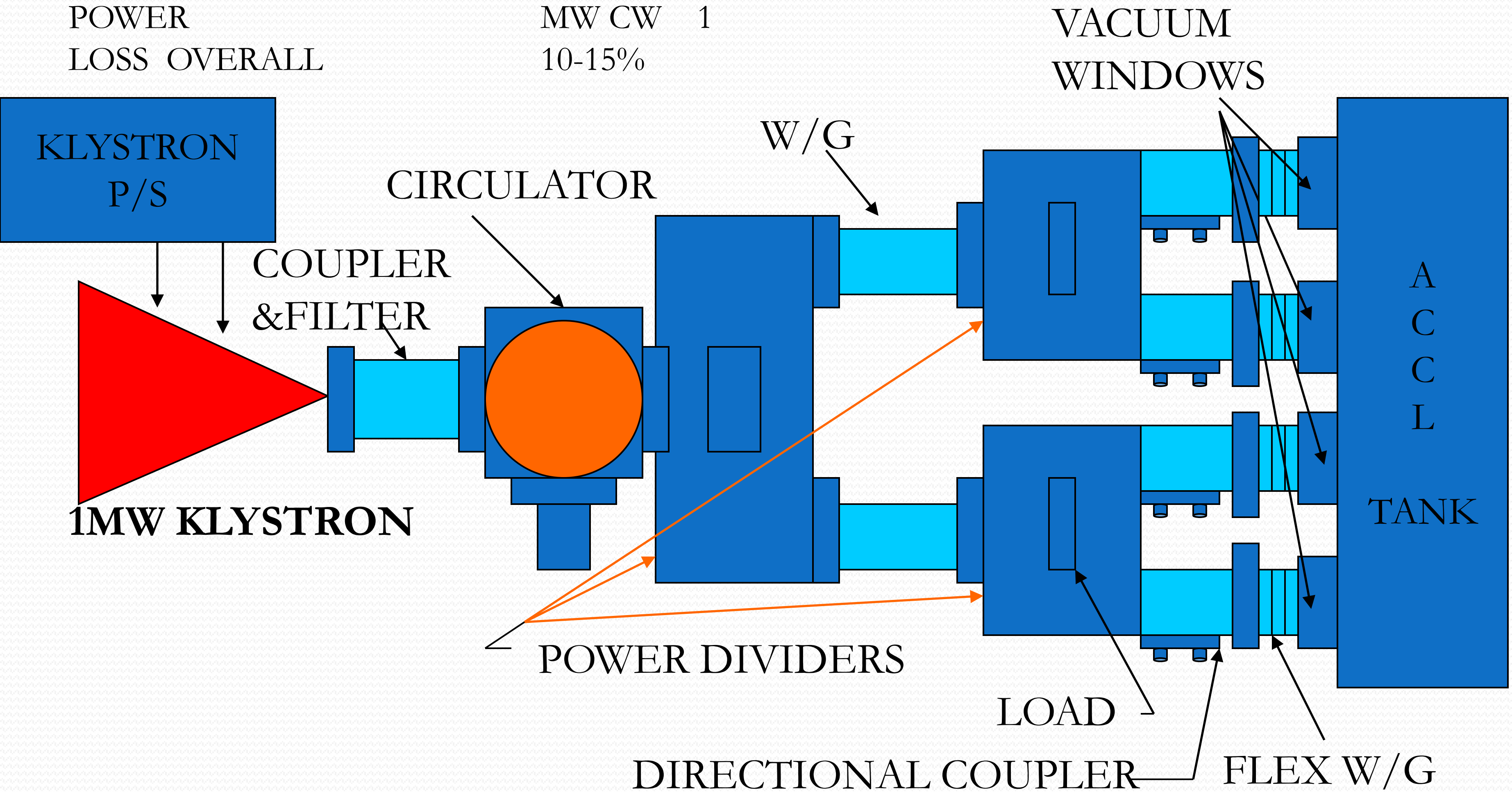
Courtesy : Dr. M. Vretenar, CERN.

Specifications of 100kV Solid state bouncer modulator developed by RRCAT under DAE CERN NAT project

Parameter	Value
Solid State Klystron modulator type	Bouncer
High Voltage pulse amplitude	-10 kV to -110 kV
High Voltage pulse width measured at 70% to 70 % of peak.	800 µsec
Minimum Flat top available	600 µsec
Maximum current during pulse	24 A
Pulse repetition rate	2 Hz
Acceptable voltage drop	≤ 1.0 %
Allowed ripple on flat top (≥ 10 kHz)	≤ 0.1 %
Rise time/fall time	<100 µsec
Energy dissipated in klystron arc	10 J

TYPICAL RECTANGULAR WAVEGUIDE SYSTEM FOR PROTON LINAC

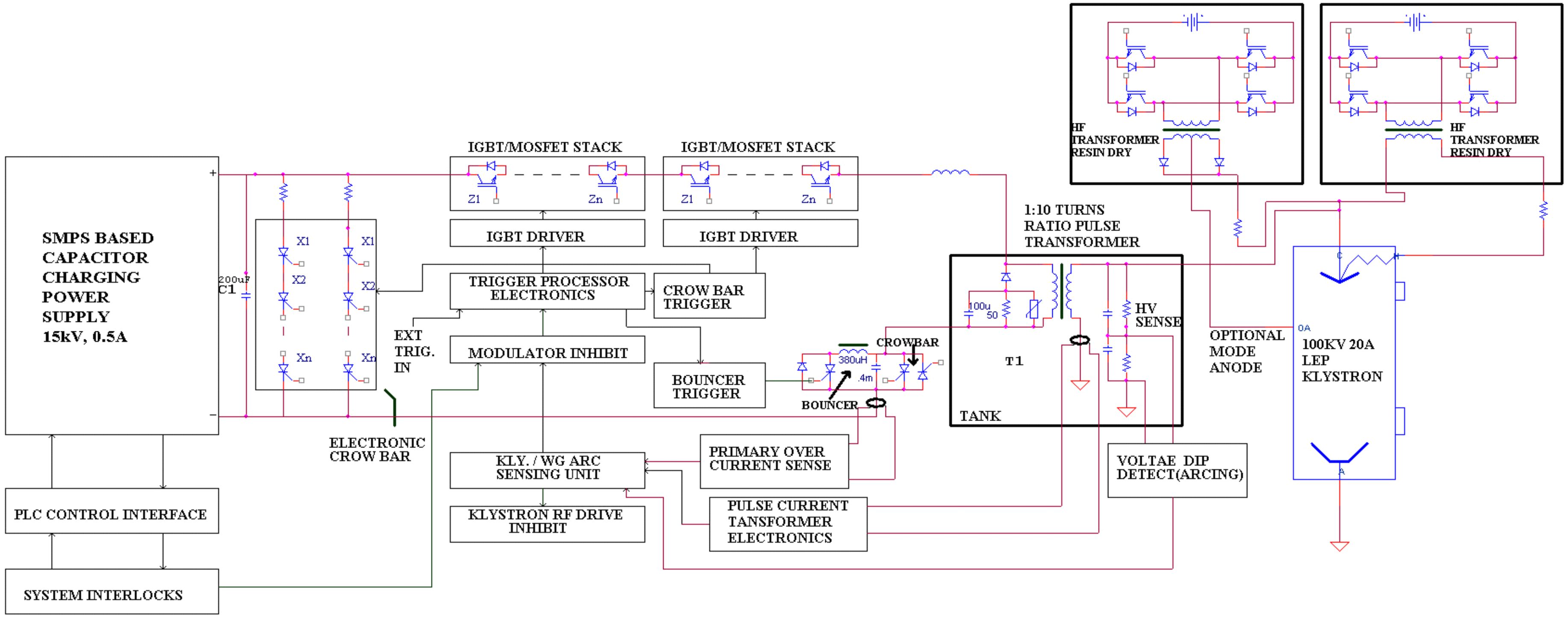
W/G MATERIAL	AL 6061 ALLOY
FREQ	MHz 350/700
POWER	MW CW 1
LOSS OVERALL	10-15%



Main Features of Bouncer Klystron Modulator :-

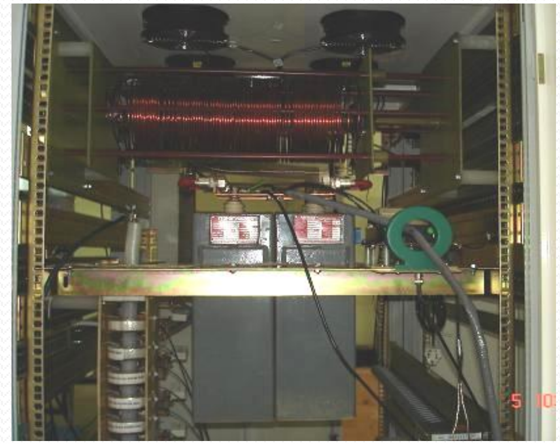
- Simplified Hard switch type design as compared to bulky PFN & difficult PFN tuning of Line type scheme.
- Klystron arc energy < 10J, Protection by fully controlled series switch.
- Reduced Main Capacitor size by using droop compensation design.
- Output voltage droop <1% by droop compensation using bouncer network
- Excellent pulse to pulse stability
- Adjustable Bouncer switching time for droop compensation setting

Solid State Modulator for LINAC 4 Project at CERN



Solid State Modulator for LINAC 4 Project at CERN

Modulator connected to 110kV resistive load



Bouncer elements and HV switch assembly

Charging and filament supplies

Interlock, control and trigger chassis.

Bouncer Results

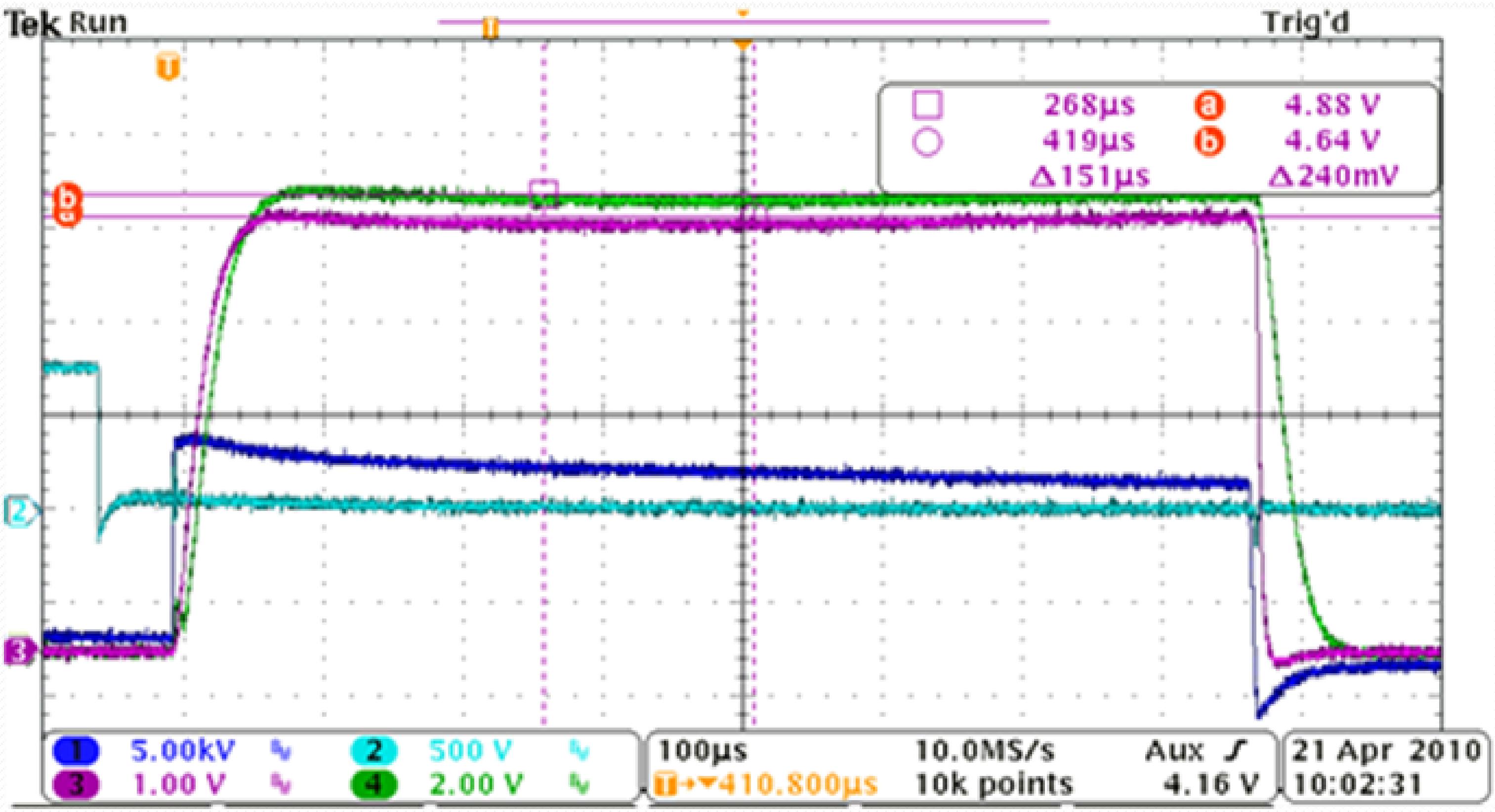
Bouncer Specifications

Parameter	Design Targets	Achieved results
Klystron modulator type	Solid state Bouncer	Solid state Bouncer
High Voltage pulse amplitude	-10 kV to -110 kV	-10kV to -110kV
High Voltage pulse width at 70% to 70 % of peak.	800 µsec	800 µsec
Minimum Flat top available	600 µsec	600 µsec
Maximum current during pulse	24A	24A
Pulse repetition rate	2Hz	2Hz
Acceptable voltage drop	$\leq$ 1.0 %	$\leq$ 1.0 %
Allowed ripple on flat top ($\geq$ 10 kHz)	$\leq$ 0.1 %	$\leq$ 0.1 %
Rise time/fall time	<100 µsec	<80 µsec
Limiting energy dissipated in klystron during its arc	<10 J	<10 J
Peak output power	2 MW	2 MW
Average output power at 2 Hz PRR	3.2 kW	3.2 kW

