RF System for 650 MHz Superconducting RF Cavities

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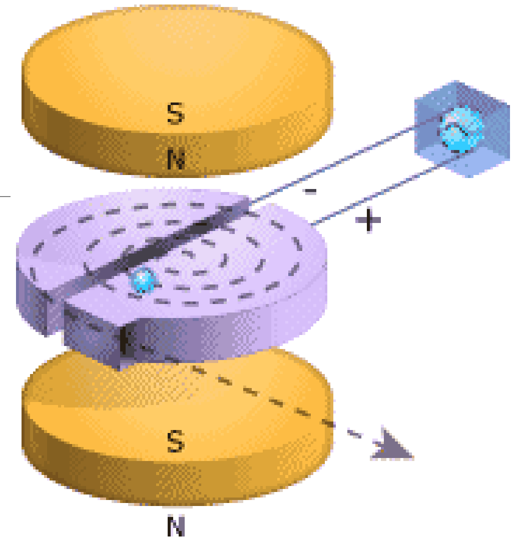
(On behalf of team RF Systems Division, RRCAT)

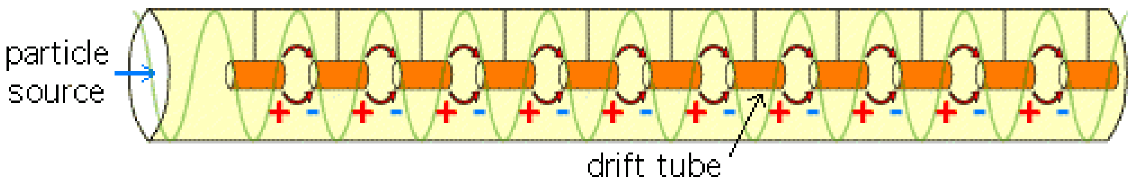
Outline

- Types of RF amplifier Systems
- Solid State RF amplifier System
- Support technological development for RF
- Issues & Challenges in Solid State RF Amplifier
- LLRF Control System for SC Cavities

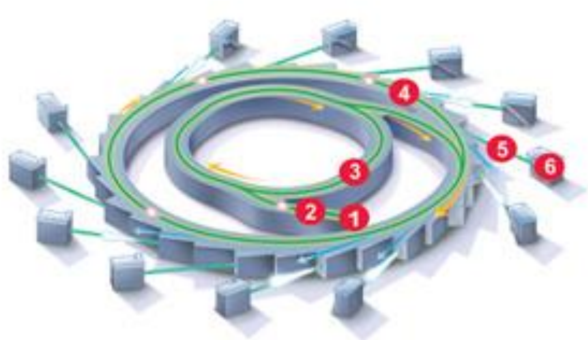
Types of RF Accelerators

Cyclotron





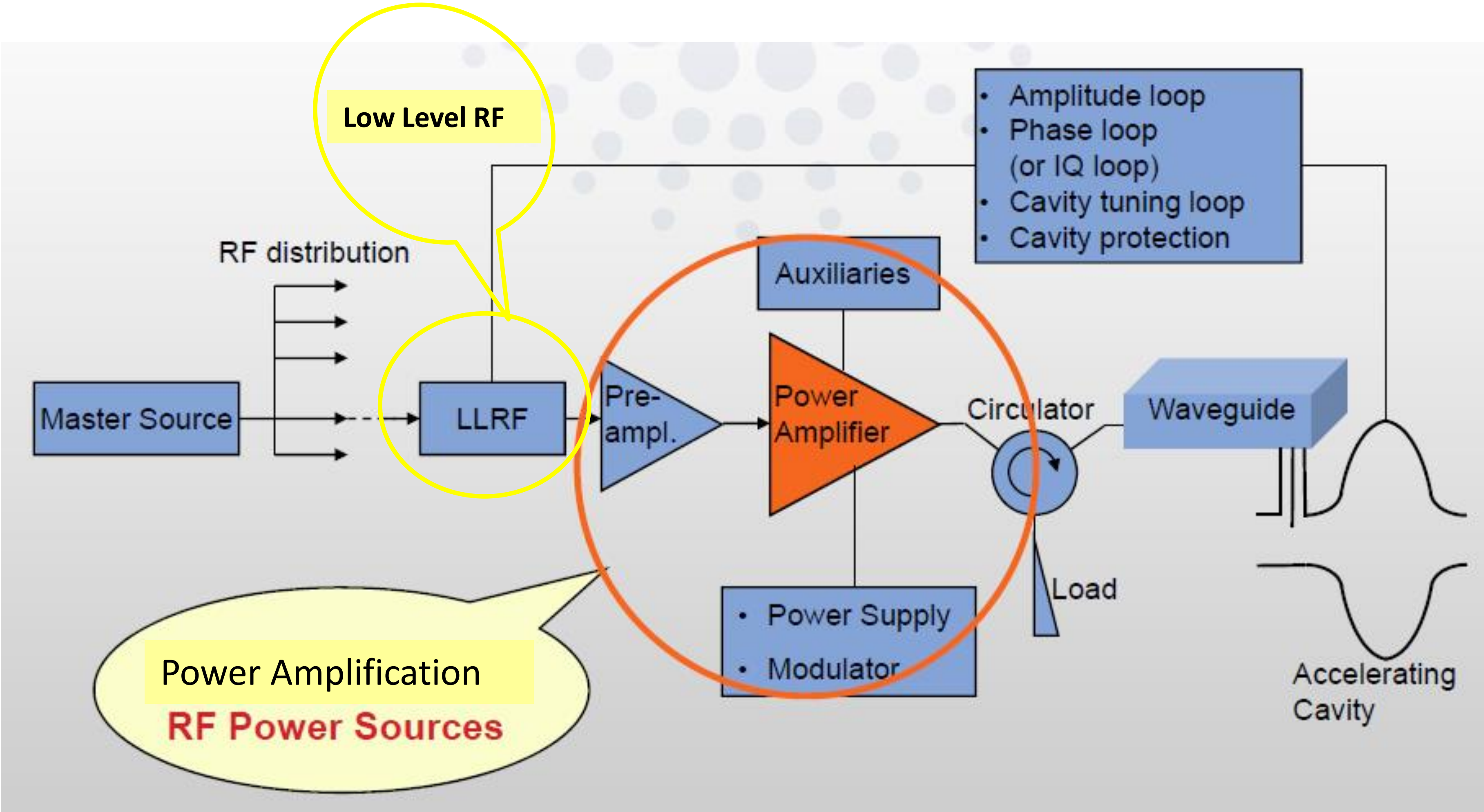
Linear Accelerator (Linac)



Circular Accelerator

Microtron

RF/Microwave System for Particle Accelerator

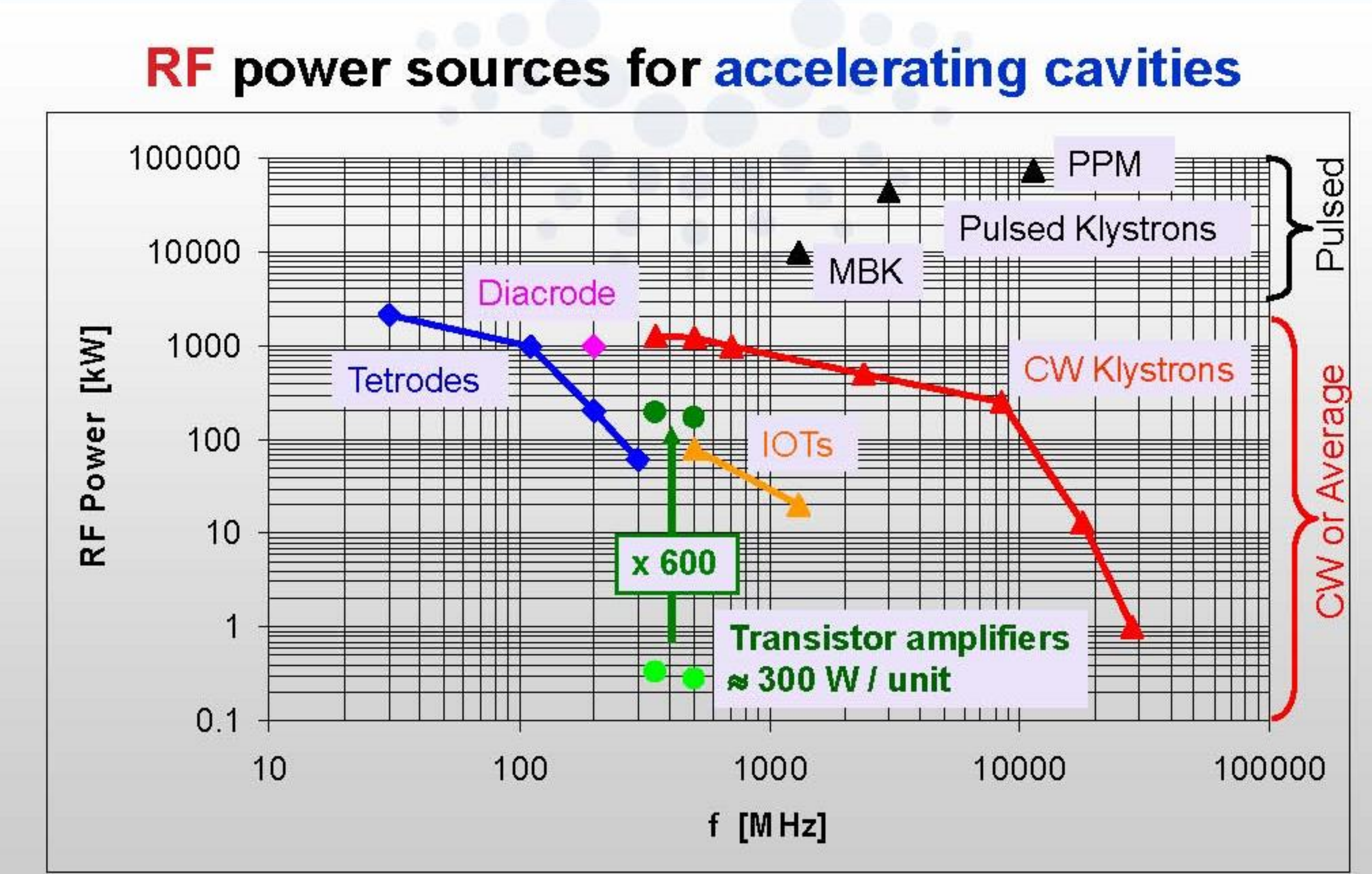


Major Sub systems of RF System

The general scheme for RF transmitter module consists of a synthesized signal generator supplying few mW of power , this Low power is further amplified by solid-state driver amplifier & finally Tetrode/Klystron/IOT/SSPA to higher power level ; which is phase ,amplitude & frequency controlled by Low level RF Control

1. **RF Generator (Synthesized Source)**
2. **Low level RF Control Electronics (analog or digital)**
3. **Driver & High power RF Amplifier (Triode/ Tetrode/Klystron/IOT/SSPA)**
4. **High power Transmission line & components**
5. **RF Accelerating Structure (NC/SC)**
6. **Bias Power Supplies (Low /High Voltage)**

Available Technologies



High Power Vacuum Tube 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

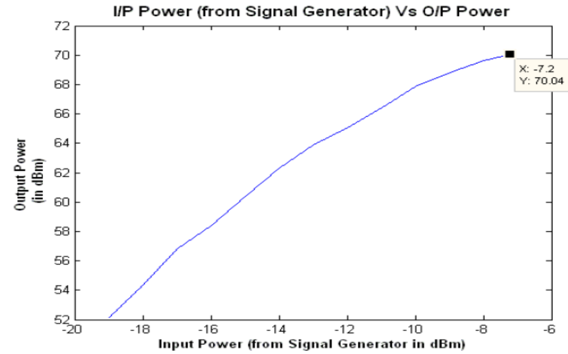
Intrinsic Low Gain

Limited Life

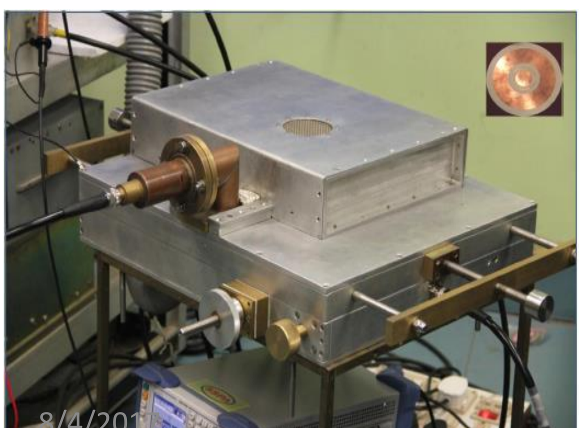
Planar triode based 476 MHz Cavity Amplifier for IRFEL having better phase and amplitude stability

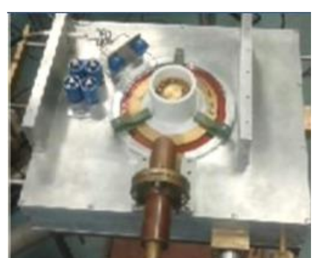
Amplifier configuration and Salient Features

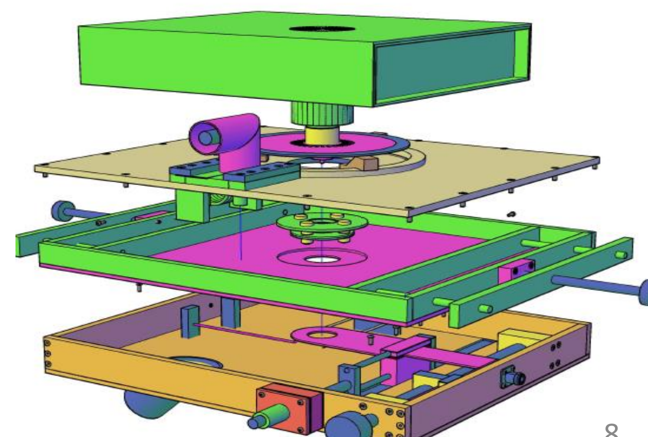
- Cavity amplifier, lower RF losses , inherently shielded structure.
- The triode tube,YU176,is configured in grounded grid mode; Grid is grounded for DC as well as RF providing good stability.
- Biased to operate in class AB_1 mode. Cathode is biased at +100VDC and modulated by-40V, 100µsec, 50Hz rectangular pulse; therefore, quiescent anode current flows only during the pulse, thereby minimizing heat dissipation at the anode simplifying the anode cooling requirement.
- Anode is biased to 7.5kVDC with help of a energy storage capacitor of 5µF provides the required DC pulse power of 35kW for the duration of 50µsec with pulse repletion rate of 50Hz.
- Beam is inductively coupled to the output cavity and spent beam is collected by anode and by passed to the RF round through film capacitor ; thus no RFC is put for anode biasing.
- RF output taken through inductive post coupler. No possibility of arc being excited.



