Development of 505.8 MHz Solid State RF Amplifiers at RRCAT

P R Hannurkar *, A. Jain, M R Lad, Ramesh Kumar, M K Badapanda, Nitesh Tiwari, Deepak Sharma, Alok Gupta, Ashish Tiwari, P S Bagdual, Nageswar Rao, Rinki Upadhyay, Rajiv Arora, M Prasad, Vasanthi Sekar, and P D Gupta

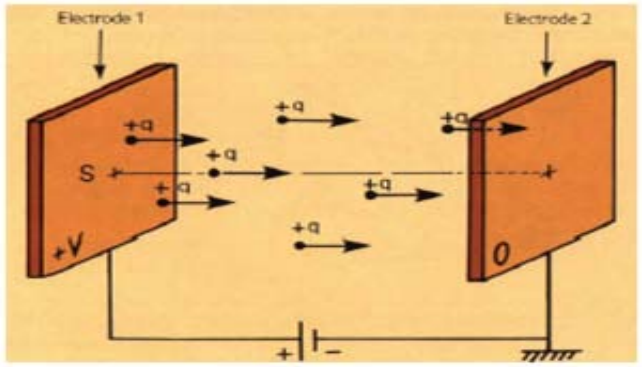
RAJA RAMANNA CENTRE FOR ADVANCED TECHNOLOGY, INDORE

OUTLINE

- Need for RF Power for the Accelerators
- Types of RF sources and Frequency range used
- Indus Accelerator complex at RRCAT
- Technology development for Solid State RF Power Amplifiers(SSPA)
- High Power Coaxial RF components required for SSPA
- 20 kW and 30 kW RF amplifiers Development and their Deployment in Indus-2
- Results obtained
- Conclusion

Particle Accelerator

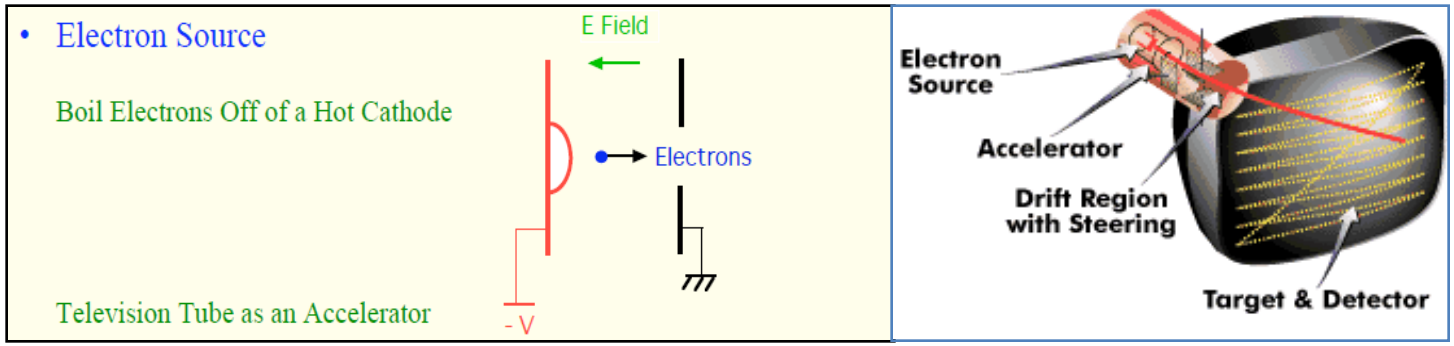
A **particle accelerator** is a device that uses electromagnetic field to increase the energy of charged particles and to contain them in well-defined beam.



the energy gain W of a particle of charge q moving through a potential V is:

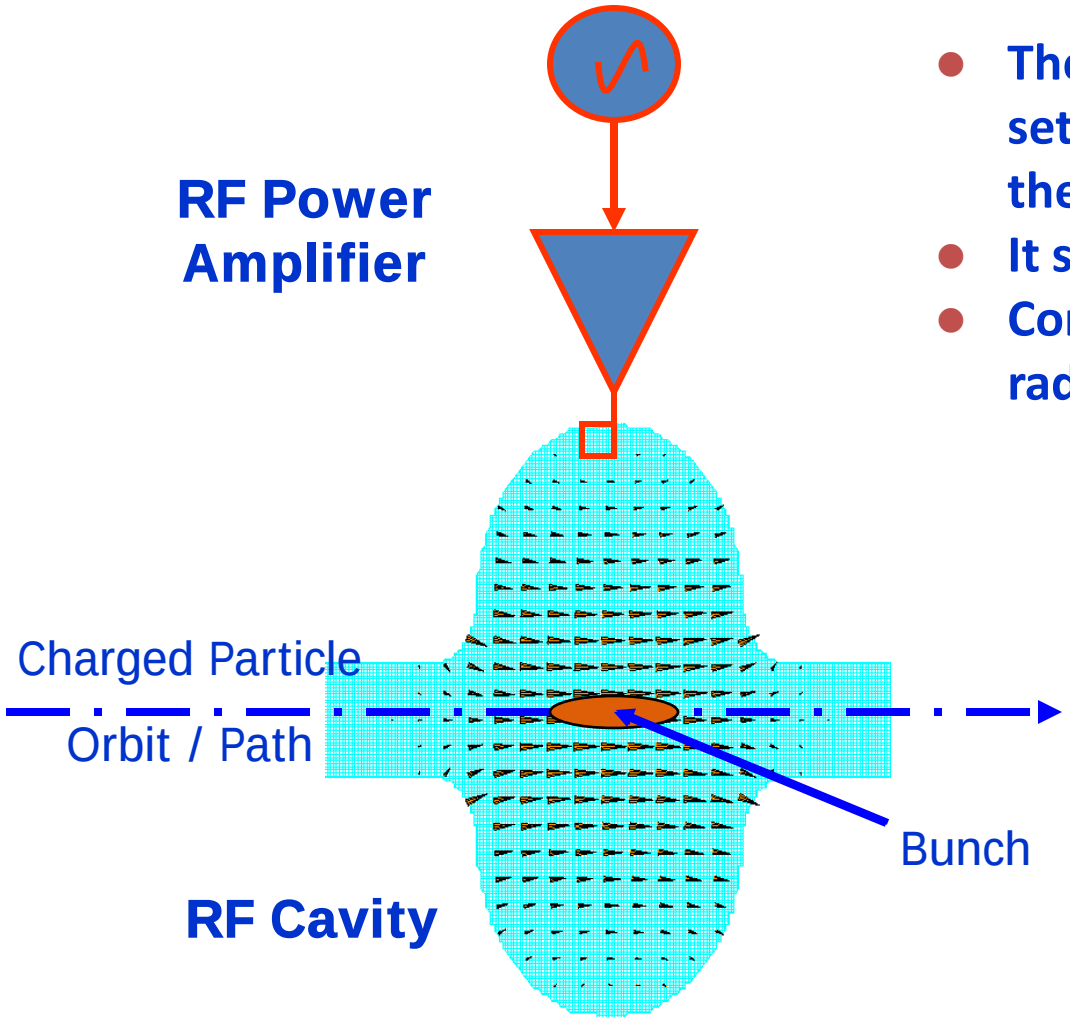
$W = q\,V$

CRT television set is a well known example of an accelerator

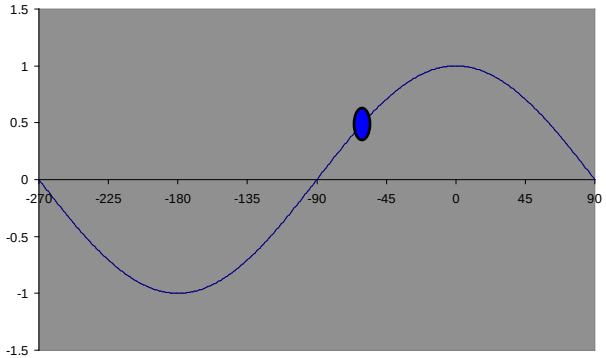


- The Max. Energy of DC Accelerator is limited to a few tens of million volts because of Electrical breakdown and sparking.
- Oscillating Electromagnetic field (RF) for high energy accelerators.

Basic principle of RF Acceleration



- The RF source supplies power to setup oscillating electrical field in the cavity.
- It supplies energy to the beam
- Compensates for the synchrotron radiation losses.



Electrical Field setup in the cavity

High Power RF sources

Depending on the type of particle and energy of the accelerator, RF source in the frequency range from few MHz to tens of GHz are employed.

