

# HIGH POWER RF AMPLIFIER SYSTEMS AND ASSOCIATED TECHNOLOGIES FOR ACCELERATORS

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## *Abstract*

High Power RF amplifier system is an integral part of a particle accelerator required for energizing the Resonating structures. Particles to be accelerated are made to propagate through these resonating structures and RF amplifier system creates required electromagnetic field inside this resonating structure which in turn accelerates the particles to desired energy level and also compensate synchrotron radiation losses. This paper describes various high power RF amplifier systems and associated technologies, developed at RRCAT.

## *Introduction*

Indus Accelerator complex at RRCAT consists of two storage rings; Indus-1 and Indus-2. 700 MeV booster synchrotron serves as common injector for these storage rings. Three major RF systems namely booster RF system, Indus-1 Storage ring RF System and Indus-2 Storage ring RF System have been developed and deployed for these accelerators. Booster and Indus-1 RF system operating at 31.6 MHz were conventional Tetrode tube based system and were being used for more than 10 years. Indus-2 RF system consists of four Klystron based amplifier systems operating at 505.8 MHz with maximum output power of 64 kW each. In Indus-2 storage ring, 100 mA of beam current at 2 GeV has been stored successfully in March 2010 and since then Indus-2 is operating in round the clock shift operation. To achieve final target of 300 mA of stored beam current at 2.5 GeV, additional 80 kW IOT based RF systems are being developed and will be commissioned in near future.

With rapid development in high power Solid state RF devices, Solid state RF power amplifiers (SSPA) have become viable solution of moderate power level required for energizing superconducting resonating structures for various particle accelerator applications. Due to their inherent advantages of graceful degradation, low maintenance, better quality of signal and absence of high voltage points as compared to traditional tube based RF amplifiers, SSPAs of several tens of kW of RF power level are being successfully deployed in many particle accelerator laboratories worldwide. For high power Solid State Amplifiers power combining is a mandatory requirement due to power limitation of individual solid state RF devices so development of power combiner is a critical requirement. Individual Solid state RF devices are now readily available in 1 kW output power range so development of hundreds of kW of SSPA is possible in

near future. Booster RF system has been already replaced by Solid State RF amplifier system and is working satisfactorily and Indus-1 RF system will also be replaced by Solid state RF Amplifier system. It is also proposed to replace Klystron based RF system for Indus-2 with Solid State Amplifiers.

## INDUS-1 RF SYSTEM

Indus-1 is a synchrotron radiation source with 450 MeV Storage ring and a booster synchrotron as injector. Two RF systems at 31.613 MHz have been deployed, one for Booster synchrotron and other for Storage ring required for energizing capacitively loaded re-entrant type RF cavities. Storage ring high power RF amplifier is based on Tetrode Tube CX 15000, whereas Booster High power amplifier has recently been upgraded by replacing Tetrode tube based amplifier by a 1 kW Solid state RF amplifier. Both RF systems have LLRF system that provides required amplitude and phase stability of 1% and 1° and keeps the RF Cavity tuned within the desired range. It also has interlock system that switch off the RF drive to the High power RF amplifier using a fast RF switch in case of any malfunction or parameters going beyond the normal operation range. LLRF system has different operation modes like regular CW operation, pulsed mode with variable Duty cycle, which is used for conditioning the RF Cavity and manual mode which is used for diagnosis and testing the RF system. High power RF amplifiers are protected using Circulator.  $1\frac{5}{8}$  in rigid Co-axial line is used for High power transmission from Amplifier to the RF cavity with components like directional coupler, bends, flexible section installed at appropriate places.

## INDUS-2 RF SYSTEM

Indus-2 RF system [1,2,3] comprises of four bell shaped RF cavities at 505.8 MHz which are being energized by four Klystron based RF amplifiers. These amplifiers are designed with multi-beam, integral cavity klystrons. The multi-beam klystron gives more than 65 % of RF efficiency at gain of 43 dB. The beam voltage requirement is 20 kV, lower compared to single beam klystrons. The operating frequency is 505.8 MHz with bandwidth of 5 MHz. This klystron amplifier requires DC supplies of various ratings for its filament, ion pump and mod-anode all floating at beam supply voltage of 20 kV. It is driven by an indigenously developed 10 watt solid state driver amplifier. A Y-junction 75 kW coaxial

