भाभा परमाणु अनुसंधान केंद्र
BHABHA ATOMIC RESEARCH CENTRE

RF power for 325 MHz Superconducting RF Cavities

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On behalf of RFSS,

ACnD, BARC

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BARC

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Outline

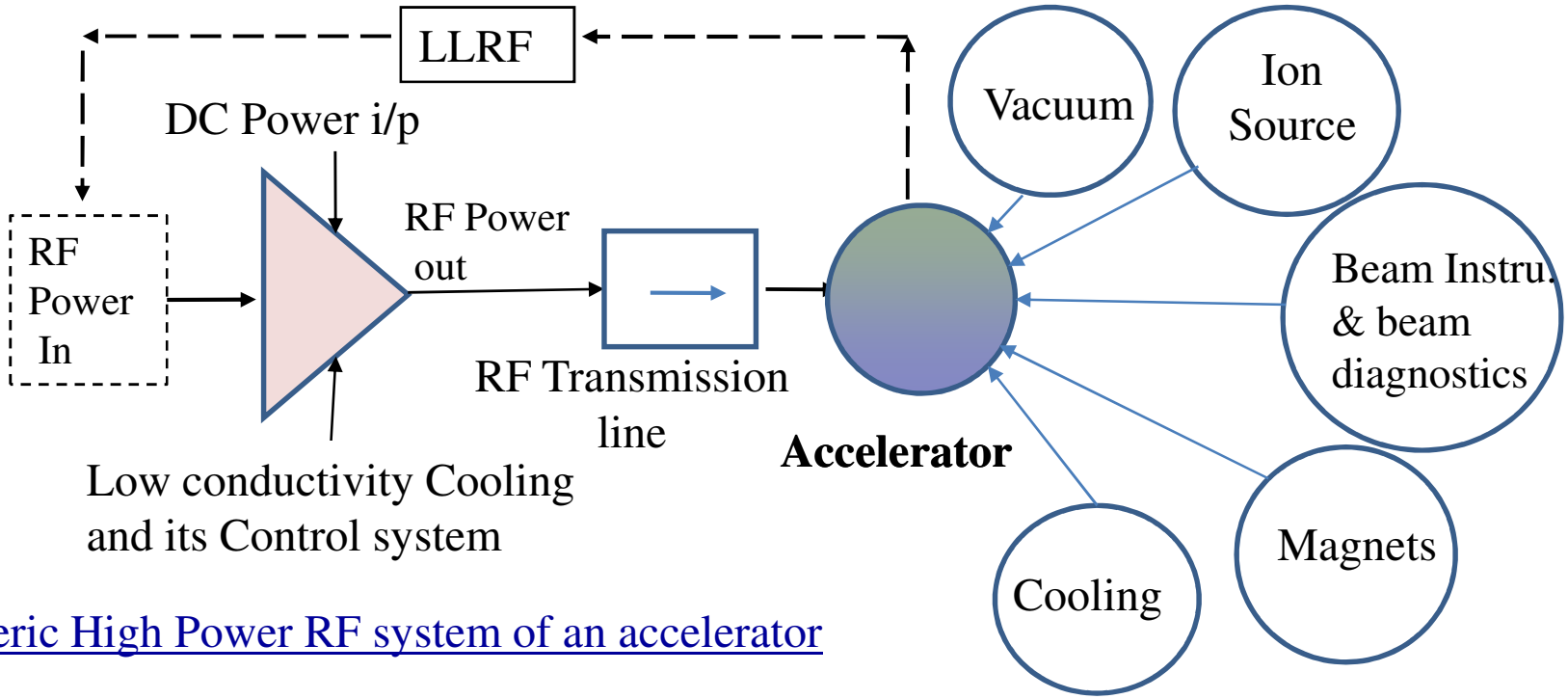
- RF Power for SC accelerators
- RF technology development
- Comparison of indigenous development
- Other indigenous developments

Accelerator subsystems

1.High Power Radio Frequency systems
2.Low Level RF & control systems
3.Beam Instrumentation and diagnostics
4.Vacuum
5.Ion source
6.Accelerator cavities
7.Cooling

Various disciplines involved in RF power

1.High voltage engineering
2. Vacuum
3. RF engineering
4. Fast protections & interlocking
5. Effective thermal management
6. RF interference (RFI) suppression
7. Successful grounding techniques for DC and RF subsystems etc.



Generic High Power RF system of an accelerator

SC RF

- Super conducting accelerators have gained popularity due to their efficient operation and compact size compared to normal conducting counterpart. Uses of accelerator technology for the basic physics studies, food industry, security, nuclear-waste management has motivated this accelerator development.

- Due to technology development in cryogenic and super conducting RF (SCRF) cavities , RF power requirement has come down drastically.

- Super conducting RF (SCRF) cavities offer very high quality factor and large accelerating field per kW of RF power compared to normal conducting cavities. Power lost in the accelerating structure is very small part of the total feed power. RF power required for accelerating gradient of same magnitude in a Niobium super conducting cavity (viz. Single spoke resonators) is order of magnitude less compared to the power required in normal-conducting cavities.