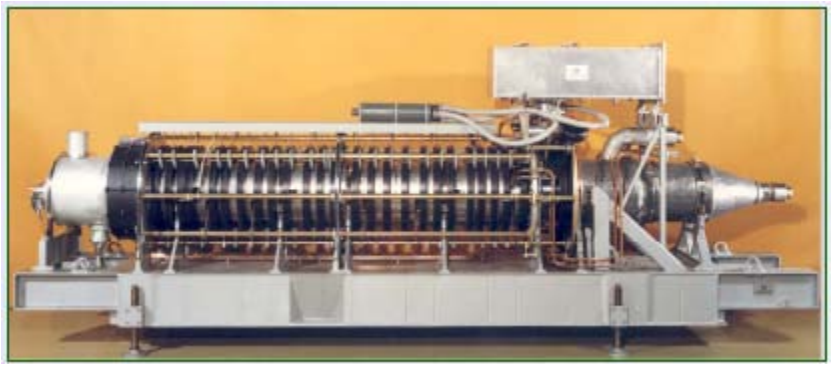
Klystron

Only option for very high power (MW) at very high frequency (GHz), High Gain

Low efficiency, Very few manufacturers

Poor phase noise performance

Limited Life



IOTs : Inductive Output Tubes

Good efficiency ≈ 70%

Compact

Better phase noise performance

Intrinsic low Gain

Limited Life

Tetrode Tube

Compact, rugged

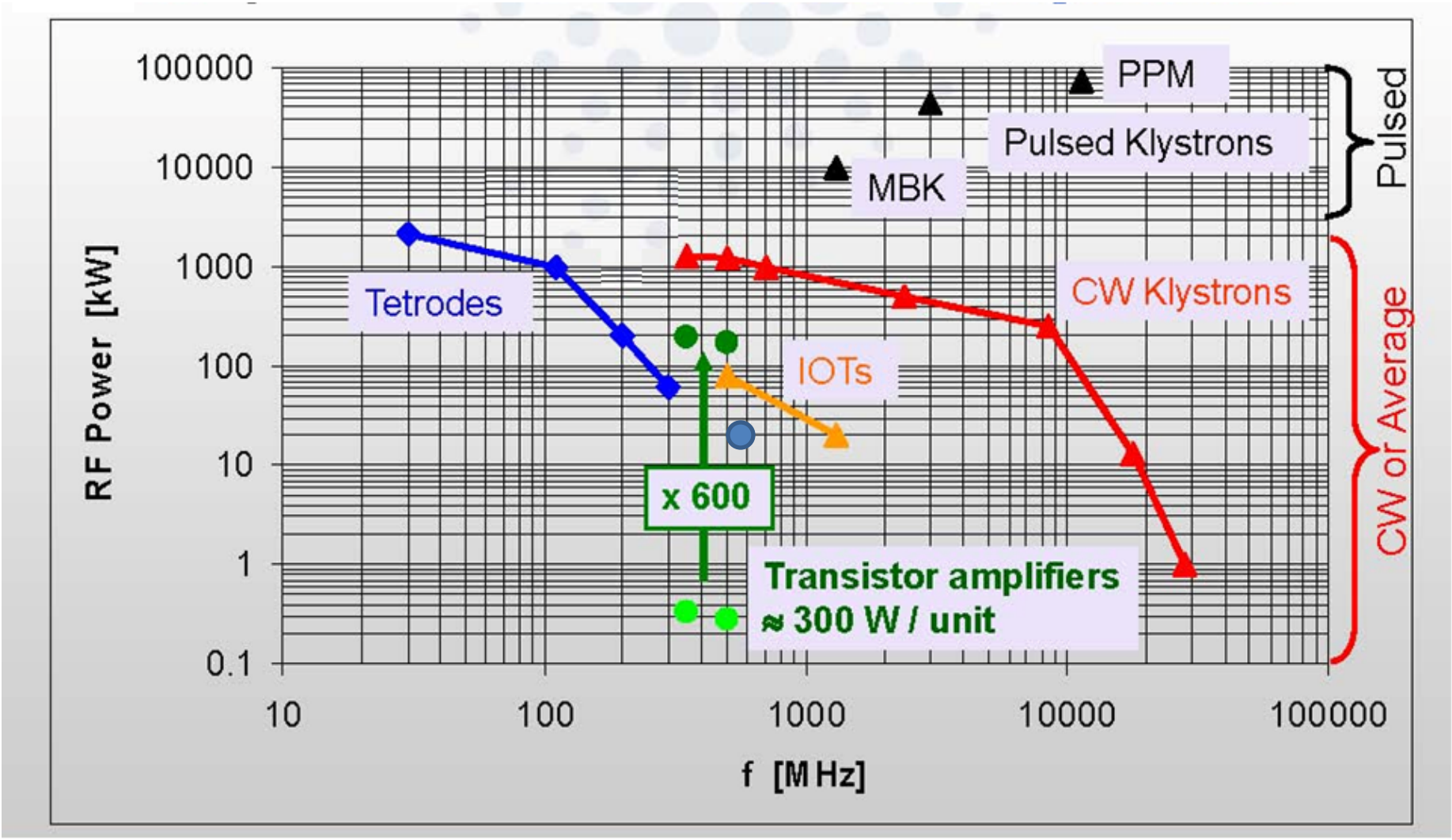
Limited to Low RF frequencies

Tuning circuit at high power needs maintenance

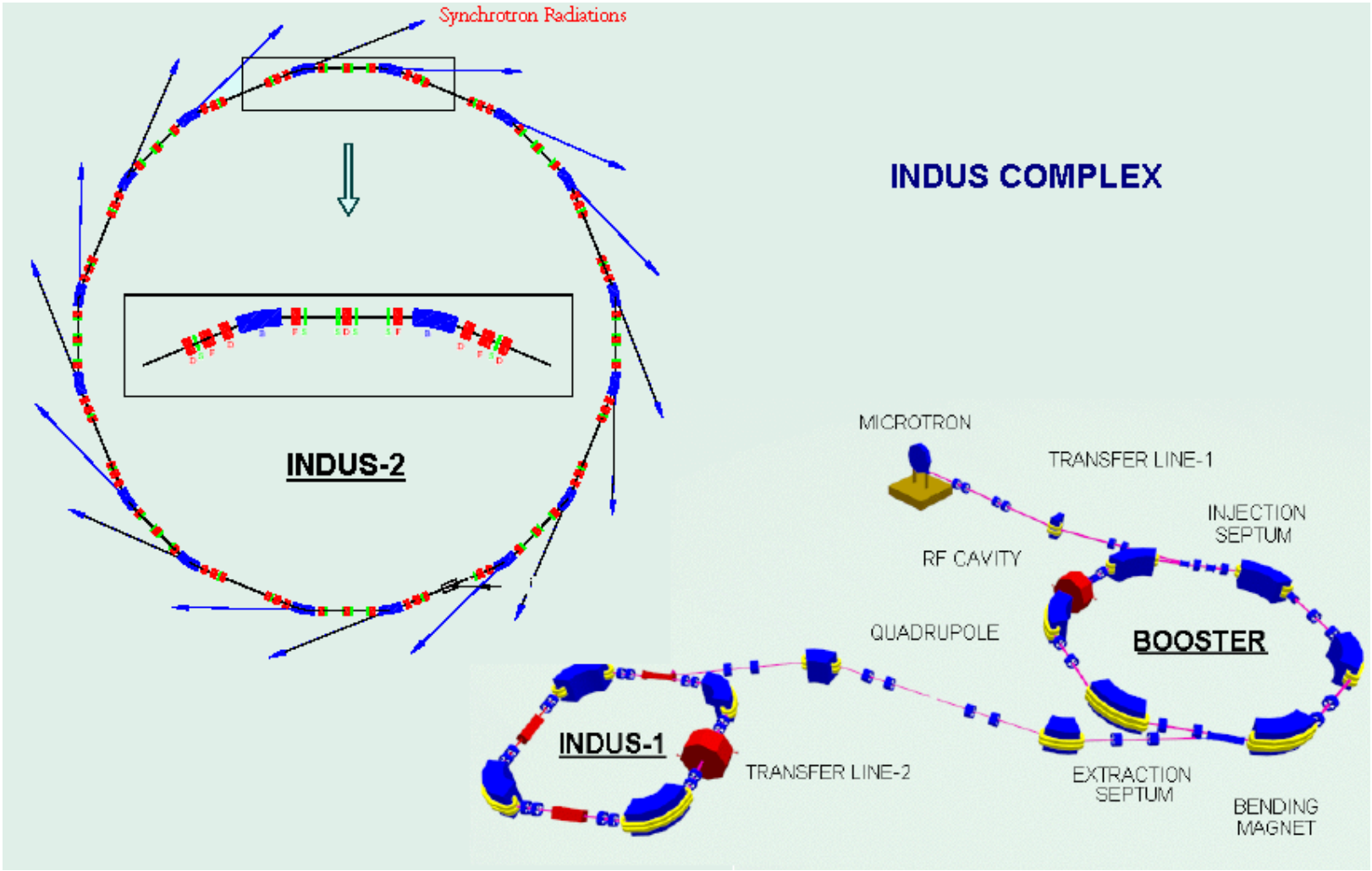
Intrinsic Low Gain

Limited Life

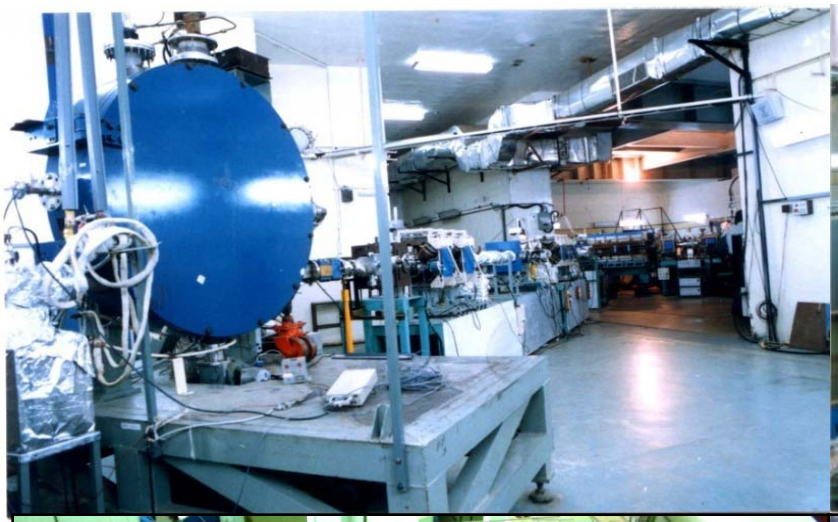
Available RF Devices

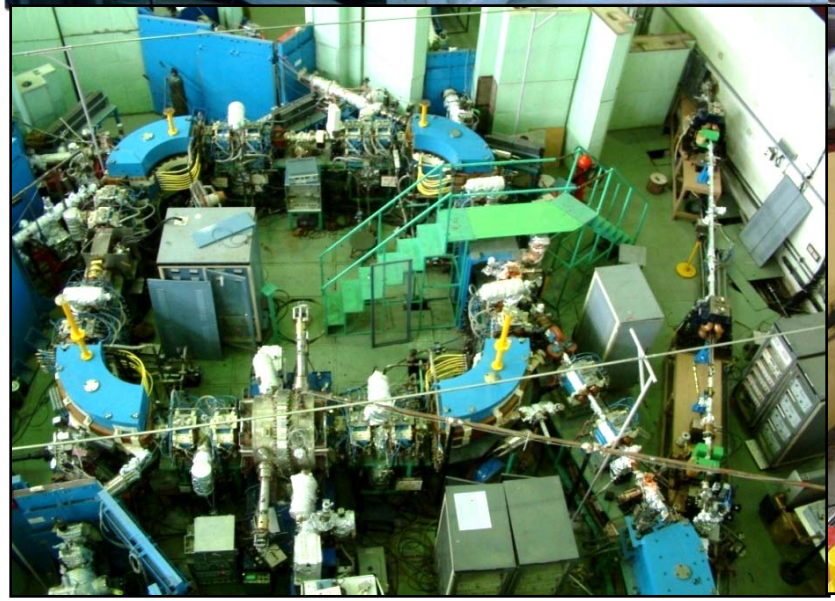


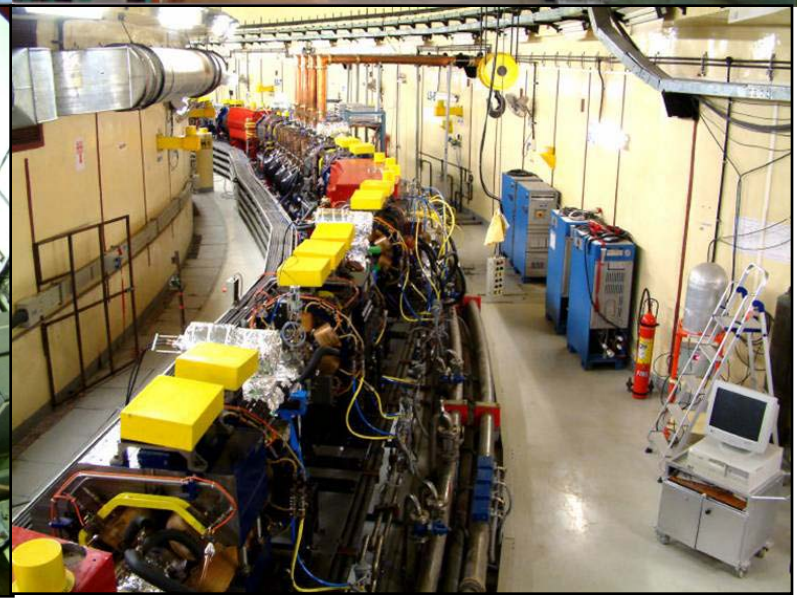
INDUS COMPLEX LAYOUT



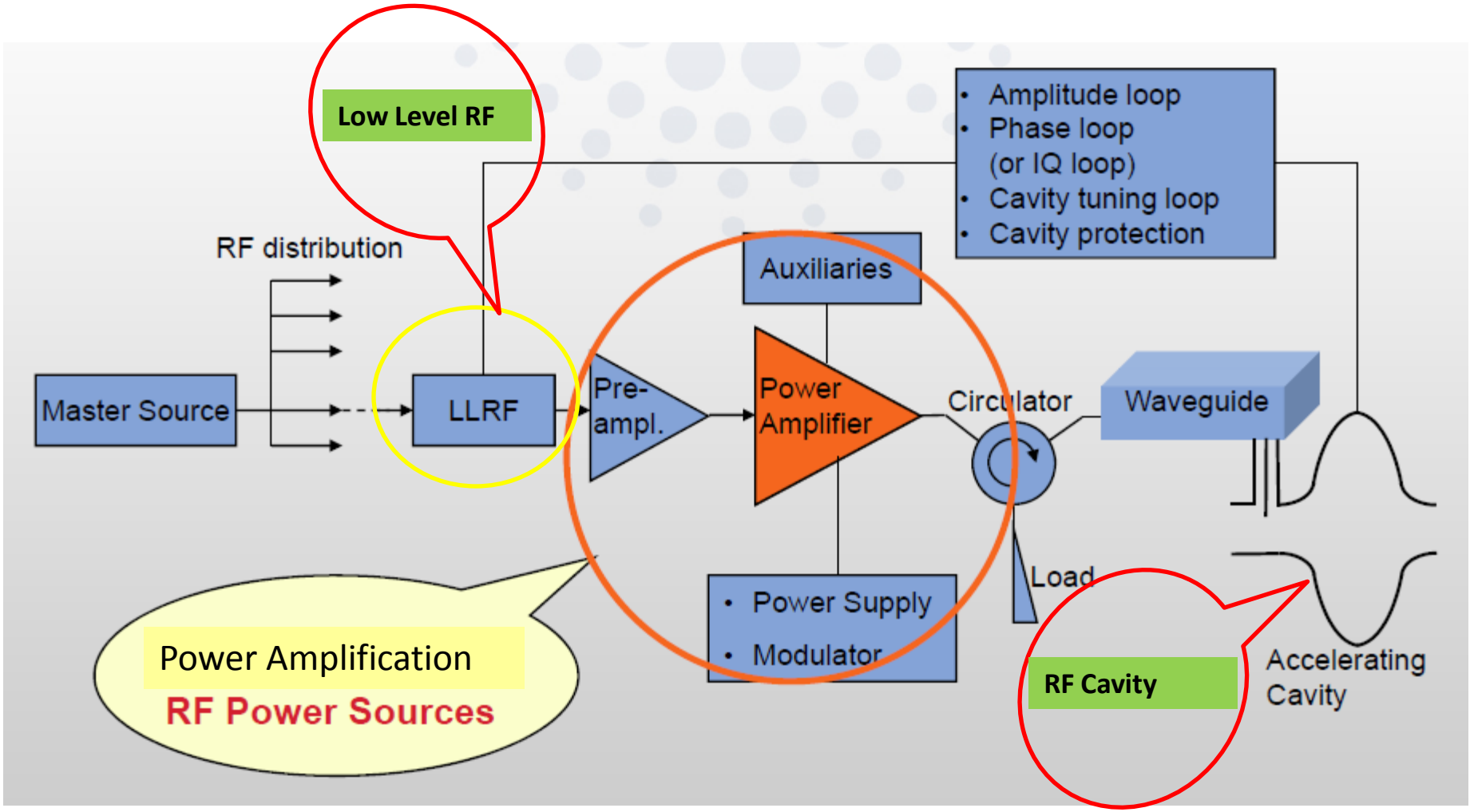
INDUS ACCELERATORS







Typical RF System for Accelerator



Indus-2 RF System

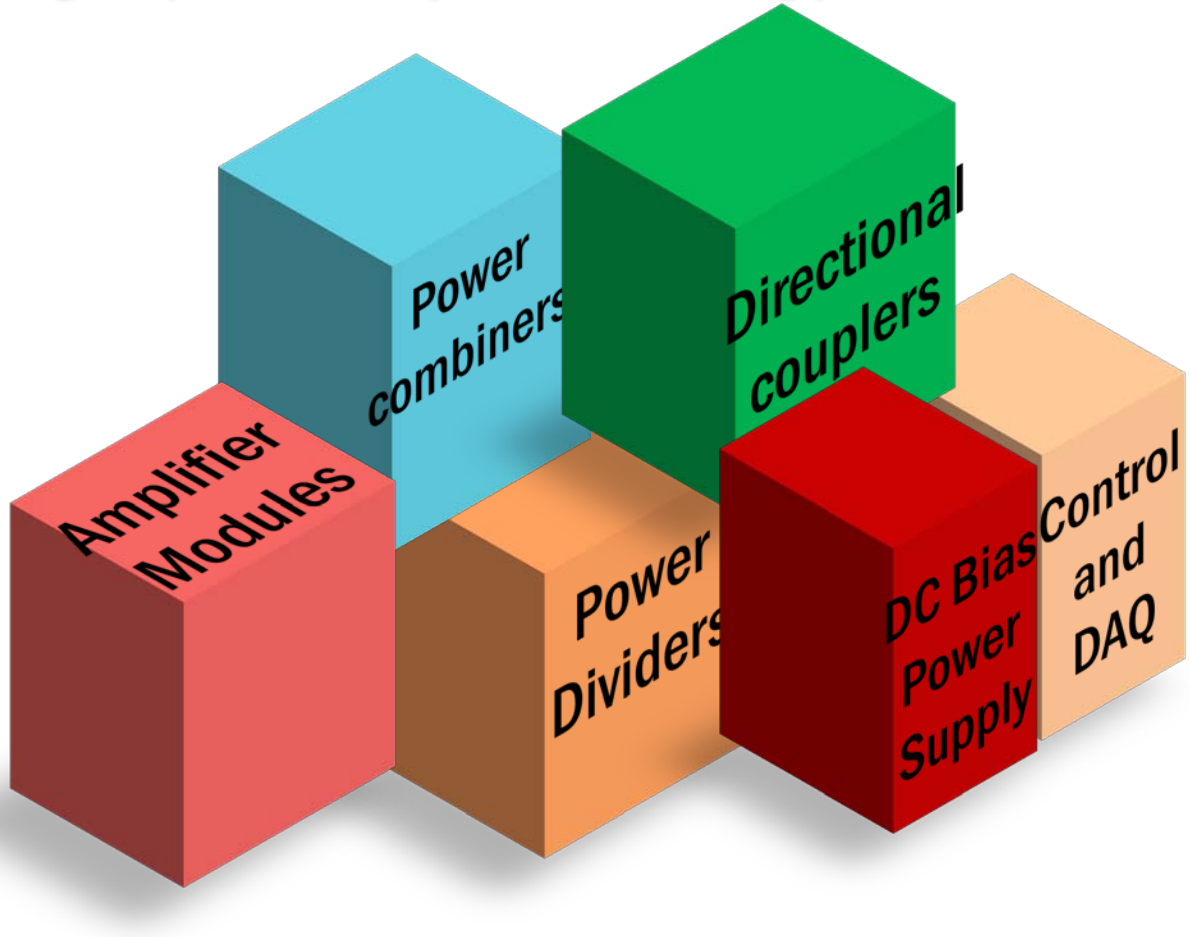
- **Major subsystems : RF cavities, Multibeam klystron Amplifiers, 6-1/8" transmission line, HV power supplies, LLRF systems, precision cavity temp. control systems.**
- **Four RF Stations each with 60 kW output power at 505.812 MHz.**
- **Total cavity gap voltage 1500 kV with four cavities.**

Solid State RF Amplifiers

- The advantages of solid state amplifier:
  - No High Voltage and Vacuum requirement
  - No filament, no warm up time and simple start up procedures
  - High Reliability
  - Modular Design
  - Graceful Degradation
  - Easy and Fast Maintenance
  - Better RF signal (Harmonics, Phase Noise etc.)
  - Overall moderate Cost
- Expected decrease in Price/Watt and Size/Watt due to world-wide R&D efforts

Solid State Amplifier: Building blocks

