T.1: Development and deployment of solid state RF amplifiers for Indus SRS facility

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Indus Accelerator complex at RRCAT consists of two synchrotron radiation sources (SRS);450 MeV Indus-1 and 2.5 GeV Indus-2. The 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 cavities operating at 31.6 MHz are now using in-house developed solid state amplifiers of 1 kW and 2 kW RF power ratings respectively which were earlier energized by Tetrode tube based amplifiers. Both RF systems for Indus-1 and Booster synchrotron have Low Level RF(LLRF) control 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 cuts 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.

Indus-2 RF system employs four bell shaped RF cavities operating at 505.8 MHz. Two of these cavities are energized by Klystron RF amplifiers and the remaining two are energized using in-house developed high power solid state amplifiers. 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 was operating in round the clock shift operation. In Dec 2011, 100mA stored current was achieved at designed energy of 2.5 GeV with the support of indigenously developed solid state amplifiers as an alternative to imported klystrons. High power 6 1/8" coaxial line is used to transmit power from high power RF amplifier 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. LLRF control system is used for RF cavity field control, 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.

Recent advances in transistor technology are making solid-state RF amplifiers an increasingly viable alternative to tube systems in accelerator applications. Also the solid state high power amplifiers offer many advantages like extreme modularity, high reliability, graceful degradation, no high voltage and vacuum requirement, and low maintenance. However they are not commercially available in high power. Difficulties were faced in getting the klystrons for Indus-2. In view of the above, RRCAT has taken up an R&D programme on technology development of solid state amplifiers for accelerators. Development and deployment of solid state RF amplifiers operating at 505.8 MHz for Indus-2 and 31.6 MHz amplifiers for Booster synchrotron and Indus-1 has been accomplished for Indus synchrotron Radiation sources.

Development of Solid State RF amplifiers for Indus-2

Solid State Amplifiers with RF output of 100 kW operating at 505.8 MHz have been developed and successfully deployed in Indus-2 Synchrotron Radiation Source to achieve beam current of 100 mA at 2.5 GeV energy for the first time.

Fig. T.1.1: High power Klystron and cavity based RF system in Indus-2 SRS

Indus-2 RF power system was built employing four 60 kW imported multi-beam klystrons, making up total installed capacity of 240 kW of RF power at 505.8 MHz (Fig. T.1.1.). As the replacement of the aged klystrons from foreign sources was uncertain due to export control conditions, indigenous development of solid state high power amplifier was taken up as a substitute for these Klystrons.

The high power solid state amplifiers were developed from the scratch and two failed klystrons were replaced with 100 kW of indigenously developed solid state amplifiers. With the crucial support of these amplifiers, Indus-2 beam energy could be increased up to 2.5 GeV at 100 mA. Such RF amplifiers operating at frequency above 500 MHz have been developed and deployed in synchrotron radiation sources (SRS) for the first time in the world. Such high RF power is obtained using modular combination of several 13 kW amplifier units operating at 505.8 MHz. The RF power of 13 kW is obtained by paralleling the modest RF power from many numbers of basic power modules with the help of suitable power combiners. The basic module was designed after detailed simulation studies to match the input and output impedances of the RF transistors (MOSFETs). Considerable R&D effort was put-in to ensure phase and amplitude matching between large number of amplifier modules. The novel 16-way combiners, directional couplers, RF loads and 2-way high power combiners used in these amplifiers have been also developed in-house. This technology development is very important for achieving self reliance in strategic area of RF power and will be greatly useful for building proton linacs for large scale projects like Spallation Neutron Source (SNS) and Accelerator Driven Systems (ADS) applications.