Linearlity:0.4%
Power Gain:15.9dB (15.5dB)
Efficiency:56%(57.6%)







31.613 MHz RF Systems For Booster Synchrotron & Indus 1 SRS

The final power amplifier was built using BEL make ceramic power tetrode tube of type 4 CX15000 which operates in class B grid driven configuration. To transform input and output impedances of tube to standard 50 ohms, pi-type impedance matching networks are used. Output matching network uses a high power choke and vacuum variable capacitors. The complete power amplifier was assembled in a copper shielded box to have good RF ground and shielding

Klystron Amplifier

Multibeam (7 Beams) Klystron Tube

RF Output Power 60 kW

Power Gain 43 dB

Efficiency 65%

SCR Controlled Klystron Power Supply

Cathode Voltage 20 kV

Beam Current 5 A

Regulation < 0.3%

Inductive Output Tube (IOT) based 505.8 MHz RF amplifier for Indus-2

As an alternative to Klystron tube, IOT tube based amplifier has been developed. The amplifier is assembled with high voltage deck and necessary sub systems, it was tested for 50 kW output power

60 kW IOTamplifier at 505.8 MHz

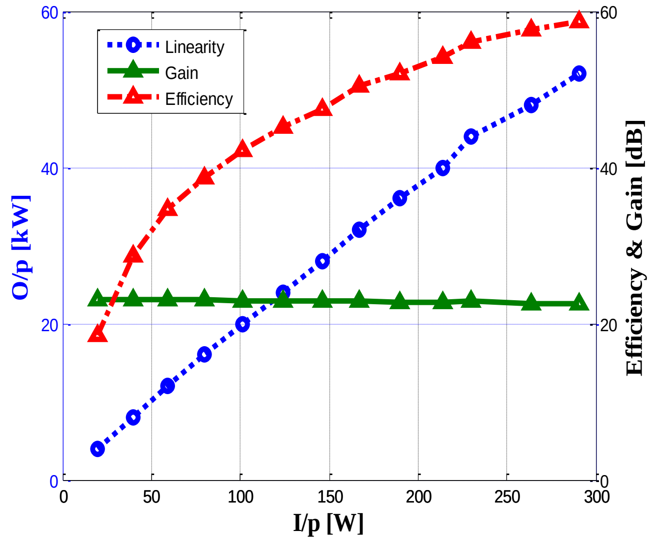
IOT Tube Specifications

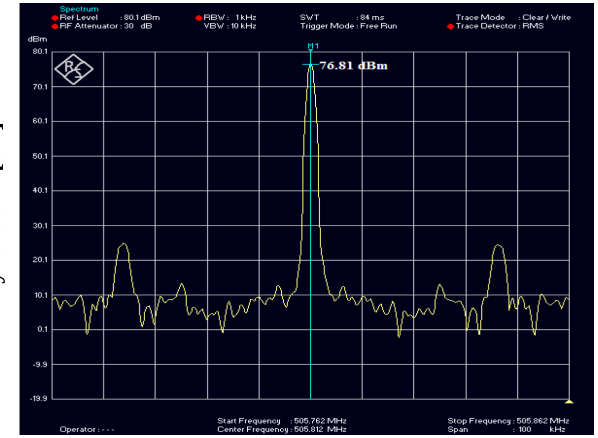
RF Output Power	80 kW	Power Gain	23 dB
Operating Frequency	505.8 MHz	Efficiency	70 %

Solid State Crowbarless anode DC Power Supply

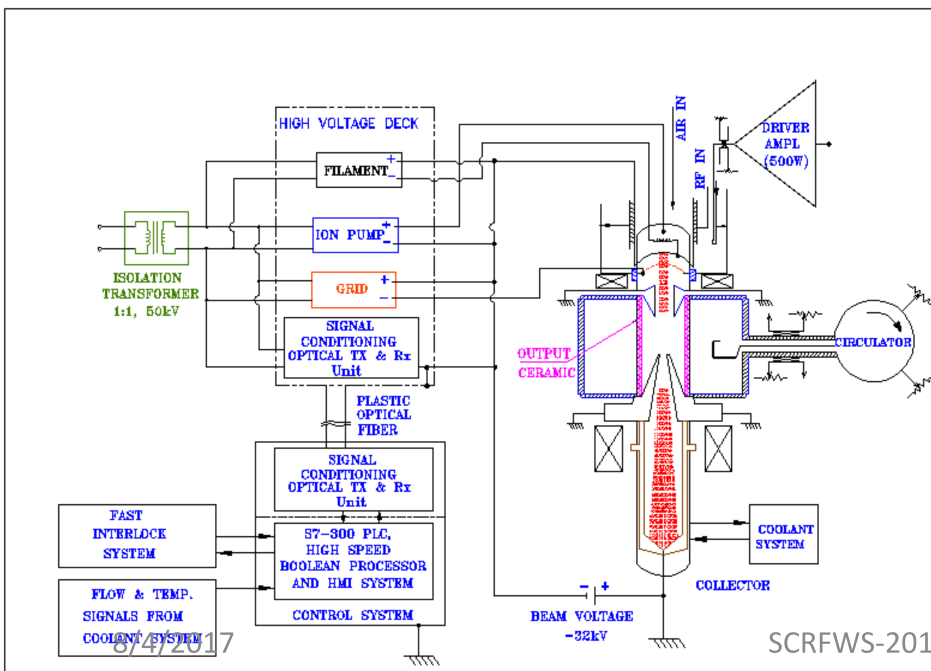
Anode Voltage	36 kV
Beam Current	5 A
Regulation	< 0.3%

IOT based RF power system@505.8MHz as an alternate to Klystron based RF system





Output RF spectrum @48kW @505.812 MHz



SN.	Parameter	Value
1.	*Tested RF Power output*	*50 kW*
2.	*Power gain@50 kW*	*22.5 dB*
3.	*Operating frequency & 1-dB Bandwidth*	*505.812MHz& 1.8 MHz*
4.	*Harmonic distortion*	*-36 dBc*
5.	*Wall-to-plug Efficiency*	*>50%*
6.	*Protection: O/v,O/I, Excess reflected power at output, IOT arc, Circulator arc, Excess I/P drive, Underflow of air & LCW*	

High Voltage IOT bias Power Supply

High voltage Solid State Crowbarless 36 kV /20 A DC bias Power Supply is indigenously developed,

this can drive multiple IOTs in parallel.

All the Subsystems like 11 kV breaker panel, Main Transformer rectifier unit, DC-DC Converter Power Modules and DSP based control and protection system have been fabricated and tested.

This Power supply is installed at RRCAT and its Commissioning is in advanced stage.

Salient Features :

1. Input feeder 11kV line
2. 24 Pulsed Input system
3. No Input Filter Requirements
4. No Output Filter Requirement
5. Low output Stored Energy< 10 J
6. No Crowbar Requirement for Sensitive Loads like Klystron
7. High Output Stability ~ 0.3%
8. High Overall Efficiency >95%

11kV Transformers

Rectifier Panels

Switch Power Modules

1 MW, 352 MHz test facility

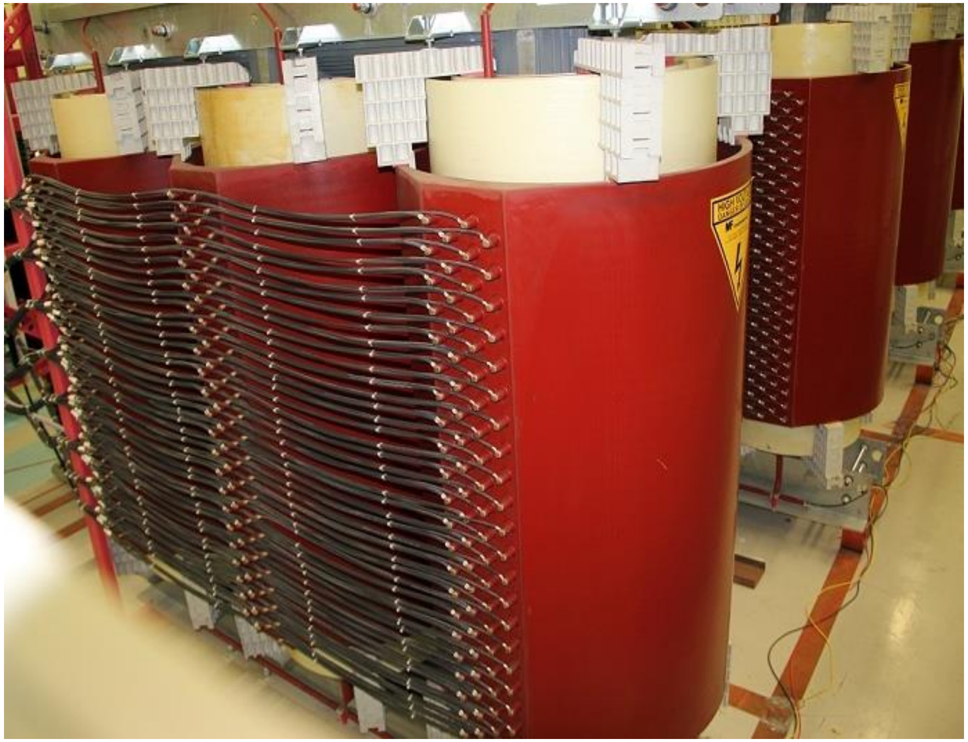
TH 2089 klystron and its power supplies

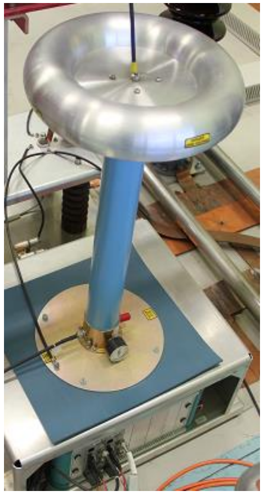
1MW, 352 MHz TH 2089 klystron requires several power supplies namely:

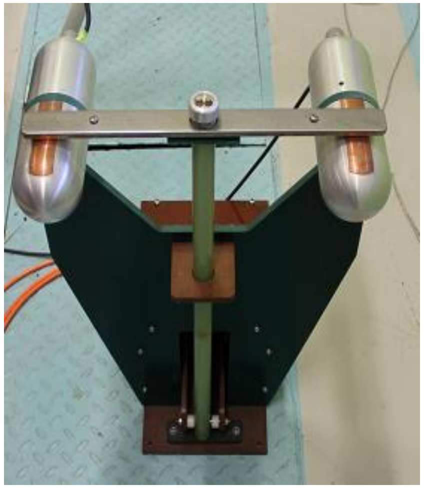
1. -100 kV, 25 A DC beam bias power supply (1 no.)
2. 100 kV, 12 mA mod anode power supply (1 no. floating at -100 kV DC)
3. 20 V, 25 A DC filament power supply (1 no. floating at -100 kV DC)
4. 5 kV, 10 mA ion pump power supplies (2 nos.)
5. 300 V, 12 A DC electromagnet power supplies (2 nos.)

The control-monitoring of mod-anode power supply and filament power supply floating at -100 kV DC, is a challenging task. Hence a high voltage floating platform has been designed and developed to accommodate and energise these floating power supplies.

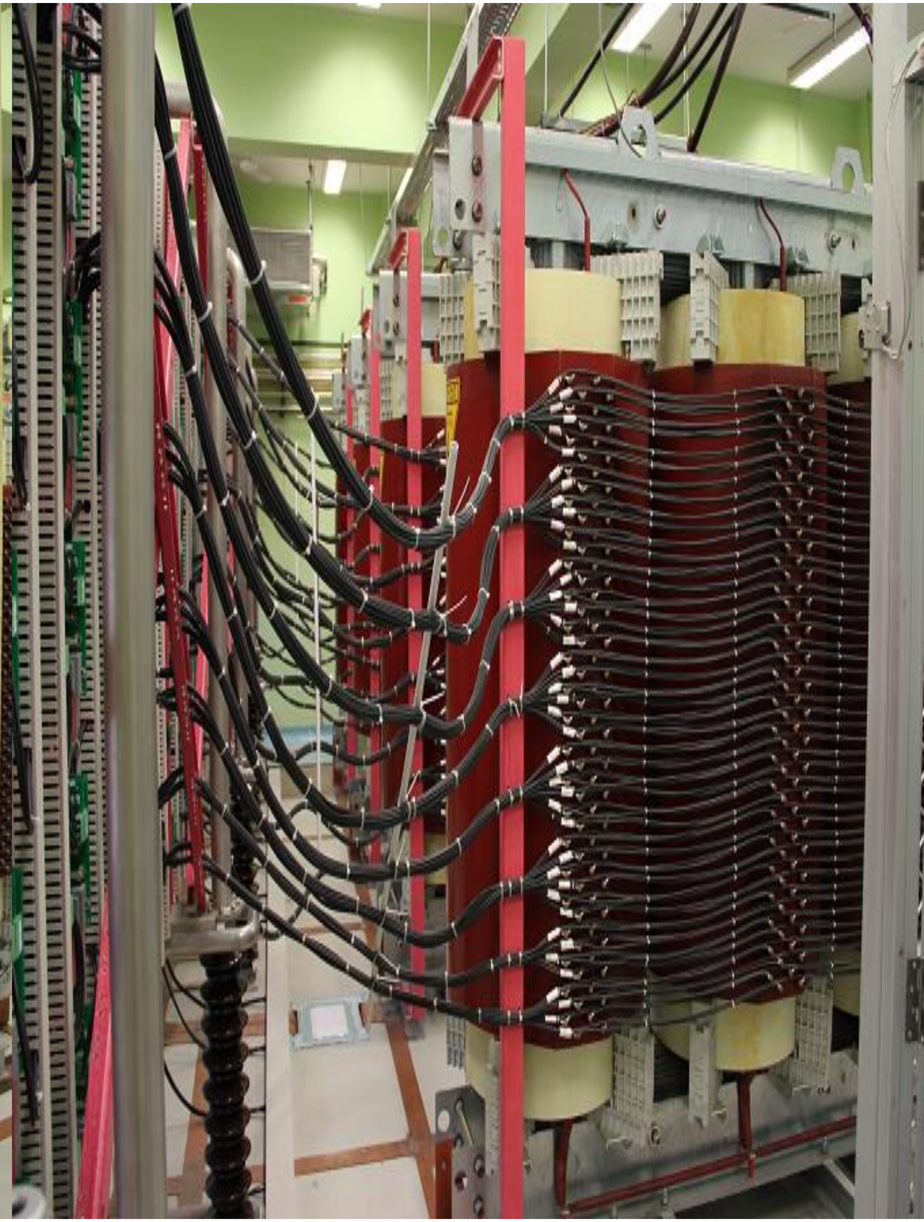
Subsystem of -100 kV, 25 A DC power supply







Subsystem of -100 kV, 25 A DC power supply(contd.)



Issues in Vacuum tube based RF Amplifier : A Challenge for RF Engineers

- Tube based RF amplifiers like Tetrodes, Klystrons, IOTs are sensitive devices, which demands stringent performances towards protections at high RF power (i.e. EMI) and in high voltage bias power supply. All control & interlock and data acquisition circuitry ,should have suitable filters at high frequency, proper isolation at high voltage/high current monitoring, sampling etc.
- All power supplies need to be operated in a particular sequence for proper operation of tube based amplifier and reverse sequence is to be followed during turn- OFF
- Choosing suitable configuration to suit high power, high voltage, high temperature environment for better amplitude and phase stability.
- The power amplifiers requires the availability of nonlinear model and simulation for evaluating performance.
- In high voltage crowbar DC bias large size output filters are employed at the output to reduce output voltage ripple which in turn results in high output stored energy. Low output ripple and low output stored energy are two contradictory requirements for any controlled DC power supply. Crowbar systems often have reliability problems specifically under transient conditions and hence the protection of load is not fully assured

Choice of Solid State RF Amplifier

- Requirement for development of Solid State RF amplifiers (SSPA) is primarily due to non availability of vacuum tube from sources.
- With modest RF power requirement in SC RF cavity RF system ,SSPA are better choice due to the fact that the solid state high power amplifiers offer many advantages like

•Modularity,

•Graceful degradation

•No high voltage requirement

•Low maintenance.

- Further increasing use of solid state amplifiers is contributing towards improvement in performance and reduction in cost.
- Following similar philosophy, at RRCAT in RF Systems Division in-house technology development programme to build 2 kW solid state amplifiers at 31.6 MHz for use in Booster Synchrotron and Indus-1 SRS & 75 kW *4 (total 300 kW) at 505.8 MHz for use in Indus-2 SRS was accomplished and is then continuing for future projects at 325 and 650 MHz.