Output RF power of individual solid state device is rather modest, being of the order of few hundred Watts. Hence kW level RF power will be obtained by summing output of multiple devices using power combiners.



320 W, 505.8 MHz RF Power Amplifier Module

- Amplifier modules with output RF power level of 320 W at 505.8 MHz have been developed.
- Each module uses two numbers of MOSFETs.
- Circulator is used for protection from reflected power.
- Amplifier includes necessary monitoring and interlock circuits.
- RF power module is mounted on a water cooled copper heat-sink.

320 W solid state amplifier module

505.8 MHz 320W RF Amplifier

Specifications:

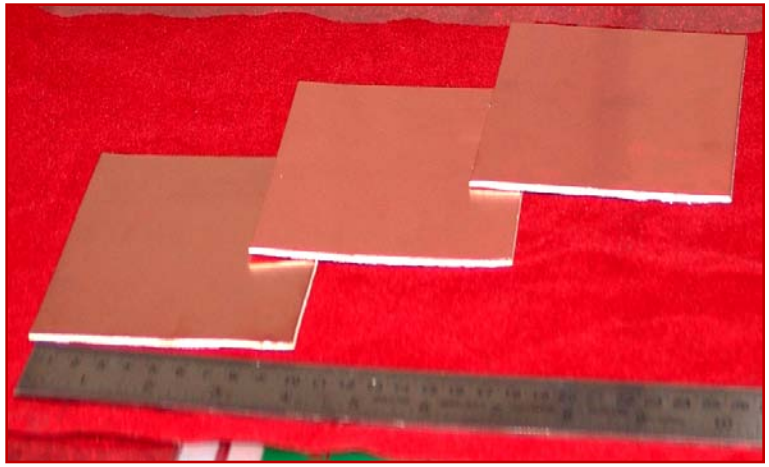
Sr.	Parameter	Value
1	Rated RF Power Output	320 W
2	Operating frequency and 1 dB Bandwidth	505.8 MHz, ± 5 MHz
3	Power Output @ 1db Compression	300 W
4	Operating Mode/ Class of operation	CW/ AB
5	Power Gain	15 dB
6	Input and output Impedance	50 Ω
7	Power Added Efficiency	50 %
8	Harmonic Distortion	-30 dBc
9	Spurious Output	-35 dBc
10	Input VSWR	1.2
11	Cooling	Water Cooled
14	Primary Power	300-415V, 47-63Hz, 3 Phase
15	Protection	Excessive Reflection, over temperature, overdrive

RF Power Module

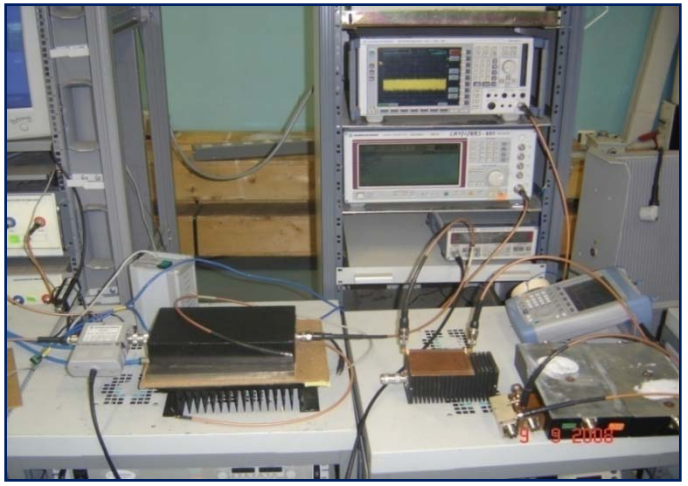
Heat Sink Assembly

Microwave Substrate

- Due to huge requirements of microwave laminates required for building RF amplifier modules , a project funded by Board of Research in Nuclear Sciences (BRNS), with Centre for Material for Electronics Technology (CMET) was taken up for their development.
- The laminates with permittivity of 4.5 and loss tangent of 0.002 have been developed and used successfully for making high power amplifier power modules.