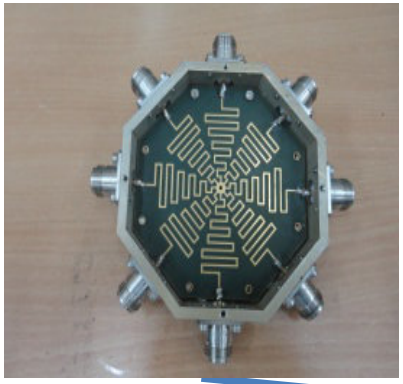
RF power at 325 MHz

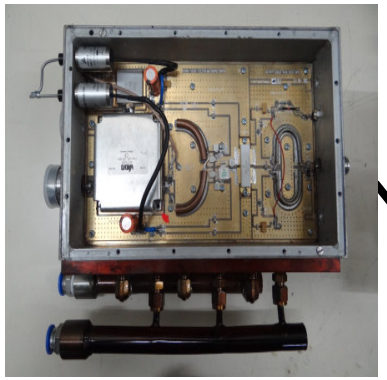
- BARC, India is involved in design and development of solid state radio frequency power amplifiers (SSRFPAs) at 325 MHz with features like compact size (power to size ratio), high Efficiency (~70%) and high power gain. SSRFPA offer best efficiency when they are used at the designed power level which is normally its maximum RF output power.

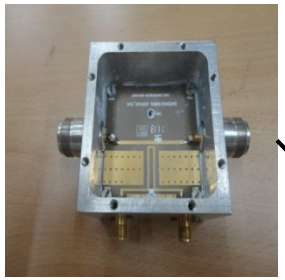
- These RF amplifiers @ 325 MHz will be used in three big accelerator projects viz., PIP-II, Indian SNS (I SNS) and Indian ADS (I ADS)

- Radio frequency MOSFET based high efficiency SSRFPAs operating at 325 MHz, have been designed, developed and successfully tested for Indian accelerators and as a part of Fermilab collaboration. These SSRFPAs are used for coupling RF power to single spoke resonator (SSR) - a superconducting accelerator module for proton beam acceleration.

Solid state RF Power Amplifier







Power Meter

1:8 Divider

8:1 Combiner

Power Meter

3-1/8" line

Dir Coupl.

Dir Coupl.

50 ohm Transmission line With Circulator

RF Coupler

SSR

RF Switch

SSPA Driver

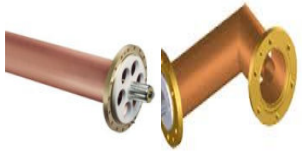
Signal Genera tor

Interlock Protection and measurement system

Interlock signals

DC 50V, 30A (8)

Water cooling system



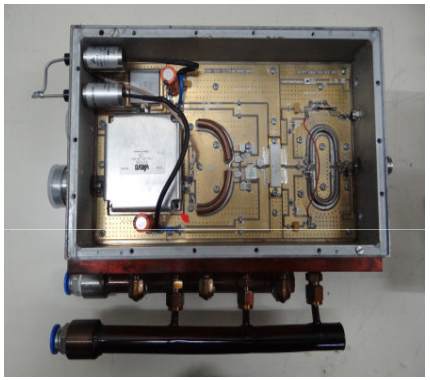
Detailed technical requirements are described under following items:

- Interfaces: Hardware and electrical
- Architecture of 7 kW RF Power amplifier
- Hard wired interface signals
- Technical specifications of 7 kW RF power amplifier
- Interlock and protection system flow diagram
- RF Amplifier operational details
- Quality assurance plan and Acceptance test procedure

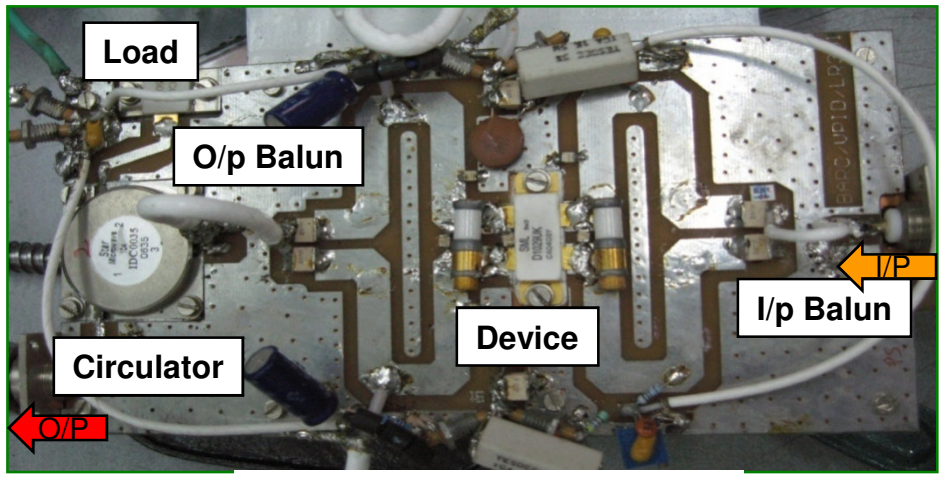
SSRF Power Modules Developed

- Center Frequency : 350, 352, 325 MHz
- Bandwidth (3 dB) : 10 MHz
- Power output (sat.) : 100 W, 300 W, 800W, 1000 W
- Power Gain : 8.5-22 dB
- Efficiency : 50 - 68%
- Protection : Circulator

