

High Power RF/Microwave Systems R & D for Linear Electron Accelerators at RRCAT and status of contributions to CLIC collaboration



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Outline

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3. High Power microwave system for drive beamlinac for IR-FEL .
4. High Power microwave systems for 10 MeV electron Linacs for Agricultural Irradiation Applications
5. Contributions to CLIC collaboration and further R & D work
6. Concluding remarks

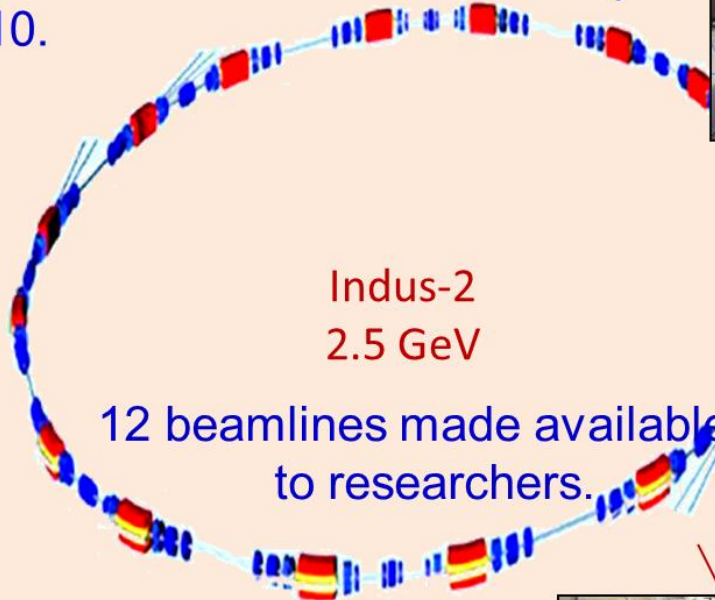
INTRODUCTION



- RRCAT, Indore is home to India's biggest Synchrotron Radiation Sources Indus 1 (450 MeV) and Indus 2 (2.5 GeV)
- Electron linear accelerators are also developed for as drivers for IR-FEL and irradiation of agricultural products.
- High power microwave systems from 2 MW to 45 MW at S Band have been developed at RRCAT.
- 10kW solid state amplifier at 476 MHz for injector LINAC for CUTE-FEL and IR-FEL.
- 20kW wide band SSPA developed and supplied for CLIC sub harmonic buncher at CERN.
- A solid state 500W, 1.3 GHz RF system has been developed for SCRF cavity tests under IIFC collaboration.
- RRCAT has also made spare PETS bars for CLIC

Indus Accelerator Complex

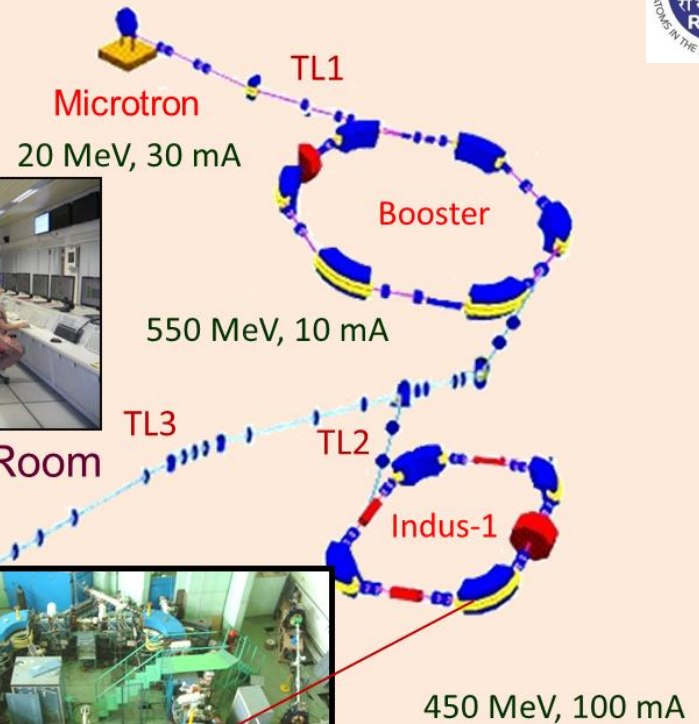
Indus-1 and Indus-2 synchrotron radiation sources are national facilities operating in round-the-clock mode since February 2010.