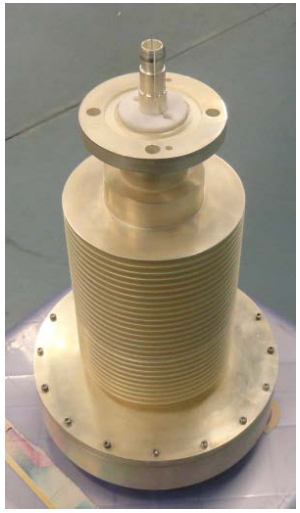


microwave substrates



Testing and evaluation at RRCAT, Indore

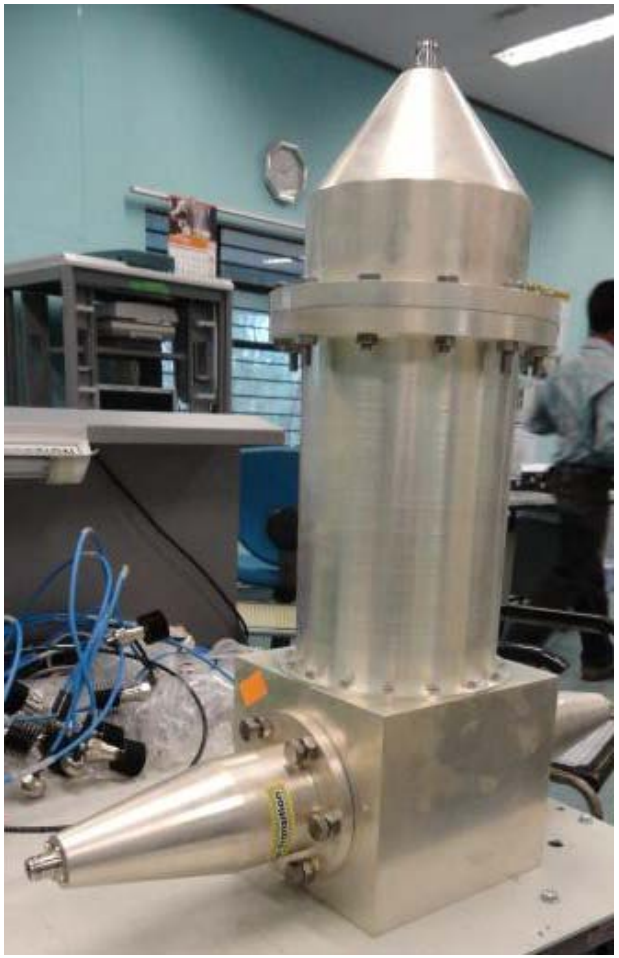
Rigid coaxial transmission line Power combiners at 505.8 MHz



16-way 4 kW Power Combiner at 505.8 MHz

2-way 20 kW Power Combiner at 505.8 MHz

All power combiners are made up of silver coated brass material. Output power is taken from 1-5/8", 3-1/8" and 6-1/8" coaxial lines respectively in 4 kW, 20 kW and 40 kW combiners.



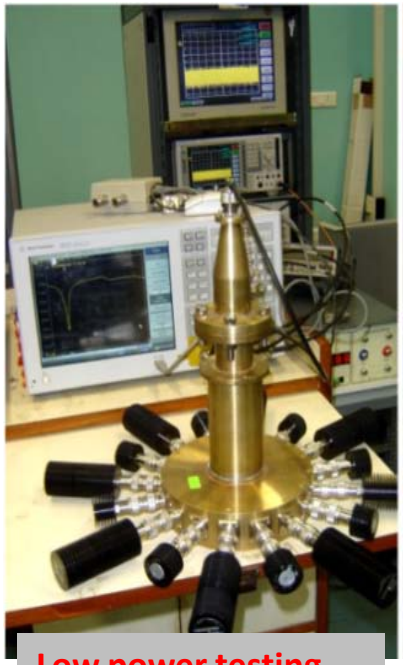
2-way 40 kW Power combiner at 505.8 MHz

Combiner measurements

RF measurement of all power combiners and dividers was performed at low and high CW and pulse RF power.

At low power, measurement was carried out using vector network analyzer for complete scattering parameter matrix measurement.

Standard back to back measurement was performed for amplitude and phase imbalance.

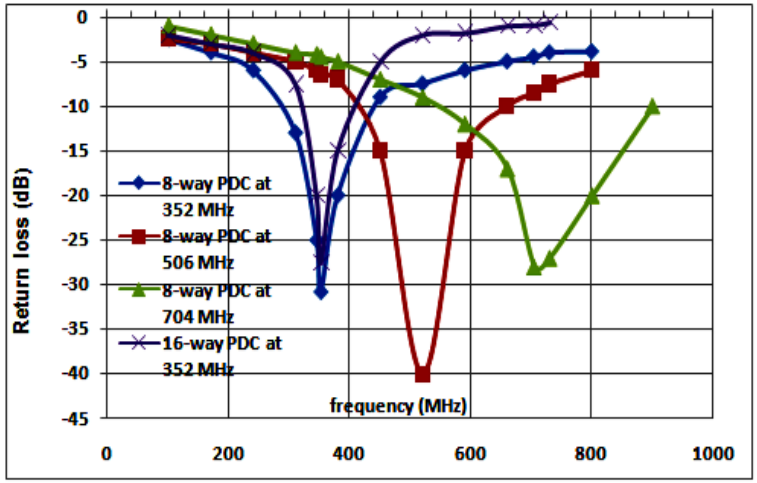


Low power testing

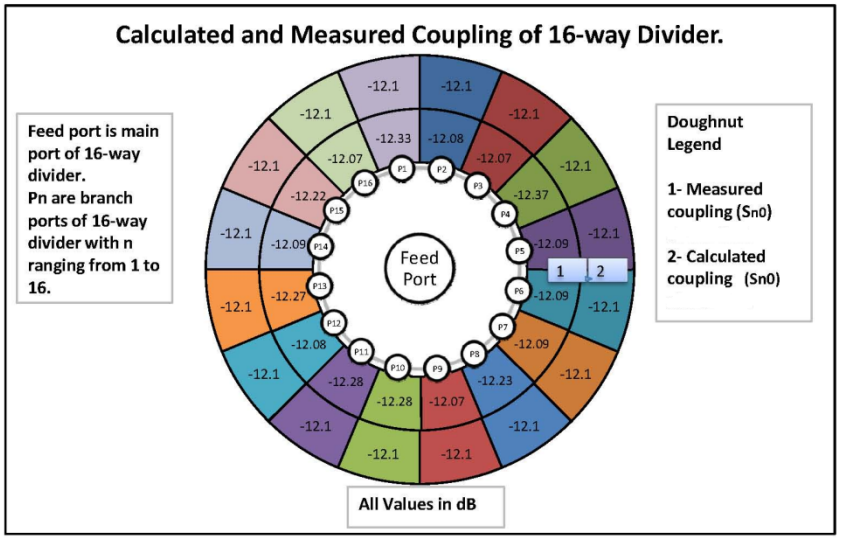
High power testing

High power Imbalance testing

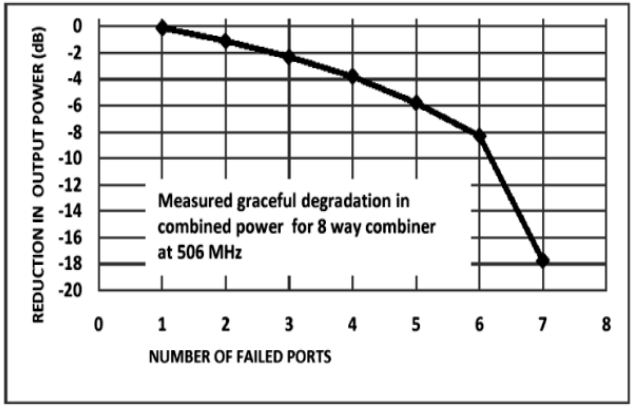
Measured Performance of power combiners



measured Input impedance match



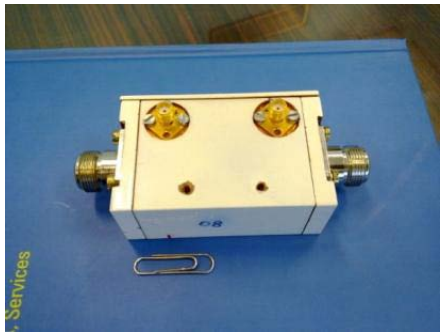
Coupling of 16-way Combiner



Graceful degradation

Typically for 16-way combiners worst case return loss is better than 25 dB, while insertion loss is less than 0.1 dB, corresponding to combining efficiency of 97%.