High Power Solid-State RF Amplifier

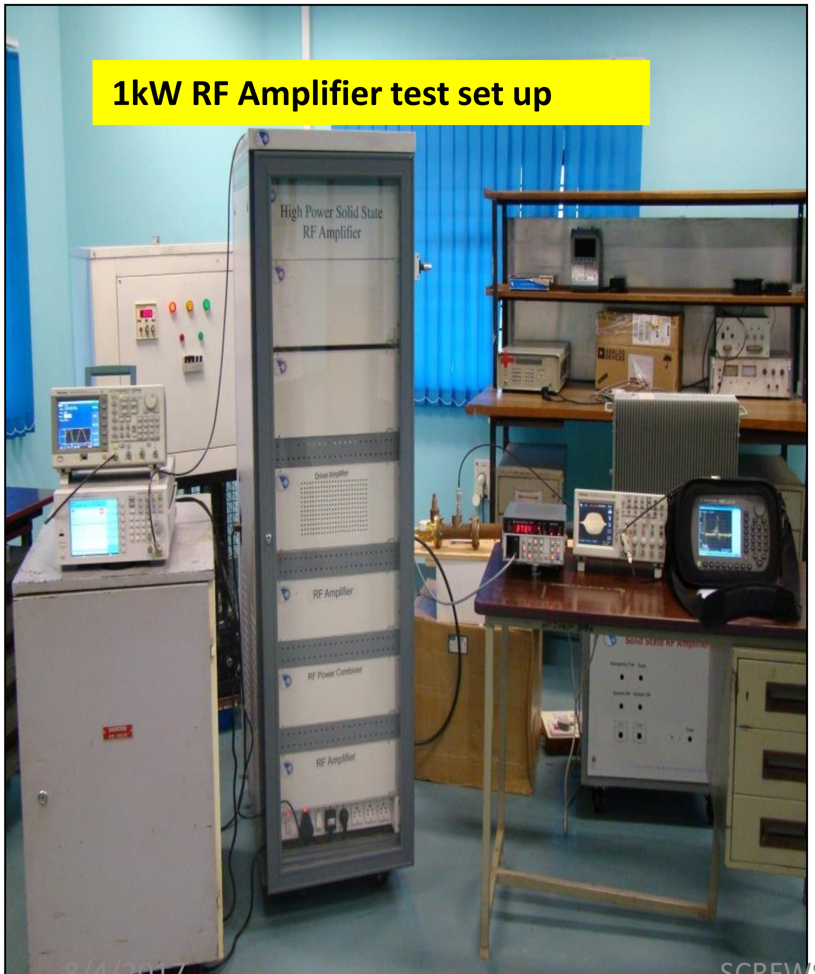
- A high-power solid-state RF amplifier has become better alternative RF source for SC RF systems of particle accelerators
- A high-power solid-state RF amplifier (SSRFA) combines the RF power from hundreds of power-amplifier elementary modules in few stages, each equipped with a RF power transistor capable of delivering only a few hundred watts. .

Major sub-systems

1. **Power Amplifier (PA) modules** with water cooled enclosures, RF components and RF connectors
2. **Rigid Coaxial RF components** like directional couplers, divider, combiner, mounting hardware etc.
3. **Flexible RF coaxial cables**
4. **Amplifier Cabinets with** electrical system, DC bias supplies, water sub-system temperature measurement hardware etc.
5. **Embedded SSRFA control subsystem** including FPGA Controller, digital, analog input, output modules, RF Detectors, Industrial PC, directional sensors etc.

1 kW Solid State RF Amplifier for Booster

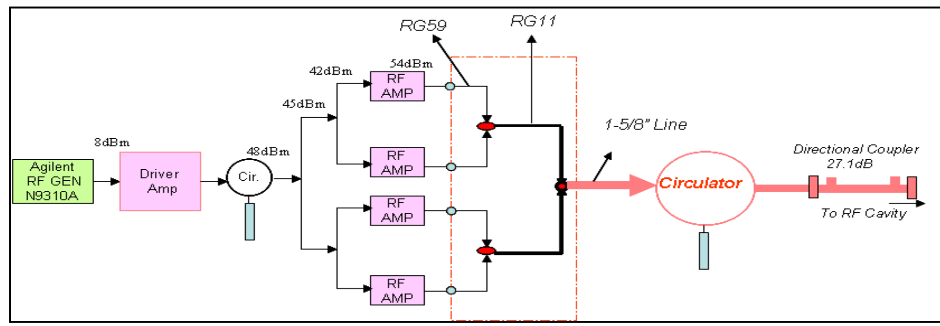
Booster ring accelerate the beam from 20MeV to 450MeV or 550MeV for Indus-1 and Indus-2 respectively. Booster synchrotron of Indus Accelerator is in operation for nearly 15 years. Recently in March 2010, its Tetrode Tube based RF Amplifier has been replaced by indigenously designed and developed 1kW Solid State RF Amplifier. This has resulted in improved performance .



1kW RF Amplifier test set up

Main Specifications

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

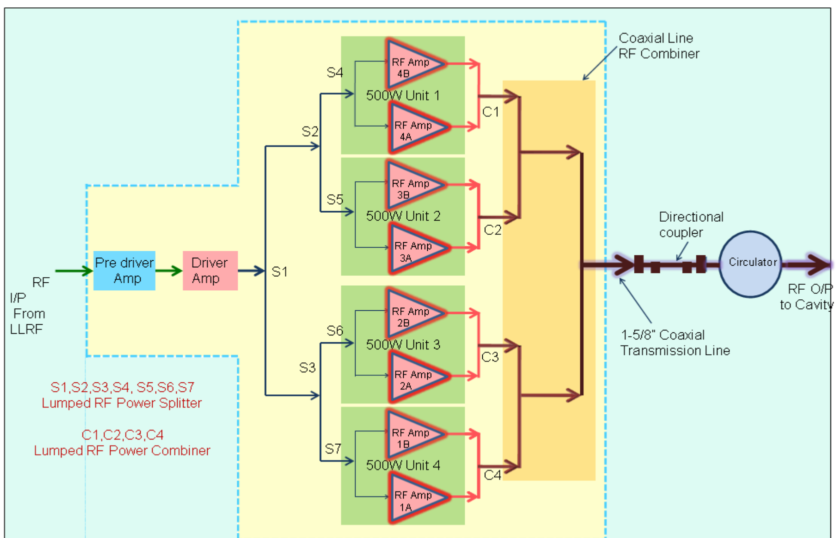


One of the four amplifier Modules (250 W) used in 1kW amplifier

Basic building block of the amplifier is a 300W power module based on MOSFET device. Power from 4 such modules is combined using RF power combiners in stages.

31.6MHz, 2kW Solid State RF Amplifier for Indus-1 SRS

To replace the existing tetrode Tube based RF amplifier of Indus-1 Synchrotron radiation source, a 2 kW solid state RF amplifier was developed. Basic building block of the amplifier is a 300W power module based on MOSFET device. Power from 8 such modules is combined using different RF power combiners in stages. All the components used for the amplifier like Pre-driver amplifier, Driver amplifier, Lumped power Splitters (7 Nos.), RF filters (10 Nos.), Lumped power combiners (4Nos.) and a 4:1 Coaxial line high power combiner were developed in-house. All these components were tested characterized and assembled in a 19” rack. Testing of the solid states amplifier was done with 50 Ohm dummy load at full 2kW out put power. Measurement of important parameters like gain, signal purity, efficiency, amplitude stability and phase stability for full operation range was done with satisfactory results. The amplifier was commissioned in March- 2012 and is used regularly for 125mA beam current.



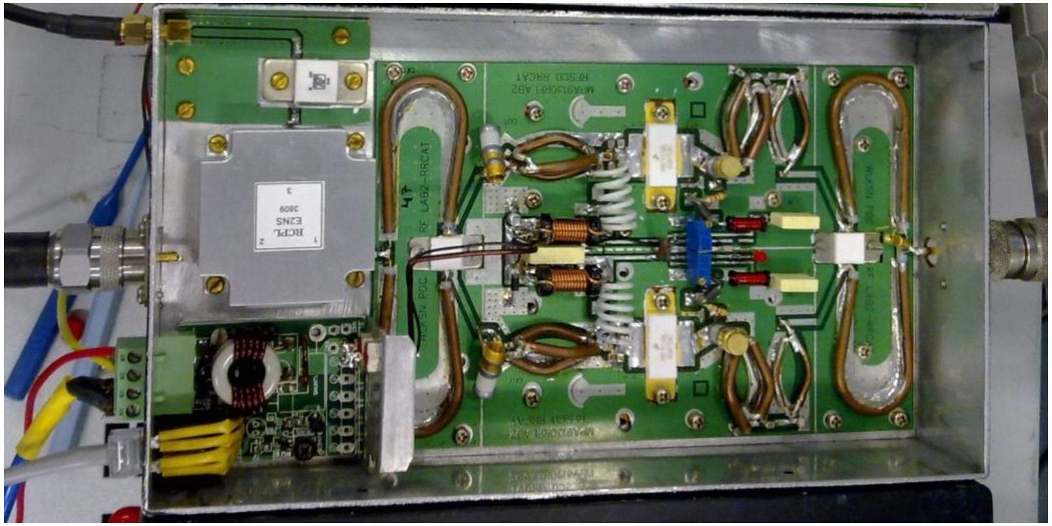
Schematic of 31.6MHz, 2kW Indus-1 Solid State RF Amplifier

Schematic of 2kW solid state amplifier

Indus-1 2kW solid state RF amplifier under testing at full power

500 W, 505.8 MHz RF Power Amplifier Module for Indus-2

- Amplifier modules with output RF power level of 500 W at 505.8 MHz was developed.
- Each module uses two numbers of MOSFETs.
- Each one is protected by a circulator.
- Amplifier includes necessary monitoring and protection circuits.
- This module is mounted on a water cooled copper heat-sink.



500 W solid state amplifier module

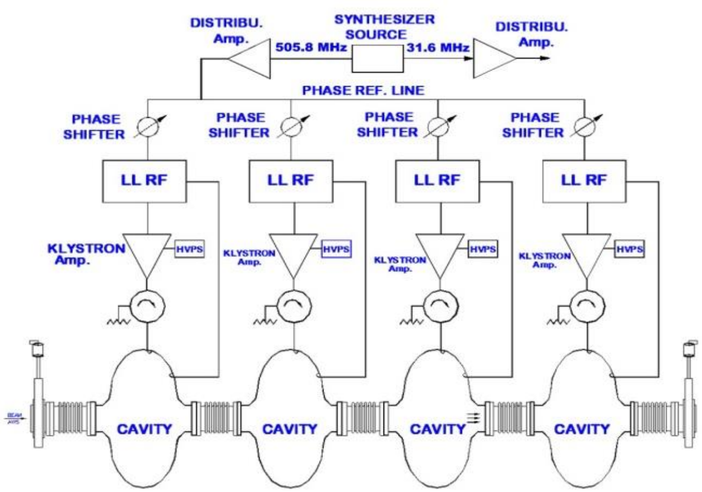
Indus-2 RF System

•Modular Indus-2 RF system employs five bell shaped RF cavities operating at 505.8 MHz generating 1500 kV cavity gap voltage.

•Four SSPA (total~300 kW)and one Klystron based RF stations

Major RF Components:

- RF cavity
- High power klystron amplifier
- High voltage (20kV) power supply
- Co-axial transmission line (6 1/8")
  - Dual directional coupler
  - 90 degree & 45 degree coaxial line bends
  - Circulator
  - 80kW coaxial load
- Solid state driver amplifier
- Low level RF control system
  - Phase control
  - Amplitude control
  - Frequency control
- Lab-VIEW based supervisory system



Scheme of RF power feeding to cavity

Indus-2 RF equipment Hall

Compact system with higher RF power per unit volume of cabinet/enclosure

- From system integration point of view, there is requirement of compact system with higher RF power per unit volume of cabinet/enclosure.
- Most of the space in such enclosures is occupied by RF cables connecting different components.
- If some integrated structure is devised, to accommodate amplifier modules, divider and combiner in close vicinity, while maintaining ease of operation and serviceability, it can save lot of energy, loss in such connecting RF cables.

8 kW, 505.8 MHz Solid State Amplifier

Year 2011

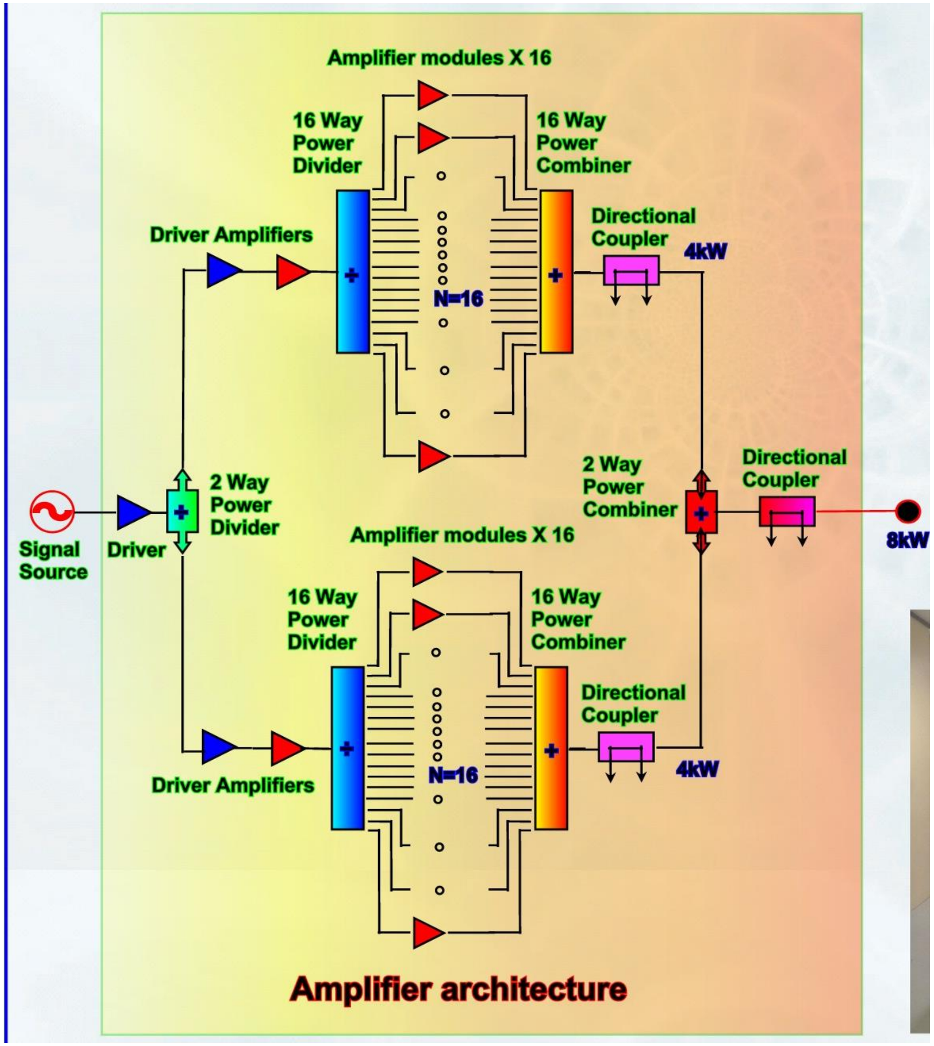
15 kW, 650 MHz Solid State Amplifier

Year 2015

(same enclosure/cabinet)

Compact PA modules at 500W was qualified. It consists of two 500W PA on each side of a common cold plate