Solid State RF Amplifier

As described above, Indus-2 RF power system was in operation with four multi-beam klystron amplifiers. Since these klystrons are imported and strategic items, difficulties are encountered to get their replacement because of import control conditions. Nowadays RF transistors, in the frequency range of few MHz to GHz and delivering continuous as well pulse power of the order of 300 W to 1 kW are available. The solid state high RF power amplifiers offer many advantages like extreme modularity, high reliability, graceful degradation, no voltage requirement, and low maintenance as compared to tube devices. Also increasing use of solid state amplifiers is continually contributing towards improvement in performance and reduction in cost. In view of many advantages of Solid State Power Amplifiers (SSPA) development of high power solid state RF amplifiers was taken up for replacement of klystron based amplifiers. For this work necessary efforts were directed towards design studies, amplifier architecture selection, component selection and RF characterization.

Under this technology development program, high power is realized by using scalable and modular combination (Fig. T.1.2) of 13 kW amplifier units operating at 505.8 MHz. RF power from two such 13 kW amplifier units have been combined in a two-way 40 kW combiner to obtain 25 kW of RF power. Again two such 25 kW amplifiers were combined to get 50 kW of output power using two-way 65 kW high power combiner.

Due to moderate power of solid state RF devices, 13 kW solid state amplifier (Fig. T.1.3) was designed as basic high power unit which can be used as building block to realize very high power. It employs 32 Power Amplifier (PA) modules, each one operating at 500 watts.As shown in Fig. T.1.4, RF power from 16 power amplifier modules is combined in a 16-way radial combiner to get 6.5 kW of output power. Power from two such identical sections is again combined in a two-way combiner to get 13 kW of RF output power.

A low power 1 kW directional coupler is inserted between output of each PA and input of 16-way combiner for monitoring forward and reflected power from each PA module. Each 500 W PA module is individually powered by a compact switched mode power supply (SMPS) capable of delivering 20 A at 50 V DC with 3 phase AC input. A 20 kW directional coupler is used for measurement of RF power from the 13 kW unit. A graphical code developed in-house using LabView™ RT software is used for data acquisition and providing control and interlock functions for the13 kW amplifier unit.

50 kW solid state amplifier described above employs 500 W basic power amplifier modules, 16-port radial power divider and combiner, 2-port high power combiners and directional couplers. All of these RF components, forming basic building blocks of 50 kW amplifiers, were designed and fabricated successfully using in-house facilities. Description of these components is given below.

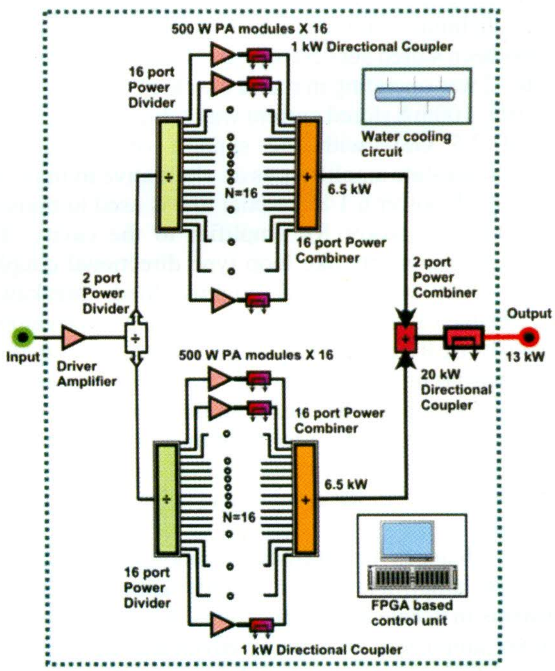

Fig T.1.2: 13 kW solid-state RF amplifier scheme

Fig. T.1.3: 13 kW solid-state RF amplifier developed unit

500 W Power Amplifier module

The heart of the 13 kW solid state power amplifier unit is 500 W RF amplifier module. The LDMOS RF device type BLF 573 was selected for building the basic RF power module based on load-line matching, power match and impedance matching design considerations. Specifications of this power module built using BLF 573 RF devices are given in Table T.1.1.