Control Room

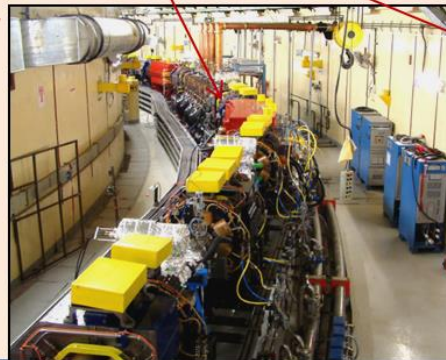


Indus-1



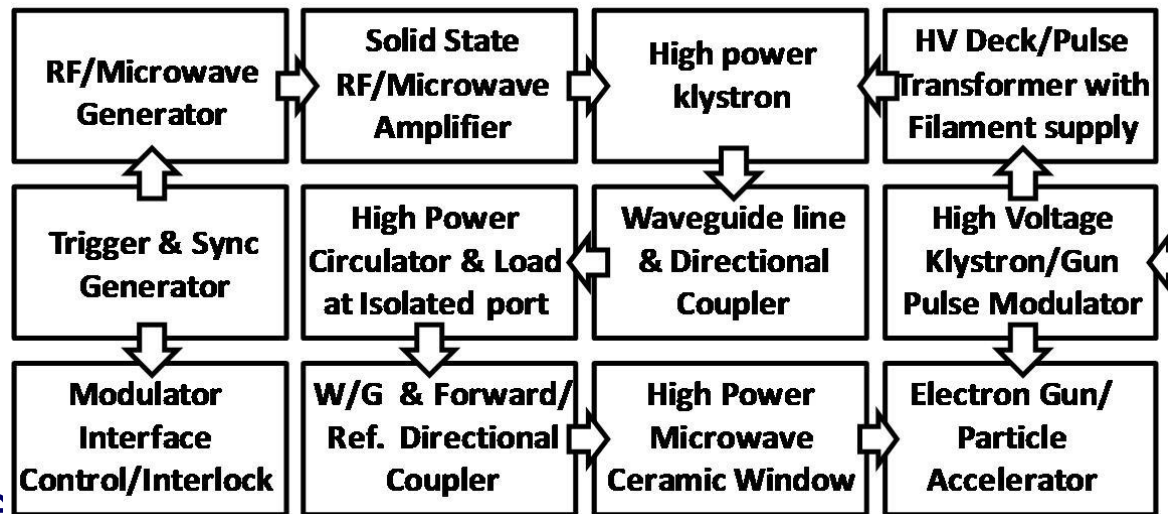
Indus 2 is driven by 4 stations of solid state amplifiers developed by RRCAT amounting to 280kW CW power at 505MHz

A section of Indus-2 tunnel (172.5 m)



Subsystems for RF/Microwave drivers for accelerators

1. Generator
2. LLRF controls
3. Driver amplifier
4. Circulators
5. RF cabling
6. High power amplifier
7. O/p transmission line
8. RF/Microwave Window
9. Particle accelerator cavities
10. Interlock and controls, PC based automated controls
11. Interfacing to the master control of accelerator
12. RF/Microwave and ionizing radiation Safety protection systems.



Application	Peak power	PW us/ PRR Hz	Device	
2856 MHz (Klystron), 2998 MHz (Magnetron)				
20 MeV Microtron (old)	5 MW	3/1	Kly.	CPI
20 MeV Microtron (new)	5 MW	3/2	Kly.	CPI
8.0 MeV Microtron	2 MW	2.5/200	Mag .	E2V
10 MeV Linac (ARPF)	6 MW	14/280	Kly.	Toriy
10 MeV Linac (TW)	6 MW	14/200	Kly .	Thales/CP I
30 MeV injector Linac	45 MW	4.5/10	Kly.	Toshiba
20 MeV IR-FEL linac	24 MW	12	Kly.	Thales
1300 MHz & 650 MHz				
SCRF cavity tests @VTS	500 W	CW	Solid state	RRCAT
476 MHz & 499 MHz (Wide-Band) for buncher cavities				
CUTE-FEL linac	10kW	50us/10Hz	Solid state	RRCAT
InfraRed-FEL linac	10kW	50us/10Hz	--,, --	RRCAT
CLIC injector Linac	20kW	140us/50Hz	--,,--	RRCAT
352.21 MHz				
3 MeV RFQ Test Stand @CERN LINAC4 & RRCAT (solid state modulator)	1MW	0.5& 0.8ms/1- 50Hz	Kly.	Thales