12.5 kW Solid State Amplifier Scheme for Indus-2

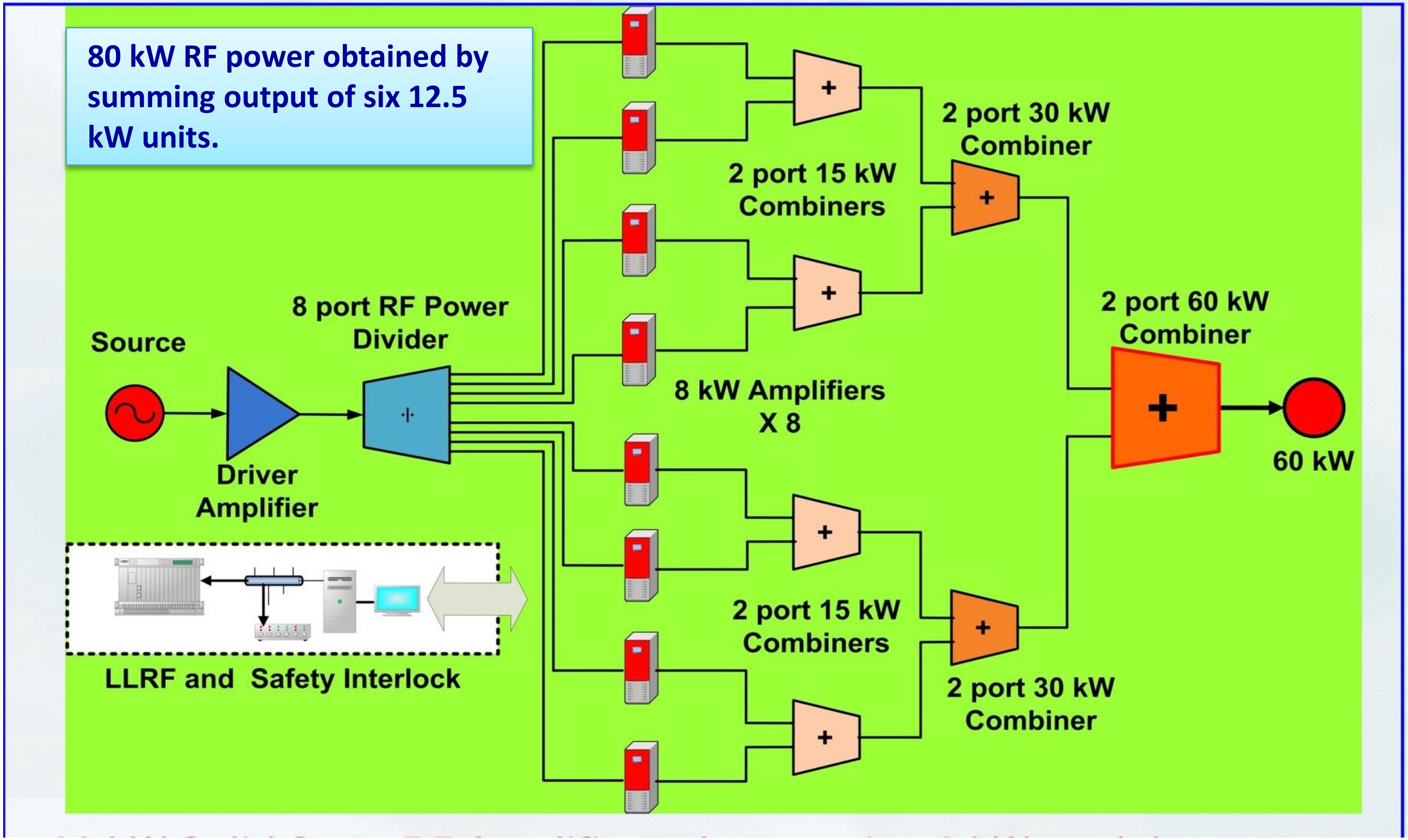


12.5 kW Solid State Amplifier architecture

- 12.5kW unit is housed in a single euro rack with 32 amplifier modules of 500W RF power .

12.5 kW, 505.8 MHz Solid State Amplifier

Solid State Amplifier Scheme for Indus-2



Solid State RF Amplifiers Deployed in Indus-2

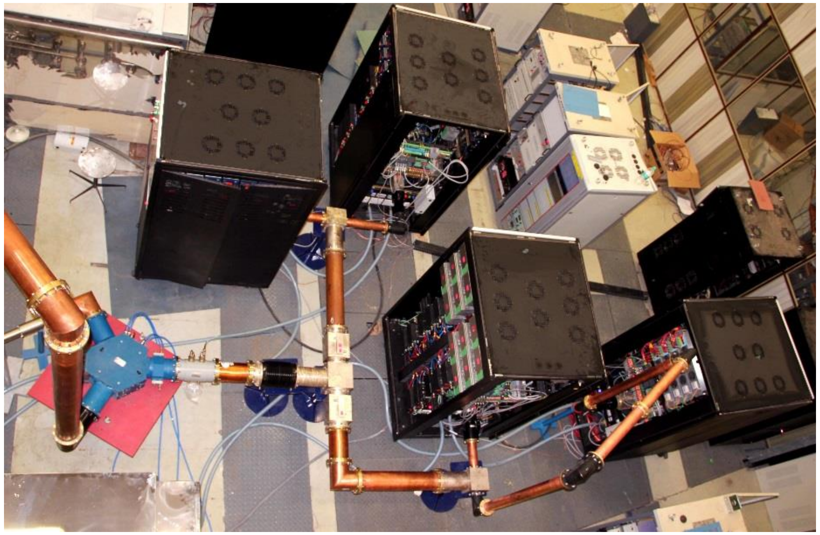


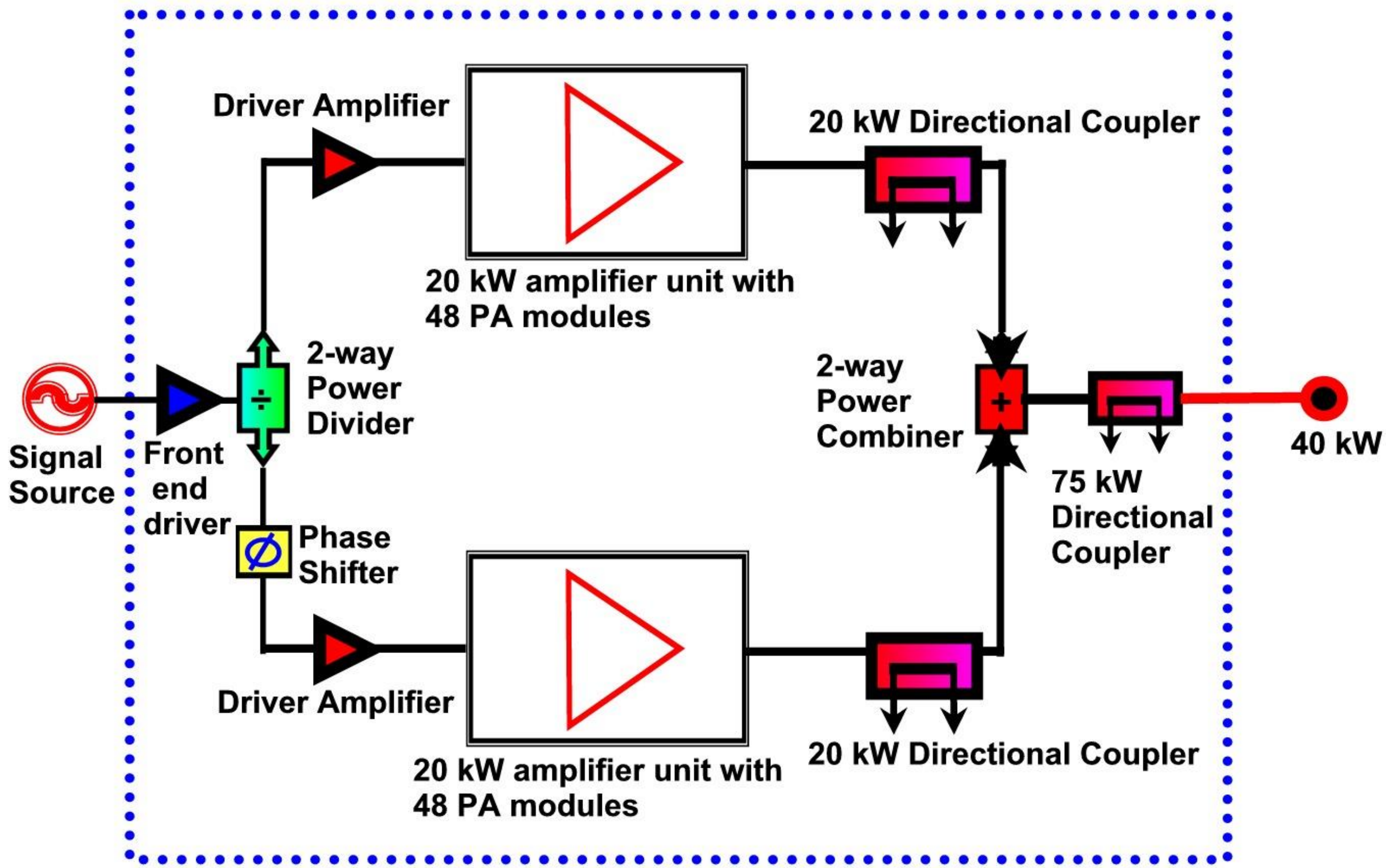
Fig 1: 50 kW SSPA coupled to RF cavity # 1

Fig 2: 75 kW SSPA coupled to RF cavity # 2

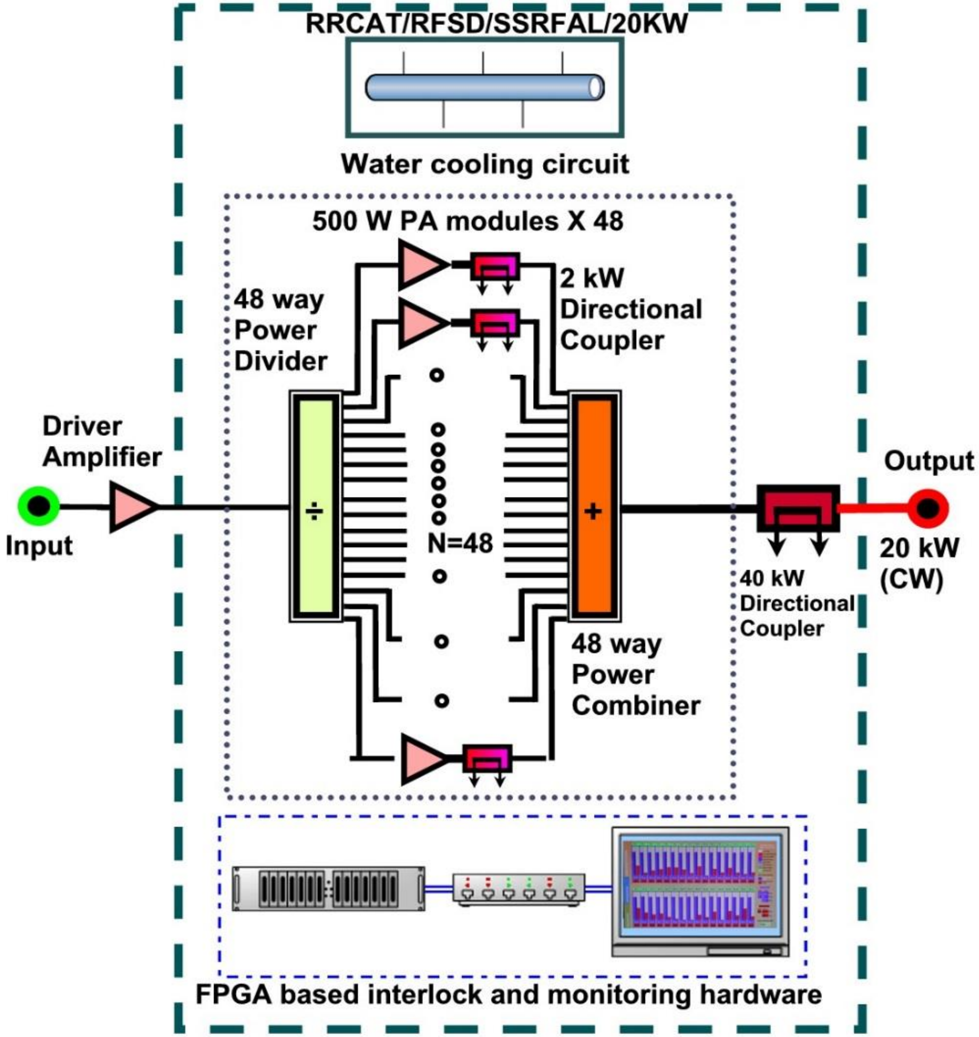
Fig 3: 75 kW SSPA coupled to RF cavity # 3

Fig 4: 75 kW SSPA coupled to RF cavity # 5

40 kW 650 MHz SSRFA Scheme



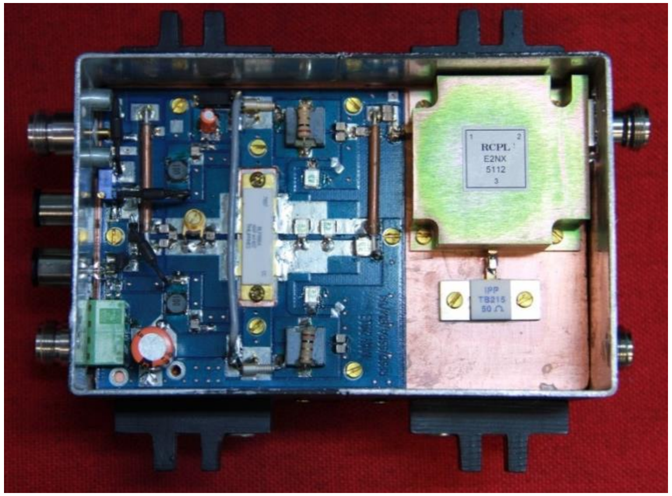
20 kW 650 MHz SSRFA Unit

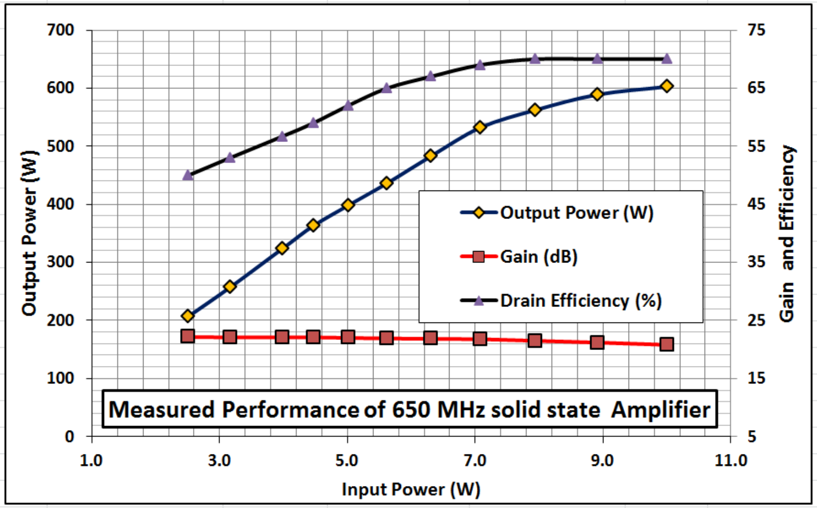


The 20 kW unit, housed in a single euro rack, is equipped with DC bias power supplies, PA modules, divider, combiner, electrical components, water cooling circuit and control/interlock hardware.