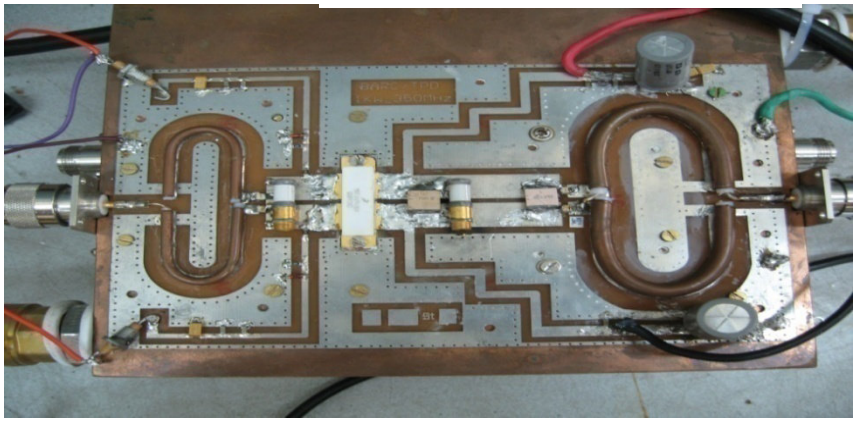
300W Amplifier module



1kW Amplifier module



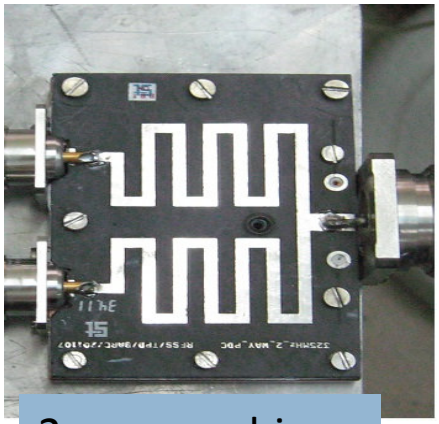
250W Amplifier module



800W Amplifier

Power Combiners/Dividers

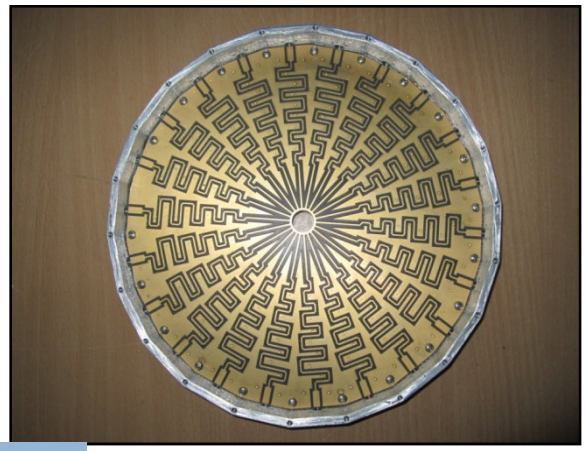
- 2, 4, 8, 22 way combiners
- Power levels 100 W, 1 kW, 8 kW, 10 kW.
- Return loss of >20dB at input ports
- Return loss of better than 25dB at output port.
- Isolation among input ports better than 25dB.
- Transmission loss < 0.15dB