100kV, 20A, 800us, 2Hz Bouncer Modulator

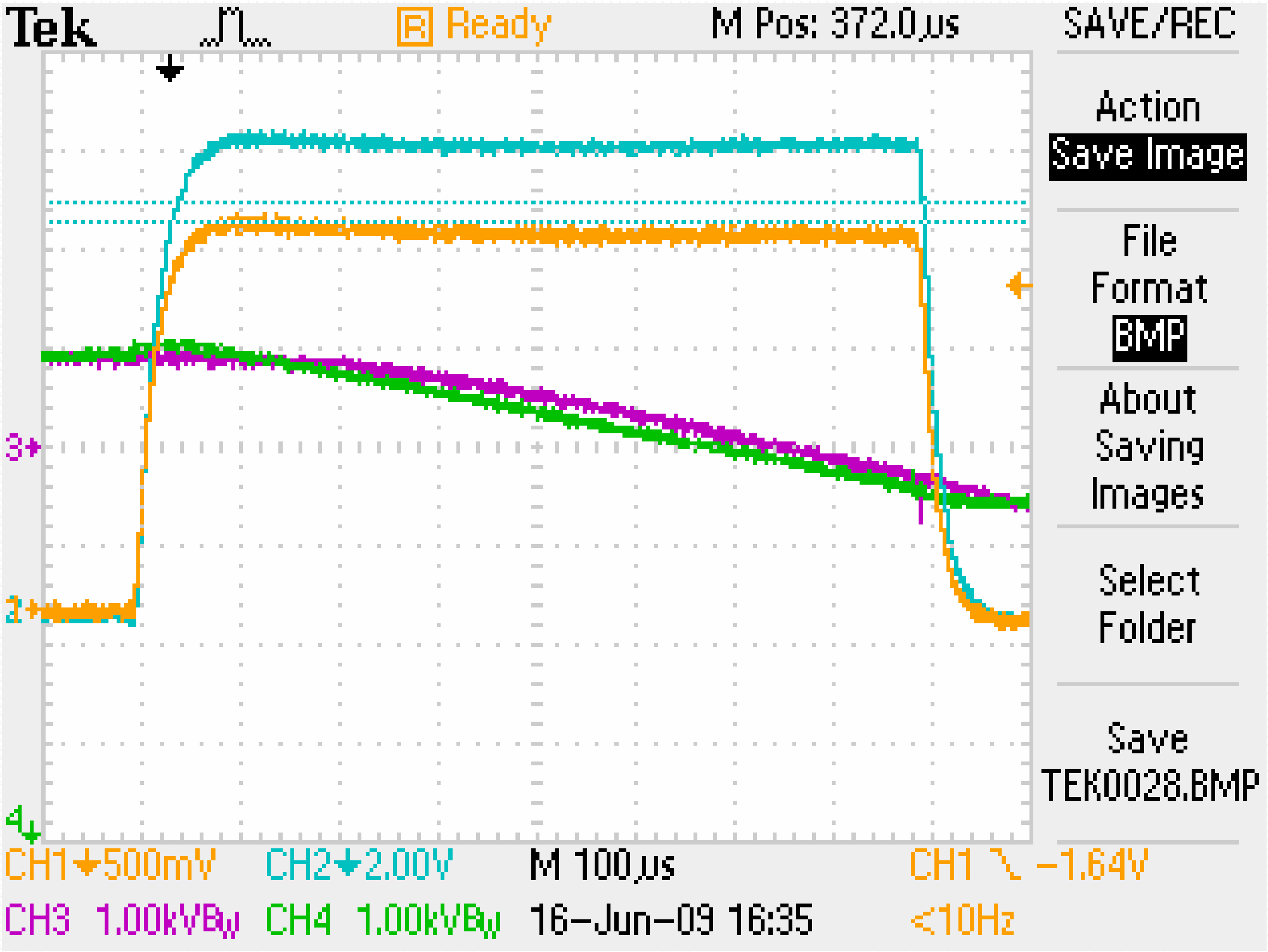
Sl.No.	Main Component	Parts with description	Quantity
1	Charging power supply 12kV, 1A	Capacitor charging power supply 15kV, 1	1Nos.
2	Filament power supply 30V, 35A with 120kV floating terminals	Floating power supply 30V, 35A	1Nos.
3	Modulating Anode power supply	DC power supply 40kV, 15mA	1Nos.
4	Pulse transformer unit	Pulse transformer 110kV, 1:10, 2 Hz	1Nos.
		Biasing Supply (10V, 10A DC power supply)	1Nos.
5	Undershoot network	Resistors 50Ohms, 20kV, 250 W each	4Nos.
		Diodes 20kV, 750 A pk	1Nos.
		Capacitor	
6	Main Switch	IGCT based stacked switch assembly (20kV, 300A),	1 Nos.
		Drivers auxiliary power supplies	1 set
		20kV, Isolation transformers for auxiliary supply	1 set
		Optical driver unit	1Nos.
		Optical fiber cables with connectors (1m length)	1 set
7	Safety Discharge Device	25 kV Electromagnetic relay with auxiliary contacts	1Nos.
		Resistors 1kOhms, 250W, 20kV, 10kJ each	2 Nos.
8	Crowbar 1 Network	24kV, 8 kApk SCR based switch	1Nos.
		Diode 20kV, 750 Apk Behlke make **(FDA 200-75A)**	1Nos.
		Resistors 50 Ohms, 20kV, 2 kApk each	4 Nos.
9	Main Capacitors	55 uF, 15kV	2 Nos.
10	Bouncer network	Capacitors 100uF, 3kV, 10A avg., 500A pk each	2 Nos.
		IGBT Switch 2400V, 600Apk , 400A DC	1Nos.
		Inductor 650 uH, 20 A rms, Air core	1Nos.
11	Control, Interlock and other auxiliary items	Cabinets, sub racks, high voltage cables, high voltage connectors, low voltage cables, low voltage connectors, electronic cards etc.	

Waveforms of 100kV, 20A, 800us, 2Hz Bouncer Modulator



1 : Primary high voltage terminal signal w.r.t. ground on normal scale (5kV/div.)
2 : Bouncer switch voltage signal on normal scale (500V/div.)
3 : Primary current signal (0.05V / 2A) on normal scale (1V/div.)
4 : Secondary output voltage signal (10000 : 1) on normal scale (2V/div.)

Waveforms of 100kV, 20A, 800us, 2Hz Bouncer Modulator



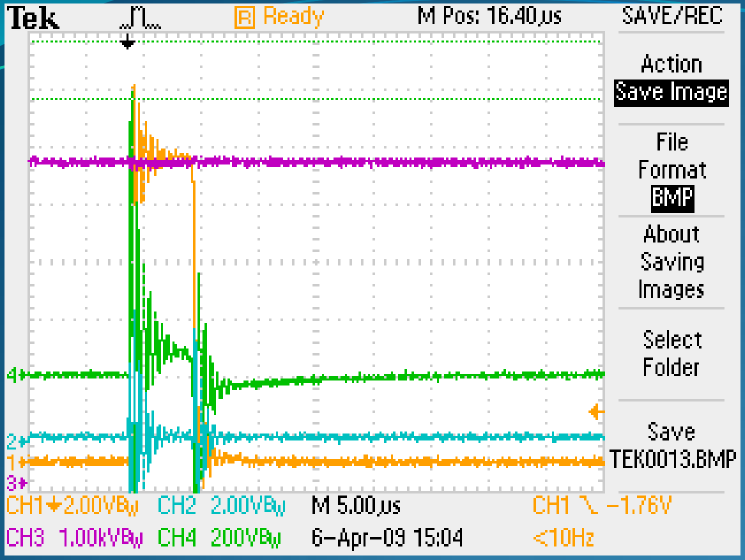
CH1 : Load current signal (CT factor = 0.1V/A)

CH2 : Output voltage signal (Divider Ratio = 10400 : 1)

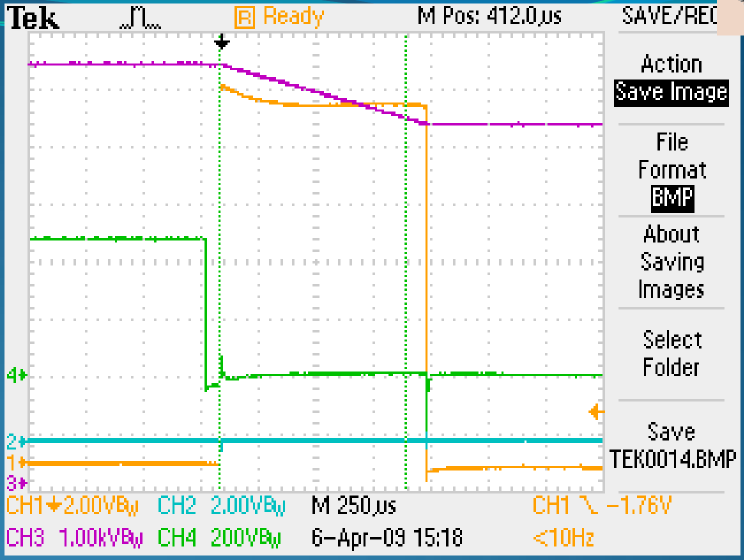
CH3 : Bouncer voltage signal using Tek Probe (1000:1)

CH4 : Main capacitor voltage signal using Tek Probe (1000:1)

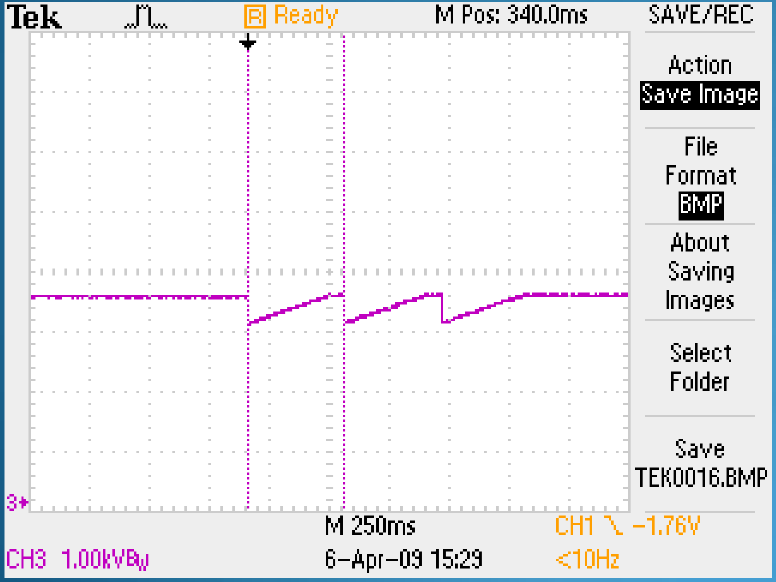
Modulator fast fault protection circuit testing for different faults



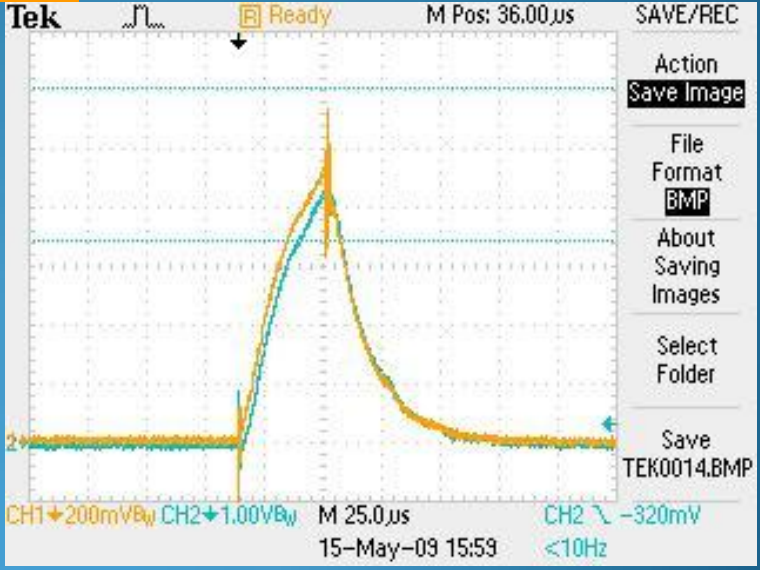
Pulse shut off due to 'Short circuit' fault @ 100 A setting