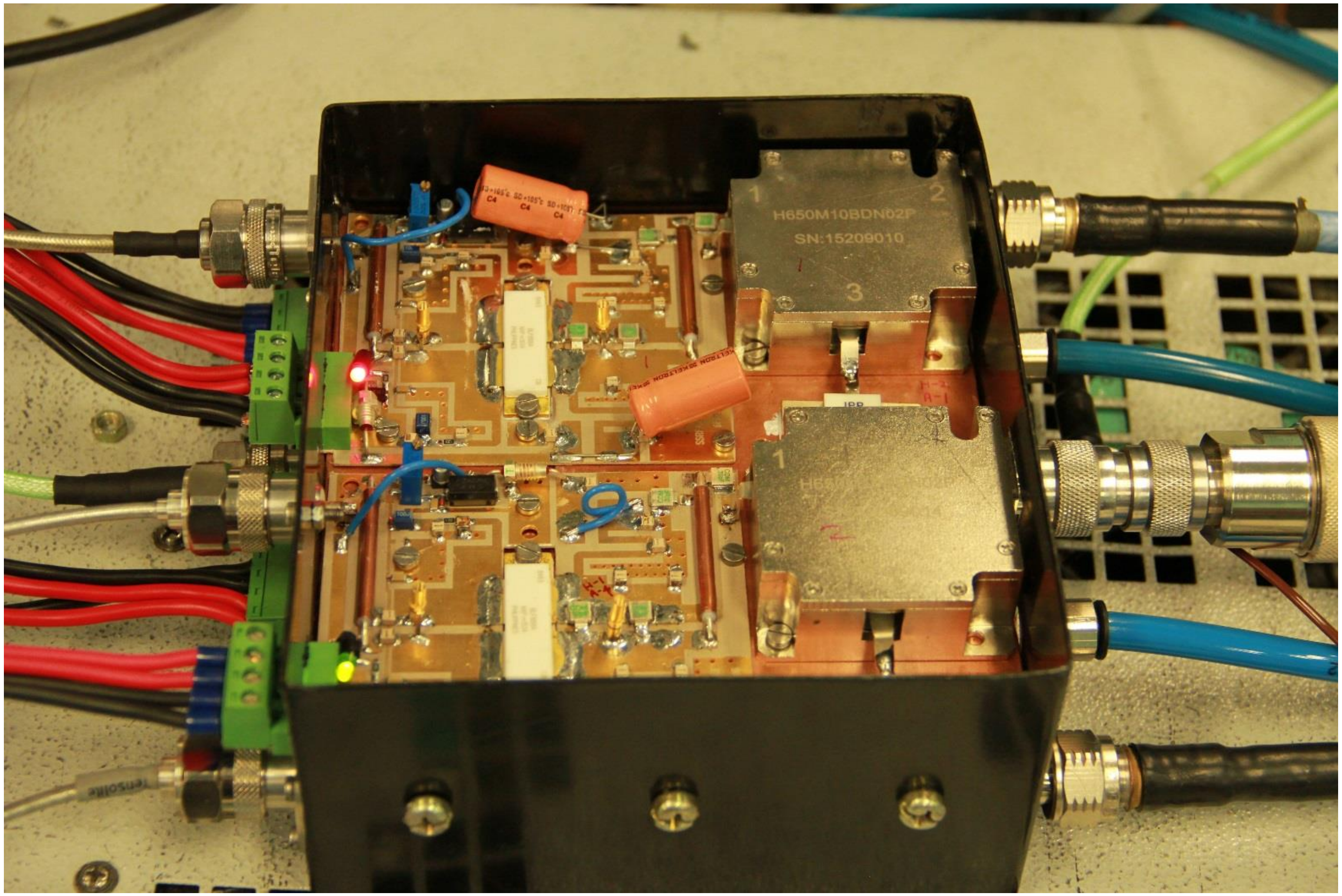
500 W RF Power Module

- Operating frequency: 650 MHz
- Output Power: 500W (CW)
- Gain: 18 dB
- Bias Voltage: 50 V DC
- Drain Efficiency: > 67%
- Input/Output: N type connector
- Cooling: Water Cooled
- Protection: against excessive VSWR at output

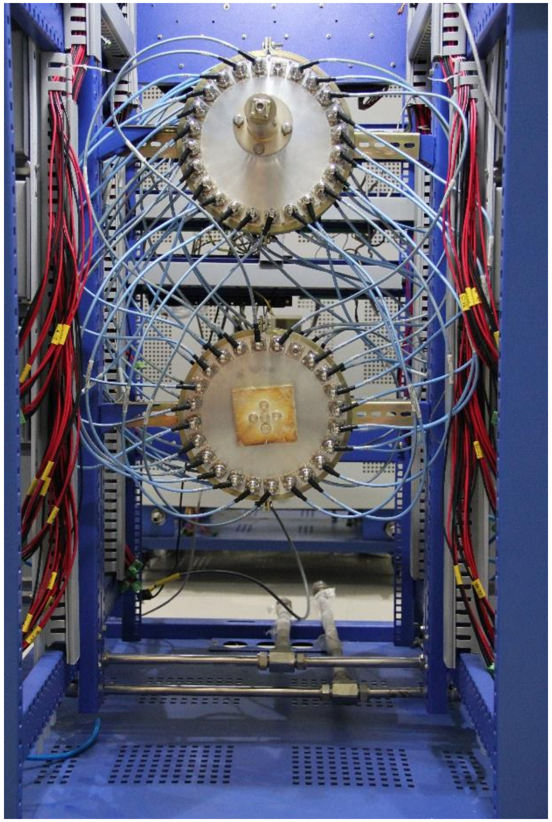




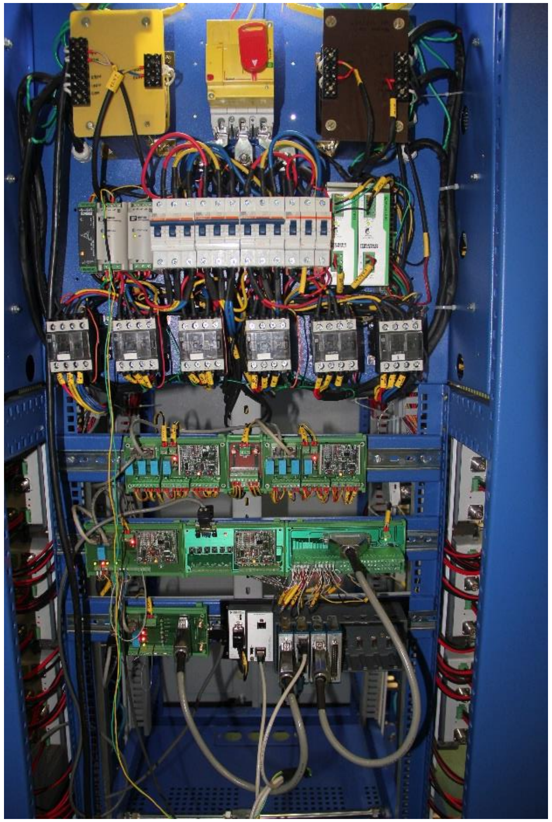
2kW (500*4)W RF Power Module



650 MHz, 40 kW Solid state RF Amplifier: Major Sub systems



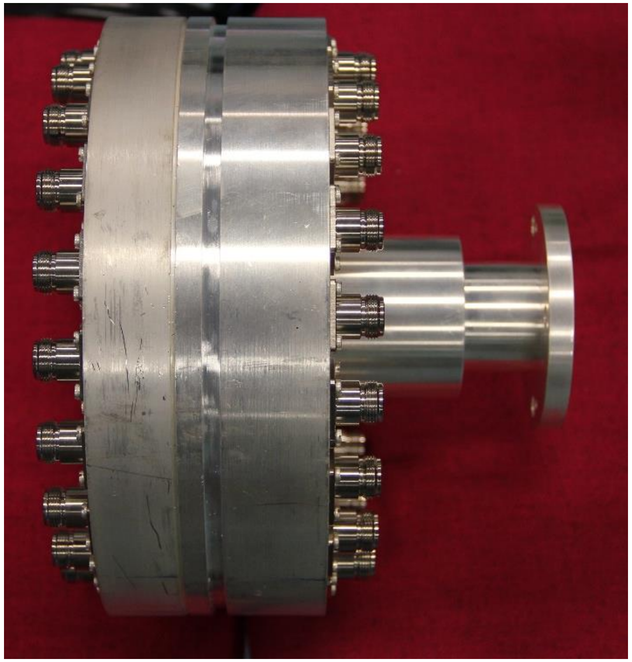
48 way Power divider and combiner

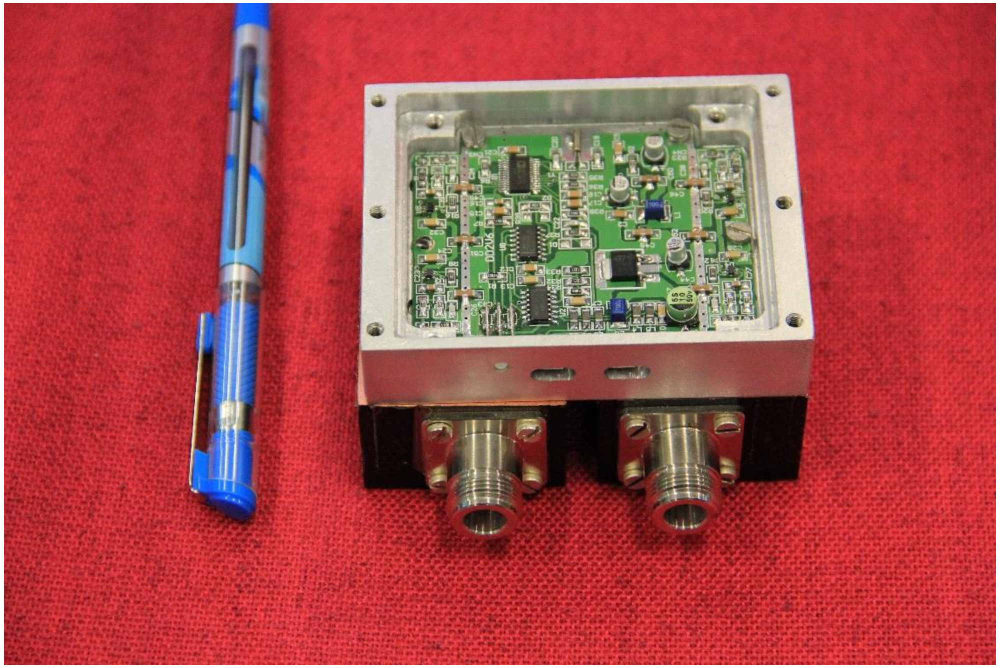


Electrical and embedded control sub systems

Combiner/Splitter & Digital Detector

48 way RF Splitter and 48 way high power RF Combiner are used in each rack and 24 nos. of DD for measuring Fwd. and Refl. RF power of two PA modules ,it provides RF power and thermal trip as it is mounted on same heat sink as PA.





48 way Power divider   & combiner

Digital Detector

High power Directional couplers

Directional couplers are required in multiple in order to measure RF signal. The present design is with rigid structure for main line as well as auxiliary line.

Type	Max. forward power	Coupling factor	Main line connectors	Minimum directivity	Minimum return loss
Low power design	1 kW CW	40 dB	N type	30 dB	25 dB
Medium power design	5 kW CW	50 dB	1-5/8” EIA	28 dB	25 dB
High power dual coupling design	20 kW CW	50 dB	3-1/8” EIA	28 dB	25 dB
High power dual coupling design	65 kW CW	50 dB	6-1/8” EIA	26 dB	23 dB

Designed 1 kW, 5 kW and 20 kW directional couplers

650 MHz, 40 kW CW Solid state RF Amplifier (as per FRS under IIFC finalized)

Operating frequency: 650 MHz, Output Power: 50 kW ,harmonics < -30 dBc

Gain: 70 dB, RF radiation<0.1 mW/cm2 at 1m, Input Mains supply: 3 Phase AC

650 MHz, 50 kW (Pulse) Solid state RF Amplifier

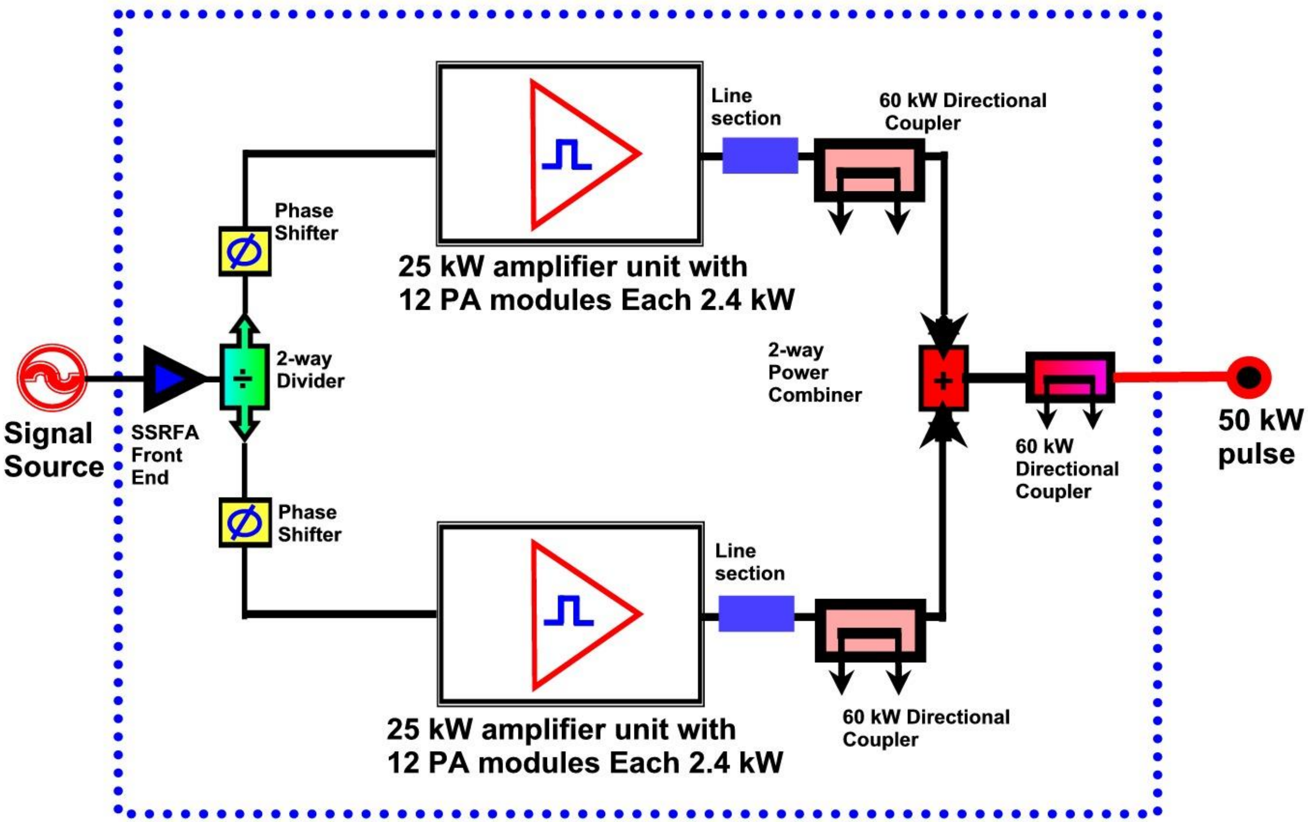
Operating frequency: 650 MHz

Output Power: 50 kW pulse

Gain: 70 dB

Bias Voltage: 50 V DC

Input Mains supply: 3 Phase AC

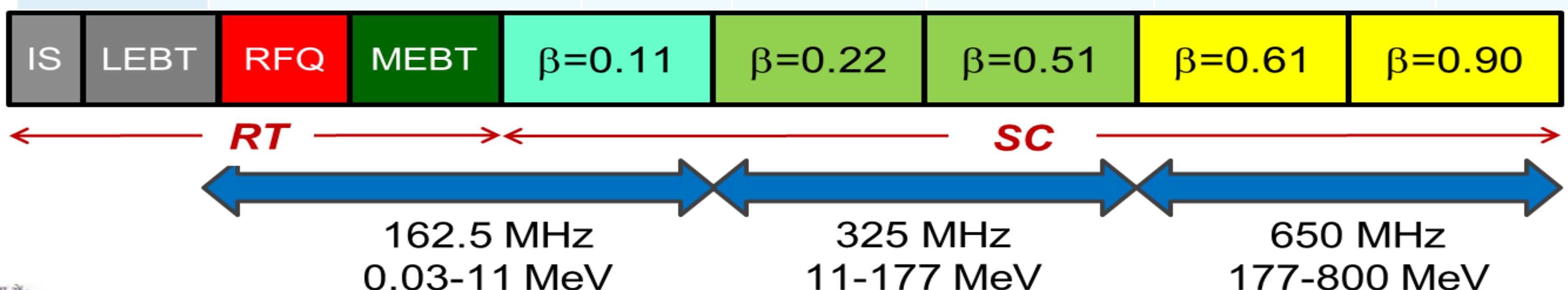


For ISNS , Beta = 0.6 and Beta =0.91 SC elliptical cavities several SSPA modules in the power range of 50,100,200 kW and more will be needed.

Schedule as per Addendum I

650 MHz RF Power Systems (Section 7.1)

Milestone	Major Milestone	Quantity	Responsibility	Delivery date (as per JPD)	New Delivery Dates	Remarks
1	Design of 650 MHz 30 kW RF System		DAE	Done	Completed	#1
	Design of 650 MHz 40 kW RF System		DAE	31 Dec 2015	31 July 2017	#2
2	Fabrication and testing of 2 nos. of 40 kW, 650 MHz RF System for HTS-2 for Fermilab and 2 nos. for HTS-2 for DAE laboratories.	4	DAE	30 Jun 2017	31 July 2019	#3
	Fabrication of 6, 40 kW 650 MHz RF System for CMTF being fabricated by DAE laboratories for Fermilab	7 [$1]	DAE	31 Jan 2018	28 Feb 2020	



RF Substrate Development with Joint venture of C-MET Trissur and RRCAT- at a Glance

- 2005-2007 – BRNS project

  - Feasibility study completed successfully at RRCAT Lab. Successfully completed.