Directional couplers

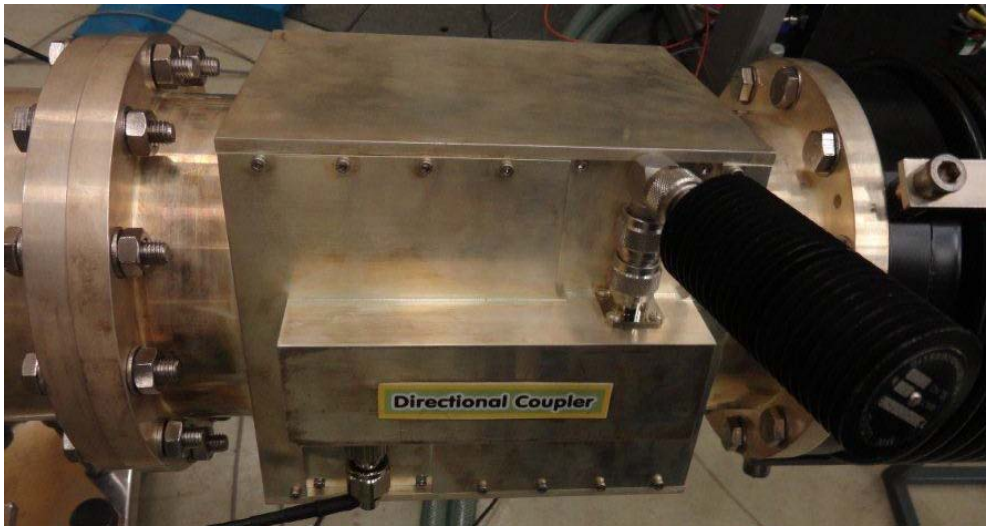


1 kW

4 kW

20 kW

Directional Coupler type	Coupling	directivity	Insertion loss
1 kW	**40 dB**	28 dB	< 0.05 dB
4 kW	**50 dB**	26 dB	< 0.05 dB
20 kW	**50 dB**	24 dB	< 0.05 dB



80 kW

RF Loads Developed

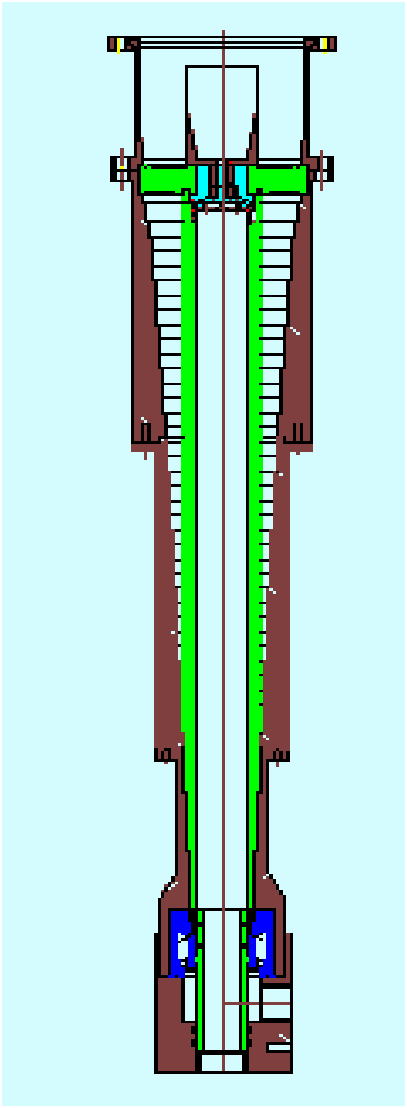
VSWR : ≤1.07 up to 750MHz
Coolant : Low Conductivity water
Pressure Drop : 1.5 kg/cm^2 to 4kg/cm^2

RF Power capacity: 30 kW CW

75 kW CW

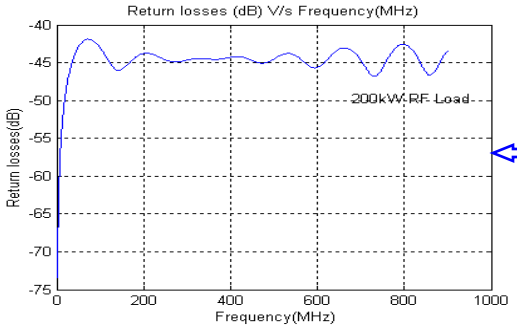
200kW CW

HIGH POWER COAXIAL DUMMY LOAD

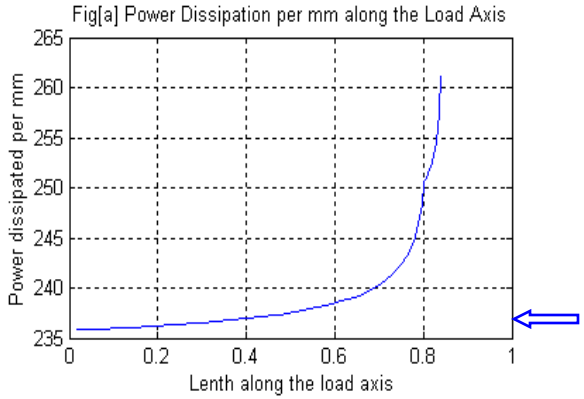


SPECIFICATIONS

RF Power Rating:	**200 kW(CW)**
Frequency Range:	**DC-650MHz**
Cooling:	**Normal Water**
RF Input Port:	**6-1/8"EIA Coaxial**



Input matched for Wide Band



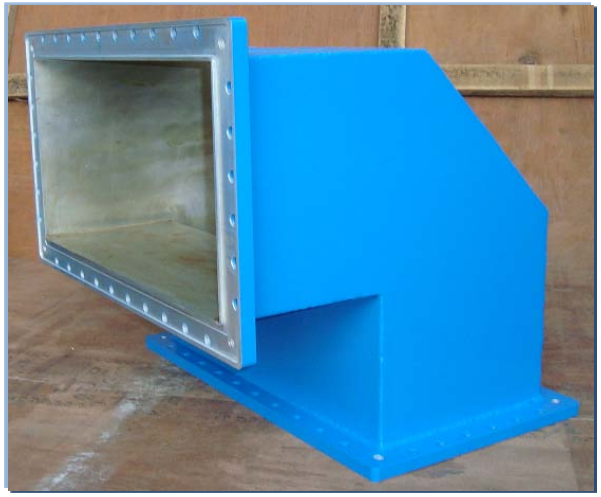
Power Dissipation along the load is uniform

Wave-Guide Components Development

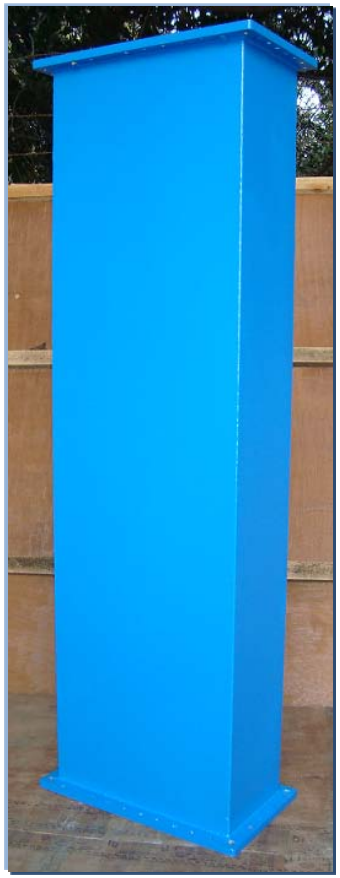
Straight Section

Rectangular Waveguide		
Type	WR	1800
Freq.	MHz	410-620
Matl.	AA	6061 T6
Attn.	dB/100ft	0.06
Dim.	mm	457.2 x 228.6
Tol.	mm	± 0.51
Peak Power	MW	700
Avg. Power	MW	1.5
Finish	MIL-C-5541	Chromate conversion