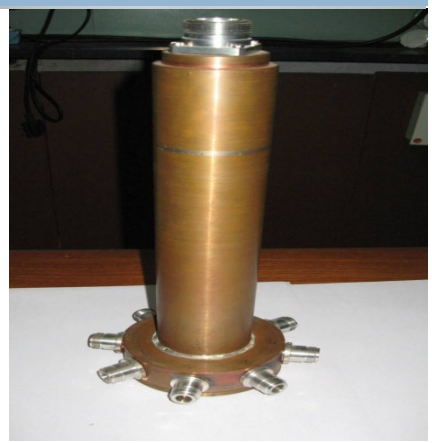
2-way combiner

1 kW Combiner

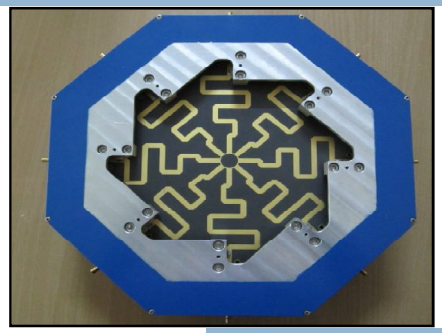
8- way power Combiner (8 kW) & splitter



22 - way splitter



2.5 kW, 8 way Combiner



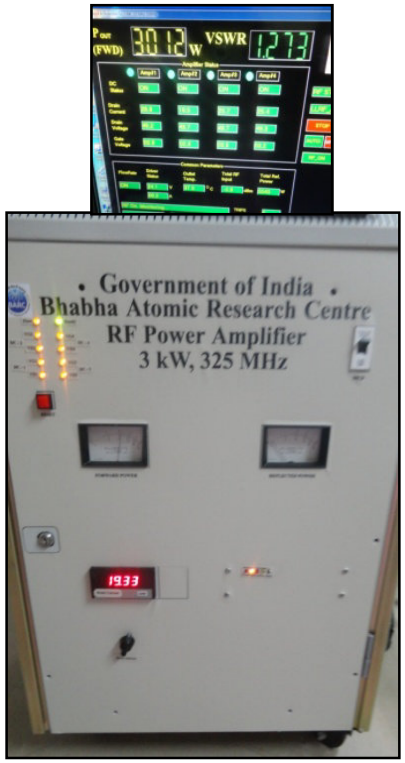
8 - way splitter

Contribution under IIFC: Solid State RF amplifiers at 325 MHz: Addendum -V

All are stand alone RF amplifiers and are designed and developed indigenously

1 kW Amplifier

- Power: 1 kW
- Overall Gain: > 65dB
- Efficiency : 61 %
- 2nd Harmonics: - 41.5 dB
- Status: Completed



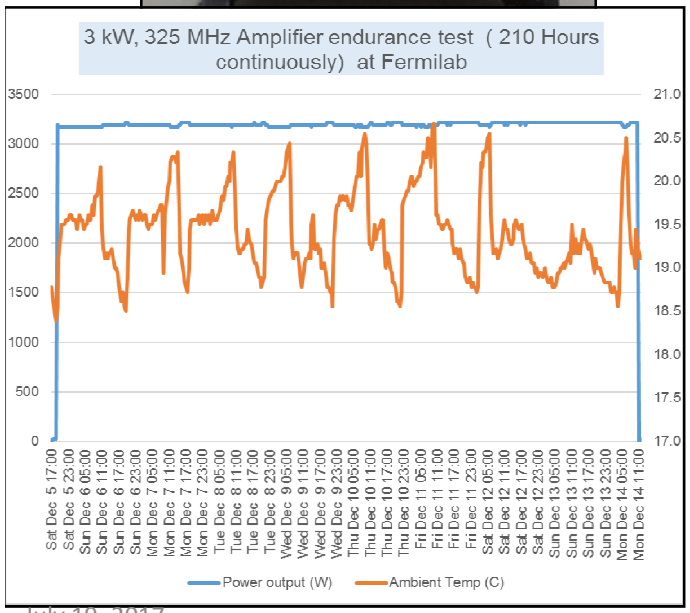
3 kW Amplifier

- Power: 3 kW
- Overall Gain: > 65 dB
- Efficiency : 65 %
- 2nd Harmonics: - 41.9 dB
- Status: Completed and delivered

7 kW Amplifier

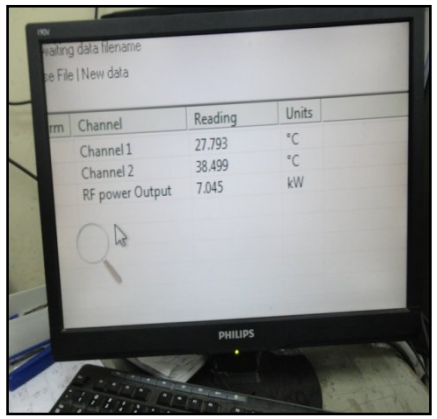
- Power: 7 kW
- Overall Gain: > 90 dB
- Efficiency : 68 %
- 2nd Harmonics: - 41.9 dB
- Status: Completed

325 MHz, Solid State RF Amplifier Results



325 MHz, 7 kW Solid State RF Amplifier Results

Display of Calorimetric measurement of RF Power



Sensor data of Calorimetric measurement of RF Power

RF Power Waveform at 7 kW on spectrum analyzer

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Revised 325 MHz, 7 kW Solid State RF Amplifier - Fermilab collaboration

352 MHz, 10 kW Solid State RF Amplifier for Buncher cavity of LEHIPA

New RFPA: 20 kW, 325 MHz in development stage

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Pre-compliance test for Radiated emission (RE) of 1 kW RF modules using omni-directional antenna

RF Radiation Pick up at Distance = 3 meters	IEC std. Value at 3 m	Remark
67 dBuV/m	57 dBuV/m	Reading is higher, as measurement is not done in proper set up. Compliance test will be performed on the unit

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Electrical specifications of SSRFPA

	Parameter	Value/range
1	RF output (kW), CW and pulse	0-7.0 kW Minimum pulse width of 100 microseconds, Maximum pulse width 6 milliseconds, maximum 20 Hz repetition rate
2	Centre Frequency (MHz)	325
3	1 dB Bandwidth (MHz)	7 MHz
4	Power gain (dB)	62-68
5	1. DC to RF Efficiency (at 7 kW) 2. AC to RF efficiency	65% ~ 60%
6	1 dB compression power (kW)	>7.0 kW
7	Noise Figure:	20 dB max
8	All Harmonics (dBc)	<-25 dBc
9	Spurious (dBc)	< -60 dBc@ 60 Hz and < -80 dBc @ 100 kHz