- 2007-2010 - BRNS project

  - Required technical parameters were fixed for earlier Indus-2 solid state RF amplifiers. 50 Nos were delivered for high power testing at RRCAT Lab. Quality was improved to make it at par with commercial product. Successfully completed in 2009 before scheduled time.

- 2009-2010 - BRNS, C-MET, RRCAT MOU was signed,

  Dr. Srikumar Banerjee, former Chairman, Atomic Energy Commission suggested to go for pilot production in two phase. MOU Production first phase was signed and pilot production plant building was planned, US patent was filed.

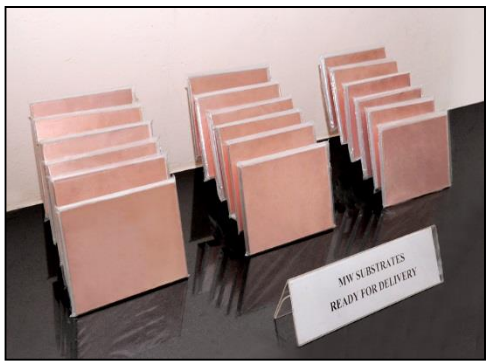
- 2014 - 2017 , BRNS, C-MET, RRCAT MOU Second phase of MOU

  Pilot production plant was started in 2011 at C-MET Trissur. Properties of the substrate were optimized to make it better than commercial counterparts.

Development of Novel Microwave Substrate for High Power RF Amplifier

(BRNS Project: C-MET and RRCAT)

C-MET and RRCAT have developed and characterized novel low-loss PTFE-ceramics based microwave substrate for making high power solid state RF amplifier.



Substrate developed by C-MET (ε_r=4.3, Loss factor=0.0018, $\tau_{\varepsilon r}$= 30 ppm/^{o}C) 2010

250 W (CW) RF amplifier developed at RRCAT

- Copper cladding on PTFE-ceramics based substrate
- Import substitute of TMM4 (polybutadiene and polyisoprene thermoset) substrate of M/s Roger Inc. USA
- Suitable for large power applications
- Cost effective ~ 20% of imported

- Optimization of substrate composition to reach desired permittivity, thermal coefficient and loss factor
- Pilot plan production facility at C-MET
- International patent being applied

US009505902B2

(12) **United States Patent**
Ravendran et al.

(10) **Patent No.: US 9,505,902 B2**
(45) **Date of Patent: Nov. 29, 2016**

(54) **CERAMIC FILLER, METHOD OF PREPARING THE CERAMIC FILLER AND APPLICATIONS AS RESONATOR AND LAMINATE THEREOF**

(71) Applicants: **SECRETARY, DEPARTMENT OF ELECTRONICS AND INFORMATION TECHNOLOGY, GOVT OF INDIA**, New Delhi (IN); **EXECUTIVE DIRECTOR, CENTRE FOR MATERIALS FOR ELECTRONICS TECHNOLOGY (C-MET)**, Thrissur (IN); **SECRETARY, DEPARTMENT OF ATOMIC ENERGY**, Mumbai (IN)

(72) Inventors: **Ratheesh Ravendran**, Thrissur (IN); **Stanley Jacob Kollannoor**, Thrissur (IN); **Kodakattumana Purushothaman Murali**, Thrissur (IN); **Akhilesh Jain**, Indore (IN); **Pundlik Rama Hannurkar**, Indore (IN)

(73) Assignees: **SECRETARY, DEPARTMENT OF ELECTRONICS AND INFORMATION TECHNOLOGY, GOVT OF INDIA**, New Delhi (IN); **EXECUTIVE DIRECTOR, CENTRE FOR MATERIALS FOR ELECTRONICS TECHNOLOGY (C-MET)**, Thrissur (IN); **SECRETARY, DEPARTMENT OF ATOMIC ENERGY**, Mumbai (IN)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 113 days.

(21) Appl. No.: **14/228,342**

(22) Filed: **Mar. 28, 2014**

(65) **Prior Publication Data**

(51) **Int. Cl.**
C08K 3/22 (2006.01)
C04B 35/495 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***C08K 3/22*** (2013.01); ***C01G 35/006*** (2013.01); ***C04B 35/495*** (2013.01); ***C04B 35/6261*** (2013.01); ***C04B 35/62675*** (2013.01); ***C04B 35/634*** (2013.01); ***C04B 35/64*** (2013.01); ***C08K 3/24*** (2013.01); *C01P 2002/82* (2013.01); *C01P 2004/03* (2013.01); *C01P 2004/61* (2013.01); *C01P 2004/62* (2013.01); *C01P 2006/40* (2013.01); *C04B 2235/3217* (2013.01);
(Continued)

(58) **Field of Classification Search**
USPC 524/408, 544; 264/614
See application file for complete search history.

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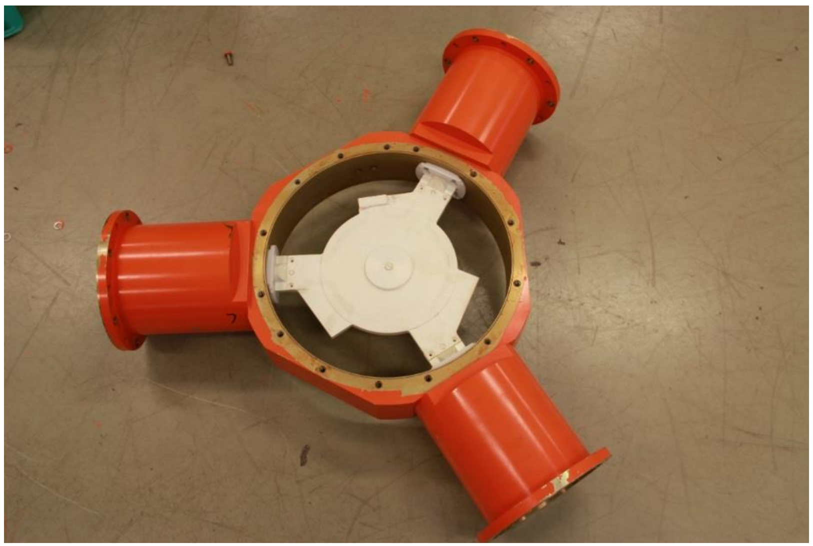
(Continued)

Primary Examiner — Peter D Mulcahy
Assistant Examiner — Henry Hu
(74) *Attorney, Agent, or Firm* — Hamre, Schumann, Mueller & Larson, P.C.

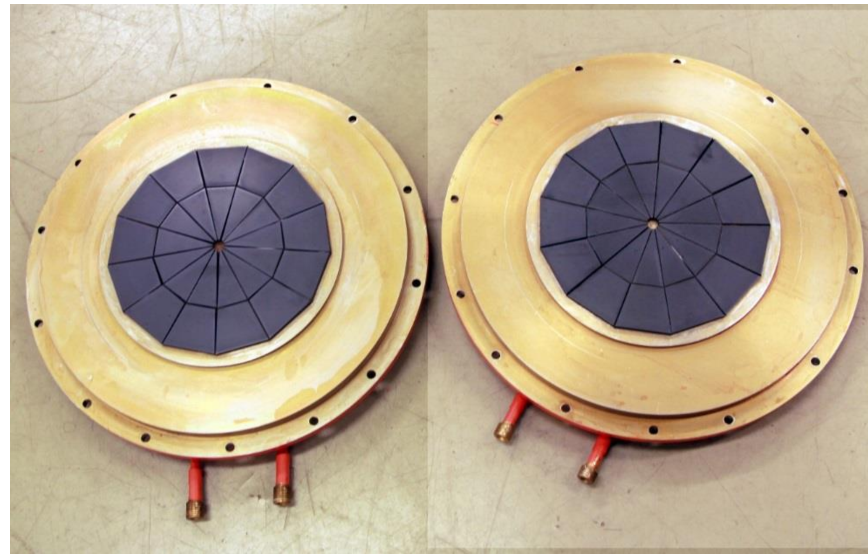
(57) **ABSTRACT**

The present disclosure relates to ceramic fillers and methods for preparing said ceramic fillers. The present disclosure further relates to dielectric resonator, fluoropolymer-ceramic filler compositions and their corresponding laminates along with their respective methods for preparing the same from the ceramic fillers. The present disclosure further provides a dielectric resonator and fluoropolymer-ceramic filler laminates having enhanced dielectric properties. The present disclosure also relates to various microwave applications of such fillers, resonators and laminates including microwave devices and circuits.

60 kW High Power Circulator development (at 505.8 MHz)



Y-Junction Circulator @505.8MHz



Ferrite affixed on cooling plates

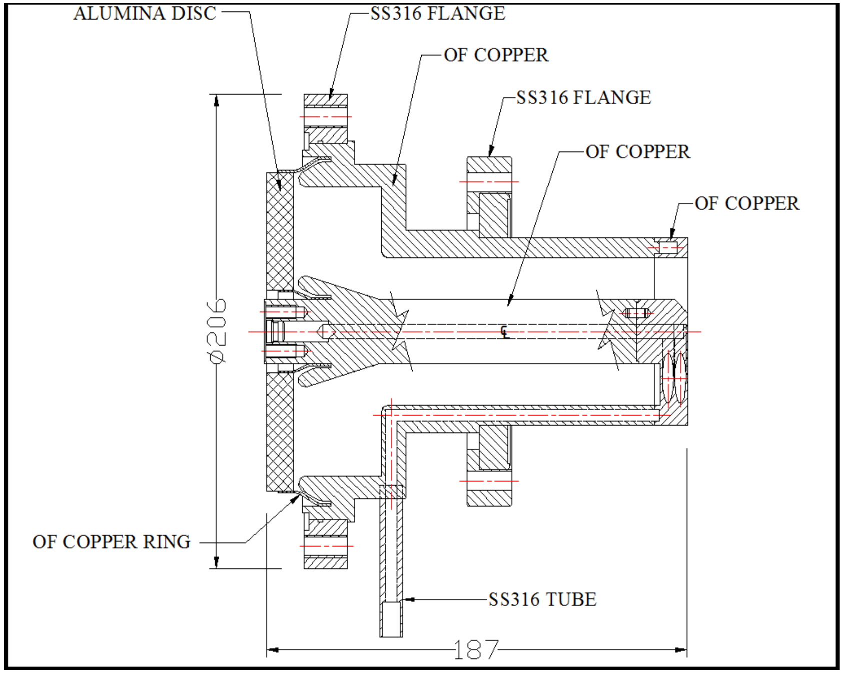
➢ <u>Typical Parameter of Ferrite (being used in Circulator development at RRCAT)</u>

1. Saturation magnetization,4PIMs : >900 Gauss
2. Resonance line width ,3db (FMR) : < 50 Oe.
3. Dielectrics Real part : ~ 14
4. loss tangent : < 2 x 10-4
5. Curie temp : 280 deg.C

505.8 MHz High Power RF coupler Development for Indus-2

PARAMETERS OF INPUT COUPLER	
Operating Frequency	505.81 MHz
Max. Forward RF power	120 kW
Power loss on Ceramic disk	22 W
Power loss on Steatite disk	150 W
Coupling Range	1 to 3.6

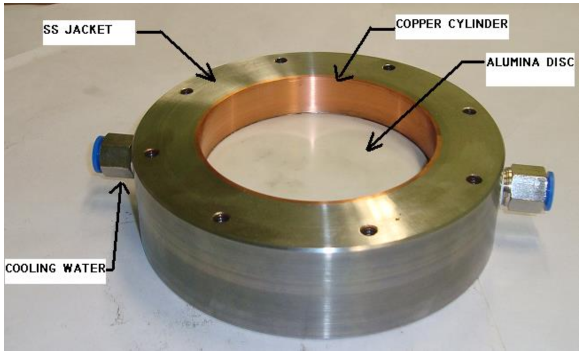
Tested up to 33kW CW power



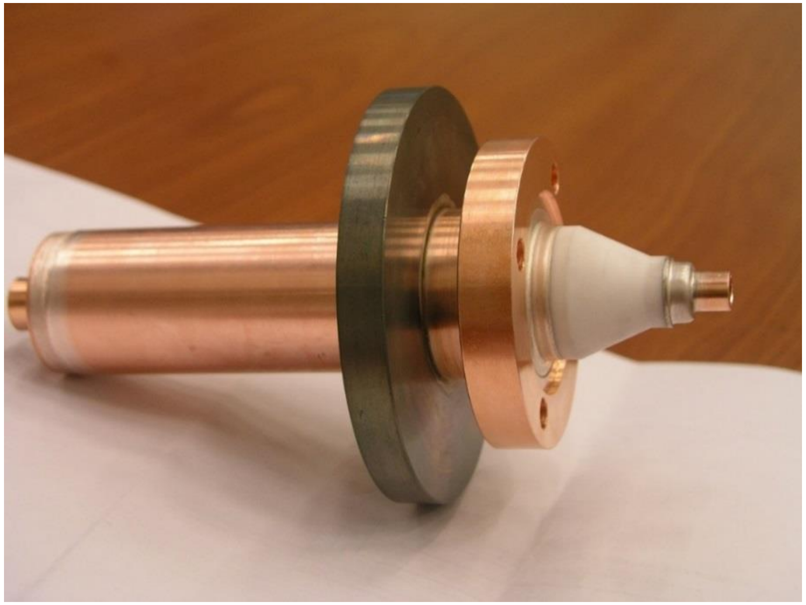
Fully brazed and processed at CEERI

Various Couplers/RF Windows developed at RRCAT

Sensing Loop Coupler for Indus-1 RF cavity @31.6MHz



Planar RF window



Power coupler for Indus-1 RF cavity @31.6MHz

Challenges: Solid-State RF Amplifier

A solid-state RF power transistor with great ruggedness is desirable for its application to particle accelerators. Some of the challenges towards this efforts are listed as

1. Thermal management issues
2. Minimum imbalance of amplitude and phase
3. Choice of amplifier architecture
4. System level simulation
5. Compact system with higher RF power per unit volume of cabinet/enclosure

Thermal management issues

- LDMOS devices are very sensitive to any increase in junction temperature during operation. With increasing power of transistor, one needs to study better liquid cooled or compressed gas cooled heat sink design.

- with present technology, an average power density up to 230 W/sq cm is dissipated [1] on the RF power transistor. Because the lifetime of semi-conductor products degrades exponentially proportional to its die temperature, the enduring reliability of the amplifier depends upon this temperature.

- Thus is a real challenge for stable and reliable operation of SSRFA.

1. Trends in RF Technology For Applications To Light Sources With Great Average Power, Chaoen Wang, NSRRC, Taiwan, Proceedings of IPAC2014, Dresden, Germany

Challenges in high power Solid-State RF Amplifier combining scheme (minimum imbalance of amplitude and phase)

- Effect of the amplitude/phase imbalance needs to be studied for high power amplifier, encompassing multiple components [2].
- Such study predicts real operating time conditions and system performance and efficiency [3].
- A mechanism needs to be devised inside individual amplifier module so as to compensate this imbalance automatically with the help of some data acquisition and control system.
- Alternatively amplitude and phase trimmers can be incorporated with the power combiner itself for individual PA phase adjustment.

2. M. S. Gupta, "Degradation of Power Combining Efficiency due to Variability Among Signal Sources," *IEEE Trans. Microw. Theory Tech.*, vol. 40, no. 5, pp. 1031-1034, May 1992.
3. “System efficiency and performance analysis for high power solid state radio frequency transmitter”, Akhilesh Jain, D.K. Sharma, A.K. Gupta, M. R. Lad, P. R. Hannurkar, S. K. Pathak, *Rev. of Sci. Instruments,* Feb. **2014**, *Vol*. 85, No. 024707, p. 024707-1-8.