H-plane Bend

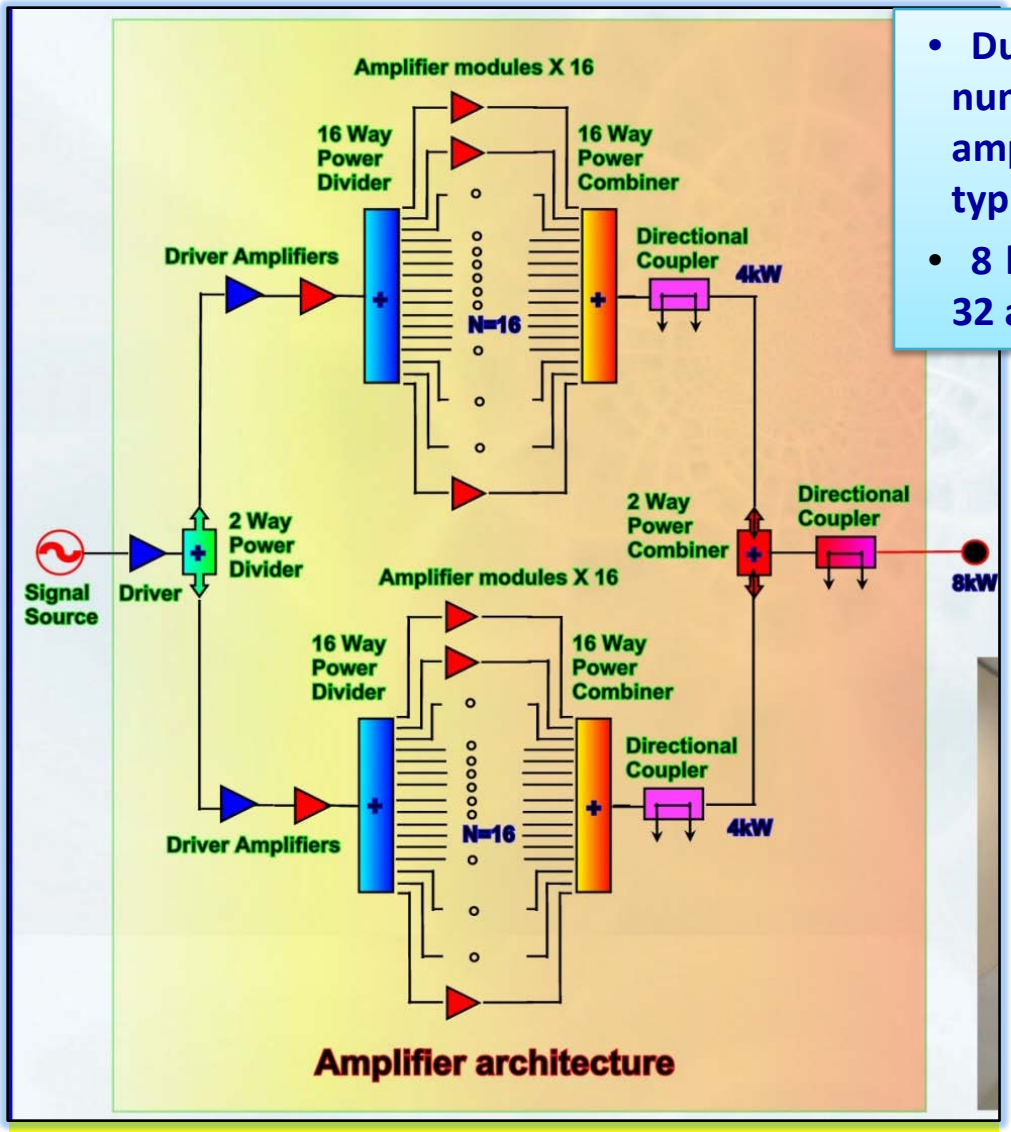


E-Plane Bend



Straight Section

8 kW Solid State Amplifier Scheme for Indus-2



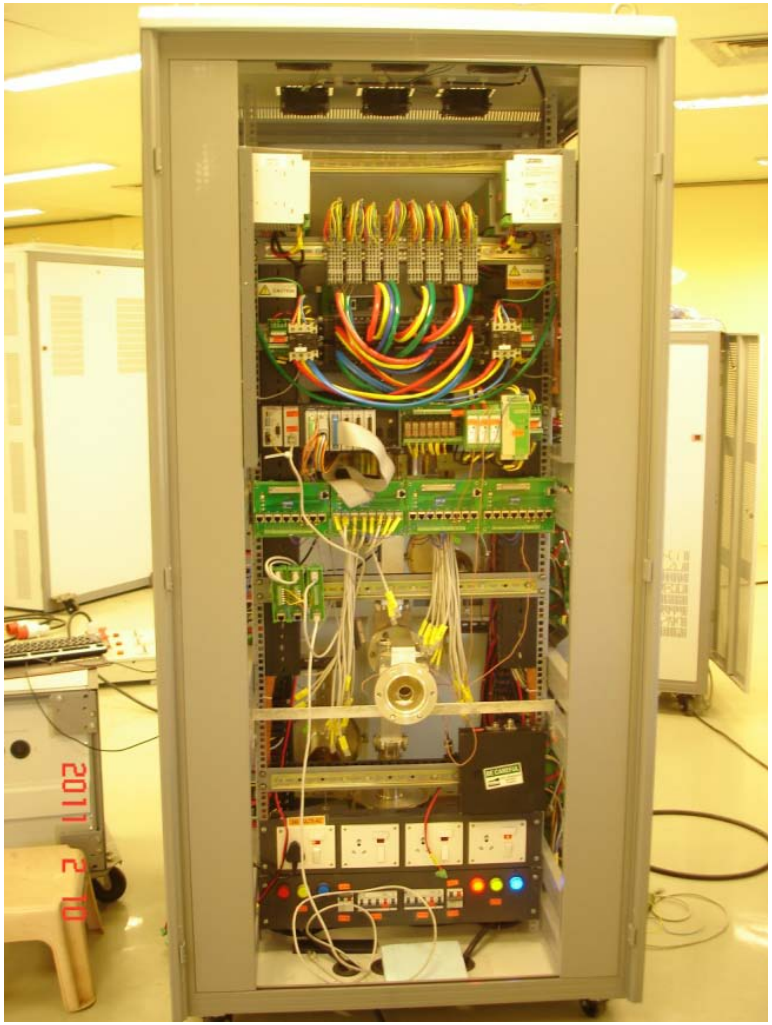
8 kW Solid State Amplifier architecture

- Due to divide and combine strategy, large numbers of PAMs synchronized together in amplitude and phase, are used in making a typical kW level SSPA
- 8 kW unit is housed in a single euro rack with 32 amplifier modules of 320 W RF power .

8 kW SSPA

8 kW ,505.8 MHz Amplifier

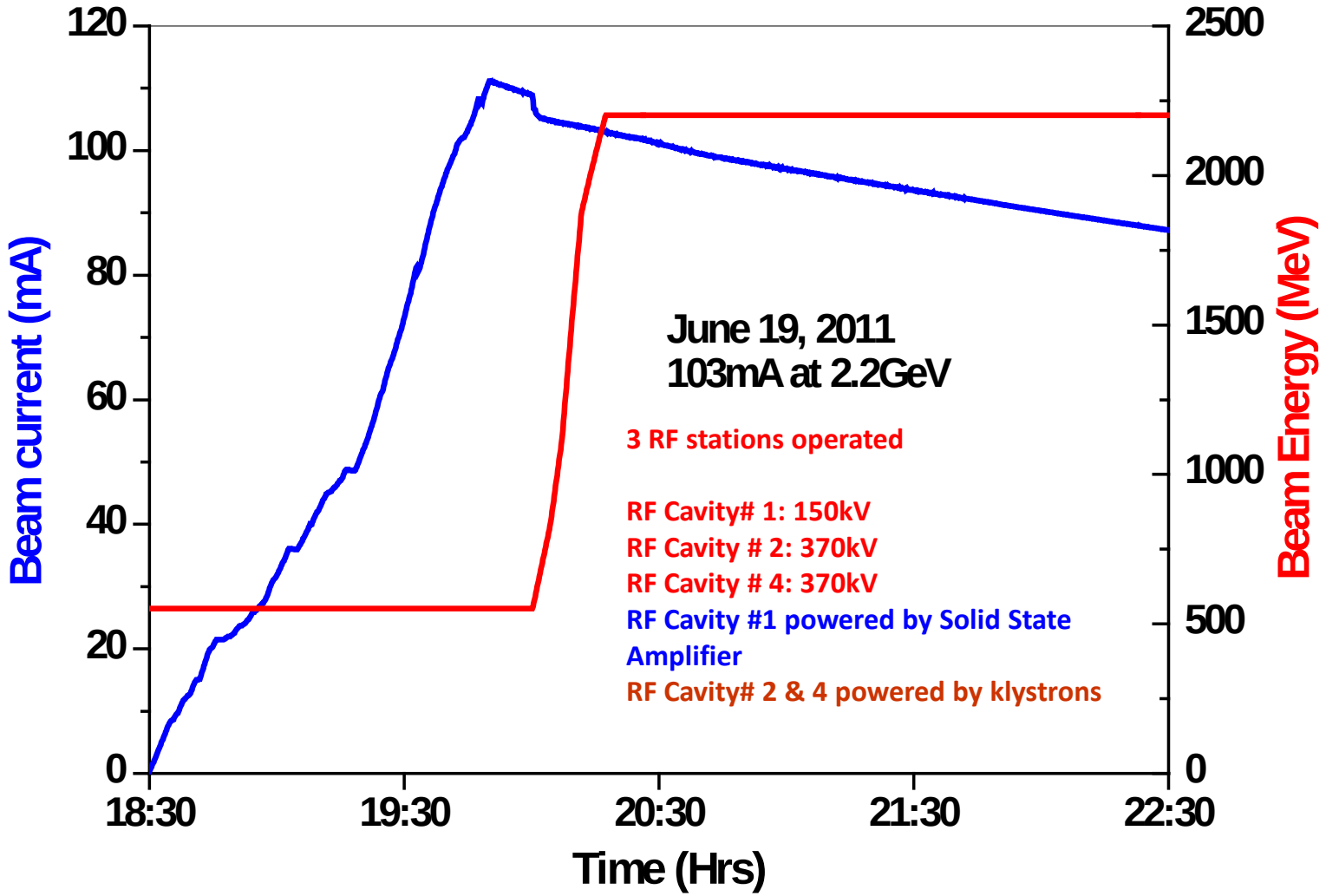
Front View of 8 kW SSPA



Rear View of 8 kW SSPA

First unit of 15 kW RF Amplifier

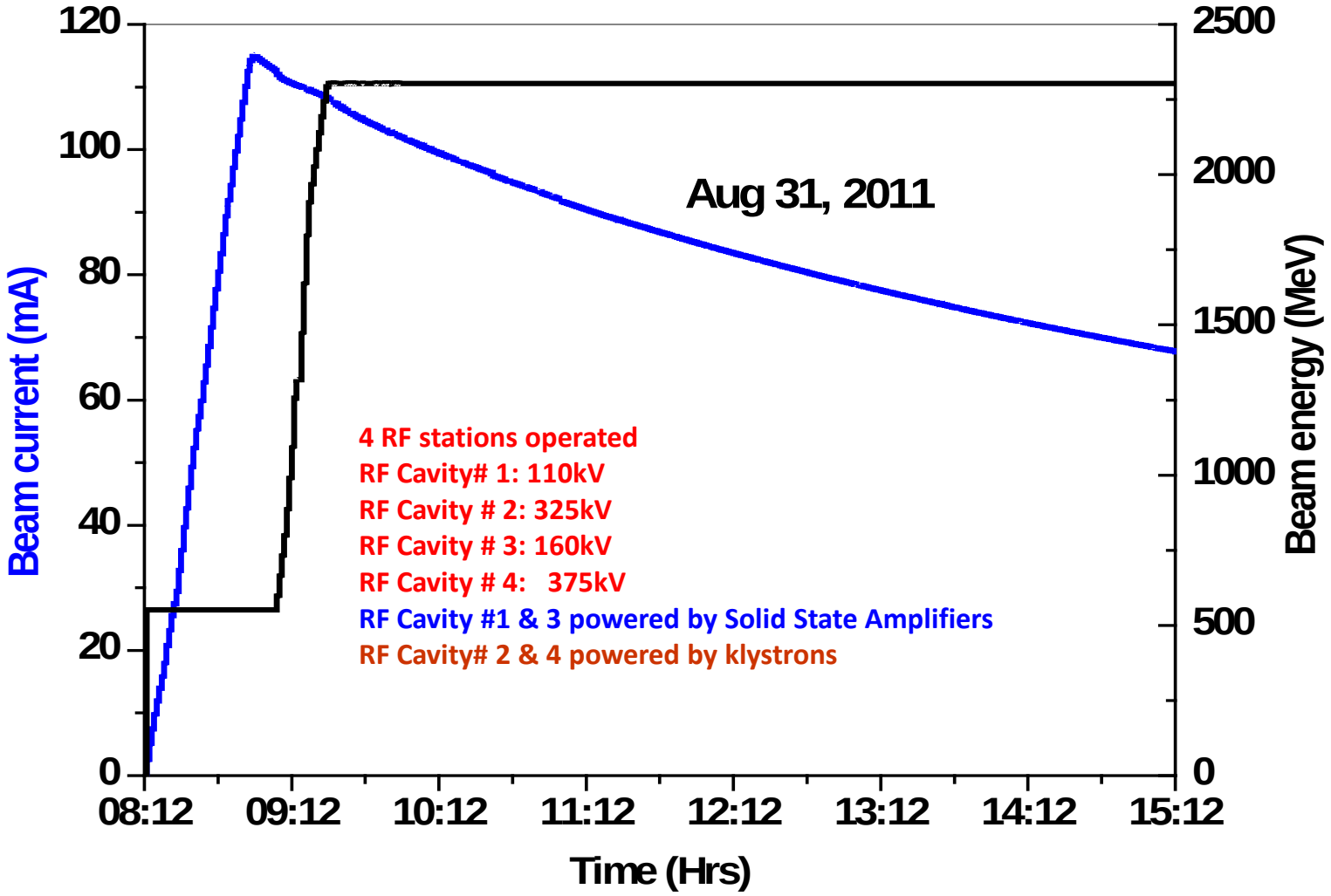
Indus-2 operation at 2.2GeV/100mA



In March 2010, 2 GeV/100 mA was achieved in Indus-2. With the support of one 15kW solid state amplifier energy could be increased to 2.2 GeV at 100 mA.