Comparison between RFPA by BARC and other commercial companies

	Specifications	Commercial amplifier-1	BARC Amplifier	Commercial amplifier-2
1	Bandwidth (1 dB)	6 MHz	7 MHz minimum	≥ ± 1 MHz
2	Saturation power (kW)	10 kW CW	8 kW CW and pulse	75
3	Gain	64 to 66 dB,	62-68 dB	69 dB for full saturated power
4	1 dB compression output power	7 kW CW	>7 kW CW	60 kW CW
5	Input power	+10 dBm for full output power Over drive protection up to +20 dBm	Over drive protection up to +16 dBm	Saturated power to be achieved with no more than + 10 dBm
6	Harmonics	≤ - 30dBc	-30 dBc including power supply modulation	≤ - 30dBc
7	Spurious outputs	≤ - 60dBc	< -80 dBc at offset of +/-100 kHz from center frequency	≤ - 50dBc

Comparison between RFPA by BARC and other commercial companies

Overall efficiency	Typically 55 % (at 10 kW), guaranteed not less than 45%	AC plug to RF output up to 60% at 8 kW, minimum of 55% at 1 dB compression power	Not Available

Comparison between RFPA by BARC and other commercial companies

Cooling	DI water for the amplifier units, and forced air for the power supplies. Maximum inlet temperature 40ºC	Water-cooled can work both on clean potable and low conductivity water (LCW) The amplifier works very well over +/- 5 C above 28 degree C (i.e. 23 to 33 degree centigrade)	Not Available
Electrical safety	All sources above 50V DC, 50VAC or capable of providing 50amps are covered by covers with at least 4 fasteners requiring a tool to remove. Main circuit breakers have covered input connections.	Amplifier follows IP-20 ingression protection guidelines. At no place, system has exposed surfaces.	Not Available

EMC compliance	Designed in accordance with CE EMC directives IEC 61326:2010	Qualified and complied IEC61204: p/s stabilized low voltage at CW operation IEC61204-3: Emission and Immunity IEC-61010-1 safety rules for the electric appliances of measurement regulations and laboratory	Not Available
Interface with other systems	Not Available	Hardwired protection, Interface to LLRF, RFPI	Not Available
Vibration and shock (Transport only)	Not Available	Vibration and shock test: IEC60068-2-27 (Shock) General test for robustness, handling and transport for land based items IEC60068-2-64 (Vibration)	Not Available

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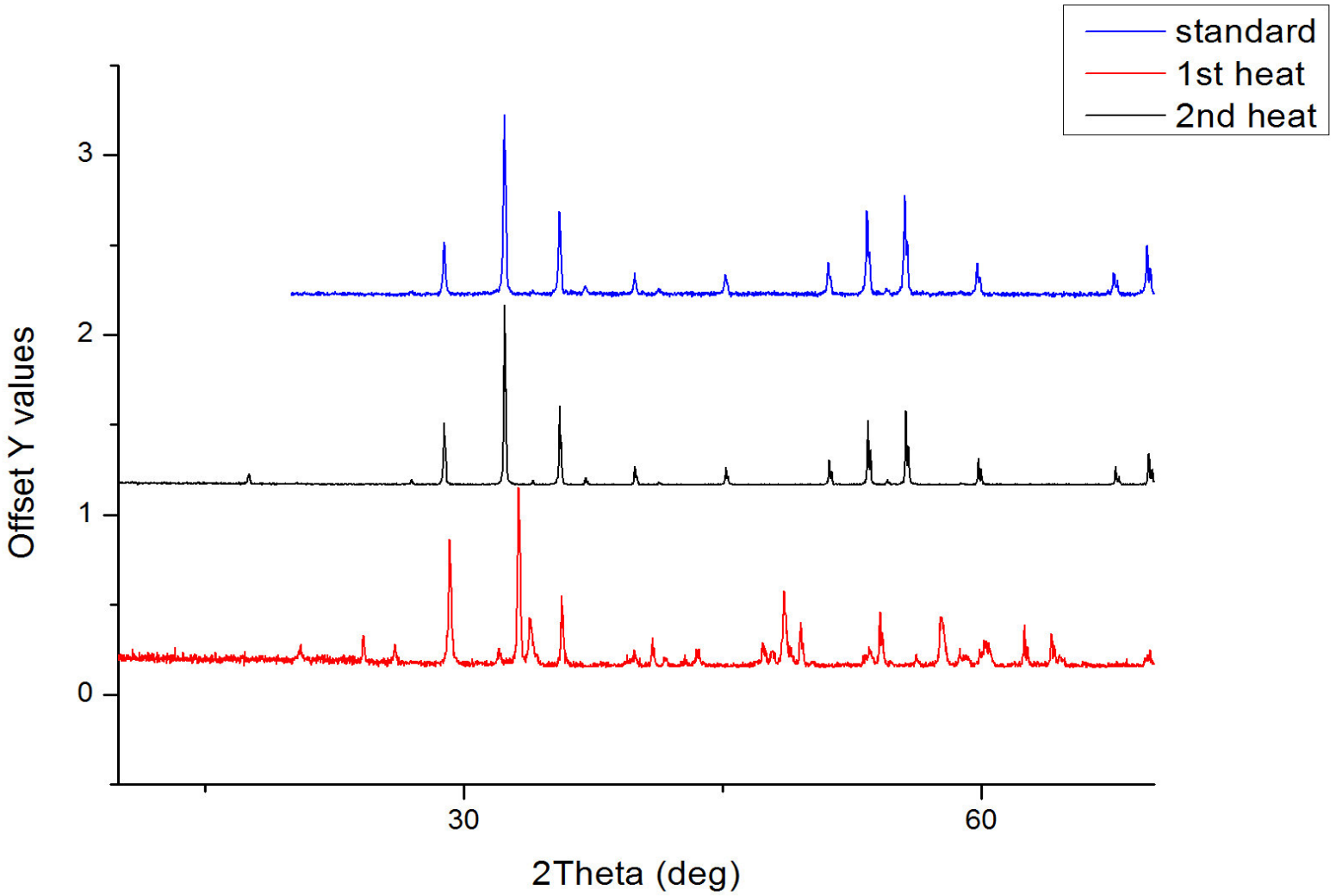
Indigenous RF Technology Development