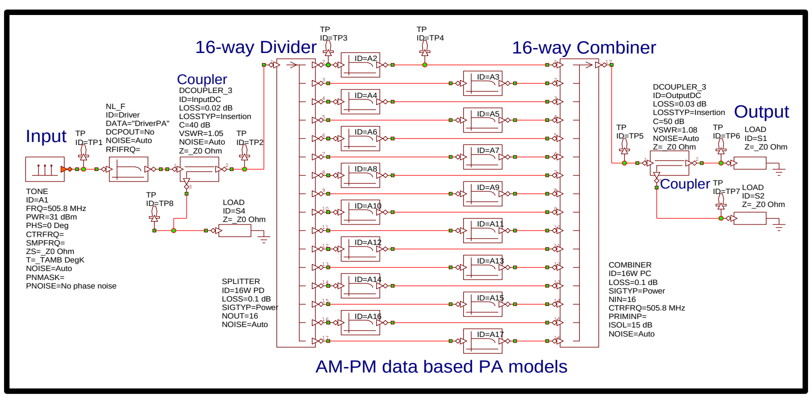
Choice of amplifier architecture

- Apart from being efficient at high power, the architecture selection [4] is also important. It should also be easy to maintain.
- Whether to use a number of smaller power PAs or a few larger power PAs is one of the basic decisions in the selection of the SSRFA architecture- gain, efficiency, linearity, cost - trade off .
- Even when larger power PAs are available, smaller power PAs often offer a higher gain, better phase linearity, and lower cost . The heat dissipation is more readily managed with a number of smaller power PAs. Advantage of using a large N for the power combiner is that the phase noise contributed by the PA-ensemble is reduced by a factor of 1/N.
- But with very large number of modules losses increases and hence system efficiency reduces

[4] Design and characterization of 50 kW solid-state RF amplifier", Akhilesh Jain, P. R. Hannurkar, D. K. Sharma, A. K. Gupta, A. K. Tiwari, M. Lad, R. Kumar, P. D. Gupta, S. K. Pathak, *International Journal of Microwave and Wireless Technologies*, Dec. **2012**, *Vol*. 4, No. 6, p. 595-603.

System level simulation

- The system level simulation [5] is a versatile tool and it needs to be used for the SSRFA system with dynamic load like RF cavity.
- Analysis of integrated high power SSRFA, system level computer aided simulation and experimental study needs to be performed for evaluating the system gain, power distribution and efficiency degradation due to impedance mismatch; resulting from the amplitude/phase imbalance in the system components.
- Presently dedicated tool for such requirement is not available in the market.



Typical system level schematic for a 16 way divider-PA and combiner topology in Visual system simulator (VSS™)

[5] "Visual System Simulator," AWR Corporation, User's Guide 2012.

Relevant Publications

“System efficiency and performance analysis for high power solid state radio frequency transmitter”, Akhilesh Jain, P. R. Hannurkar, S. K. Pathak, D.K. Sharma, A.K. Gupta, Rev. of Sci. Instruments, Feb. 2014, Vol. 85, No. 024707, p. 024707-1-8.

“Design and analysis of a high-power radial multi-way combiner”, Akhilesh Jain, D. K. Sharma, A. K. Gupta, P. R. Hannurkar, S. K. Pathak, Int. J. of Microwave and Wireless Technologies, Feb. 2014, Vol. 6, No. 1, p. 83-91.

“Compact solid state radio frequency amplifiers in kW regime for particle accelerator subsystems”, Akhilesh Jain, D. K. Sharma, A. K. Gupta, P. R. Hannurkar, S. K. Pathak, Sadhna, Academy Proceedings in Engineering Sciences, Aug. 2013, Vol. 38, No. 4, p. 667-678.

“Investigation of Class J continuous mode for high-power solid state RF amplifier ”, Akhilesh Jain, P. R. Hannurkar, S. K. Pathak, D.K. Sharma, A.K. Gupta, IET Microwaves, Antennas & Propagation, June 2013, Vol. 7, No. 8, p. 686 – 692.

“Design and characterization of 50 kW solid-state RF amplifier”, Akhilesh Jain, P. R. Hannurkar, D. K. Sharma, A. K. Gupta, A. K. Tiwari, M. Lad, R. Kumar, P. D. Gupta, S. K. Pathak, International Journal of Microwave and Wireless Technologies, Dec. 2012, Vol. 4, No. 6, p. 595-603.

“Modular 20 kW solid state RF amplifier for Indus-2 syncrotron radiation source”, Akhilesh Jain, P. R. Hannurkar, D. K. Sharma, A. K. Gupta, A. K. Tiwari, M. R. Lad, R. Kumar, M. K. Badapanda, P. D. Gupta, Nuclear Instruments and Methods in Physics Research A, June 2012, Vol. 676, p. 74-83.

“Development of high power solid state RF amplifiers and their deployment in Indus-2 synchrotron radiation source”, P. R. Hannurkar, Akhilesh Jain, M. Lad, Ramesh Kumar, Nitesh Tiwari, G. Singh, P.D. Gupta, Indian Nuclear Society News, July – Dec. 2011, Vol. 8, No. 3 & 4, p. 93-98.

“Design of high-power radio frequency radial combiner for proton accelerator”, Akhilesh Jain, D. K. Sharma, A. K. Gupta, P. R. Hannurkar, Rev. of Sci. Instruments, March 2009, Vol. 80, No. 016106, p. 016106-1-3.

Low Level RF (LLRF) control

Introduction

- In particle accelerators, EM field inside RF cavity is used to accelerate the charged particles. Power required to produce this field comes from High power RF amplifier,

- For proper injection and acceleration of the charged particles, stability of amplitude and phase of fields inside the cavity is very critical.

- Perturbation in amplitude and phase of RF signal can occur due to different reasons like amplifier gain variation, beam loading ,phase drift of components etc. this will affect the stability of RF fields.

- Automatic Low Level RF (LLRF) feedback control loops are required to keep the RF field stable with in desired limit.

Low Level RF (LLRF) control

- The Low Level RF (LLRF) System is the most critical part of the RF system, as it regulates the accelerating field in the RF accelerating structures like RFQ,DTL,SC cavities etc. It controls the amplitude, phase (Challenging for pulsed RF systems) and frequency (Challenging for SCRF Cavities due to Low bandwidth) of the RF signal finally driving the High Power RF amplifier system.
- The stability requirements of all three parameters depends on the type and specification of accelerators and are derived from beam properties as

- Derived from beam properties
  - energy spread
  - Emittance
  - bunch length (bunch compressor)
  - arrival time

- Different accelerators have different requirements on field stability (approximate RMS requirements)
  - 1% for amplitude and 1 deg. for phase (example: SNS)
  - 0.1% for amplitude and 0.1deg.for phase (linear collider)
  - up to 0.01% for amplitude and 0.01 deg. for phase (XFEL)

Sources of RF Field Perturbations

Beam loading

- Beam current fluctuations
- Pulsed beam transients
- Multipacting and field emission
- Excitation of HOMs
- Wake fields

Cavity dynamics

- cavity filling
- settling time of field

Cavity resonance frequency change

- Thermal
- Microphonics
- Lorentz force detuning

Cavity drive signal

- Amplitude and phase fluctuation in high power amplifiers, cables, circulators
- Phase noise from master oscillator
- Timing signal jitter

LLRF control contd.

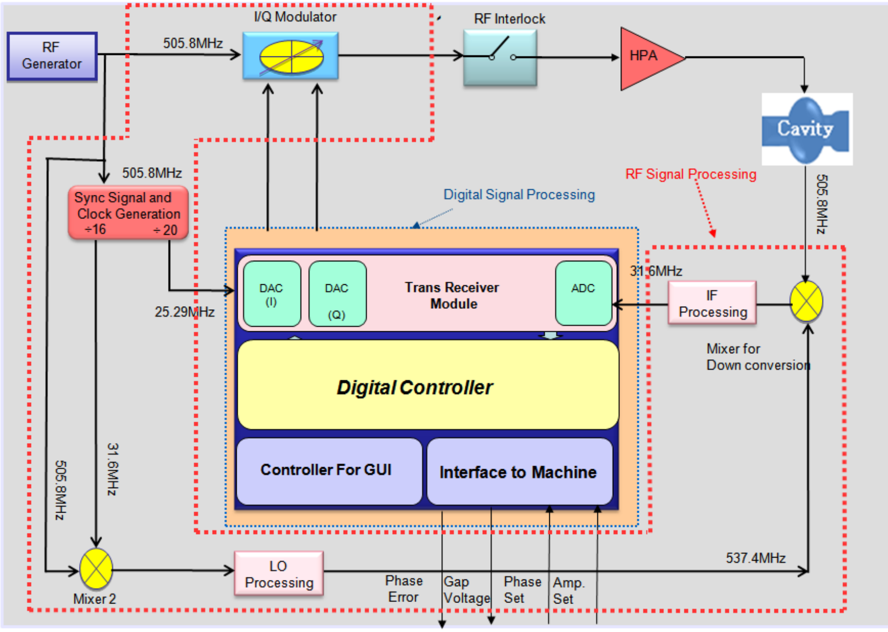
LLRF System Requirements

- Functional : Measurements (signals, conditions etc.),control actions, diagnostics (calibration of Gap Voltage, Phase, Cavity detuning) and automation (for wide range of machine operating conditions)
- Non functional: Reliability (less failure, reduced downtime, redundancy of LLRF components),Operability , Reproducibility (restore beam operation after maintenance & shutdown) or I/L trip (for safety and protection), Maintainability

Technology: Analog or Digital technology based

- Analog LLRF: Less complicated, low cost and fast
- Digital LLRF: Flexibility, adaptability, good repeatability and reduced long time drift errors compared to analog system (very useful for multiple RF systems)

LLRF System For Indus-2 RF system

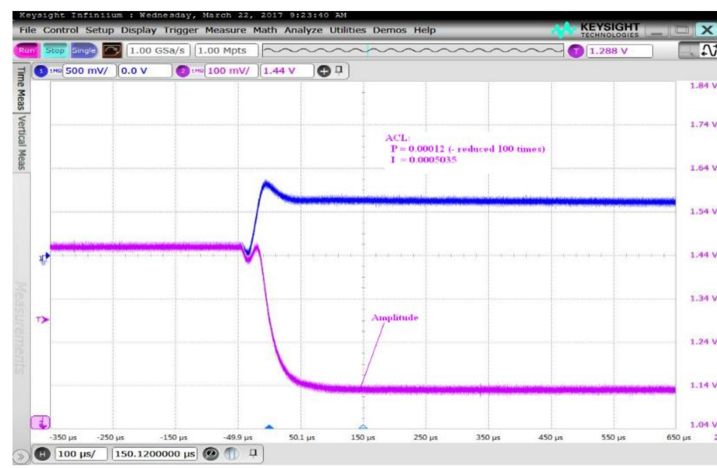


Block diagram of Indus-2 RF system.

Digital LLRF systems installed in Indus-2

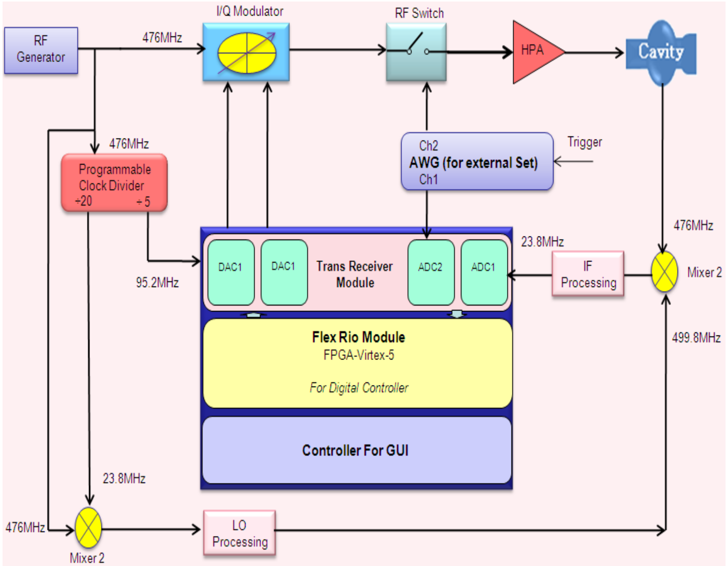
Digital LLRF system for five RF stations have been installed and are in operation in round the clock mode.

Frequency :	*505.8MHz CW.*
Amplitude stability:	*±1%*
Phase stability:	*±1 º*



Transient response of LLRF system of Indus-2

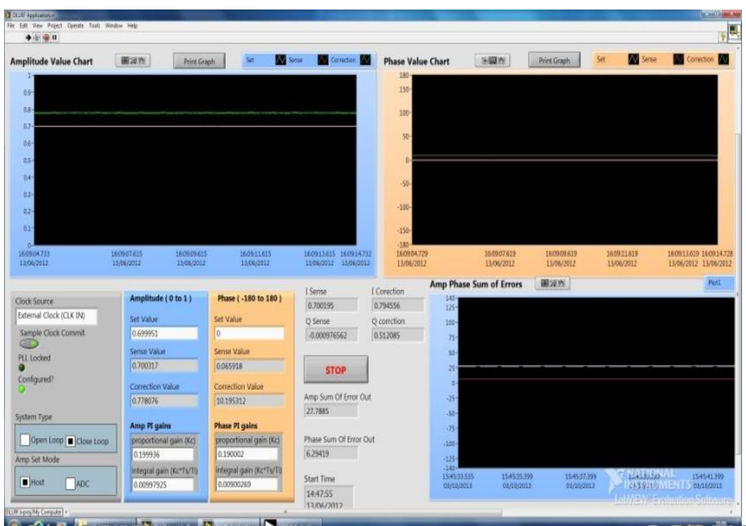
Pulsed LLRF system for SHPB of IR-FEL



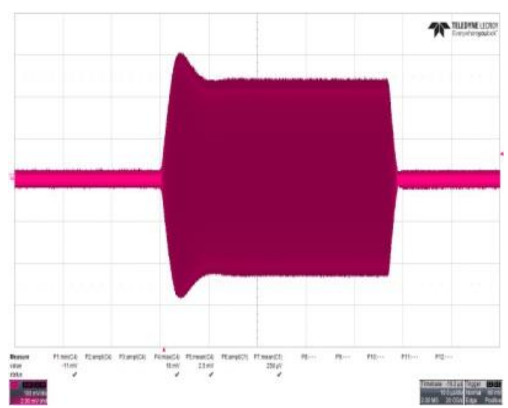
Block Diagram of Digital LLRF System

To Keep the Electromagnetic field of Sub Harmonic Buncher constant, a PXI based Pulsed Digital LLRF feedback control system at 476 MHz has been designed and developed.

Frequency: 476 MHz Pulse
Pulse width : 50µsec
Repetition Rate : 1- 10 Hz
Maximum Peak Power: 10kW



Screen Shot of GUI for Digital LLRF system



Close Loop Test results in pulse mode

Pulsed Digital LLRF System At 476MHz

LLRF System For Super Conducting Cavity

Super conducting RF Cavities have very large Quality Factor Q ~ 10^{10}

Due to Very High Q

Low Bandwidth $\Delta\omega = \frac{\omega}{Q}$ Large Fill time $t_{fill} = \frac{2*Q}{\omega} = \frac{2}{\Delta\omega}$

Due to High Q following are critical for LLRF system of superconducting Cavity

- Time of Beam injection in superconducting RF cavity so that beam sees sufficient and constant gap voltage.

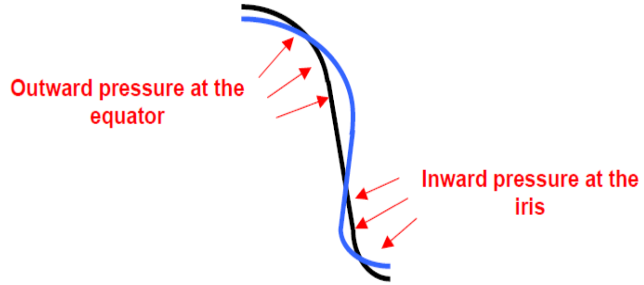
- Microphonics: Changes in frequency caused by connections to the outside world
  - Vibrations
  - Pressure Fluctuations

- Lorentz Force Detuning

  Radiation pressure : $P = (\mu_0 H^2 - \varepsilon_0 E^2)/$

  Deformation of the cavity shape:

  Frequency shift : $\Delta f = K_L * E^2$



Design and development of Digital LLRF System for pulsed operation considering above Parameters is being done.