VKS-8262 Klystron



PULSED KLYSTRON /
RRCAT
Toshiba 50 MW S Band



Thales 6 MW S Band pulsed SBK



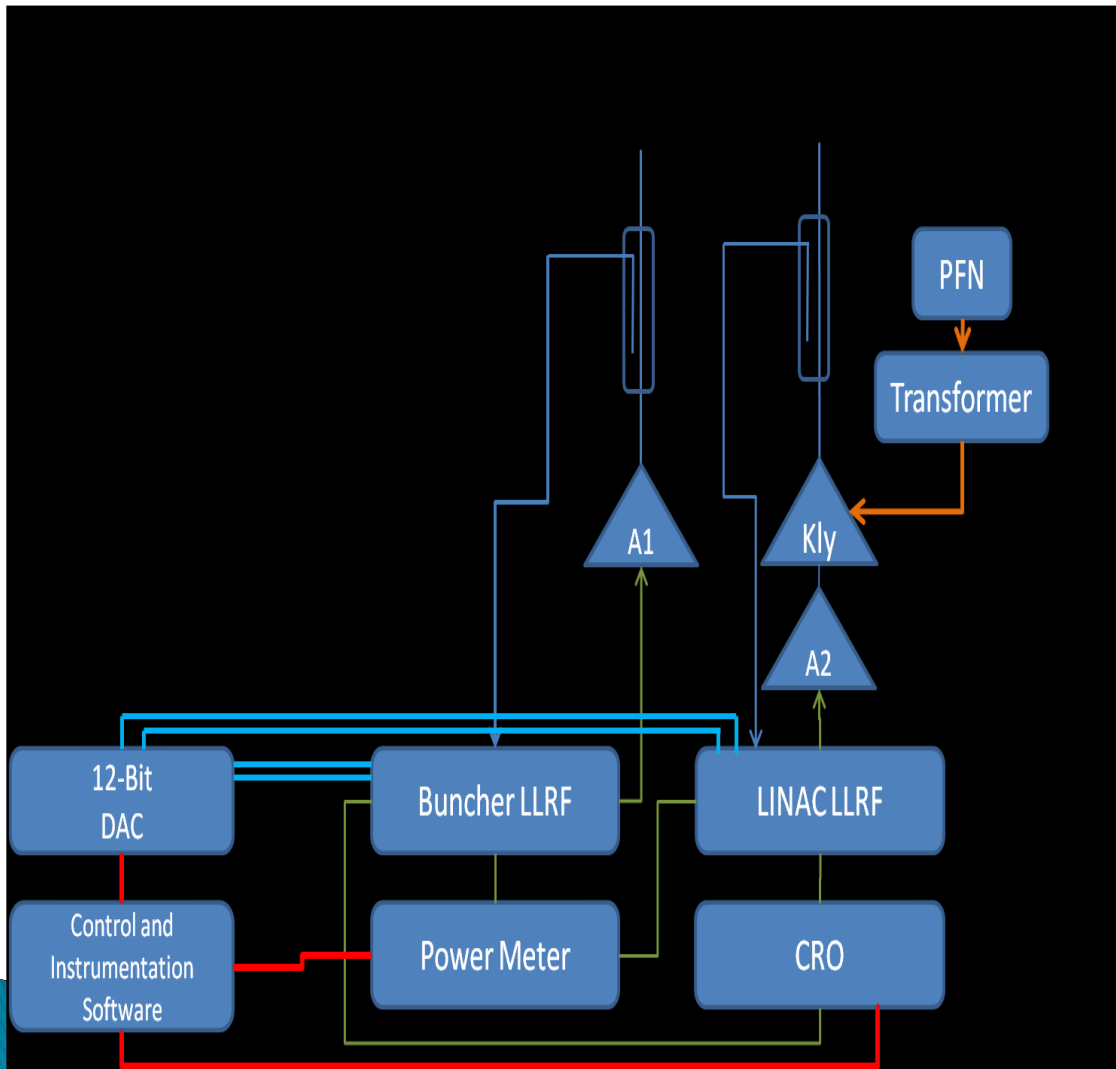
Toriy 6MW S Band pulsed MBK



High Power microwave system for 20MeV electron linac for driving IR-FEL

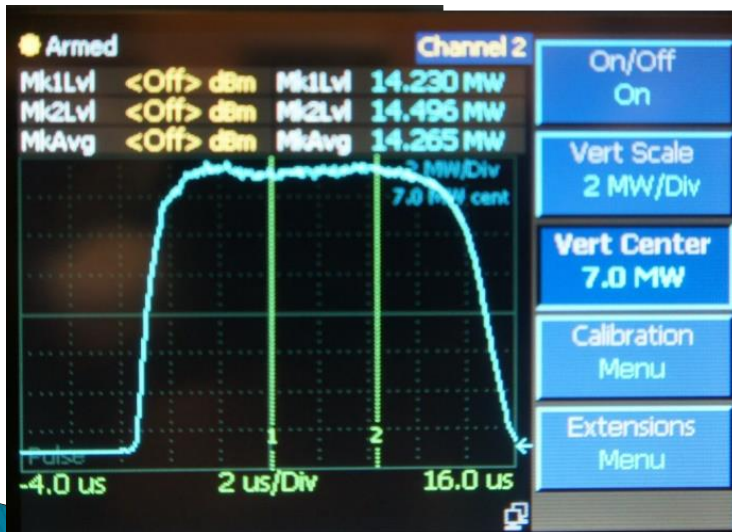
- S-Band Klystron based pulsed microwave system with Low Level RF (LLRF) control that can deliver up to 24 MW peak power, 2 μ s, PRR up to 10 Hz.
- A fast feed forward mechanism compensates beam loading and shapes the klystron output. .
- 250 kV, 200 A line type modulator with two tunable Pulse Forming Networks (PFNs) in parallel to achieve desired pulse flatness.
- The high voltage dec in oil-filled tank with a high voltage pulse transformer (1:14), filament transformer, core bias with blocking inductor supporting the klystron and focusing electromagnets. WR-284 waveguide line pressurized at 3 kgf/cm² by SF₆.
- The microwave system has been successfully commissioned at IRFEL complex and first signature IRFEL is observed using this system.