Pulse shut off due to 'Pulse width overrun' fault @ 850 us setting

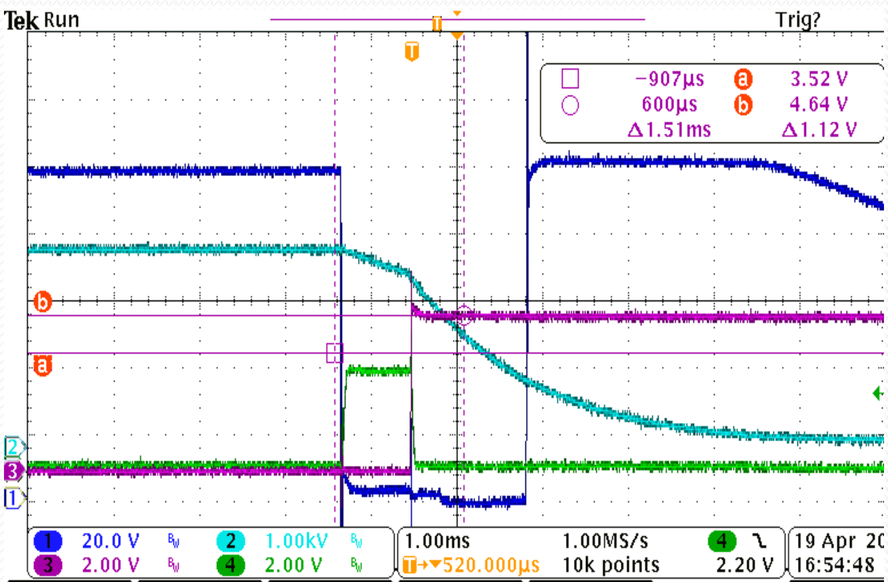


Pulse shut off due to 'Pulse repetition rate overrun' fault @ 3 Hz setting

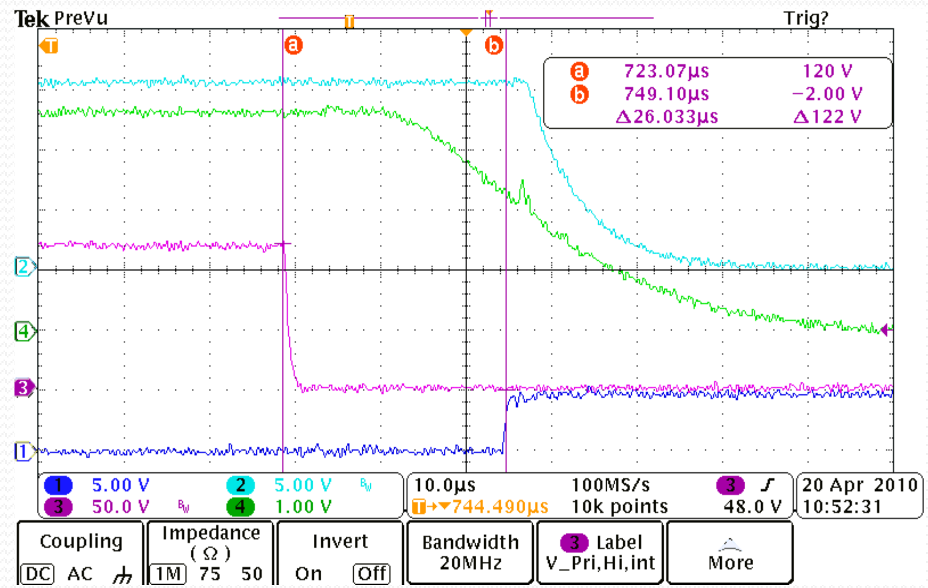


Pulse shut off due to 'Overvoltage fault' @ 40kV setting

Modulator fast fault protection circuit testing for different faults

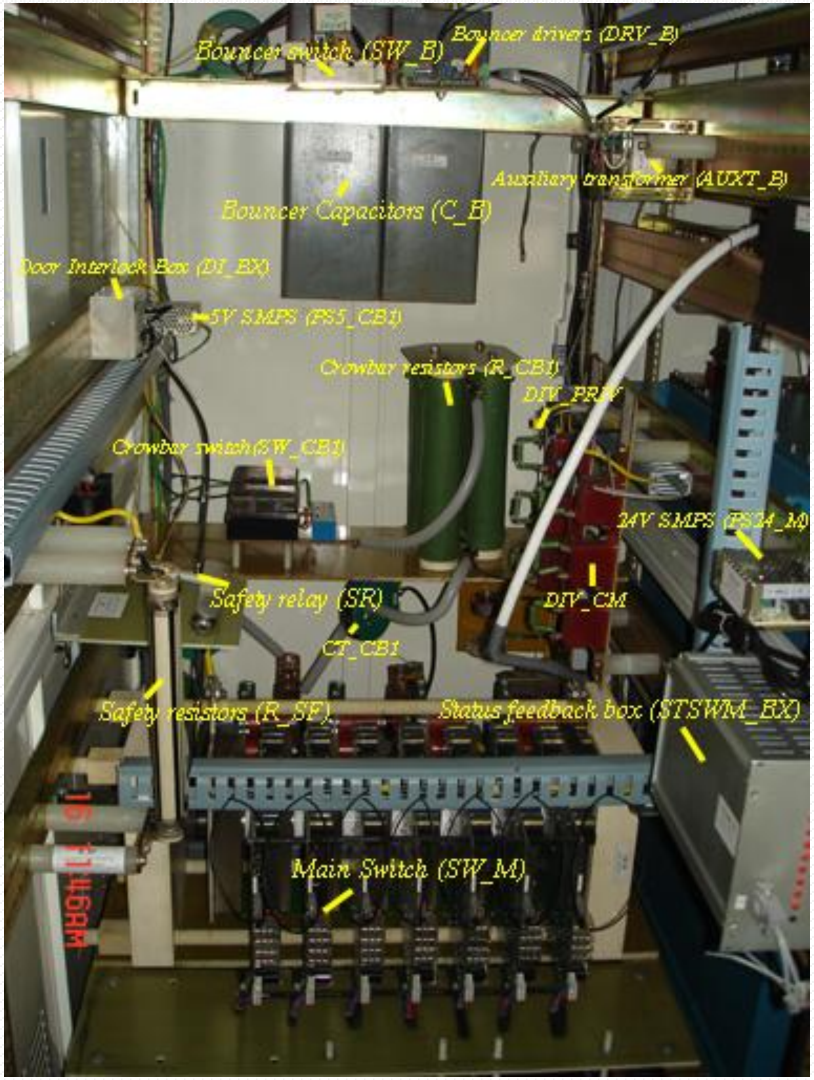


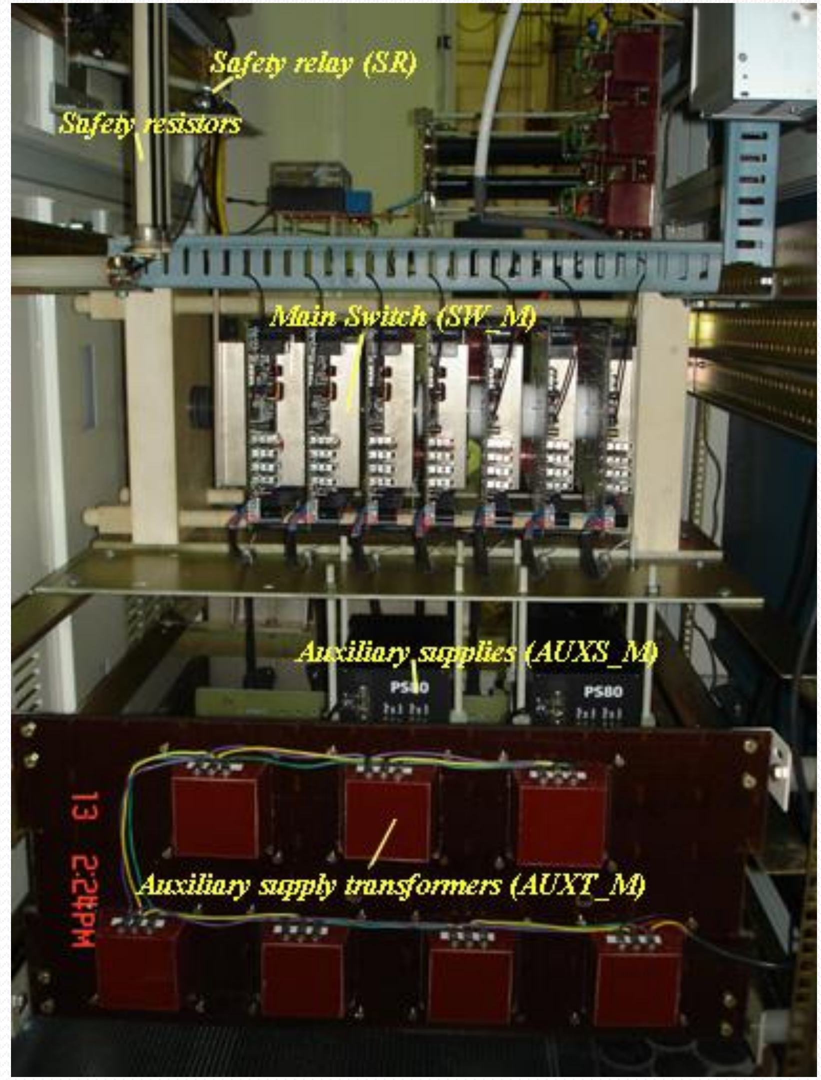
- Crowbar action & Pulse inhibit due to 'Pulse width overrun' fault @ 1ms pulse width setting



- Crowbar action & Pulse shut off due to 'Under voltage' detection at 750us

Photographs of Modulator components

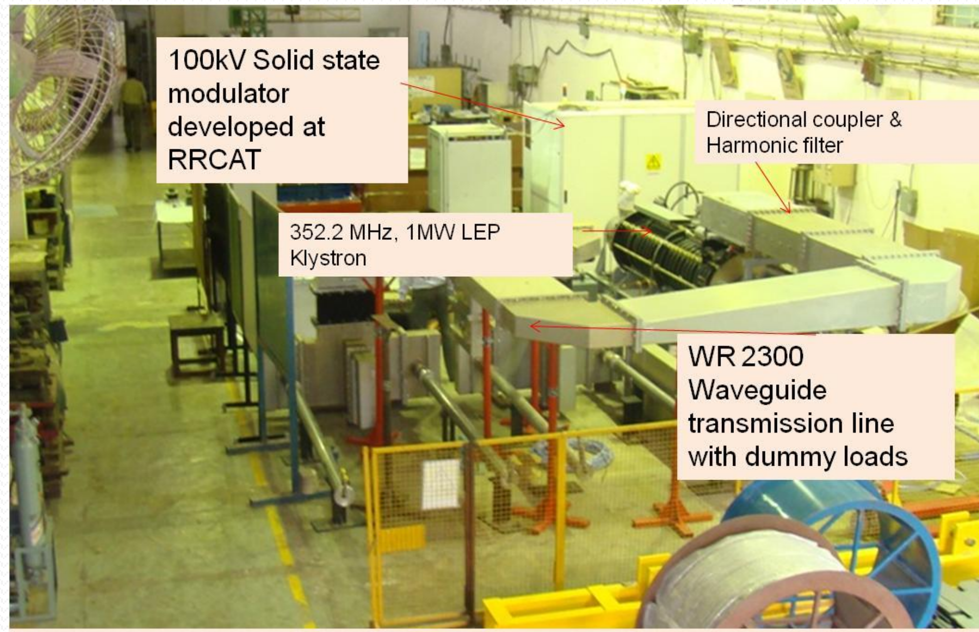




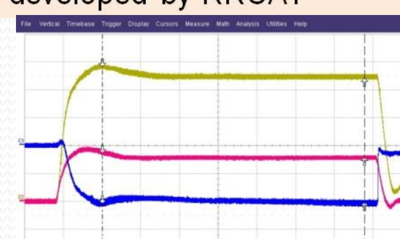
India-CERN Collaboration in LINAC 4

Two klystrons received earlier were tested to >1MW pulsed output power at 352.2 MHz at high power test stand developed at RRCAT.

Labview based modulator control and DAQ system



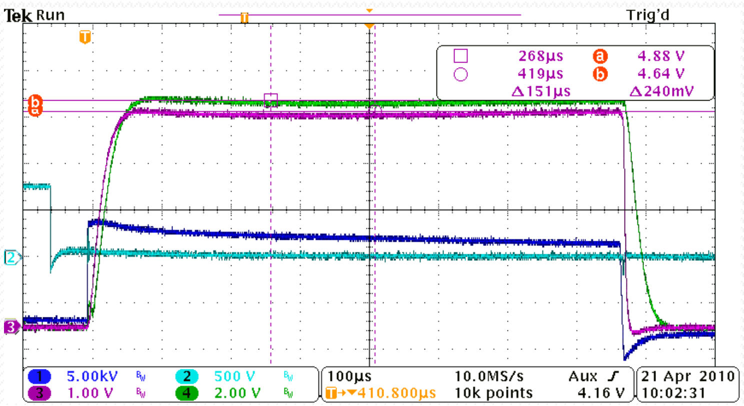
1 MW 352.2 MHz Test Stand with LEP TH 2089 Klystron and 100kV All solid state bouncer modulator developed by RRCAT



1.3MW 352.2MHz output from klystron .

