Development of 325 MHz solid-state RF amplifiers for superconducting spoke resonators of high intensity proton accelerators

A rich legacy of RF power Systems

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Outline

• RF systems
• Accelerators
• Solid State RF Power Systems - - technology development
• Other RF power systems
The Technologies used in accelerator

- Large scale vacuum
- **High power radio waves / microwave sources**
- Normal / Superconducting technology
- Very strong and precise magnets & Beam Instrumentation
- Computer control
- Accelerator physics
- Cryotechnology
Bouquets of high power RF Systems

Ion source of 14 MeV ‘n’ Gen: Solid state RF Source 100 MHz

Proton accelerator: Klystron RF Systems 1 MW, 352 MHz (3 Nos.)

SSR - SC accelerator Solid State RF systems 325 MHz / 1,3,7, 20 kW

RF energy sources

Buncher cavity: ‘p’ accelerator Solid State RF system 352 MHz / 10 kW

Deuterium accelerator: Tetrode RF system 60 kW, 350 MHz

Multi Harmonic Buncher cavity of FOTIA accelerator Solid State RF systems 20,40,60 MHz + multifrequency Tank circuit
Use of RF / Microwave Energy in scientific expts.

- RF Power source: 2 kW @ 27.12 MHz
- Solid State RF amplifiers 20 & 7 kW @ 325 MHz for superconducting accelerator
- RF Deuterium Plasma
  - RF source 250 W @ 100 MHz
- 14 MeV‘n’ generator@Purnima
- LEHIPA / KLYSTRON GALLEREY
- LEHIPA / Waveguides LINAC Gallery
- Positron Spectrometer
- 60 kW, 350 MHz RF for 400 keV RFQ Accelerator
The IADS envisages building a 1 GeV, 10-30 mA, CW superconducting proton linac, with a 325 MHz, 3 MeV RFQ (normal conducting), superconducting single spoke resonators (SSR) accelerating beam from 3-200 MeV, and elliptic (ELL) cavities accelerating beam from 200 MeV to 1 GeV.
RF Power Details for NC & SC Accelerators

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Liquid He Transfer line

NORMAL CONDUCTING SECTION

50 keV, 10 mA, ECR ion source
325 MHz, 3 MeV RFQ

3 MeV

325 MHz Klystron power
325 MHz SSRF power
650 MHz SSRF power

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Advances in solid-state Field Effect Transistor (FET) device manufacturing have enabled use of solid-state amplifiers instead of tube amplifiers at the required power levels, albeit at higher acquisition costs. The solid state RF power amplifiers at 325 MHz will cater to all the three accelerators.
**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 high power RF systems**

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

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Generic High Power RF system of an accelerator

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Solid state RF Power Amplifier

- Signal Generator
- RF Switch
- SSPA Driver
- 1:8 Divider
- 8:1 Combiner
- Interlock and Protection system
- Power Meter
- Power Meter
- 3-1/8” line
- 10 kW RF Load (50 Ohm)
- Water cooling system

DC 50V, 30A (8)

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SSRF Power Modules Developed

- Center Frequency: 20, 40, 60, 100, 350, 352, 325 MHz
- Bandwidth (3 dB): ~10 MHz
- Power output (sat.): 100 W, 300 W, 800 W, 1000 W, 1400 W
- Power Gain: 8.5-22 dB
- Efficiency: 50 - 68%
- Protection: Circulator

300W Amplifier module
800W Amplifier module
1kW Amplifier module

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Power Combiners/Dividers

- 2, 4, 8, 22 way combiners
- Power levels 100 W, 1 kW, 8 kW, 10 kW, 20 kW, 50 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
Contribution under IIFC: Solid State RF amplifiers at 325 MHz

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

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

- **3 kW Amplifier**
  - Power: 3 kW
  - Overall Gain: > 65 dB
  - Efficiency: 65%
  - 2nd Harmonics: - 41.9 dB

- **7 kW Amplifier**
  - Power: 7 kW
  - Overall Gain: > 90 dB
  - Efficiency: 68%
  - 2nd Harmonics: - 41.9 dB
325 MHz, 3 kW Solid State RF Amplifier & its test Results
325 MHz, 7 kW Solid State RF Amplifier Test Results

Display of Calorimetric measurement of RF Power

RF Power Waveform at 7 kW on spectrum analyzer

Sensor data of Calorimetric measurement of RF Power
Revised 325 MHz, 7 kW Solid State RF Amplifier & its Test Results

Solid state RF Amplifier 325 MHz, 7 kW

Harmonics Measurements

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325 MHz, 7 kW Solid State RF Amplifier Test Results

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EMI/EMC qualifications & results of 1 kW RF power modules