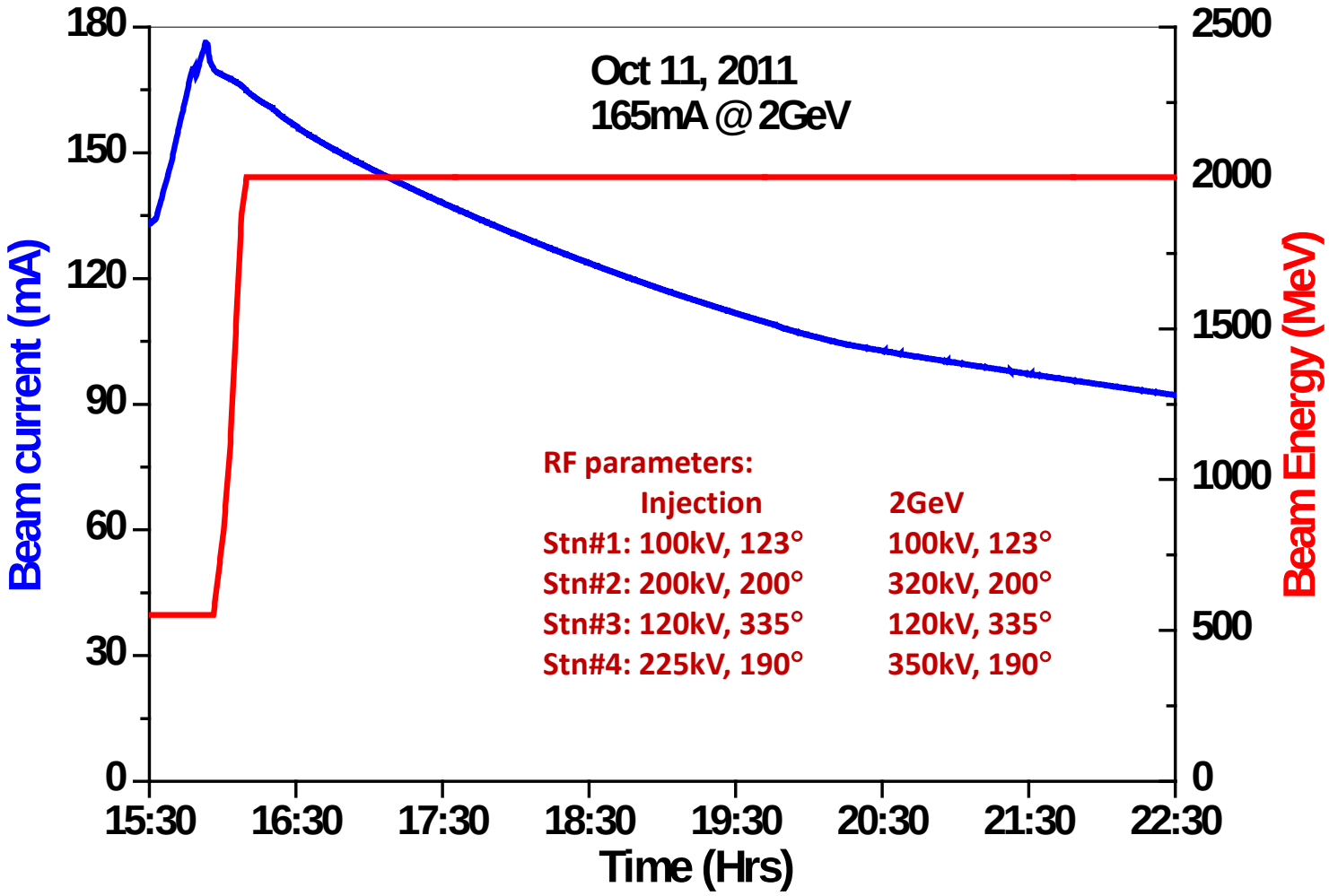
Second Unit of 15 kW RF Amplifier

Indus-2 operation at 2.3GeV/100mA



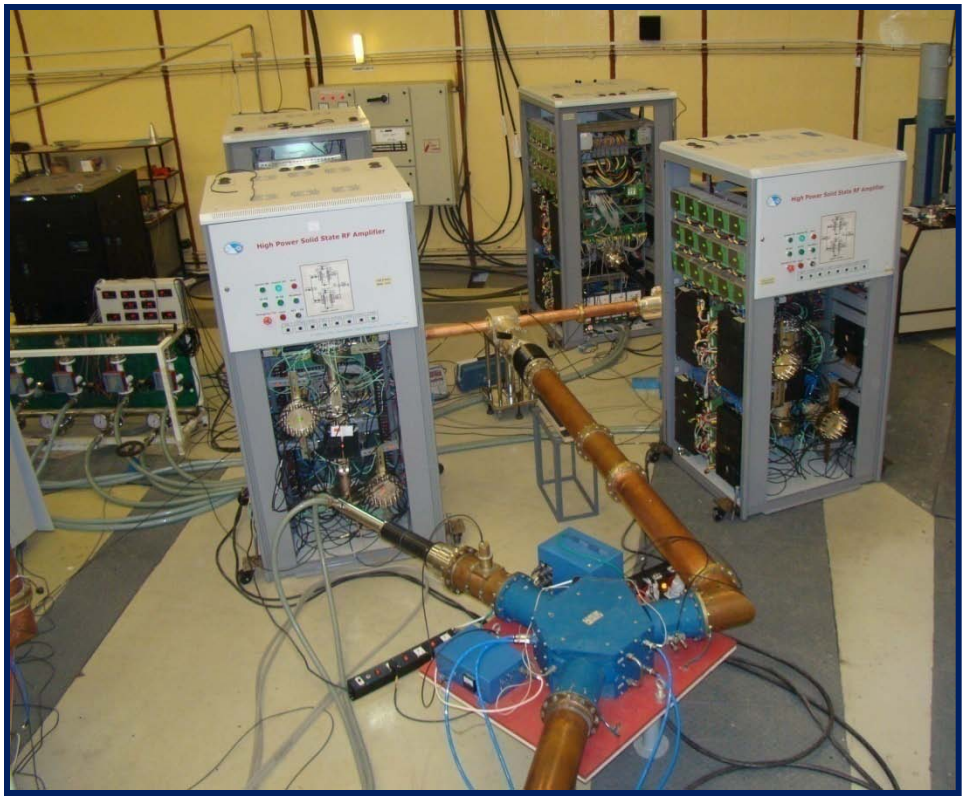
115mA was injected and energy ramping was started at 112.6mA. 108.3mA was obtained at 2.3GeV.

Indus-2 operation at 2GeV with 165mA beam current

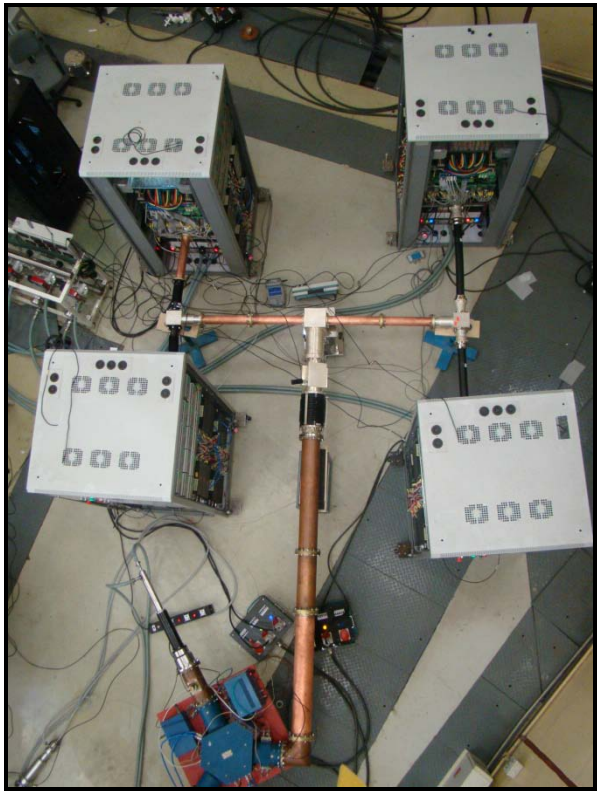


176mA was injected at 550MeV and energy ramping was started at 170mA.
165mA current was achieved at 2GeV.