Solid State Modulator for LINAC 4 Project at CERN

The solid state bouncer modulator prototype for LEP 1 MW klystrons for LINAC 4 project at CERN was designed, developed and commissioned. Modulator passed all tests at CERN and accepted. Currently it is in use at CERN at SM18 Hall.



Results of acceptance tests at CERN.
100kV, 20A, 800 µsec, 2 Hz

First use for calibrating 100kV divider at CERN May 2010

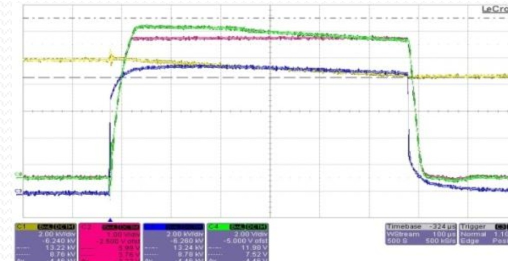
100kV RRCAT modulator during acceptance tests at CERN.

RRCAT Bouncer Modulator at CERN SM18 Hall

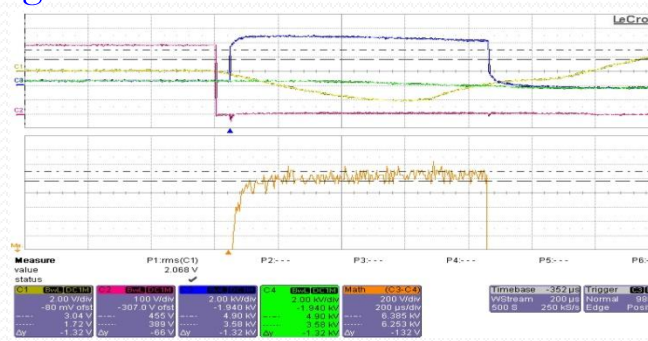
Courtesy: David Nisbet, CERN

100 kV 500 microsecs, 25Hz solid state bouncer modulator for 3MeV H- pulsed RFQ at RRCAT

Integrated modulator system



Test results without bouncer @ 10kV operation. C1: Main capacitor voltage, C2 : Primary side load current signal, C3 : Load voltage signal, C4 : Primary side load current signal with CT 410



Test results with bouncer @ 7kV operation
C1: Bouncer current signal, C2 : Bouncer switch voltage signal, C3 : Load voltage , C4 : Bouncer voltage signal. Math : Voltage across load (C3-C4) on expanded scale (±1% variation)

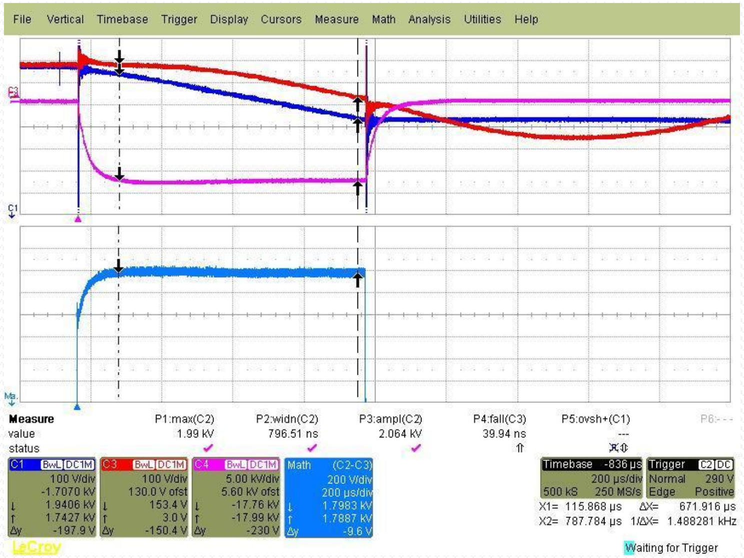
RRCAT made HV Switch

Storage and bouncer capacitors

Pulse transformer R & D efforts at RRCAT

Parameter	Stage 1 Values	Stage 2	Stage 3
Ratio	1 : 10	1 : 10	1 : 10
Max. Secondary voltage	-100 kV	-100 kV	-100 kV
Pulse width @ 100kV	200 us	500 us	1.6 msec
Rise time @ 5k Ohm load	< 80 μsec	< 100 μsec	< 150 μsec
PRR max.	2 Hz	25 Hz	25 Hz

Test results @ 18kV output



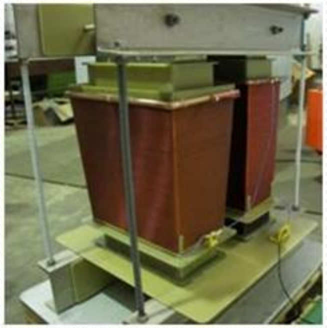
C1 : Main Capacitor voltage at 2kV

C2 : Primary high side with respect to ground

C3 : Bouncer capacitor voltage

C4 : Secondary output voltage at 5k Ohms load

Math : Primary voltage (C2 –C3)



RRCAT 100kV Pulse Transformer prototype

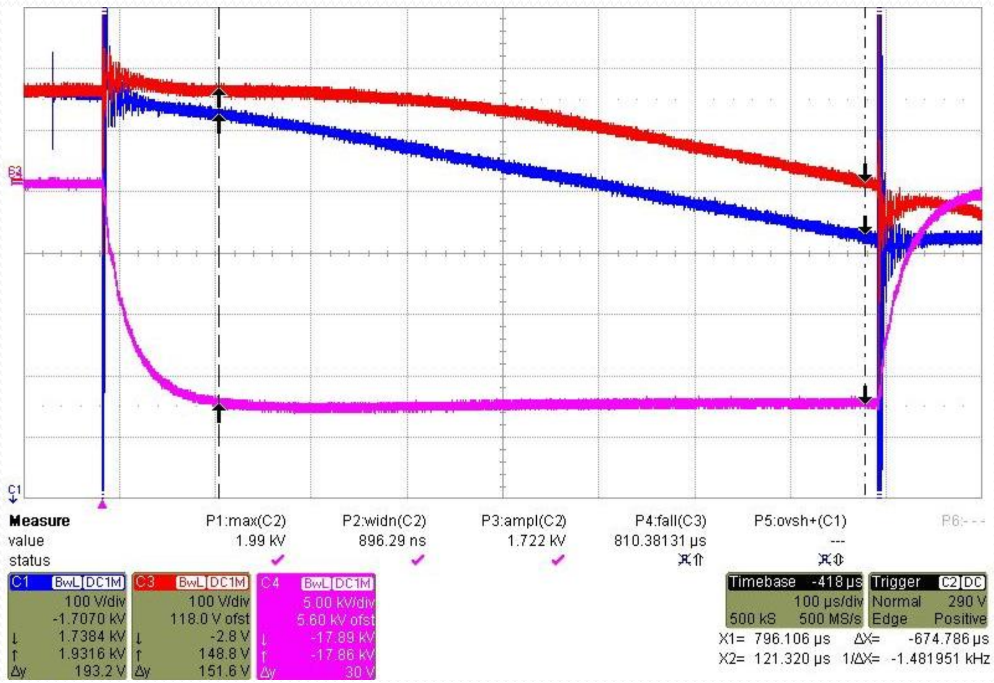
Test results of Bouncer compensated Pulse Modulator with Pulse transformer (1 : 10) and secondary load of 5kΩ 800μs Pulse output of 18kV

C1: Main Capacitor voltage (2 kV with 1000 : 1 voltage divider)

C2 : Primary high side voltage w.r.t. ground ('Channel Off', 1000 : 1 Tek probe)

C3 : Bouncer voltage (140 V with 1000 : 1 Tektronix probe)

C4 : Load voltage (-17.9 kV with 1000 : 1 Tektronix probe)



High Voltage Resistive Load Assemblies made at RRCAT

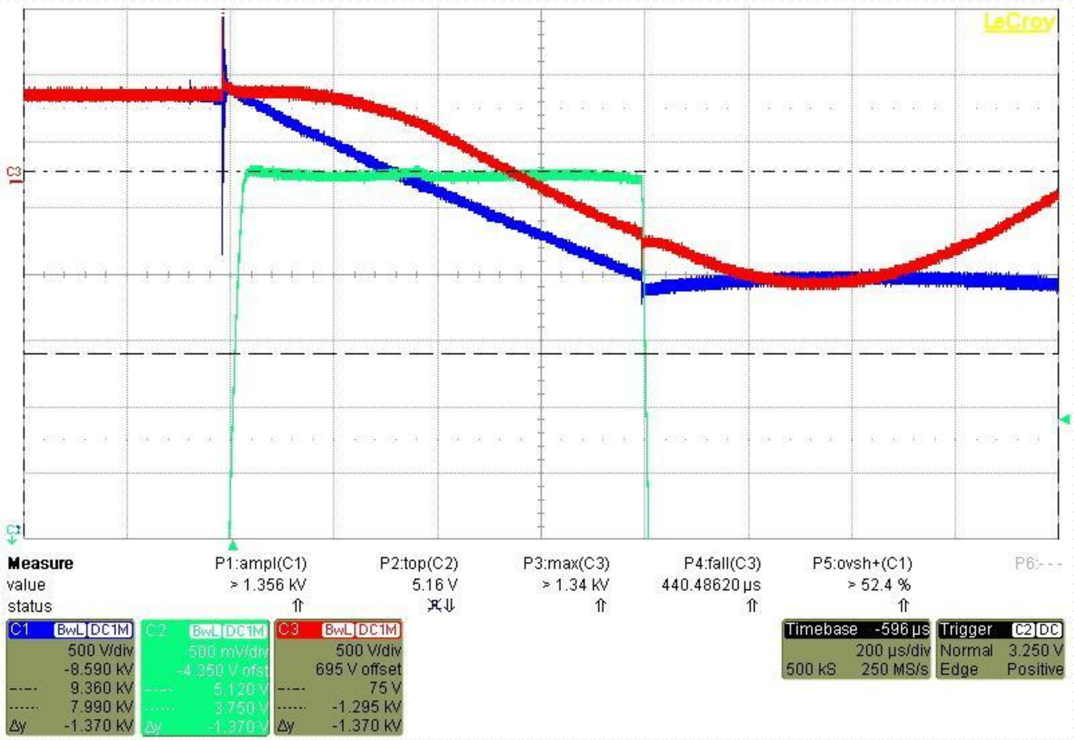
Modulator output connected to Dummy load of 5kOhms, 100kV, 4kW

Dummy load of 5kOhms, 100kV, 17kW (without oil cooling) & 100kW with oil cooling. Oil tank not shown

Load of 5kOhms, 100kV, 40kW with water cooling

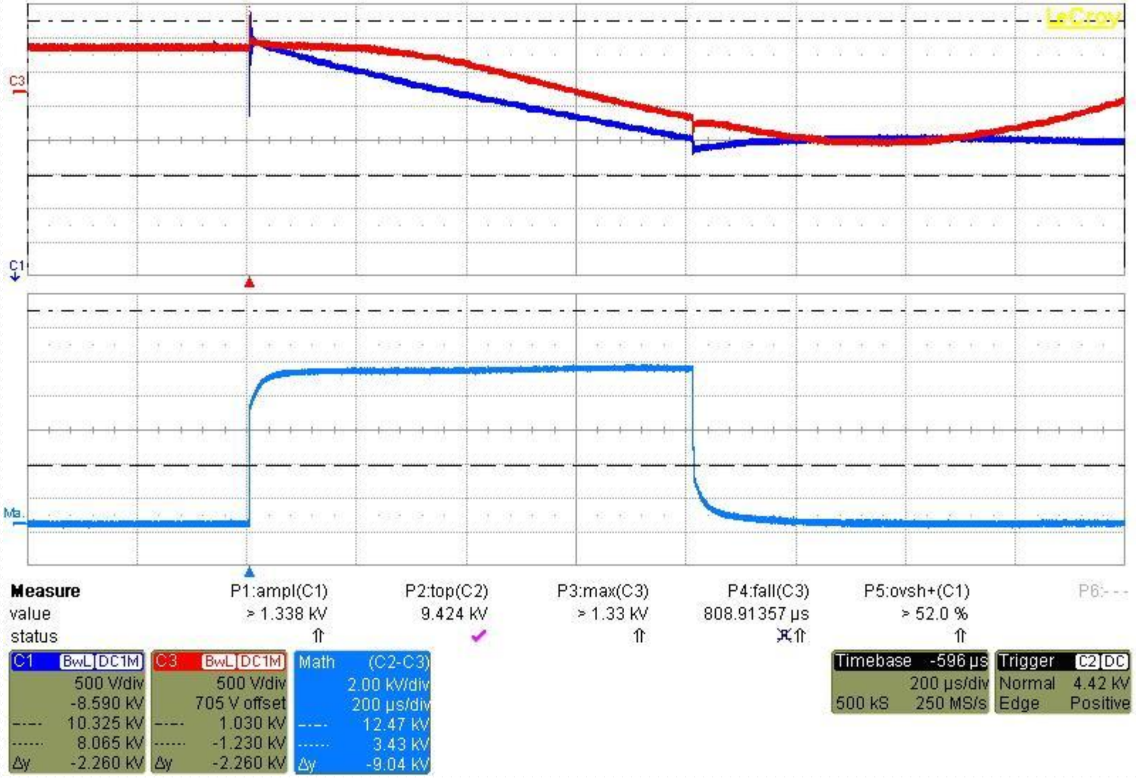
Primary side Test results of Pulse Modulator with IGBT based switch & bouncer compensation @ 10kV operation
Primary side equivalent load = 50Ω