Schematic of 24MW S Band Microwave system for IR FEL Linac

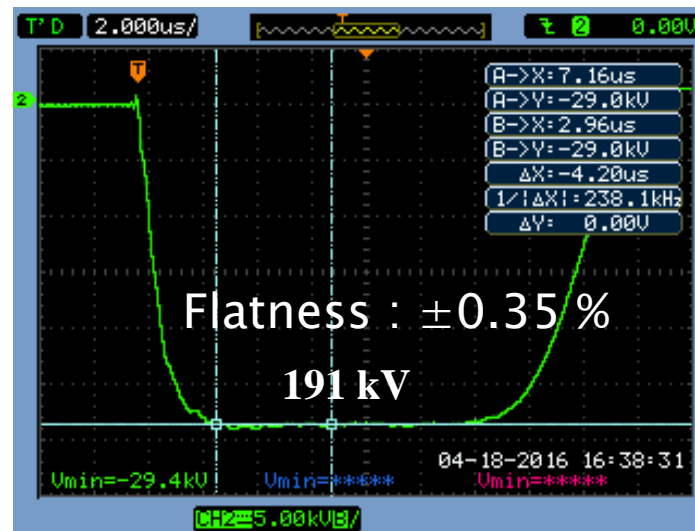




24 MW S-Band microwave system set up



Output Waveform of klystron Modulator



Waveform of microwave output power at > 14 MW

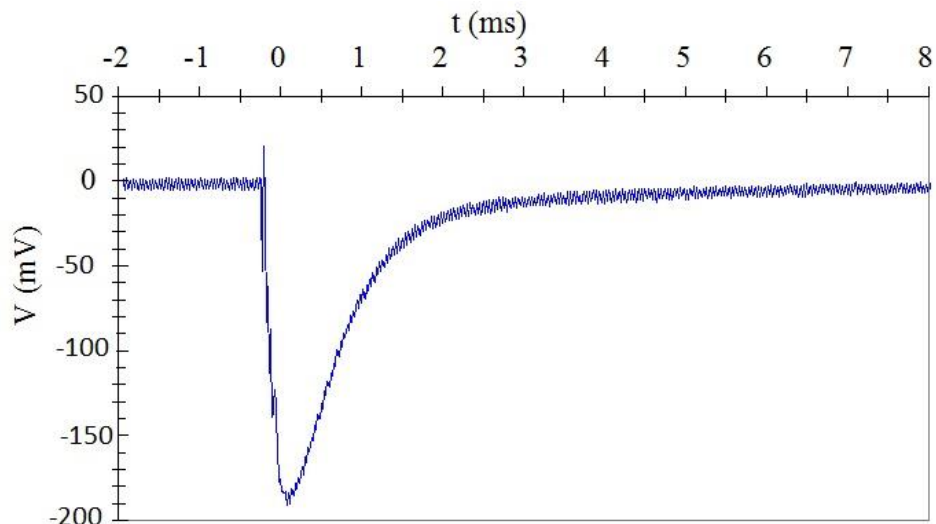
24MW S-Band Microwave system for IR FEL Linac



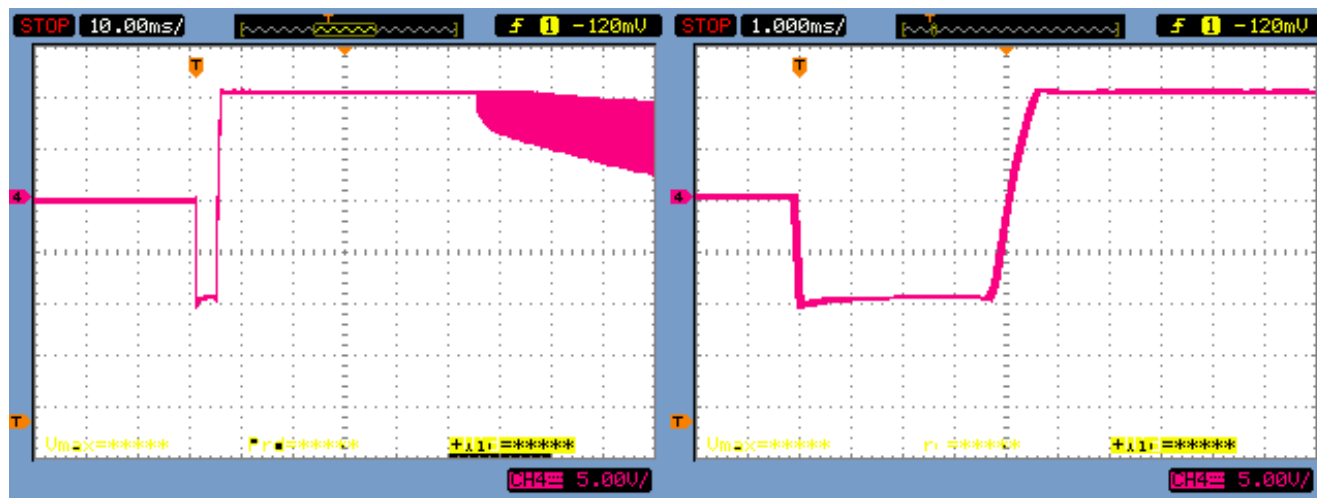
24 MW Klystron shown without shield with modulator



Waveguide system connected to the PWT linac.



Typical bolometer signal with optical cavity length detuned



Typical bolometer signals showing a high degree of saturation with optical cavity tuned to design length

Development of sub-systems for 10 MeV electron linac for Agricultural Radiation Processing Facility.

- ✓ 6.0 MW S-Band microwave systems and 50 keV triode type electron guns have been indigenously designed and developed.
- ✓ The microwave system consists of a 130 kV, 100 A, 12 μ s high voltage pulsed modulator and 6 MW pulsed klystron as a microwave amplifier.
- ✓ Two such systems have been successfully commissioned to energize 10 MeV, 5 kW linacs.
- ✓ One of the microwave systems has been shifted and installed at Agricultural Radiation Processing Facility (ARPF) site near Vegetable Market, Indore for processing of agricultural products.
- ✓ A triode type thermionic electron gun of cathode voltage 50 kV pulse and peak emission current of 1 A has been developed using dispenser cathode having long operational life.
- ✓ A in-house developed solid state switch 50 kV pulse power supply energises this electron gun.
- ✓ The electron gun is operating satisfactorily with three linac systems at RRCAT.

▶ 6 MW peak/25kW average power klystron based microwave system for 10MeV LINAC for Radiation Processing

Table 1 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
Pulse top variation	%	±1
Pulse rise time	μS	<1
Pulse-pulse stability	%	<1
Frequency stability	/day	1x10 ⁻⁸
	/°C	1x10 ⁻⁸

Table 2 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	130
Beam current	Amp	100
Output	W/G	WR 284
Input	Coax.	N type