SCRF Cavity Tuning Control

- Lorentz Force Detuning - RF field inside cavity interacts with cavity walls, which is proportional to electromagnetic field energy. (Minimize LFD)
- Helium Pressure – Helium pressure variation in cryogenic system exerts fluctuating pressures on cavity walls, which results in cavity deformations and frequency detuning. (Minimize df/dP)
- Mechanical Vibrations – Mechanical vibrations of motor, pump etc. reaches on cavity through piping system and leads to cavity deformation. (cavity natural frequency should be away from disturbance frequency. Modal analysis of dressed cavity is performed.)

SCRF Cavity Tuning Control

Motor tuner (slow)

- Large range frequency tuning or set the pre-detuning
- Not used frequently (only offline)

Piezo tuner (fast)

- Fine tuning of the cavity
- Lorenz force detuning or microphonics compensation

Feed forward control

- Suitable for Lorenz force detuning compensation due to repetitive and predictable nature.
- Slow parameter changes can be corrected with adaptive feed forward

Feedback control

- Suitable for microphonics control
- Response time has to be fast.

RF System for ISNS

1 GeV Proton Accelerator based SNS facility requires pulsed RF system of

- 325 MHz for RFQ, SSR0 SSR1 and SSR2
- 650 MHz for Low and high beta elliptical superconducting RF cavities.

Preliminary design for LLRF system of 325 MHz & 650 MHz RF system has been done.

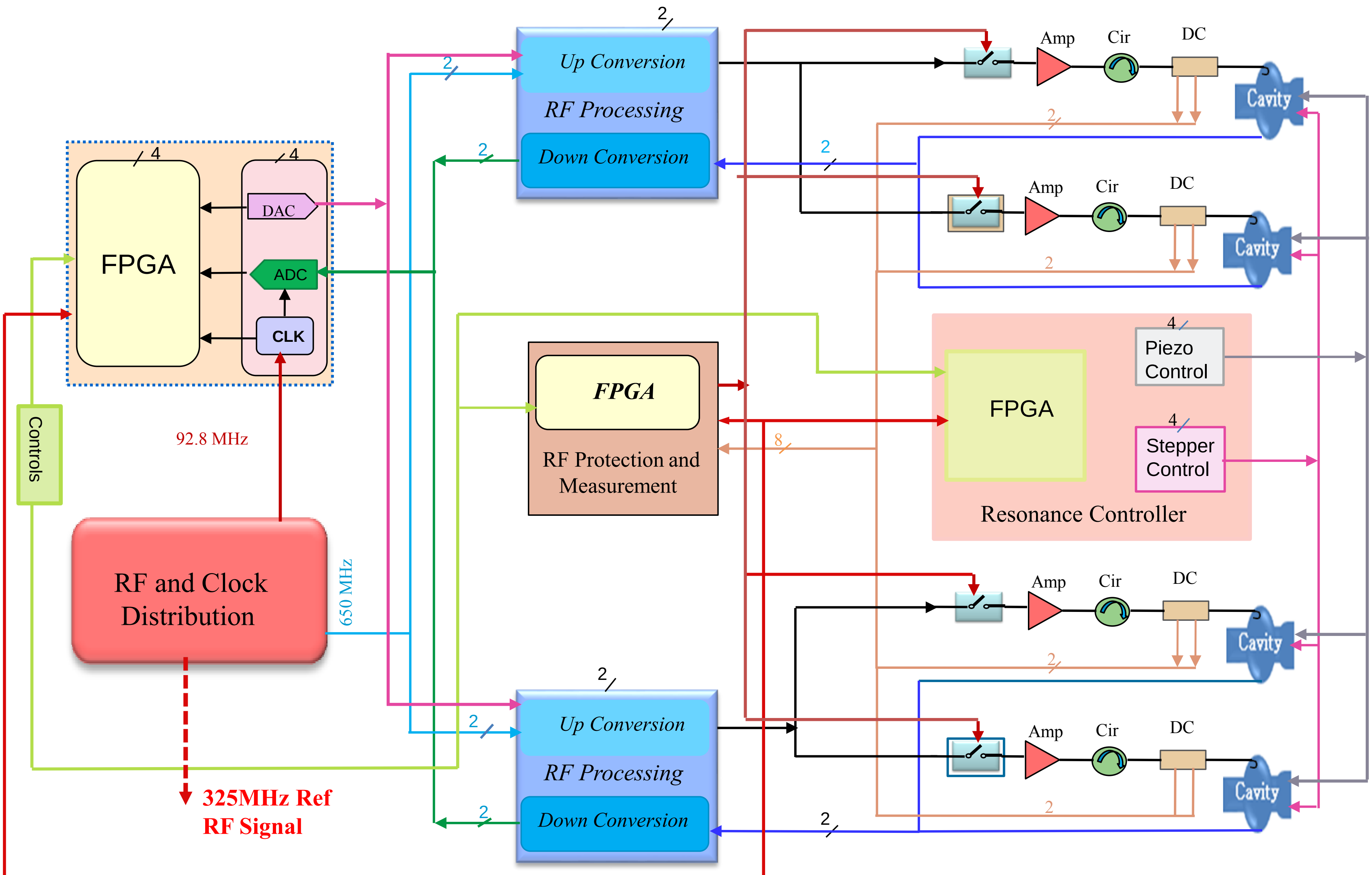
Schematic architecture of a LLRF Rack has been planned.

Each 32 U rack will be able to cater the LLRF requirement of four RF superconducting RF cavities. will consists of :

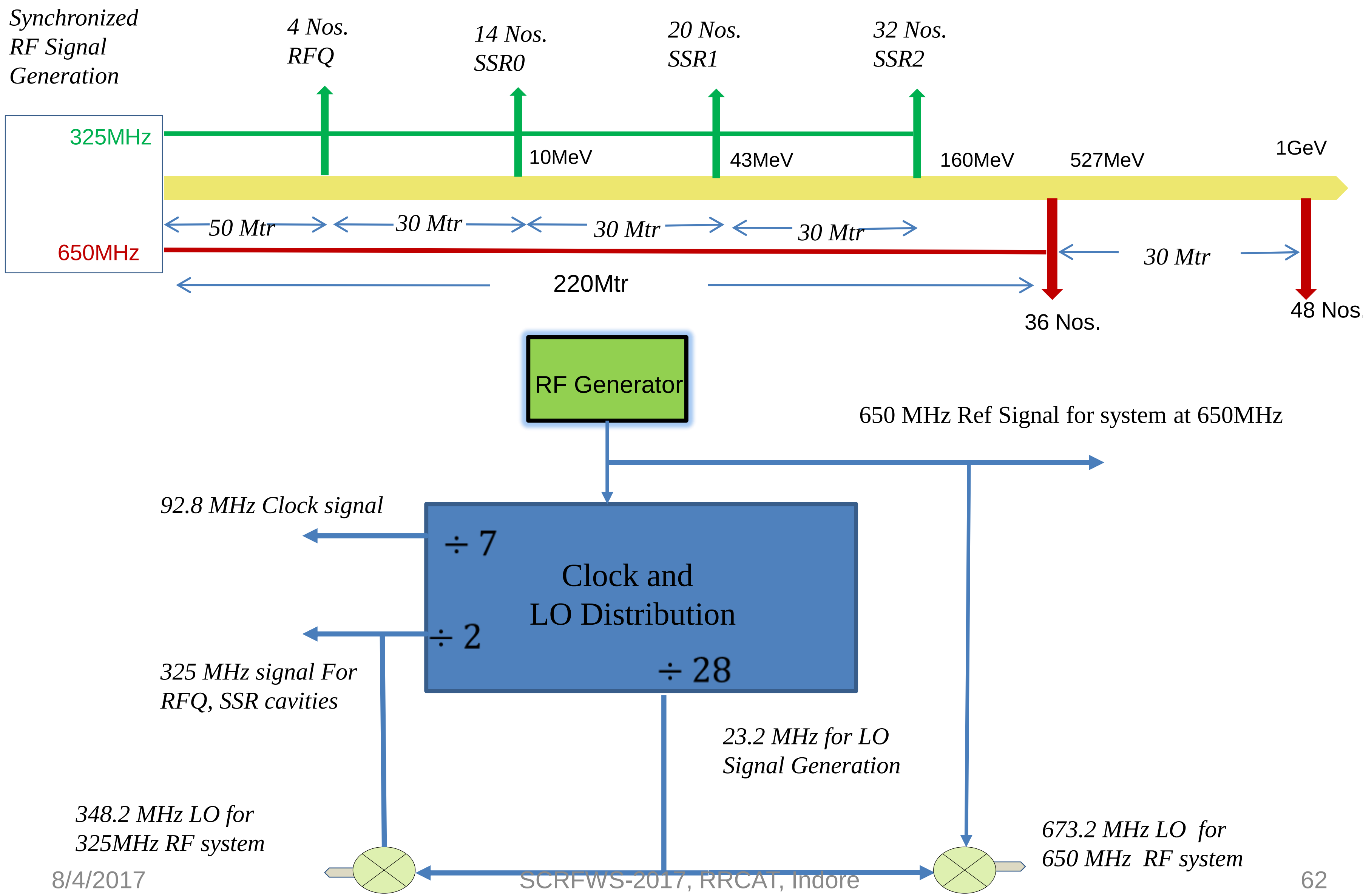
1. To control the field of 4 RF cavities two No. of RF signal processing unit.
2. One FPGAs based digital signal processing unit (4 U) to implement control algorithm for 4 RF cavities
3. Two tuner control system for 4 RF cavities.
4. One Master LO and clock signal generation and distribution Unit.
5. Interlock and power monitoring system.

With the experience gained in development of CW (505.8 MHz for Indus-2) and Pulsed LLRF system (476 MHz for IRFEL Sub Harmonic Pre Buncher RF cavity) design of pulsed LLRF system for RFQ is being done.

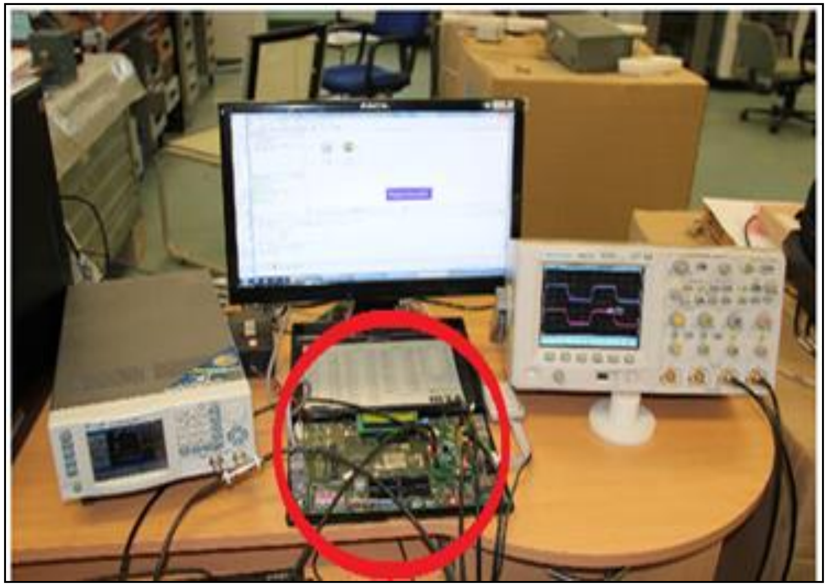
Block Diagram of 650 MHz LLRF System



MO and Clock Distribution system



Real Time RF Cavity Simulator



Real Time FPGA Cavity test setup

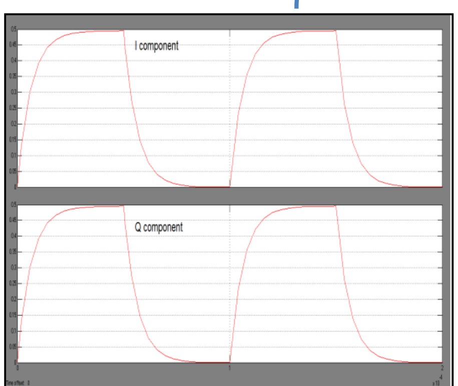
As we all know superconducting cavities are not easily available for testing of Low Level RF systems.

Hence we have developed Real time RF cavity simulator.

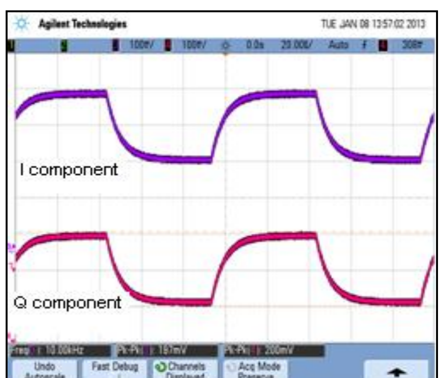
It is a hardware model implemented using FPGA to simulate the behavior of actual RF cavity.

This can be utilized for testing and optimization LLRF system parameters under various operating condition

Tuned



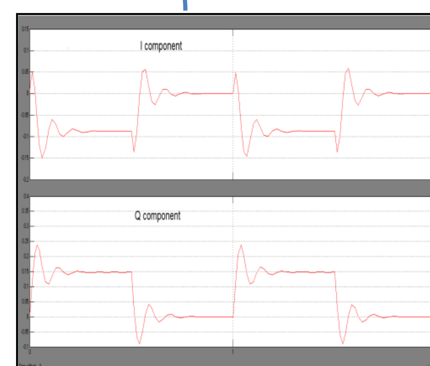
Software simulation response



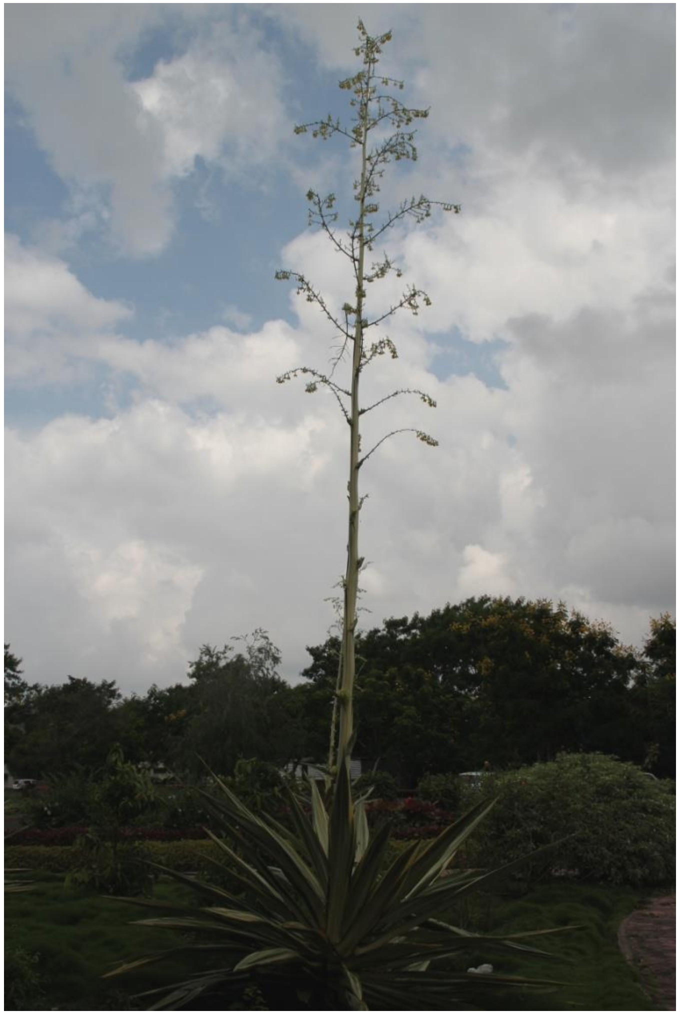
Real Time Model Response

Detuned

Real Time Model Response



Software simulation response



Thanks