C1: Main Capacitor voltage (10 kV with 1000 : 1 voltage divider)
C2 : Load current (204A with 25 mV / A current transducer)
C3 : Bouncer voltage (700 V with 1000 : 1 Tektronix probe)



Primary side Test results of Pulse Modulator with IGBT based switch & bouncer compensation @ 10kV operation
Primary side equivalent load = 50Ω

C1: Main Capacitor voltage (10 kV with 1000 : 1 voltage divider)
C2 : Primary high side voltage w.r.t. ground ('Channel Off', 1000 : 1 Tek probe)
C3 : Bouncer voltage (700 V with 1000 : 1 Tektronix probe)
Math (C2-C3) : Load voltage with equivalent load of 50Ω in primary side



Bouncer Modulator case studies:

100kV, 50A, 3.5ms, 15Hz Bouncer Modulator

Parameter	Values
Klystron modulator type	Solid state Bouncer
High Voltage pulse amplitude	-10 kV to -110 kV
High Voltage pulse width at 70% to 70 % of peak.	3.3 msec
Minimum Flat top available	2.8 msec
Maximum current during pulse	50A
Pulse repetition rate	15 Hz
Acceptable voltage drop	≤ 1.0 %
Allowed ripple on flat top (≥ 10 kHz)	≤ 0.1 %
Rise time/fall time	< 500 μsec
Peak output power	5 MW
Average output power at 15 Hz PRR	262.5 kW

Advantages

✓Simple Hard switch type design as compared to PFN based Line type scheme
✓Output voltage droop <1% by using simple droop compensating bouncer network
✓Reduced Main Capacitor size by using droop compensation design.
✓Klystron arc protection by fully controlled series switch and crowbar network.
✓Excellent pulse to pulse stability
✓Flat top ripple < 0.1%

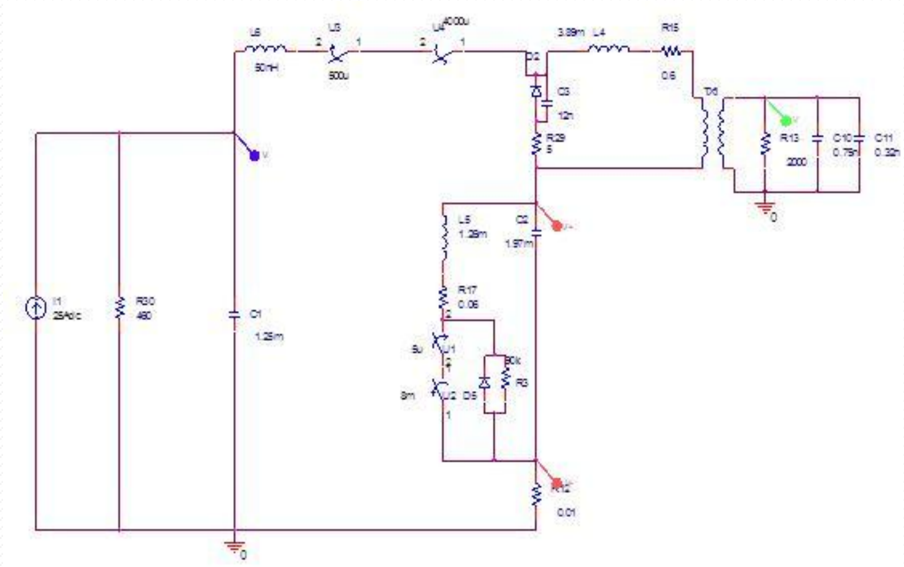
Limitations

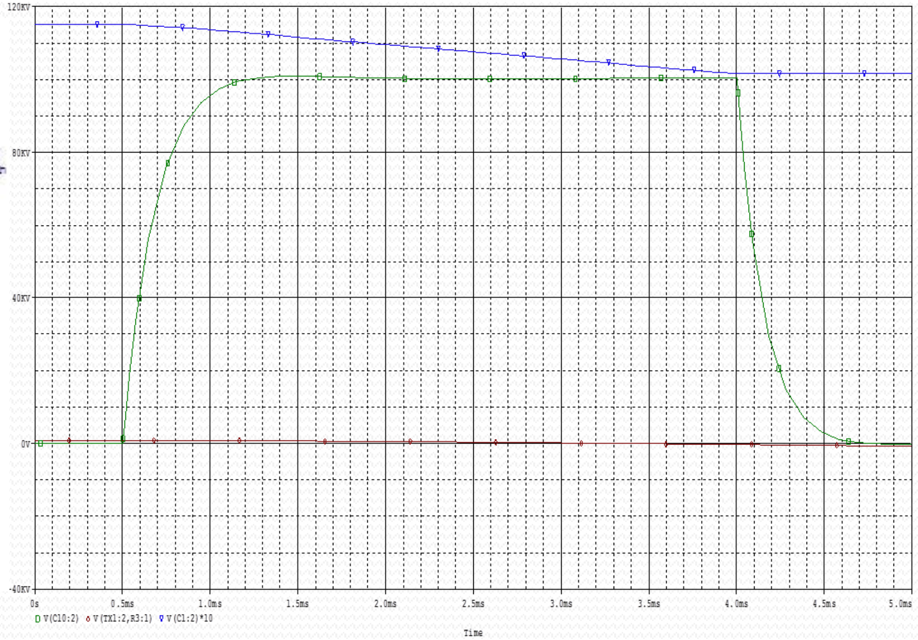
- The bouncer compensation has limited range for variations in load. For load variation >±10%, the flat top is difficult to maintain.
- Pulse width cannot be increased above design value by more than 10% for allowed droop range.
- Due to voltage limitations of solid state switches and other components, the pulse transformer is essentially required whose parasitic elements like magnetising inductance, leakage inductance & distributed capacitance affects the performance and efficiency.

Disadvantages

➢The cost and size increases too much as the output pulse width increases.
➢Less flexible from load and pulse width point of view.
➢Stored energy is higher and requires extra protections for load arcing.

Design and simulation result of 100kV, 50A, 3.5ms, 15Hz Bouncer Modulator





Green : Output voltage with ± 0.37% Flat top (0.73% total variation, t_r = 400µs)

Blue : Main Capacitor voltage (Scaled to 10 times, 11.9% droop)

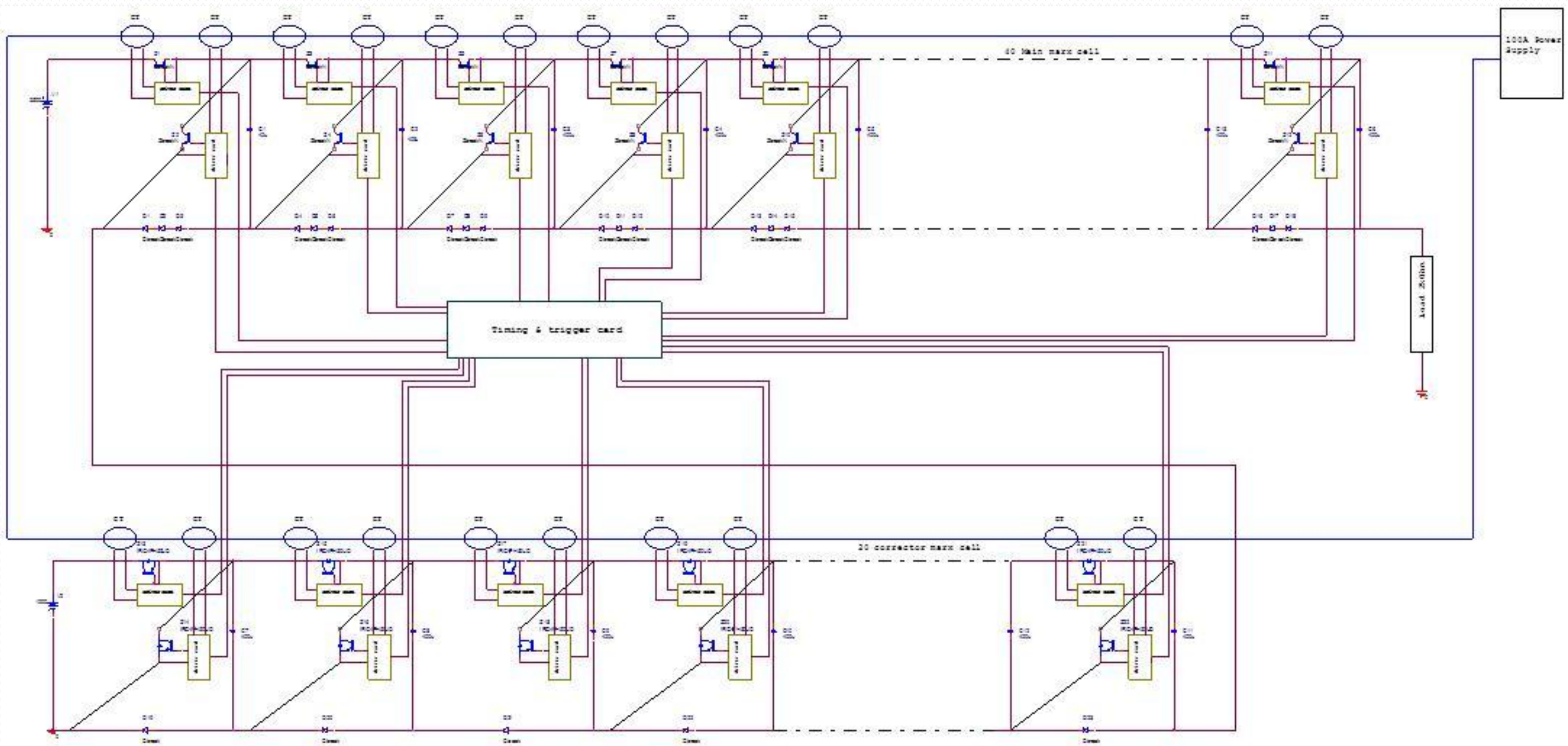
Red : Bouncer Capacitor voltage

100kV, 50A, 3.5ms, 15Hz Bouncer Modulator

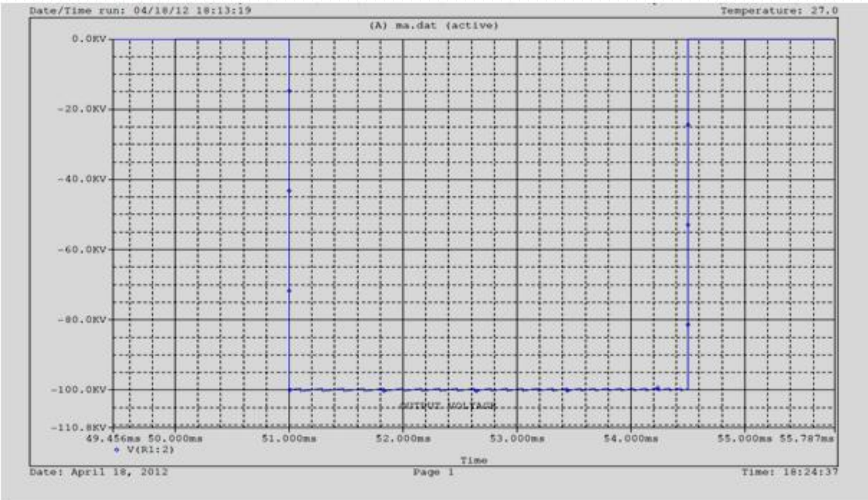
Sl.No.	Main Component	Parts with description	Quantity
1	Charging power supply 12kV, 25A		1Nos.
2	Filament power supply with 120kV floating terminals		1Nos.
3	Modulating Anode power supply		1Nos.
4	Pulse transformer unit	Pulse transformer 110kV, 1:10, 15 Hz with water cooling	1Nos.
		Biasing Supply	1Nos.
5	Undershoot network	Resistors 50Ohms, 20kV, 1kW each	10Nos.
		Diodes 20kV, 1000 Apk, 50 A RMS	1Nos.
		Capacitor 1uF, 20kV pk each	2 Nos.
6	Main Switch	IGCT / IGBT based stacked switch assembly (20kV, 600A) with water cooling	1 Nos.
		Drivers auxiliary power supplies	1 set
		20kV, Isolation transformers for auxiliary supply	1 set
		Optical driver unit	1Nos.
		Optical fiber cables with connectors (1m length)	1 set
7	Safety Discharge Device	25 kV Electromagnetic relay with auxiliary contacts	1Nos.
		Resistors 1kOhms, 250W, 20kV, 10kJ each	10Nos.
8	Crowbar 1 Network	24kV, 16kApk SCR based / Thyratron switch	1Nos.
		Diode 20kV, 1000APk	1Nos.
		Resistors 10 Ohms, 20kV, 2 kApk each	10 Nos.
9	Main Capacitors	100uF, 15kV, 10A rms, 100 A pk each	12 Nos.
10	Bouncer network	Capacitors 200uF, 3kV, 40A rms, 250A pk each	10Nos.
		IGBT / SCR Switch 3000V, 2400Apk , 800A DC	1Nos.
		Inductor 1.26 mH, 400 A rms	1Nos.
11	Control, Interlock and other auxiliary items	Cabinets, subracks, high voltage cables,high voltage connectors, low voltage cables, low voltage connectors, electronic cards etc.	