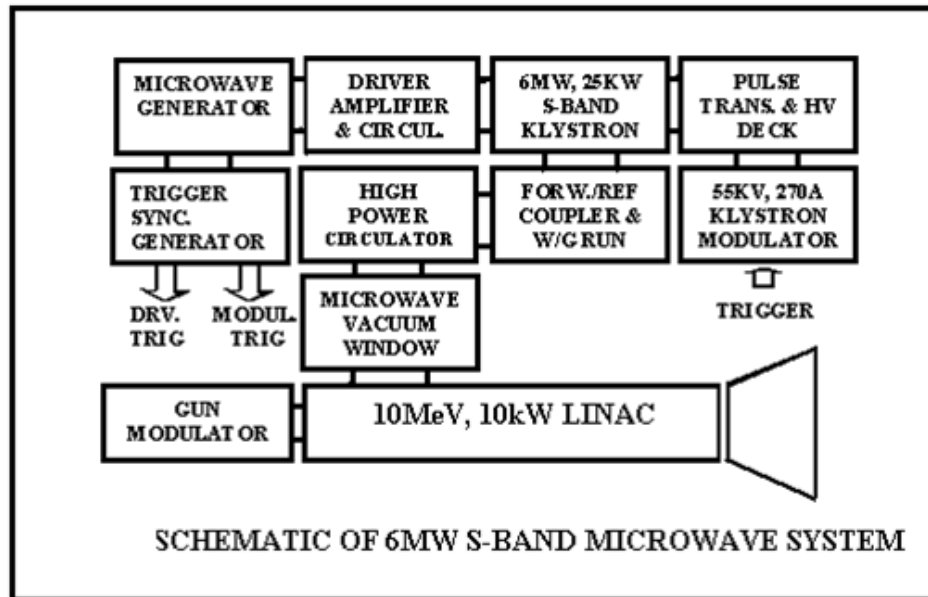
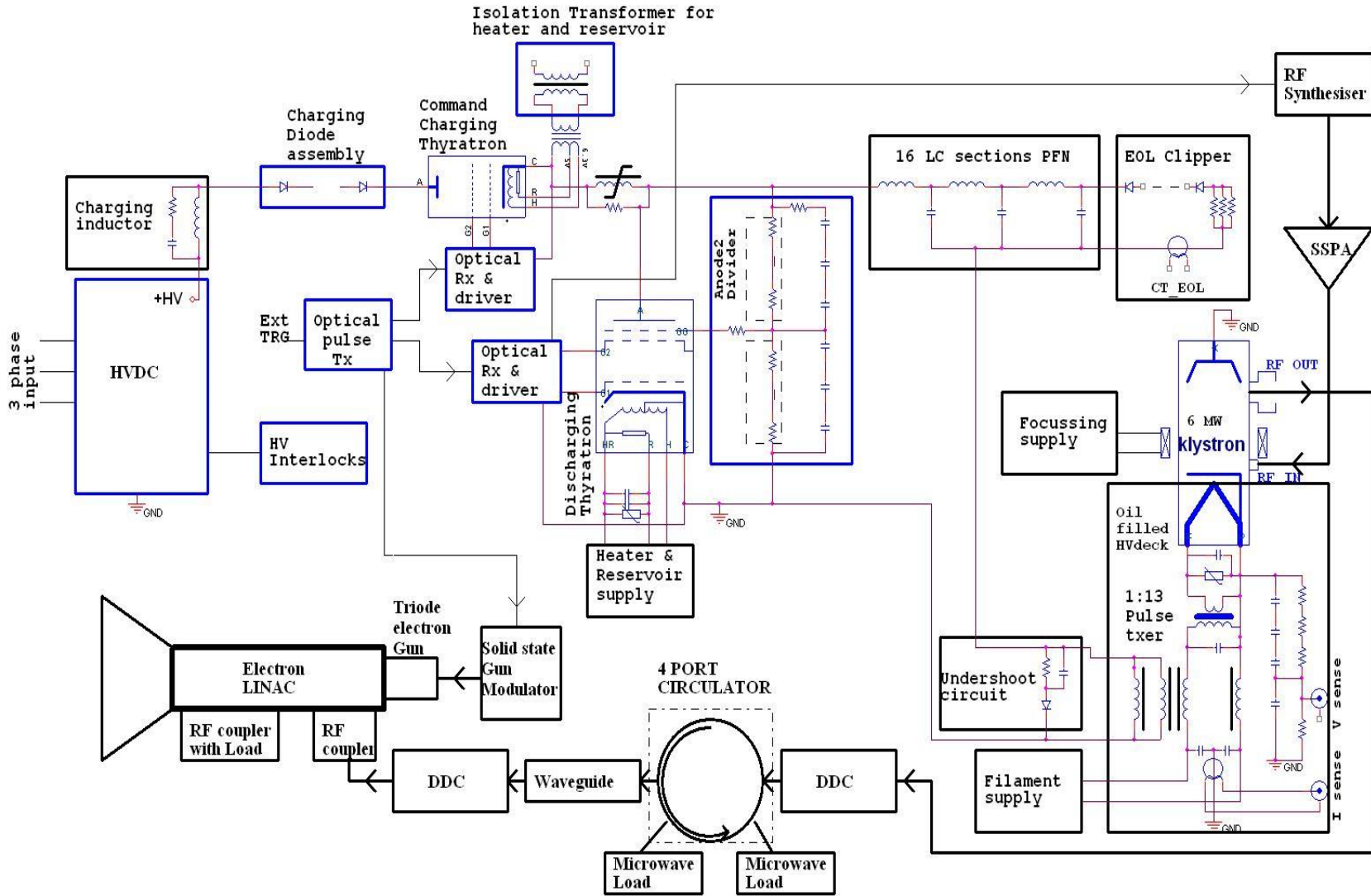


Table 3 Modulator Specifications

Pulse output power	MW	15
Pulse voltage output	kV	130
Output impedance	Ω	100
Pulse duration	μS	15
Rise time	μS	<1
Fall time	μS	<2
Flat top variation	%	< ±1
Mean output power	kW	40