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**RF Transmitters**



**RF Cavities in Indus-2 tunnel**



**LLRF system**



**Klystron and Circulator**



**High voltage DC power supply**



**Supervisory system**

circulator is used to protect the klystron from the reflected power from cavity under changing beam current in the ring. High power 6 1/8" coaxial line is used to transmit RF from klystron to the cavity. The coaxial line components like loop type directional coupler, harmonic filter, water-cooled dummy load, breakaway section, flexible line sections and bends have been developed indigenously. The 6 1/8" coaxial line harmonic filter having 0.1 dB cut-off frequency of 650 MHz is based on 12th order Chebyshev low pass filter topology realized in fin loaded coaxial transmission lines and attenuates harmonic level down to 60dBc. Loop type dual directional couplers have been designed to give coupling factor adjustable between 30 to 50 dB.

Low Level RF control system is responsible for RF cavity field stability, measurement, monitoring, frequency tuning and protection of complete RF chain through a fast interlock system. RF Supervisory Control System is also employed to monitor and log critical parameters that ensures safe and smooth operation of all RF systems and helps in diagnosis of various faults.

## **SOLID STATE RF AMPLIFIERS**

Solid State RF amplifiers are increasingly being used for the RF systems in particle accelerators and are replacing the existing vacuum tube and klystron based systems. These amplifiers improve the reliability, maintainability and availability of the accelerator RF systems. Development of solid state amplifiers operating at the RF frequencies of 352 MHz and 505.8 MHz have been taken up for Proton Accelerator and Indus machines. Design and development of 270W and 300 W of RF Power amplifier modules using MOSFET devices, at 352 MHz and 505.8 MHz respectively, has been completed. Using these building blocks, 2 kW Water cooled CW Solid State RF amplifier at 505.8 MHz has been developed. 1.5 kW Air cooled and 4 kW water cooled CW Solid state RF amplifier at 352 MHz are also developed. A 2kW Pulse Solid state RF amplifier is also developed at 352 MHz. All these RF amplifiers have been tested successfully and are working satisfactorily.



**2 kW 505.8 MHz amplifier**

The 2kW amplifier at 505.8 MHz will be used as a driver amplifier for 80 kW IOT based RF amplifier system for Indus-2. The basic amplifier module of 300 Watt is based on combined RF output of two numbers of 150W RF Power MOSFETs. This 2kW RF amplifier consists of 8 nos. of such 300 Watt amplifier modules which are again power combined by indigenously developed 1 5/8" line 8 way radial Power combiner.

Measured Return loss for this power combiner is better than 30 dB ensuing excellent combining efficiency. For power measurements at various stages in RF chain, a 1 5/8" line and Low power broad band directional couplers are designed, developed and installed in the Amplifier. Measured Directivity of both these directional coupler is better than 30 dB over desired operating range. CRIO based real time control system and data logger is also developed for reliable and safe operation of amplifier.

The 4 kW amplifier at 352 MHz uses water cooled amplifier modules of 270 Watt, based on a Push Pull RF Power MOSFET. 16 amplifier modules have been combined using a 1 5/8" line 16 way radial Power combiner at 352 MHz to achieve the final output power. Return loss for this power combiner is better than 25 dB and also has improved isolation. 1.5 kW amplifier is realized employing 8 air cooled 200Watt RF amplifier modules using 8 Way power combiner.

Based on the experience gained in the development of above mentioned amplifiers, solid state amplifier design for 30 kW 352 MHz and 60 kW 505.8 MHz amplifiers have been initiated. Also work on 30 kW 650 MHz solid state amplifiers for high power testing of SCRF cavities, has been started. Basic RF amplifier module at 650 MHz has been tested up to 200 W and also 16 Way power combiner at 650 MHz has been developed and tested.