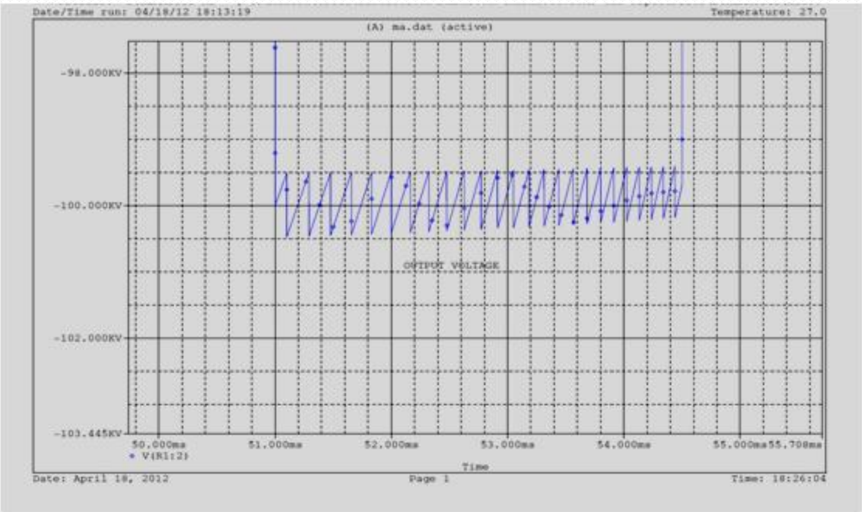
Marx Modulator case studies:

Schematic Diagram

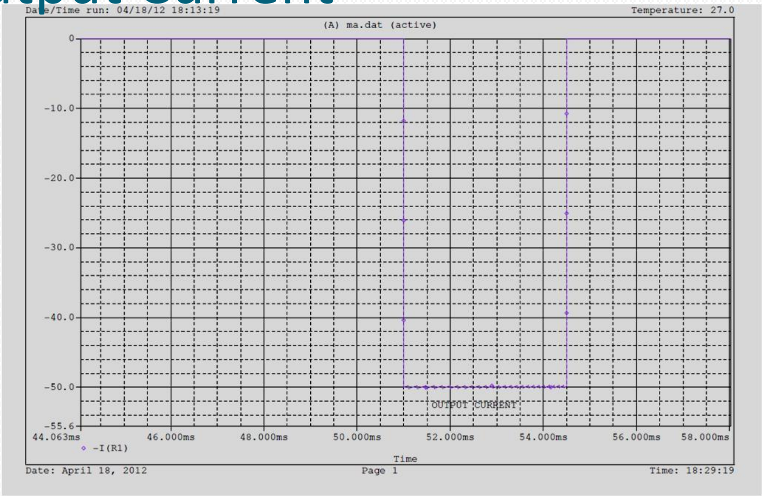


Output voltage





Output Current



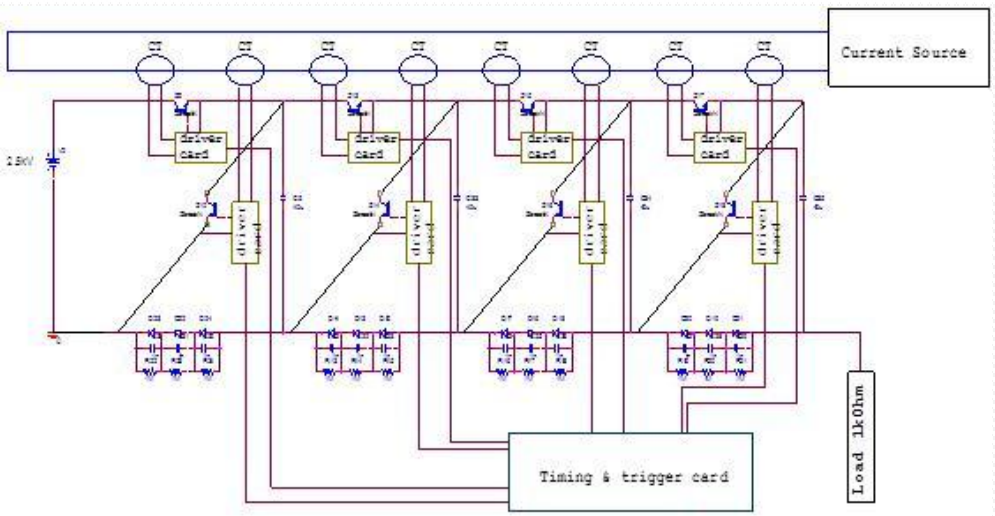
Features:

- **Oil free design.**
- **Lower IGBT currents.**
- **Pulse duration can be easily controlled by switching low voltage circuit.**
- **Finer waveform control.**
- **Transformer Less topology.**
- **Low DC voltage.**
- **Suitable design for wide range of voltage rating. Current and pulse duration.**

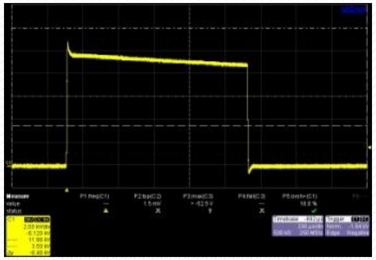
Limitation:

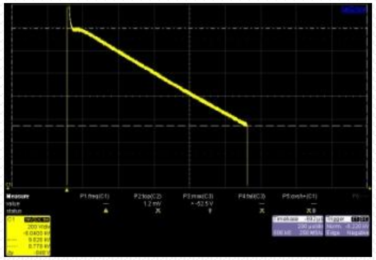
- **IGBT driver circuits float at high voltage during pulse which is needed to be isolated.**
- **There is ripple in output voltage that has to be addressed.**

Prototype 10kV Marx cell first results

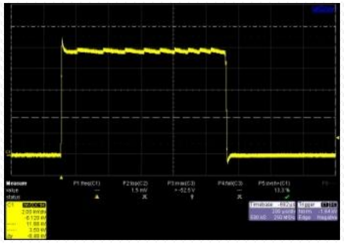


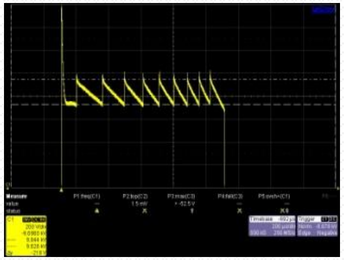
Tests on Marx cell with droop compensation networks





10kV pulse without correction

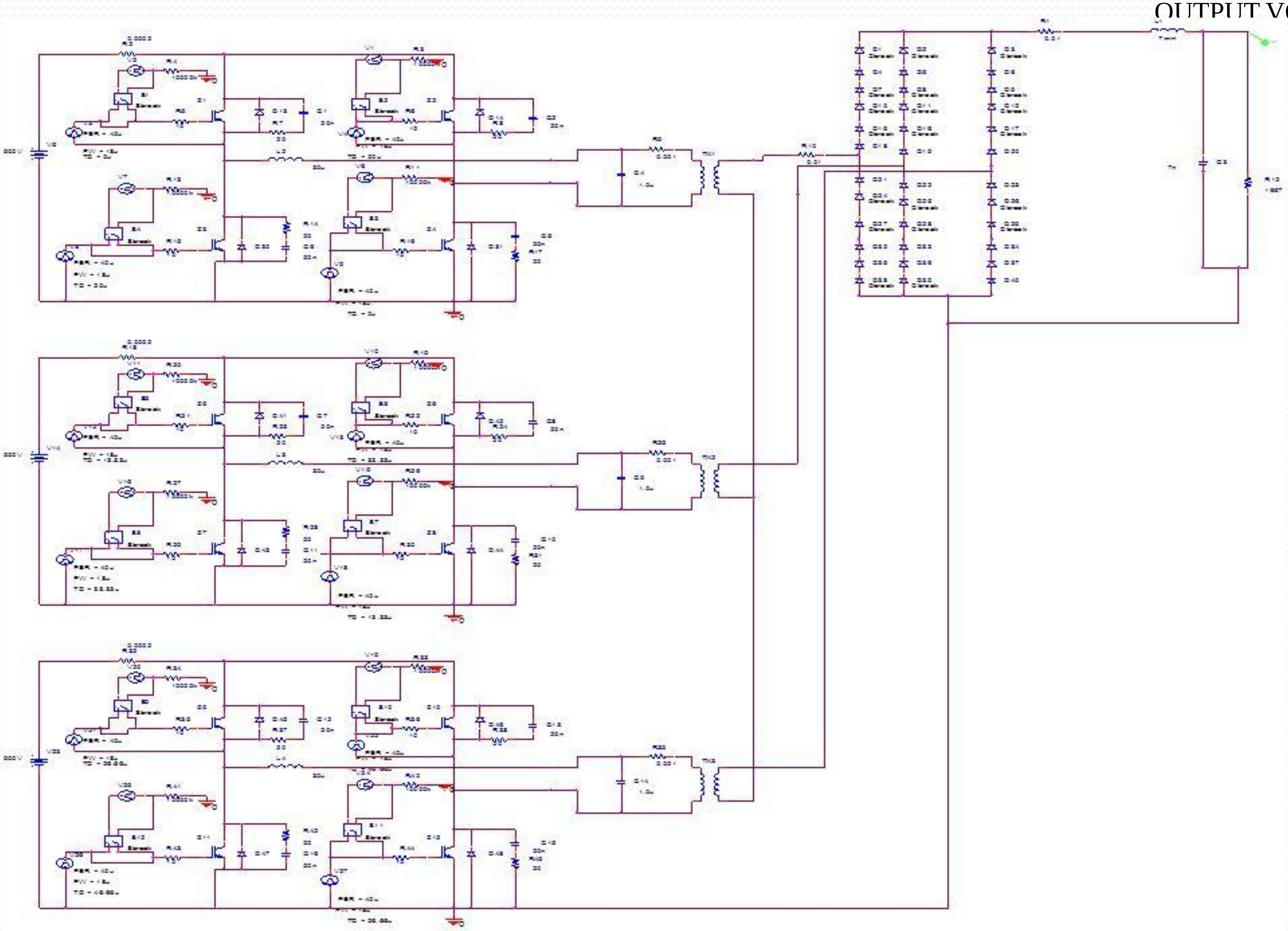




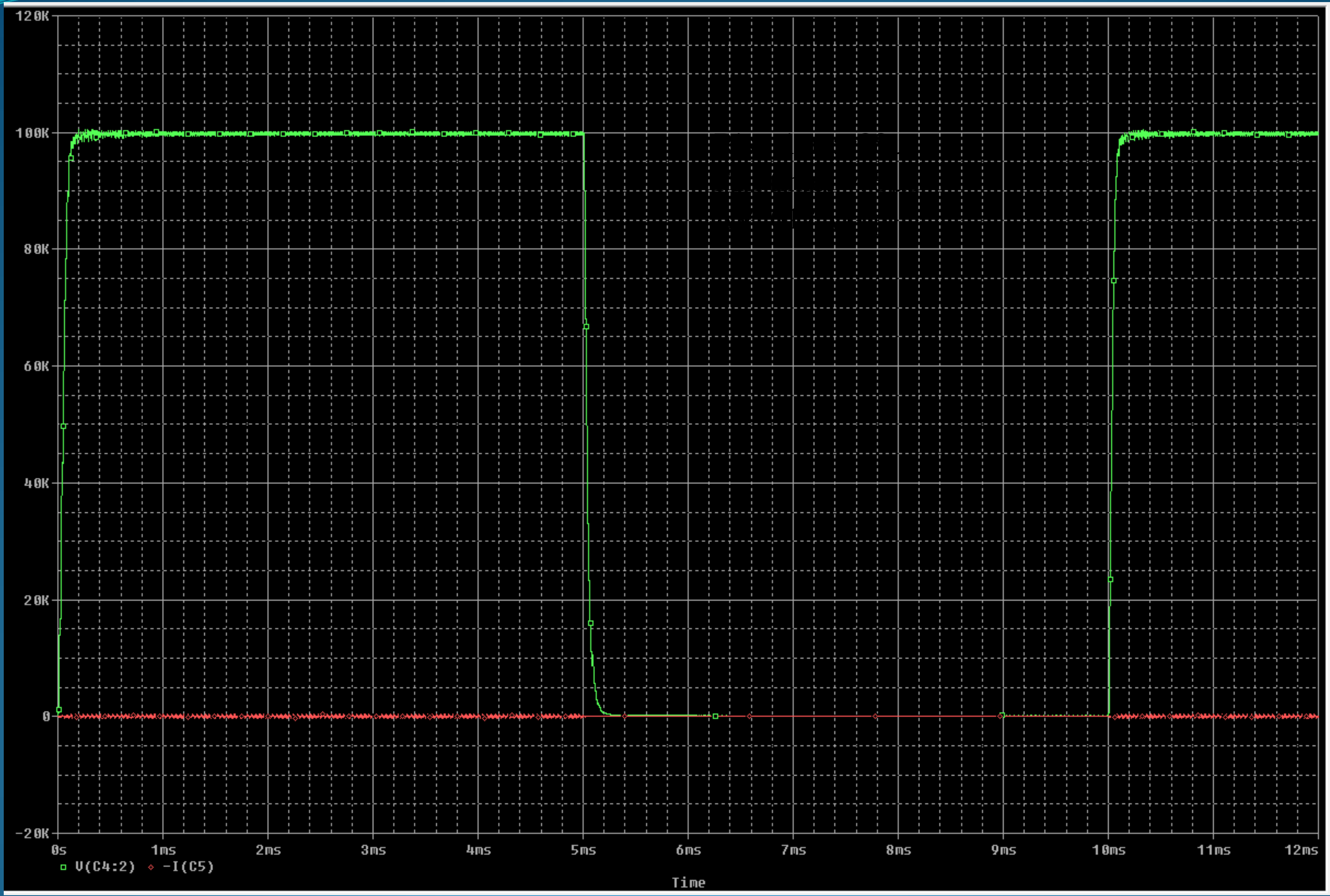
10kV pulse with correction

Converter Modulator case studies:

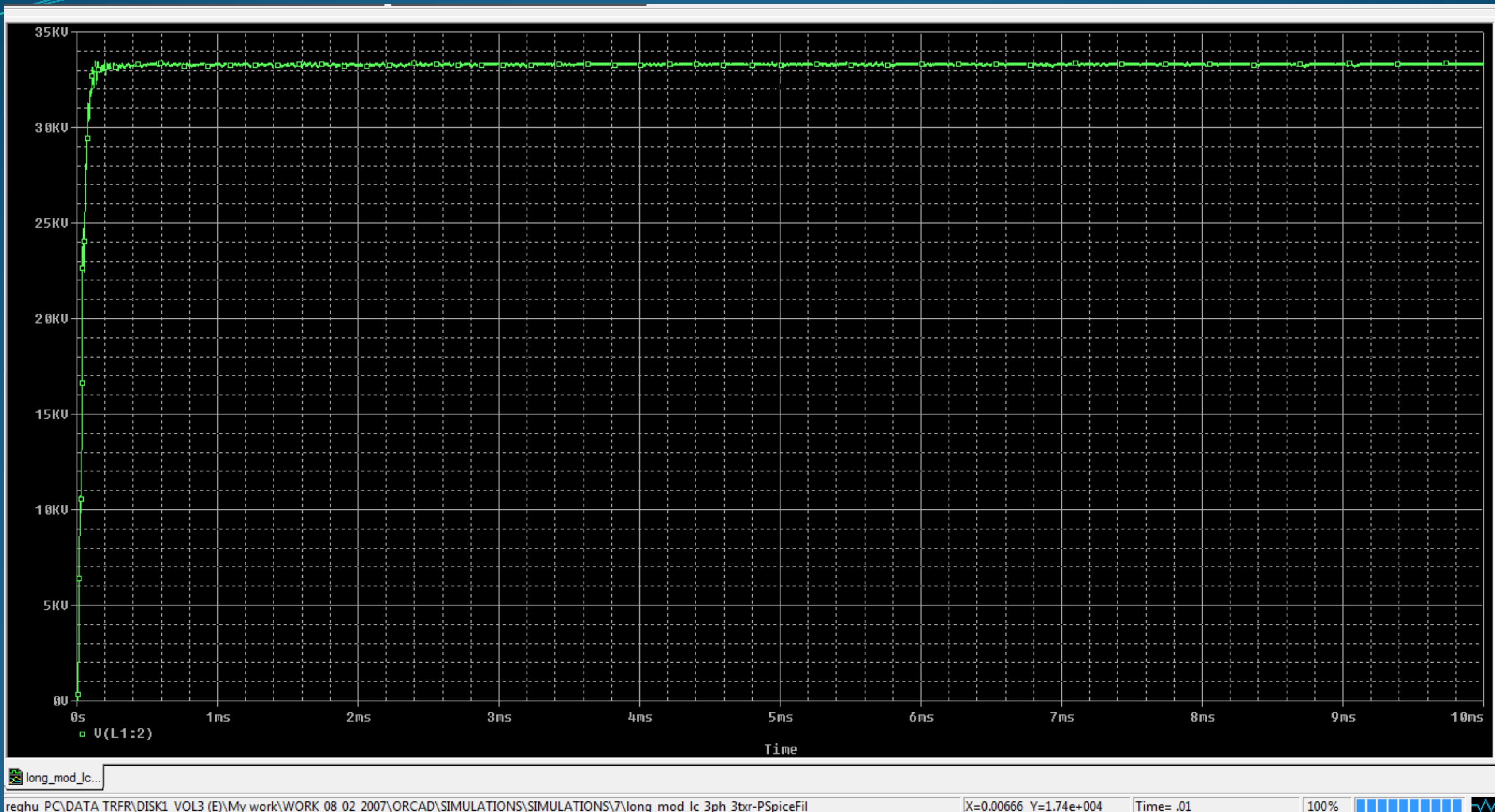
OUTPUT VOLTAGE



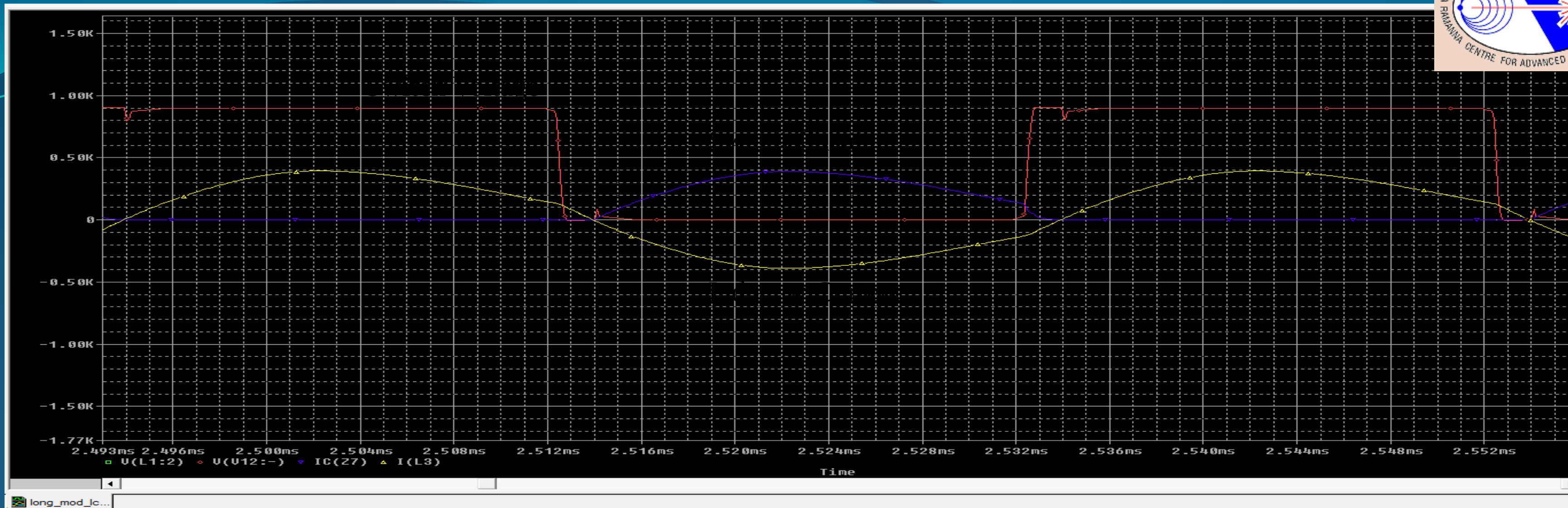
33 kV/20A PROTOTYPE CIRCUIT SIMULATION



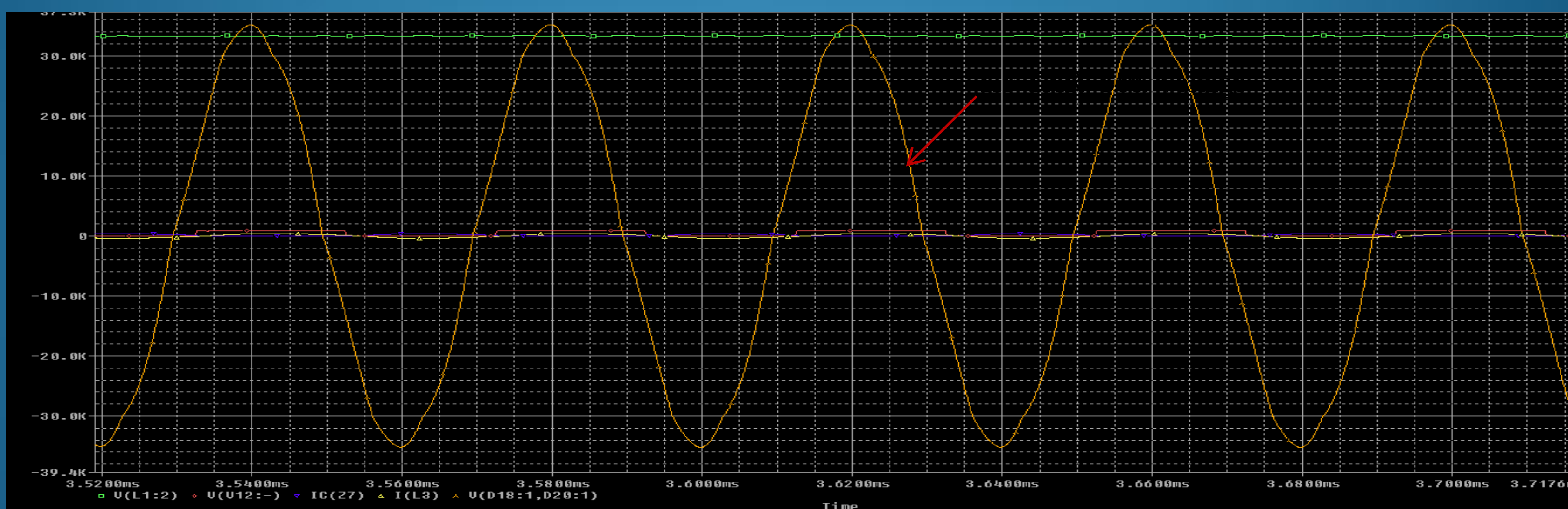
100 kV/20A Long pulse (5 ms) converter modulator output voltage



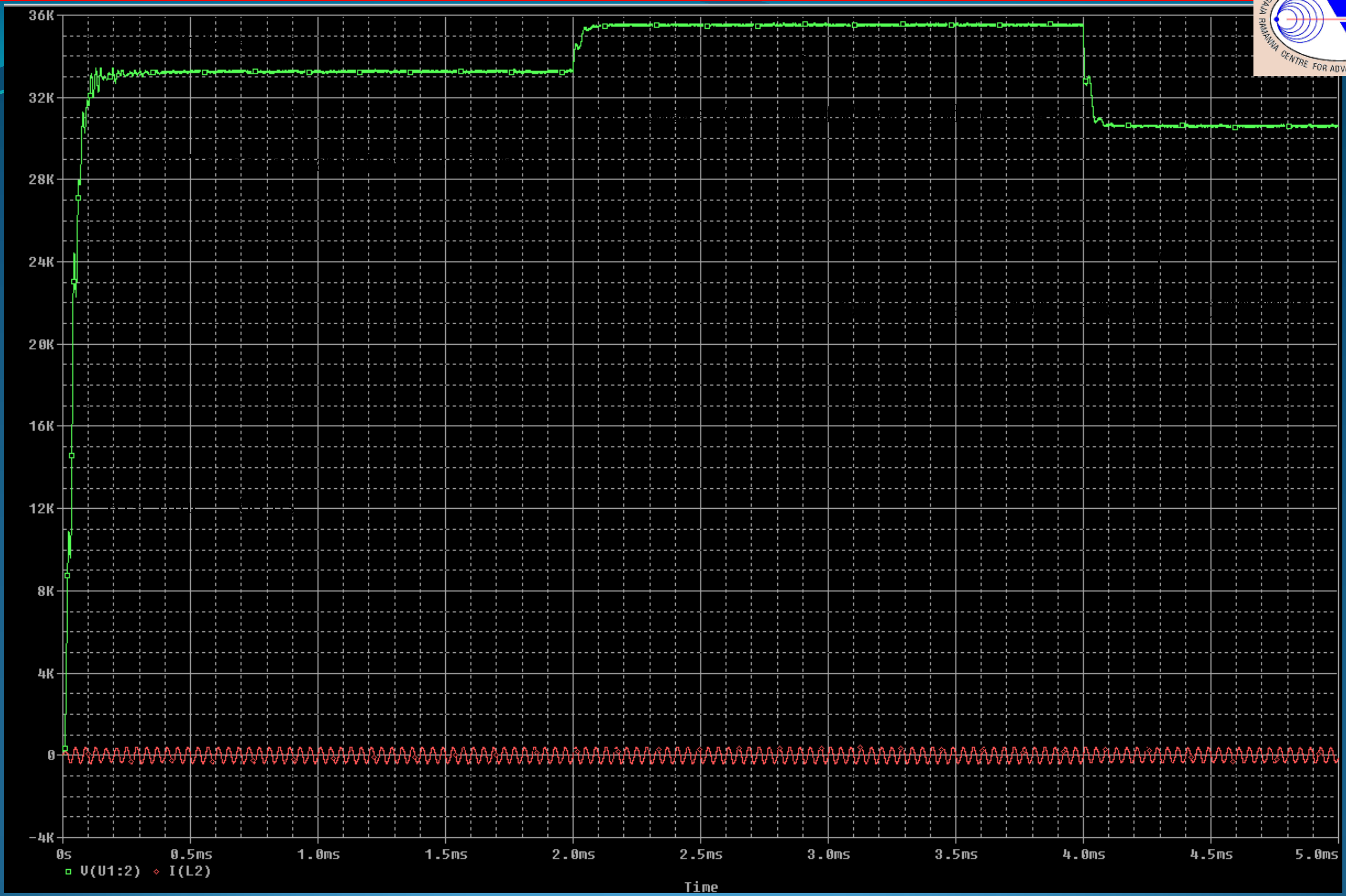
OUTPUT VOLTAGE WAVE FORM ACROSS 1667 Ω LOAD