Table T.1.: Specification of 500 W RF power amplifier modules

Sr.	Parameter	Value
1.	Rated RF Power Output	500 W
2.	Power Gain	18 dB
3.	Operating frequency and 1 dB Bandwidth	505.8 MHz, ± 5 MHz
4.	Efficiency	60%
5.	Protection	VSWR, over temperature, overdrive
6.	Harmonic Distortion	-30 dBc
7.	Cooling	Water cooled

The output power of 500 W was obtained by combining power from two RF transistors using on board Wilkinson combiner. The amplifier is designed to operate in class AB mode. In order to match gate and drain side impedances having real parts less than 2 Ω, to system impedance of 50 Ω, coaxial transformers were selected as basic impedance matching unit in addition to L section of lumped capacitors and micro strip line. Group of five such modules was mounted on a water cooled copper heat-sink measuring 45 x 25 cm^2. The inner view of one of the modules depicting all the components is shown in Fig. T.1.4. A 500 W circulator, placed before final output, protects the RF devices from reflected power. Measured performance of this module is in good agreement with calculated values (Fig. T.1.5).

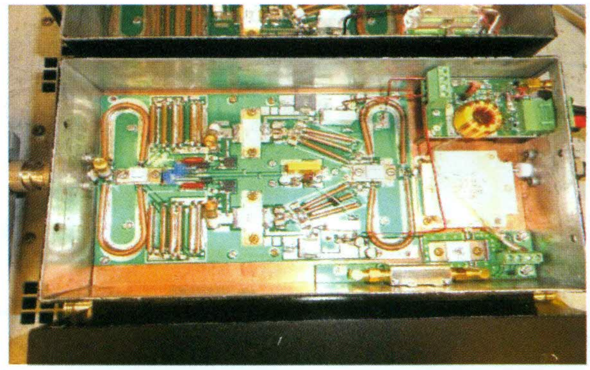

Fig. T.1.4: Power amplifier module

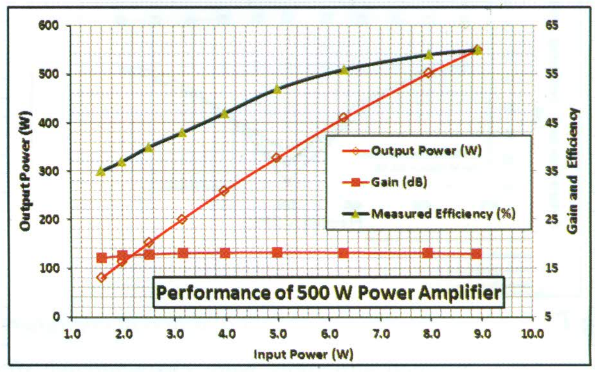

Fig. T.1.5: Measured performance of 500 W amplifier module

Rigid coaxial line components

Power dividers and combiners

Since the power available from the basic RF module is modest, coaxial RF combiners are required to obtain higher power by combining power from several basic RF power modules. In our scheme a novel lossless 16 port radial Power combiner is used to combine power from 16 basic RF amplifier modules to achieve output power of 6.5 kW. It has 16 input coaxial ports symmetrically spaced along the circumference of a parallel rigid slab type radial line with output power extracted from centre, suitably matched to system impedance. Being a reciprocal device, same structure acts as power divider with role of feed ports and branch ports reversed. For combining N sources, radial power combiners offer a superior approach with efficient, reliable and high power output in a compact housing. Full wave analysis of 16-way radial combiner/divider is carried out in 3D EM structure simulator for accurate prediction for operating parameters and optimization of Electromagnetic structure. The measured performance of 16-way combiner/divider is shown in Fig. T.1.7.

Two-port combiners are being used to combine RF power at higher power levels. These combiners have a junction of rigid coaxial lines suitably matched at combined port. Three such combiners of different power rating namely 20kW, 40kW and 65 kW have been designed and developed. These high power combiners are shown in Fig. T.1.6

Fig.T.1.6:16-port power combiner (left) and 2-port combiners (right)