1. RF Circulator
2. RF components
3. RF devices
4. RF Load
5. RF waveguide and transmission line components (Magic Tee, various bends, dir. Couplers, tapers etc.)
6. RF waveguide window

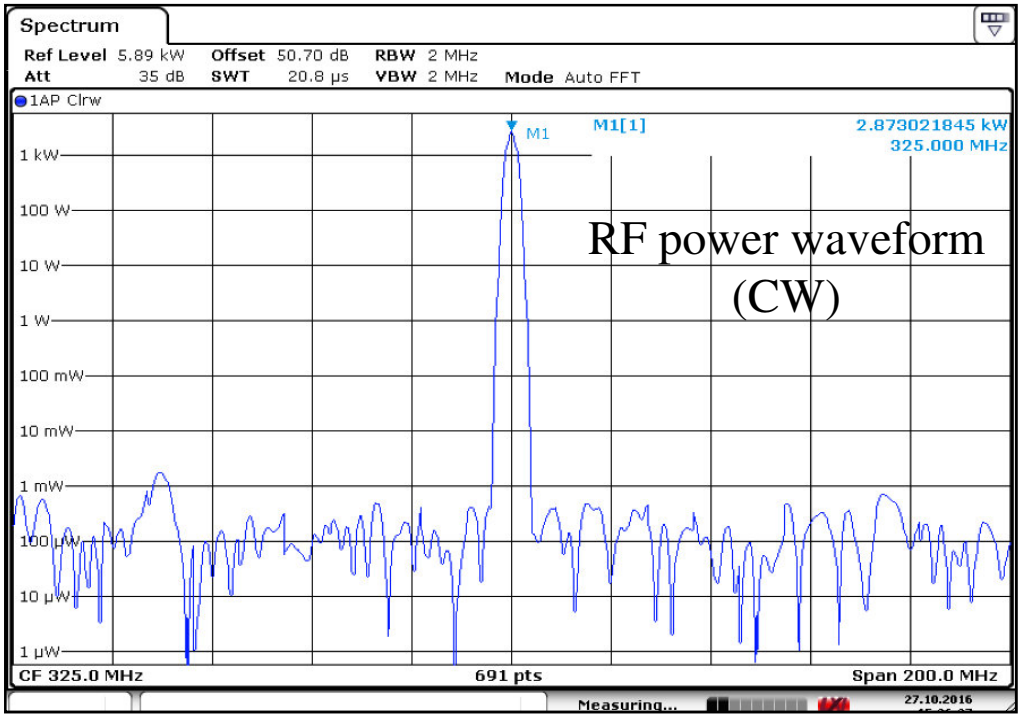
RF Ferrite synthesis and its characterization (XRD)