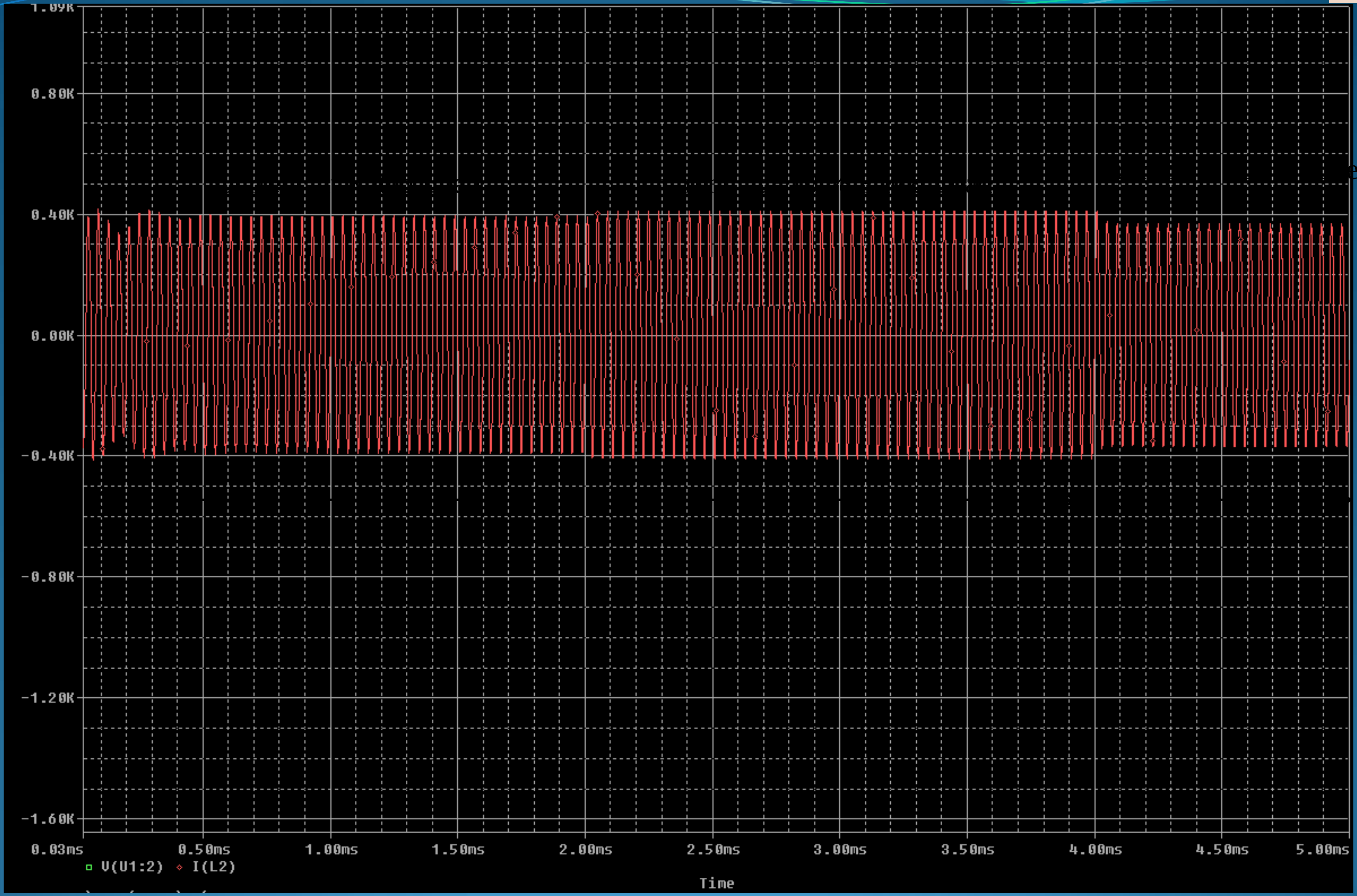
WAVE FORM ACROSS THE IGBT SWITCH



WAVE FORM AT THE SECONDARY OF HF TXR

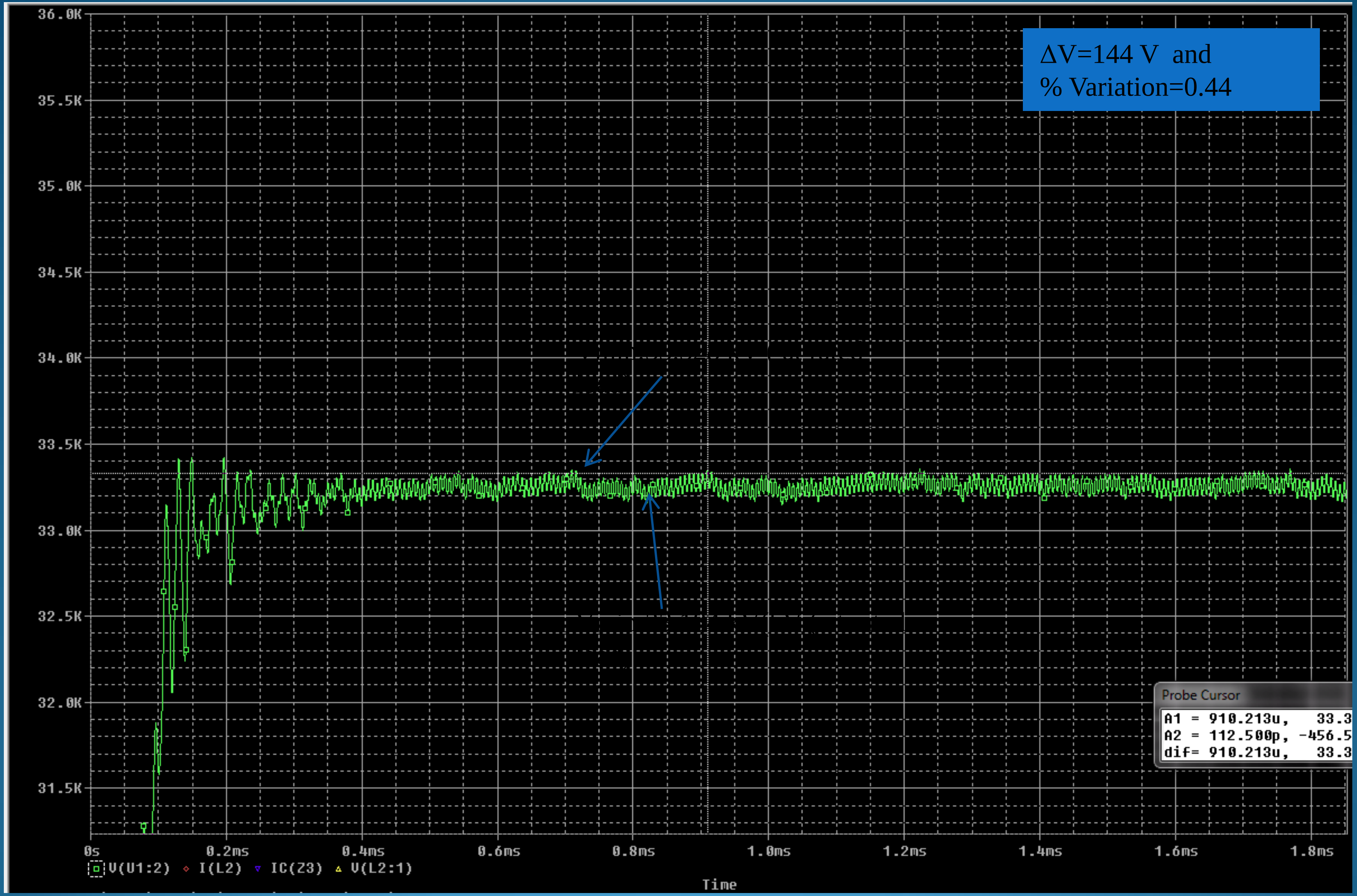


33 kV/20A Modulator O/P Voltage Waveform with ±10% Load Change



ed Load

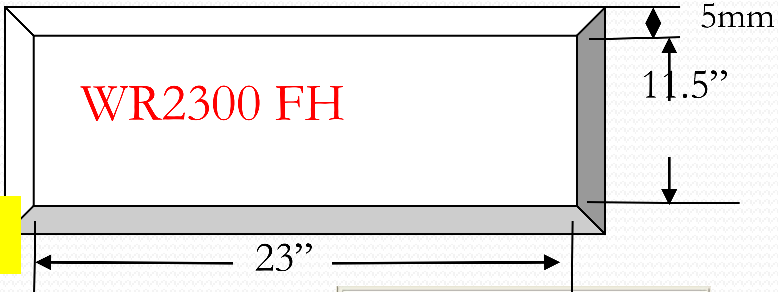
33 kV/20A Modulator resonant inductor current Waveform with ±10% Load Change



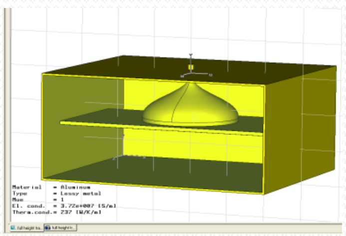
33 kV/20A Converter Modulator Output Voltage

R & D efforts on the High Power Waveguide and solid state pulsed microwave amplifiers

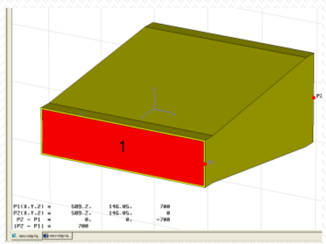
WR 2300 Waveguide Components Design, Simulation, Fabrication and Tests for CERN LINAC 4 and RRCAT H- LINAC Project



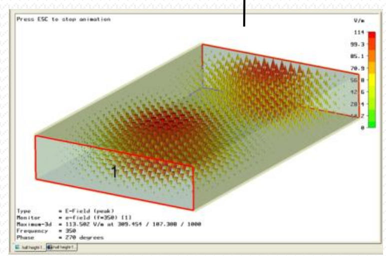
Design & analysis



FH W/G to Coax. Transition



FH to HH W/G Transition



HH W/G Straight Section

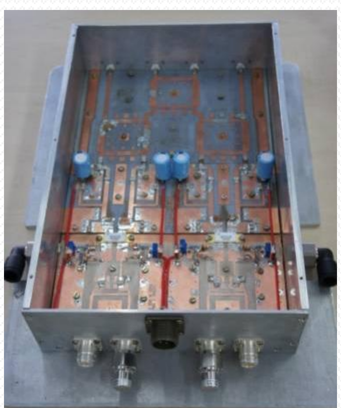
Test results

Fabricated WR 2300 W/G components

Pulsed Solid State Amplifier development

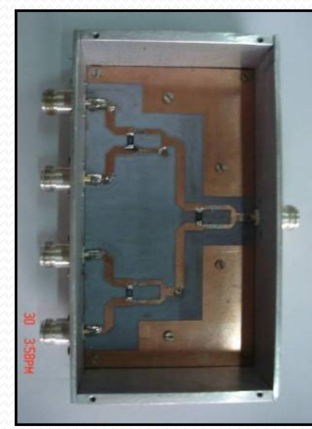
Power Measurement Module for VTS

1.3GHz , 250W pulsed amplifier



1.3 GHz 500W amplifier module assembly with divider/combiner

300W S Band amplifier module



1:4 Divider/combiner @ 2856MHz

Conclusion

- A large reservoir of experience in design, development and commissioning of conventional and state of the art modulators, high power pulsed RF/Microwave components and systems, is getting accumulated at RRCAT.
- Systems developed in-house have been performing satisfactorily in the Indian accelerator environment. Constant upgrade with latest technology is a continuous process.
- Bilateral collaborations are crucial for faster, reliable and cost effective developments. We welcome collaboration with ESS on mutually beneficial areas.

Thanks