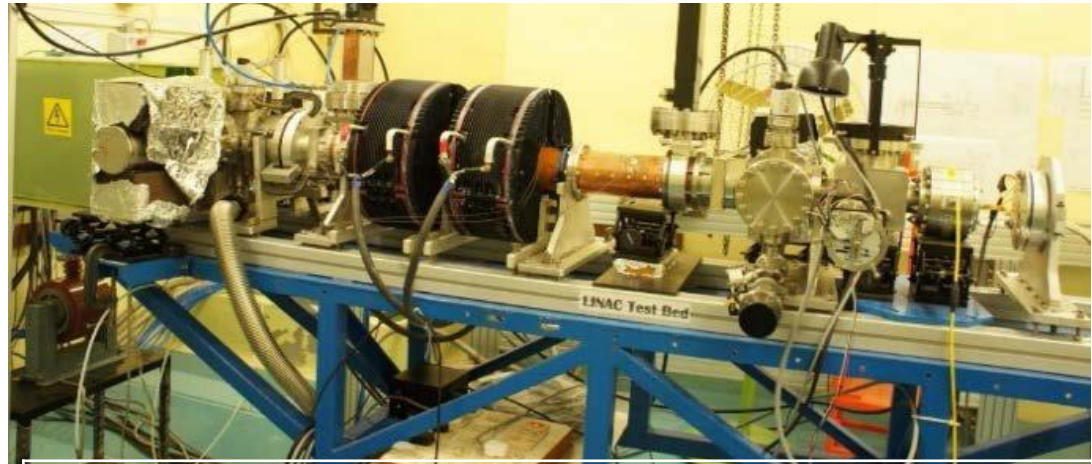
6MW peak power microwave system for the 5/10 MeV Travelling Wave Electron Linac at RRCAT. The command charging thyatron is floating



6MW peak power microwave system and 5/10 MeV Travelling Wave Linac



Standalone endurance tests on a microwave load.



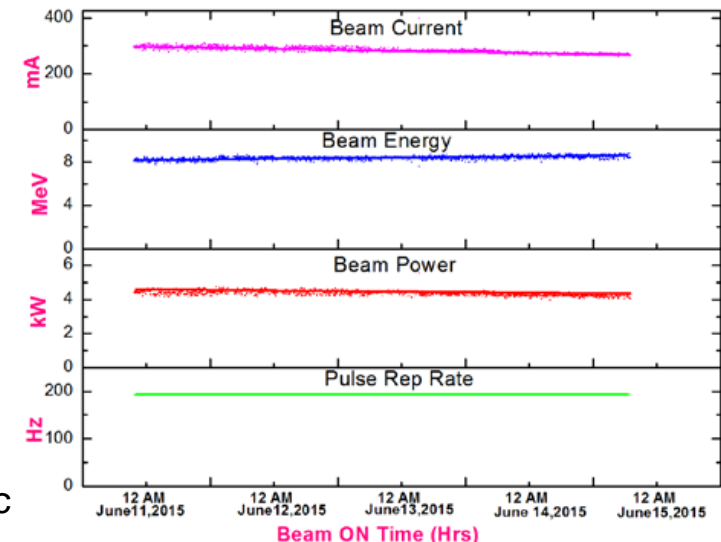
Microwave system connected to 10MeV Linac.

Date of Operation: 11-16 June 2018, Operation upto for 90 hrs

Sr. No.	PRR (Hz)	Average RF (kW)	Operating period
1	50	3.6	4 Hrs
2	100	7.2	8 Hrs
3	150	10.8	8 Hrs
4	200	14.4	8 Hrs
5	200	14.4	90Hrs



Beam trace from 10 MeV Linac



Endurance test of 10MeV TW Linac and Microwave system for > 90 hrs

6MW peak power microwave system and 5/10 MeV Travelling Wave Linac

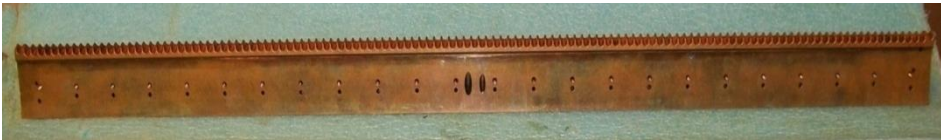


6.0 MW Microwave system, electron gun installed at ARPF site

Development of components for Compact Linear Collider (CLIC) project Novel Accelerator Technology (NAT) Protocol.

Microwave Power Extraction and Transfer Structures

They extract power from drive beam and deliver this power to main accelerating sections to achieve up to 100 MV/meter accelerating gradient.

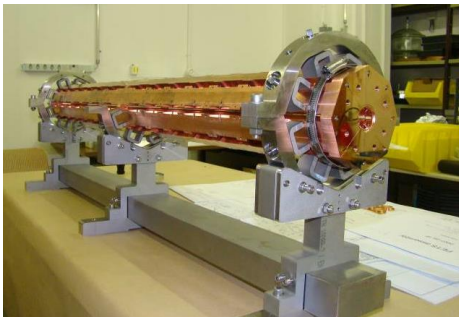


Metrology measurement at CERN showed a favorable report.

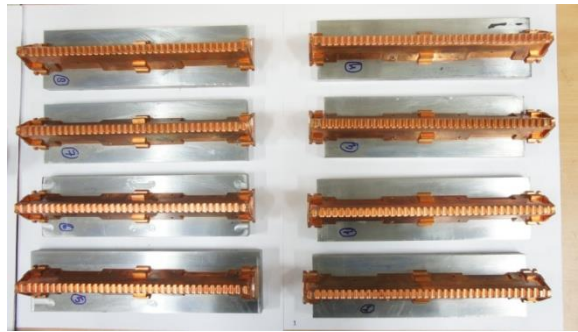


Two 800 mm PETS bars delivered to CERN in 2010

Material	OFHC Cu
One PETS needs	8 bars
Length	800 mm/500mm
Tolerance shape	+/- 20 micron
Roughness	<0.4 micron
Alignment	(+/- 0.1 mm)