EMI/EMC qualification

RE measurements

EMI/EMC qualification & results of 1 kW RF power modules

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<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value/range</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF output (kW), CW and pulse</td>
<td>0 - 7.0 kW Minimum pulse width of 100 microseconds, Maximum pulse width 6 milliseconds, maximum 20 Hz repetition rate</td>
</tr>
<tr>
<td>Centre Frequency (MHz)</td>
<td>325</td>
</tr>
<tr>
<td>1 dB Bandwidth (MHz)</td>
<td>7 MHz</td>
</tr>
<tr>
<td>Power gain (dB)</td>
<td>62-68</td>
</tr>
<tr>
<td>DC to RF Efficiency (at 7 kW)</td>
<td>65%</td>
</tr>
<tr>
<td>AC to RF efficiency</td>
<td>~ 55 %</td>
</tr>
<tr>
<td>1 dB compression power (kW)</td>
<td>&gt;7.0 kW</td>
</tr>
<tr>
<td>All Harmonics (dBc)</td>
<td>&lt;-30 dBc</td>
</tr>
<tr>
<td>Spurious (dBc)</td>
<td>&lt;-60 dBc@ 60 Hz and &lt;-80 dBc @ 100 kHz</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value/range</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>9 Protections against the fault conditions</td>
<td>Over temp, Over drive, Insufficient water flow, Drain over current/voltage, Power supply fail, Overall o/p reflected power</td>
</tr>
<tr>
<td>10 EMC compliance</td>
<td>IEC61204: p/s stabilized low voltage at CW operation</td>
</tr>
<tr>
<td></td>
<td>IEC61204-3: Emission and Immunity</td>
</tr>
<tr>
<td></td>
<td>IEC-61010-1 safety rules for the electric appliances of measurement regulations and laboratory</td>
</tr>
<tr>
<td>11 Vibration and shock test:</td>
<td>IEC60068-2-27 (Shock) General test for robustness, handling and transport for land based items IEC60068-2-64 (Vibration)</td>
</tr>
<tr>
<td>12 Interface with other sub systems</td>
<td>Interface to LLRF, RFPI and overall control system</td>
</tr>
<tr>
<td>13 Electric safety</td>
<td>IP-20 ingression protection guidelines.</td>
</tr>
</tbody>
</table>
325 MHz, 20 kW Solid State RF Amplifier
BARC recently tested another Solid State RF Amplifier 20 kW at 325 MHz. Now if we add / combine such 20 kW units in numbers, scalability in higher RF power e.g. 40 kW, 60 kW etc. ( approx. up to 100 kW+ ) can be achieved by developing high power combiners. This has established capability of BARC in technology development in high power regime in solid state RF amplifier domain.
Solid State RF Amplifier: Path Ahead

- Use of high power RF MOSFETs
- Use of max. efficiency DC supplies
- Reduction in footprint i.e. high density
- Minimize thermal impact
- Minimize internal noise, spurious etc
- Increased automation
- Increase overall efficiency and gain
- Develop around 100 kW CW SSRFPA
Other high power RF Systems
1) 350 MHz, 60 kW RF system coupled to Deuterium RFQ at BARC
2) a) Overall klystron RF system in klystron tunnel of LEHIPA

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2)b) Waveguide distribution system (1 MW) for 3 MeV RFQ / LEHIPA in Linac Tunnel
RF power performance of Klystron RF system
3) SSPA for Buncher cavity of proton accelerator

For the buncher cavity a 10 kW solid state RF amplifier at 352.21 MHz has been developed.
Overhauser sensor is a high-precision weak magnetic field sensor, used for various magnetic geophysical surveys, earth’s magnetic field measurement. It also plays a significant role in geomagnetic observations.

The Overhauser sensor consists of a resonant cavity over which resonant coil made up of silver tracks is wrapped. The excitation of protons is done by resonating the coil by a RF source.

The electronics module comprising of RF oscillator, low power amplifier, signal conditioning circuit, frequency meter etc is a part of Overhauser magnetometer.
5) Development of RF Circulator
Simulated structure of circulator & Ferrite Synthesize

A strip line type circulator has been simulated in CST microwave studio and is shown below. Ferrite synthetisation and development is in process.

An electromagnet is used instead of a permanent magnet because the adjustment of isolation at the operating frequency (325 MHz) may require adjustment of the applied bias field.

Ferrites developed

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6) 3 kW, 325 MHz RF Amplifier for ring resonator

- RF output power 3 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

![RF power waveform (CW)](image)

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7) Designing newer generation Graphene analogous systems having better device applicability – RF switch, arc detector

**Use of TMDC in FET**

(a) MoS$_2$ Drain  
(b) TiO$_2$, MoS$_2$, Drain

(c) Ti-2p and O-1s counts (a.u.)  
(d) Image of fabricated device

Using Graphene Analogous mono/few-layer and their combinatorial heterostructure fabrication of fast RF devices are under development

Courtesy: Dr. Debjani, TPD, BARC

**Use of TMDC in Diode**

(a) PH$_3$+He Plasma

Resist Mask

Phosphorus

n-region, SiO$_2$, p-region

P$^+$ Si (Back Gate)

Using Graphene Analogous mono/few-layer and their combinatorial heterostructure fabrication of fast RF devices are under development

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8) Multi Harmonic Buncher for Folded Tandem Accelerator (FOTIA) :
Multi Frequency RF systems, its Tank Circuit & MHB

Multi Frequency RF system

Tank Circuit

MHB

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Consisting of HV series resistor, Floating filament supply, Isolation transformer, Voltage dividers for voltage measurement, crowbar protection and dump switch
Each individual components insulation was tested up to 120 kV DC continuous
Rack made of Homo polymer and Teflon material
HV outputs are connectorized and whole rack is closed by insulating material. HV part not accessible to air directly.
Bottom part of rack is at Ground potential
High voltage Insulation tested between HV parts and ground. Leakage current < 100 micro amp at 120 kV DC.
Spark gap dump resistors: 5 Ohms
Operating range: 60 kV to 100 kV by changing the N2 gas pressure.

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10) 1 MW RF Load for Klystron of proton accelerator: Indigenous Development

RF Load specs.

1. Power : 1 MW pulse and 800 kW (CW)
2. Waveguide 2300 based RF load
3. Input return loss: < 30 dB
4. Heat absorbing element: 50 Ohm coaxial resistive load (water cooled)
5. Compact in size: approx.: 1.8m x 1.1m x 1.4 m
6. Input power is divided into 10 equal parts using waveguide to coaxial divider structure.
Thank You