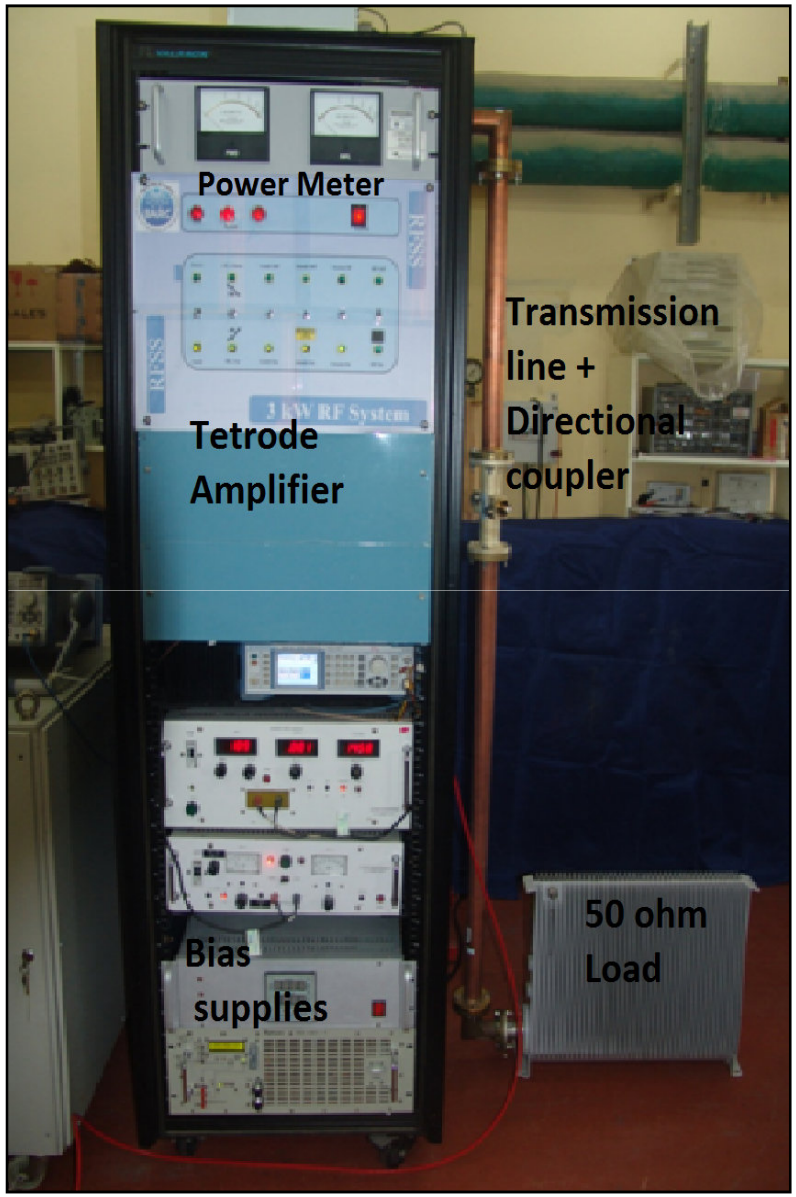


Magnetic Properties of ferrites matches with the requirements

3 kW, 325 MHz RF Amplifier for ring resonator

- RF output power measured using directional coupler and spectrum analyser,
  2.8 kW in CW and pulse mode on RF load
- Transmission line for power transmission and directional couplers for power measurement
- Inclusive of auxiliary electronics for temperature, arc and vacuum measurement





3 KW, 325 MHz Amplifier

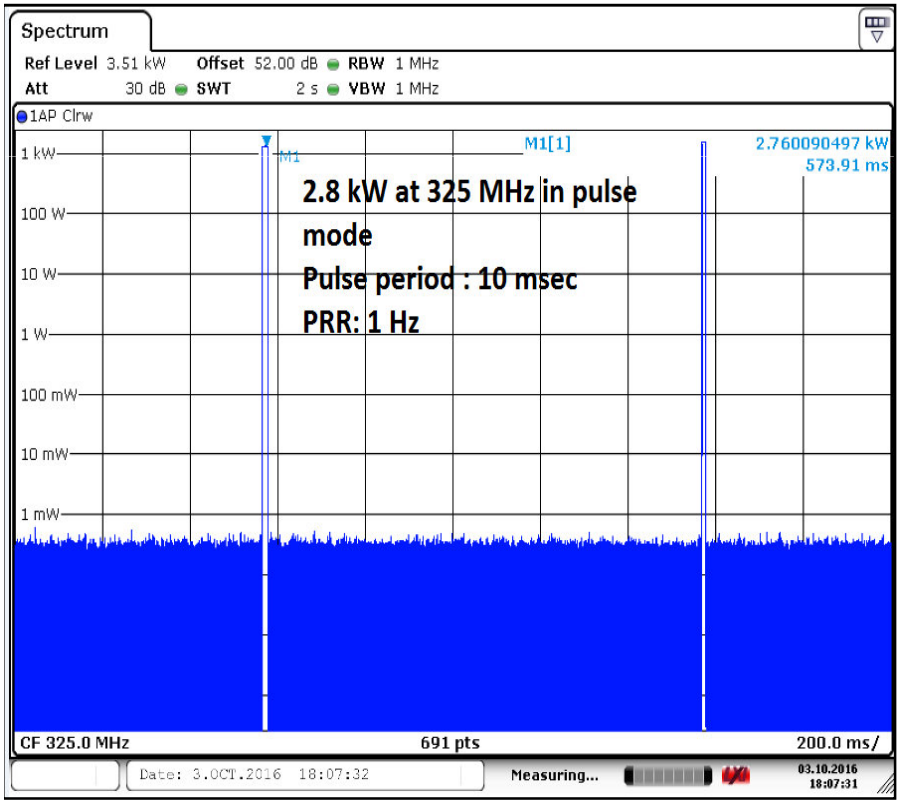
Test Results

2.8 kW RF power (Pulse)