Typical assembly of 8 PETS without vacuum envelop

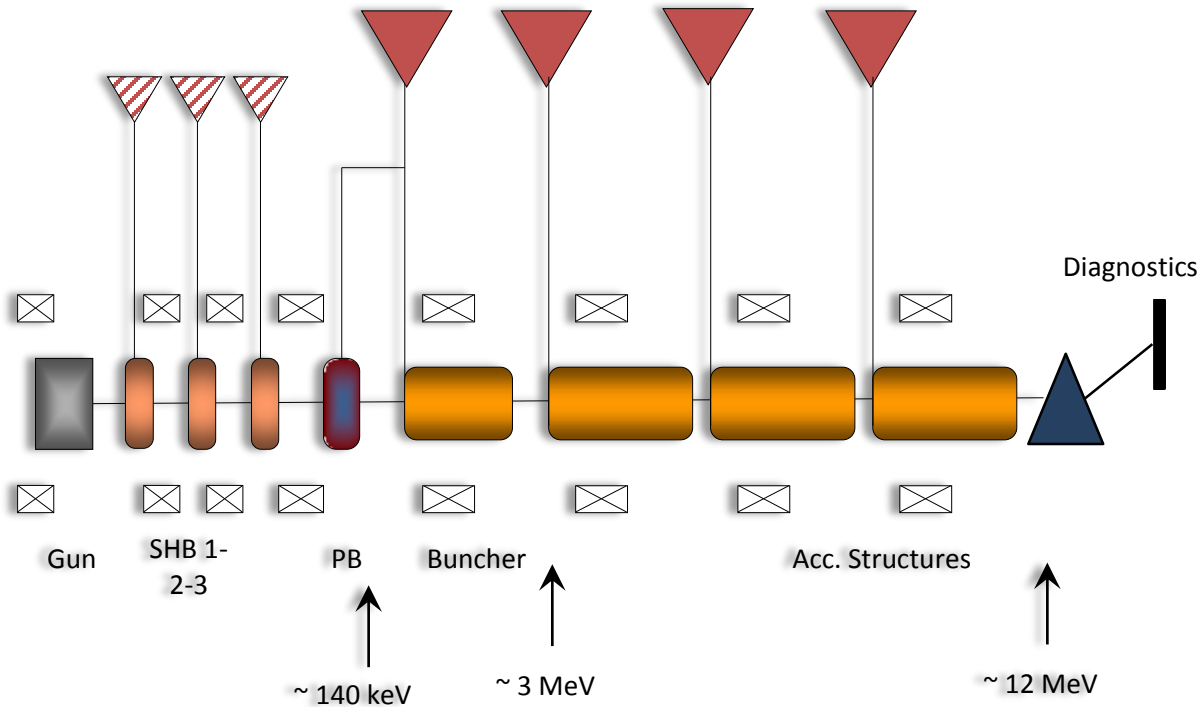


Eight PETS bars fabricated at IGTR, Indore for CERN CLIC project.

500mm short PETS bars have reached CERN in Dec 2017

CLIC DB front end, Post CDR Project at CERN

Modulator-klystrons, 1 GHz, 20 MW



Courtesy : Steffen Doebert, CERN

Development of components for Compact Linear Collider (CLIC) project Novel Accelerator Technology (NAT) Protocol.

Design and Development of a 20 kW broad band pulsed solid state amplifier for the sub harmonic buncher of the CLIC injector linac.

The installation, commissioning, and testing of the amplifier at CERN has been successfully carried out by RRCAT engineers in collaboration with the CERN team.

Parameter	Nominal value	Unit
Frequency	499.75	MHz
Pulse Length	140.3	μsec
Output power	20	kW
Band width (3dB)	58	MHz
Repetition rate	50	Hz
Phase variation shot to shot	~1	deg
Amplitude stability	~1	%



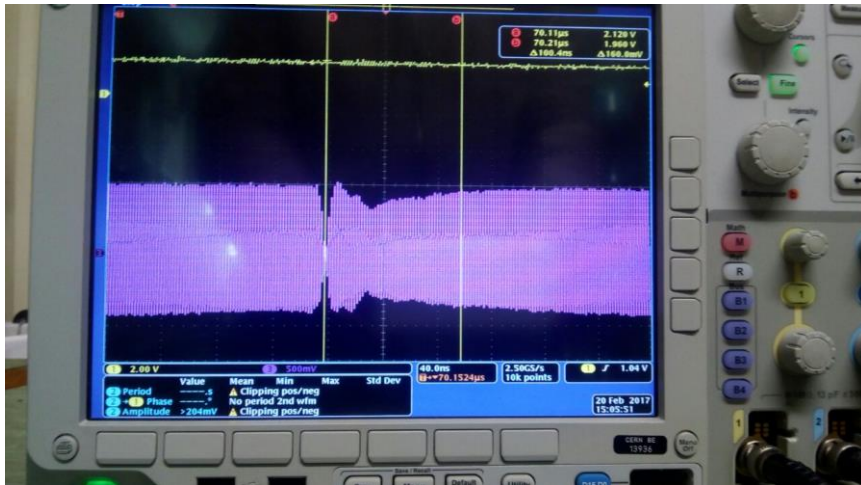
20kW SSPA Acceptance testing and Sub-harmonic buncher tests at CERN

Design and Development of a 20 kW broad band pulsed solid state amplifier for the sub harmonic buncher of the CLIC drive beam injector linac.



The amplifier was tested with sub-harmonic buncher cavity with input signal to the amplifier phase switched (180 degree phase reversal) the objective of the experiments was to study the amplifier response to the phase switched input.

The amplifier response was recorded at both power meter and CRO as below.