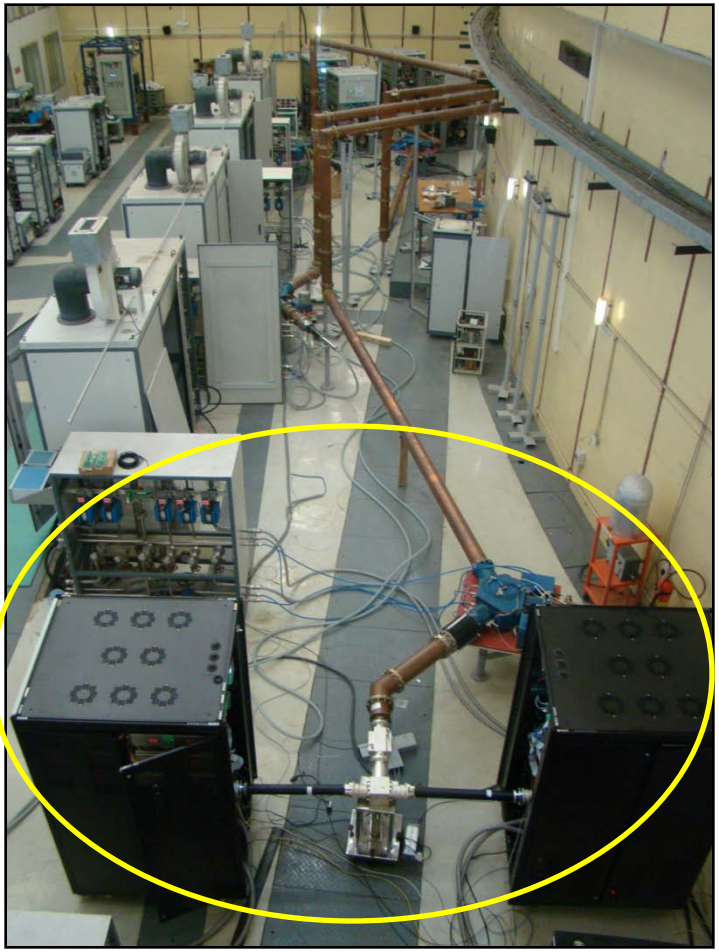
30 kW amplifier coupled to cavity # 3



Combining scheme

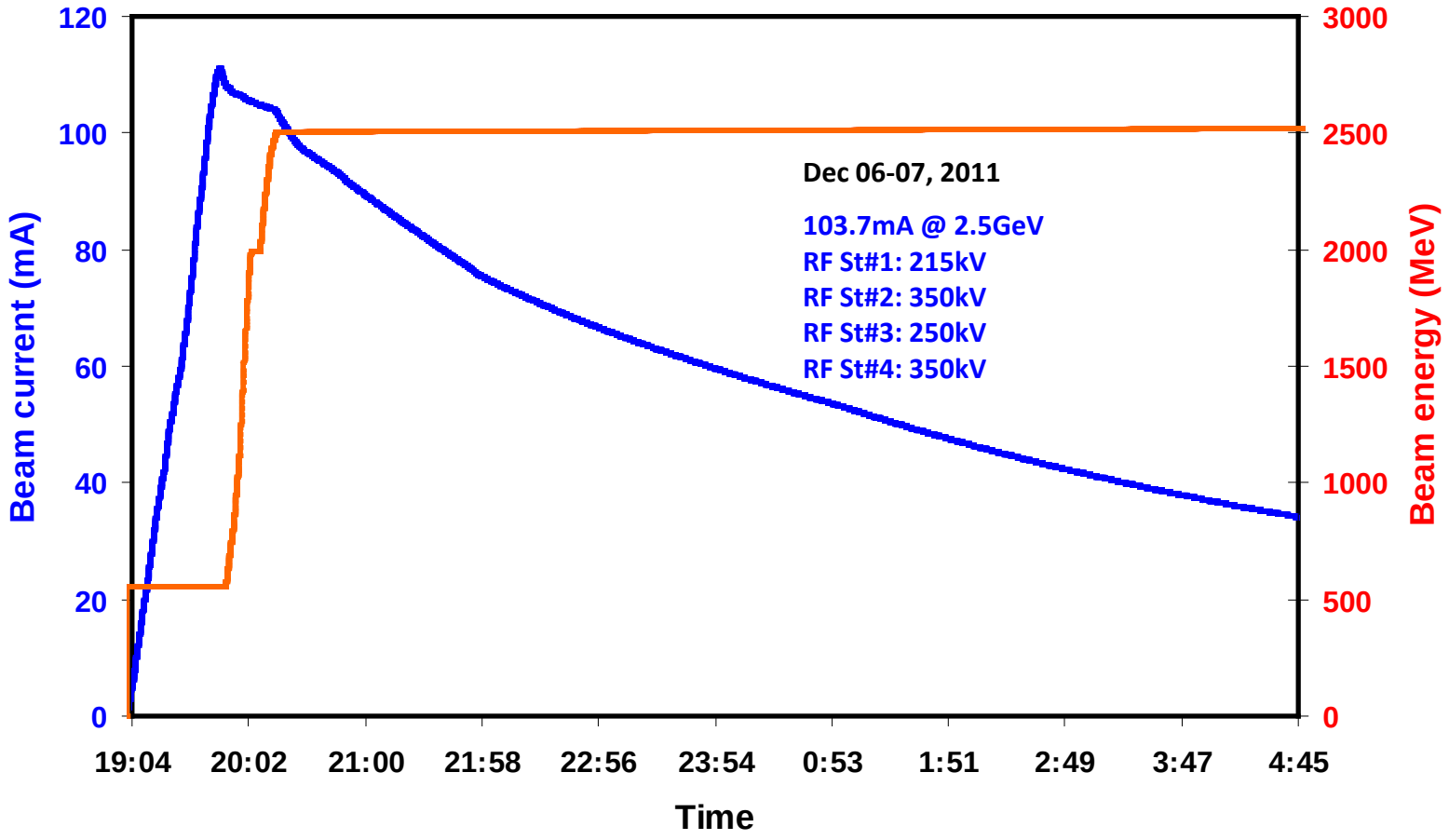


20 kW amplifier integrated with cavity 1



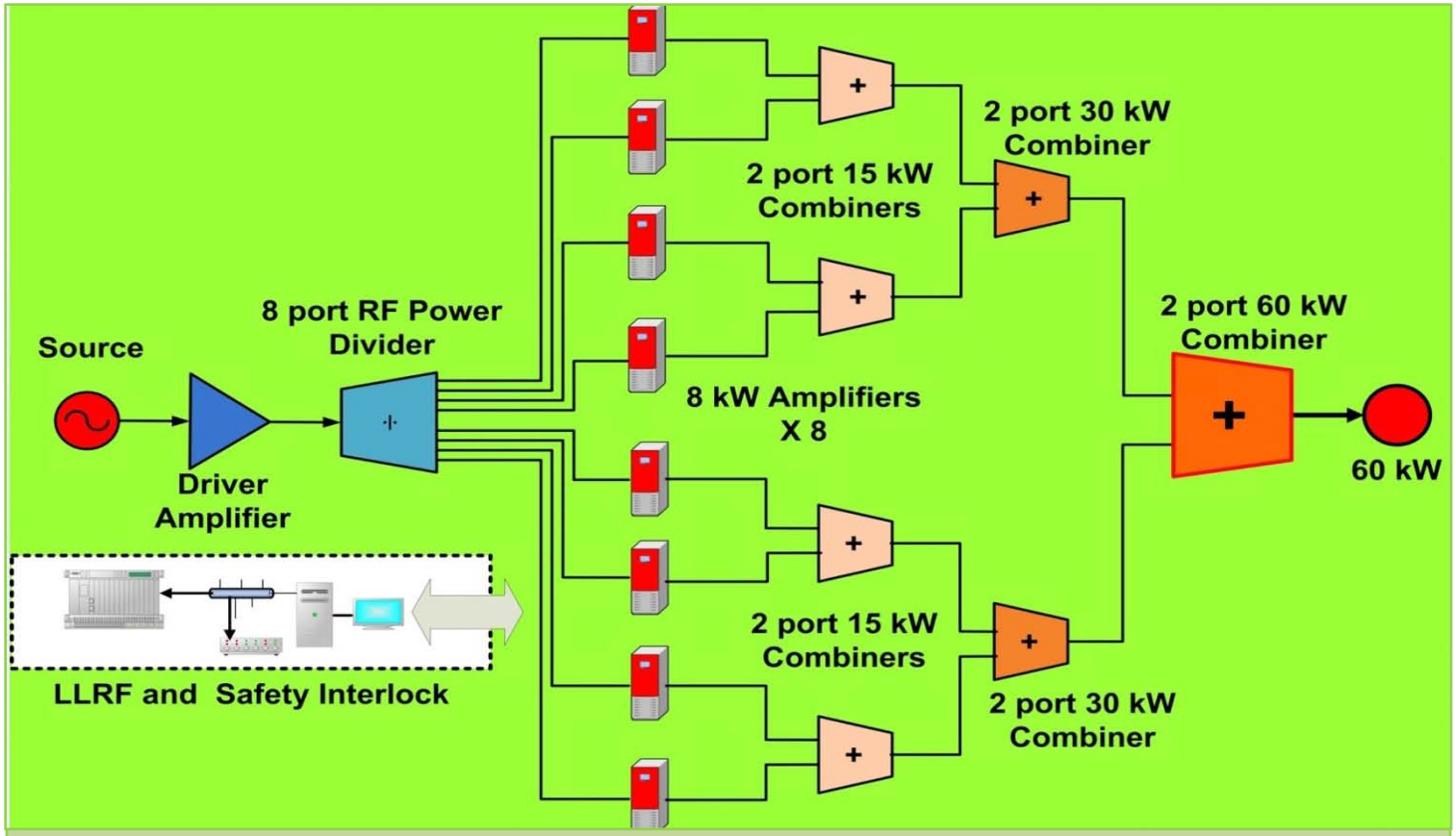
- Solid state devices in Power amplifier modules of this 20 kW system operates at 50 V bias voltage, as compared to earlier design of 29 V used in 15 kW units.
- Accordingly impedance matching network of basic power modules was redesigned, to obtain increased power of 400 W as compared to 320 W in earlier design.
- Two way rigid line combiners were upgraded to handle increased power.

Indus-2 operation at 2.5GeV,100mA



111 mA beam current was accumulated at injection energy. Energy ramping was started at 108.3 mA, 103.7 mA was achieved at 2.5 GeV. All four RF stations were in operation with a total gap voltage of 1165 kV at 2.5 GeV.

Indus-2 60 kW RF Amplifier Scheme



- 30 kW RF power will be obtained by summing output of four 8 kW units.
- Two 30 kW will be combined to get 60 kW RF power.

Conclusion

- Engineering design and technology for high power RF amplifier systems has been developed.
- Necessary components including power combiner, divider, RF Load, directional coupler, FPGA based control and interlock, have been fabricated and tested.
- 30 kW and 20kW amplifiers operating at 505.8 MHz have been fabricated and integrated with Indus-2 synchrotron radiation source and are being operated in round the clock shift mode.
- With addition of these solid state amplifiers ,Indus-2 operation at 108 mA beam current at designed energy of 2.5 GeV has been achieved.
- Development of 60 kW RF amplifier is in progress. The experience gained will be useful for the development of high power solid state amplifiers for Spallation neutron source(SNS) and accelerator driven systems(ADS).

Thank You for your attention

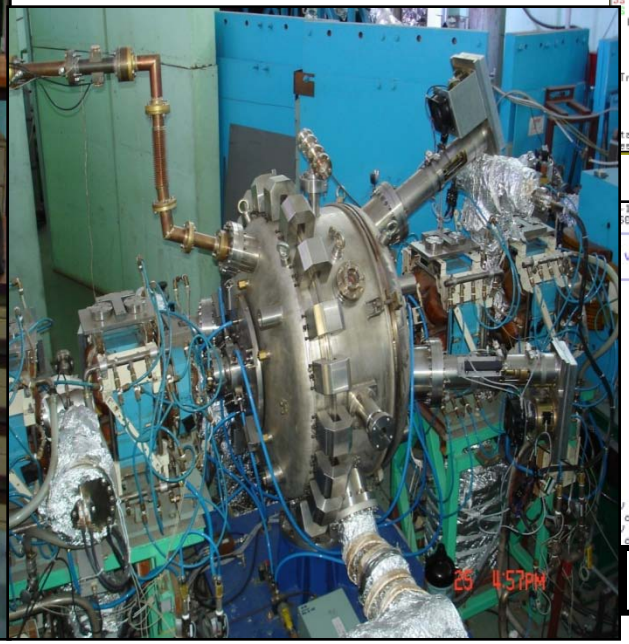
1 kW Solid State RF Amplifier for Booster Synchrotron

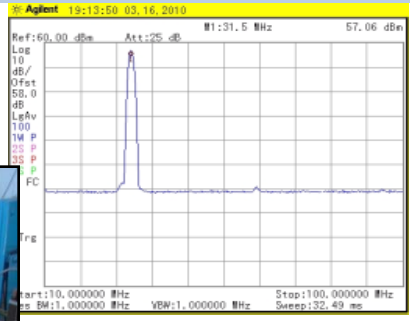
Tetrode Tube based Amplifier has been replaced by indigenously designed and developed 1kW Solid State RF Amplifier. This has resulted in improved performance .

1kW RF Amplifier

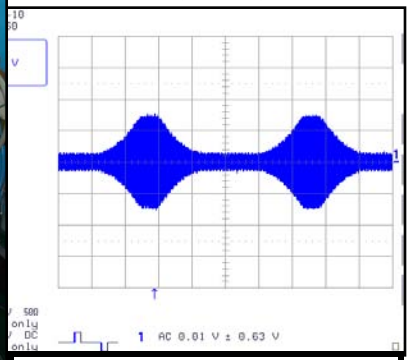
Frequency	**31.6 MHz**	**Output Power**	**1 kW**
Operation Mode	**CW**	**Gain**	**55 dB**
Harmonics	**-45 dBc**	**Efficiency**	**48 %**

31.6MHz RF Cavity





Spectral purity



RF Cavity Gap Voltage