Pulse parameters

Pulse period : 10 mS to 100 mS

PRR: 1 Hz to 10 Hz

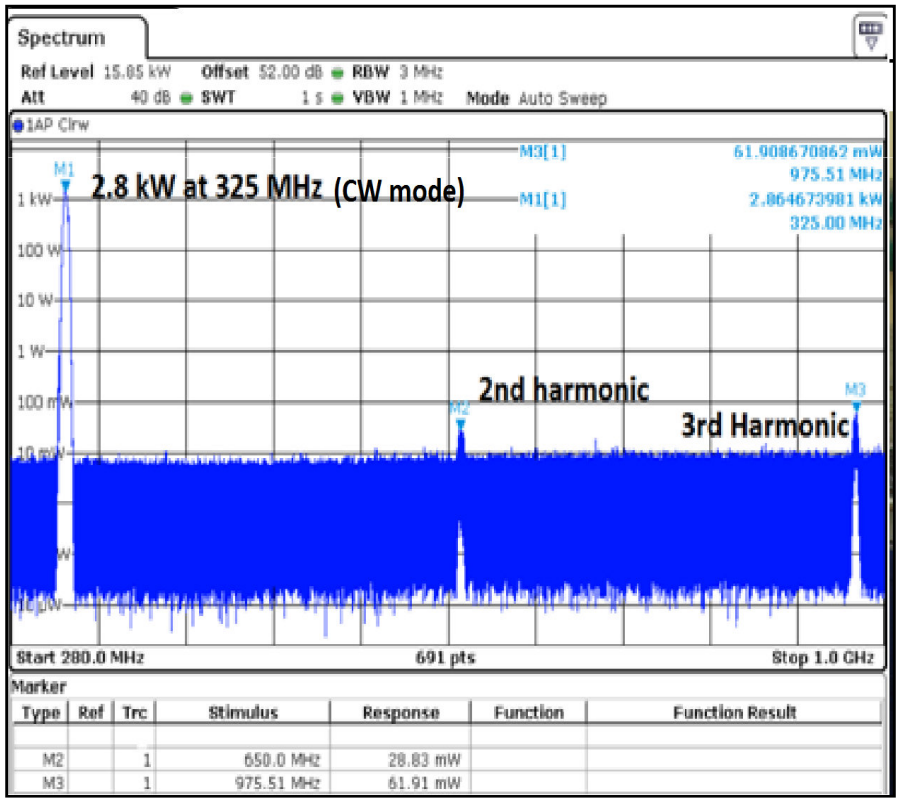


2.8 kW RF power (CW)

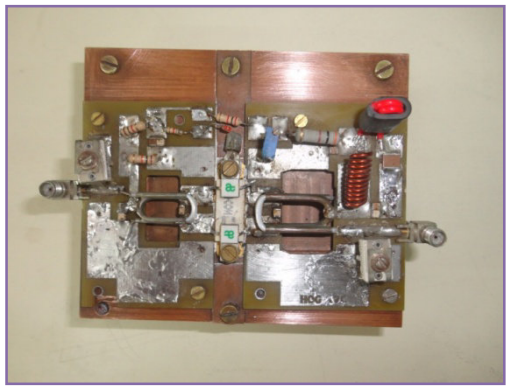
Harmonic measurement in CW mode

2nd harmonic = 30 mW

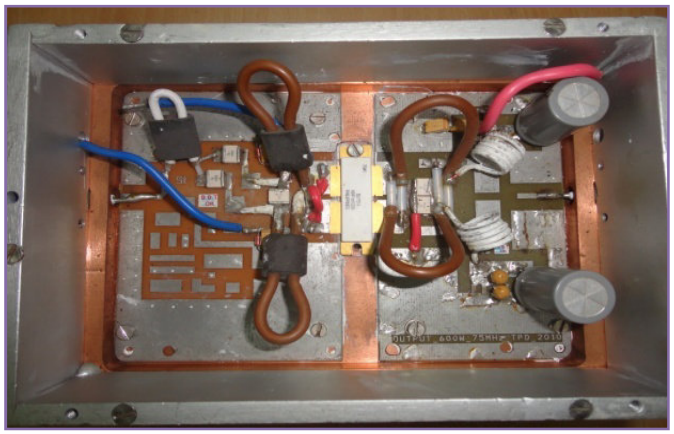
3rd Harmonic = 70 mW



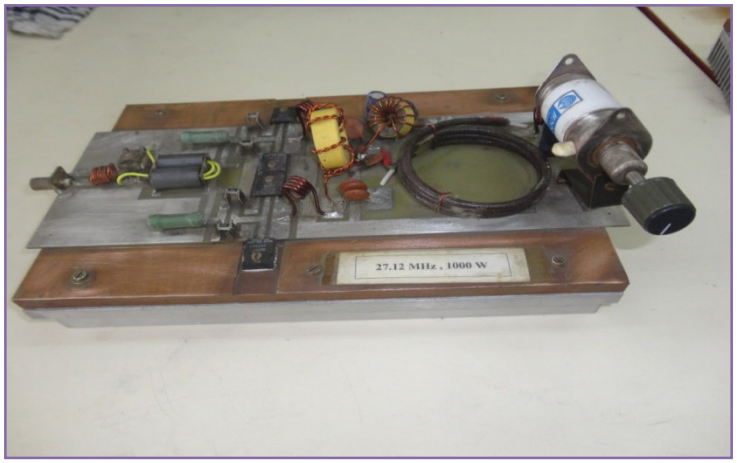
RF system developments @ other frequencies



SSRFPA – 300 W at 100 MHz for RF ion source of 14 MeV ‘n’ generator



SSRFPA 600 W at 75 MHz



SSRFPA -1000 W at 27.12 MHz

RFPA 1 kW at 76 MHz

Thank
You