CRO: amplifier operating at 20 kW, 140 μ s, 499.75 MHz. Phase switched by 180 degree by RF switches and delay lines at mid pulse. Time scale is 40ns/div. Amplifier output stabilizes after ~ 100ns

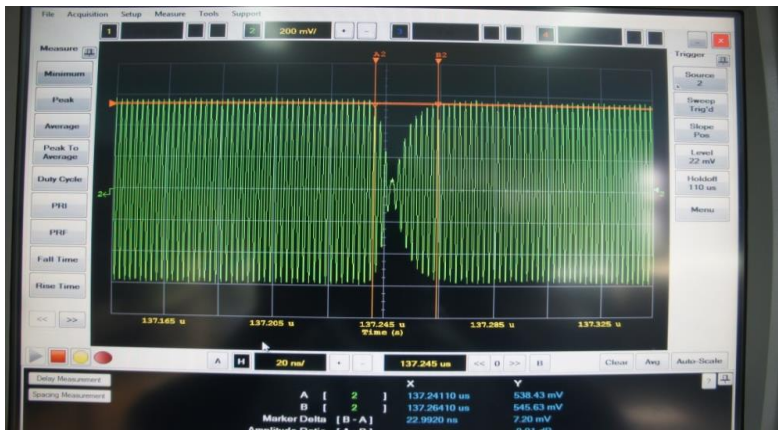


Power meter : Frequency 499.75 MHz amplifier operating at 20kW peak power. Time scale 100ns/div; vertical scale (1dB/div). Amplifier operating at 20 kW peak power. Power meter shows amplifier response stabilizing ~150ns after the phase switching

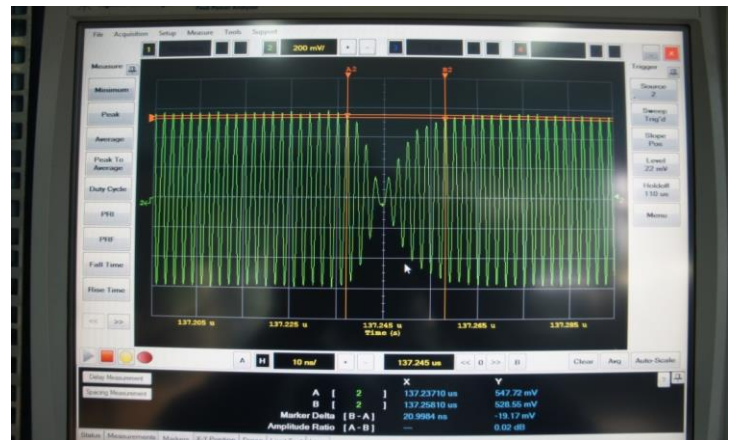
Fast phase response R & D for broad band pulsed solid state amplifier for the sub harmonic buncher of the CLIC drive beam injector linac.

Based on the study a prototype 1kW amplifier was developed to simulate the performance of a 20 kW amplifier.

The amplifier prototype proper bias ckt and damping. The resultant output waveform is obtained below .



Prototype Amplifier output power on CRO, time scale 50 ns/div (top)& 20 ns/div (bottom). Amplifier output stabilizes after ~ 21ns



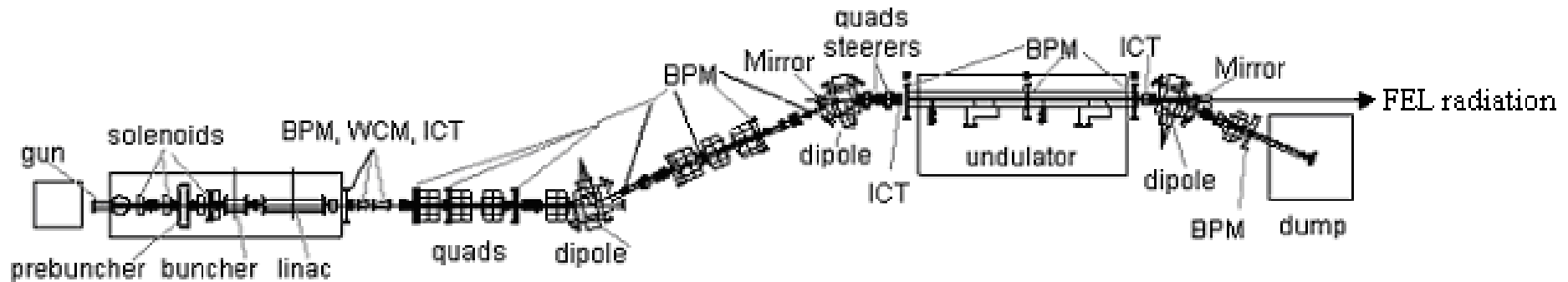
1 kW Amplifier output power as seen on CRO time scale 10 ns/div

Conclusion

- RRCAT has developed several high power RF/Microwave systems for electron accelerators from 2 MW to 45 MW peak for various applications.
- The 24 MW peak power S Band microwave system for IRFEL is in operation and first signature IRFEL has been observed, further upgrade in process.
- A 50kV triode type thermionic electron gun has been developed as and deployed for the linear accelerators.
- Two 6 MW S Band microwave systems have been developed for two 10 MeV linear accelerators. After testing of this system along with accelerator, it has been shifted to the ARPF site and under tests with linac.
- India has contributed to the construction of CTF3 and is now continuing its partnership in CLIC collaboration with recent development and supply of wide band amplifiers, PETS bars and wide band amplifier phase switching R & D, looking forward with more participation.

THANK YOU





An infrared free-electron laser (IR-FEL) that will be tunable at around 30 μm wavelength is currently being developed at the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore. The FEL will use a 15- 25 MeV normal conducting linear accelerator and a 50 mm period, 2.5 m long undulator housed in a 4.1 m long optical cavity.

wide range of research applications in condensed matter physics and chemistry.

thermionic triode electron gun delivers 1 nC charge in 1 ns FWHM pulses with a rep rate of 36.62 MHz for 10 s. This electron bunch train will then go through a pre-buncher followed by a buncher and a linac. We use a 2856 MHz linac and our pre-buncher will be operating at the sixth subharmonic of this frequency.