A 1kW, 31.6 MHz MOSFET based high power Solid State RF amplifier has been developed, installed and commissioned with the Booster RF system. Output from four modules of more than 250 watt each is combined in two stages with Wilkinson type co-axial cable combiner. Required components like driver amplifier, MOSFET based 250 watt RF amplifier modules; high power co-axial combiner, low power splitter, harmonic filter, sampler and interlock unit were



**4 kW 352 MHz amplifier**



**1 kW 31.6 MHz amplifier**

indigenously developed. This Solid State amplifier has replaced the existing Tetrode Tube based amplifier which had been running for past 10 years. The solid state amplifier system is working satisfactorily and has resulted in reduced downtime and maintenance. Fabrication of 2 kW, 31.6 MHz Solid State RF amplifier for Indus-1 Storage ring is also in progress.

## HIGH VOLTAGE DC BIAS POWER SUPPLY

High voltage DC bias power supplies are required for vacuum Tube based RF amplifiers. These amplifiers demand stringent performances from their bias power supplies like low output DC ripple, lower stored energy, better stability, high efficiency, low input harmonics and better input power factor .

Indus-1 tetrode tube based RF amplifier, employs 7kV/2A power supply which is developed, commissioned and operating satisfactorily for more than 15 years. Similarly, Indus-2 klystron tube based RF amplifier, employs four numbers of 20 kV/5A power supplies [4] which are also commissioned and operating satisfactorily for nearly a decade.



**High voltage DC Power supply for IOT**

For increasing the installed capacity of RF power, IOT based RF amplifiers will be used. For these amplifiers 32 kV solid state modular power supply has been developed indigenously. The adopted scheme neither needs any input line filters for input harmonics and power factor

improvement, nor needs any output filter capacitors for limiting output ripple thereby avoiding expensive crowbar switch to protect high power amplifier tubes. The topology used has flexibility to increase its output voltage by adding additional modules. This power supply has been installed at RRCAT and its performance optimisation is in progress

### LOW LEVEL RF SYSTEM

Low Level RF control (LLRF) system plays a very crucial role in any Accelerator by providing phase and amplitude stable electromagnetic fields in the accelerating structure. LLRF systems for Indus-1 and Indus-2 SRS are built using analog feedback techniques to control the amplitude and phase of accelerating field in the RF Cavities. LLRF system in Indus-2 also provides RF drive signal to each amplifier station and maintains the phase synchronism between all the four stations.

Digital LLRF system gives certain advantages like repeatability, reliability, low long term drifts, flexibility for different operation modes and possibility of implementing complex algorithms compared to conventional analog LLRF systems. In view of above advantages, work on development of Field Programmable Gate Array (FPGA) based digital LLRF system has been initiated. This system is being developed for CW/pulsed RF systems and for normal conducting as well as superconducting cavities. Simulation of Digital LLRF system and RF Cavity is being done and a FPGA based prototype digital feedback control system with I/Q detection scheme has been tested.

### RIGID LINE RF COMPONENTS

Coaxial line components like directional couplers RF bends, high power RF loads have been developed and are in use for Indus RF systems. 30kW, 80kW, 200kW RF



**30kW, 80kW and 200kW RF Dummy Loads**

loads have been fabricated and tested to achieve VSWR better than 1.1 up to 750MHz. A 1 MW RF load with

VSWR better than 1.06 at 352MHz has been designed using ten 200kW RF loads with a WR2300 based power divider. Waveguide components based on WR2300 in the frequency range of 320-490MHz are being developed indigenously using four corner spray arc argon welding process in precision fixture to ensure dimensional accuracies within  $\pm 0.5\text{mm}$  and mechanical rigidity for optimum RF performance. A 150kW, 505MHz high power coupler is under advance stage of fabrication. Successful development of this coupler will enable us to take up the development of high power couplers operating at different frequencies and power levels.

### 1.1 MW CW RF SYSTEM

Design and development of 1.1 MW CW/PULSE RF system at 352 MHz is under progress at RFSD, RRCAT as infrastructure test facility to characterize various high power RF components required for particle accelerators. This system consist of 1.1 MW CW klystron, WR2300 based high power circulator and 100kV/20A DC Power supply.

### SUMMARY

At RRCAT various RF systems have been operating satisfactorily. Most of the technologies required for these high power RF amplifier systems have been developed indigenously. Based on the experience gained over the years, upgradation of the existing RF systems is being carried out with modern technologies. Development of tens of kW of Solid State RF amplifier system is under progress. Various technologies like Digital LLRF system, Solid state High voltage DC power supply and waveguide based rigid line components required for future high power RF systems is also in advanced stage of development.

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