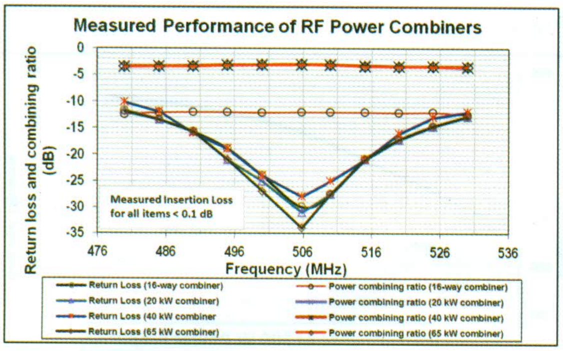

Fig.T.1.7: Coupling and return loss of different combiners

All these designed structures were characterized after rigorous RF measurements. Insertion loss for 16-port combiner is less than 0.1 dB corresponding to combining efficiency of 98%. Imbalance in transmission coefficient from one branch port to another branch port is less than 0.2 dB in amplitude and nearly 2° in phase ensuring excellent design symmetry..

Directional couplers

Directional couplers are required for measurement of forward and reflected power at different stages of the high power RF amplifier. For present application directional couplers with maximum operating power of 1 kW, 20 kW and 65 kW were designed fabricated and tested. Basic structure of these couplers is coaxial type having rectangular cross section with different sizes for different power levels. Aperture coupled section approach is used providing wide operating bandwidth of 300-700 MHz. Two such directional couplers are shown in the Fig. T.1.8.

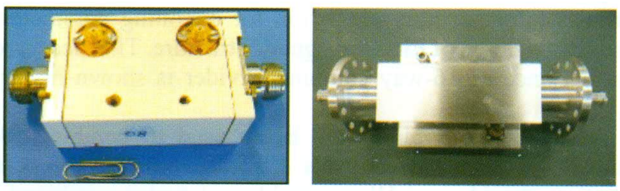

Fig. T.1.8: 1 kW and 20 kW directional couplers

Measured insertion loss for all of these couplers is less than 0.05 dB while return loss is better than 28 dB at centre frequency of 505.8 MHz. Measurement results show very good agreement with the design specifications and electromagnetic simulations. Results are shown in Table T.1.2.

Table T.1.2: Measured parameters of directional couplers

Directional Coupler type	Measured Coupling	Calculated directivity	Measured Directivity
1 kW	40.0 dB	30 dB	29 dB
20 kW	49.3 dB	28 dB	27 dB
65 kW	47 dB	28 dB	27 dB

50 kW Amplifier

Power from four 13 kW high power units is combined using suitable two-way high power combiners and rigid coaxial lines to achieve 50 kW of output power. By using variable amplitude and phase at the input of each 13 kW unit, phase balancing is done to get maximum output power and combining efficiency. At the output of the 50 kW amplifier a high power directional couplers is used to measure the forward and reflected power and Y-junction circulator is used to protect the amplifier from the reflected power. The protection and interlock system is implemented using FPGA based control system.

High power characterization using RF dummy load was carried out. Measurements of output power, gain and efficiency are performed for 50 kW amplifier and results are shown in Fig. T.1.10. Average gain of 50 kW SSPA is 88 dB while 1-dB gain compression point is beyond RF output power of 52 kW.

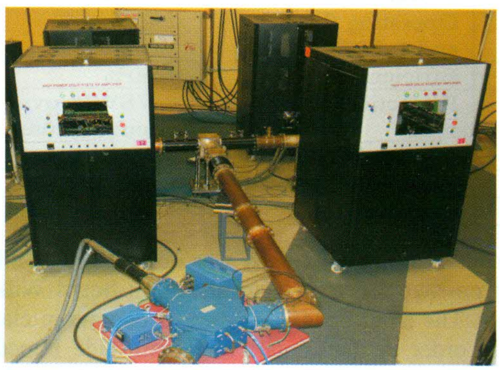

Fig.T.1.9: 50 kW solid state RF amplifier

An RF field intensity measurement was carried out close to the modules and RF leakage was found 0.1 mW/cm^2. At a distance of 1 m from the cabinet RF leakage was found up to 0.02 mW/cm^2, much lower than the permitted (1.7 mW/cm2 at 505.8 MHz).

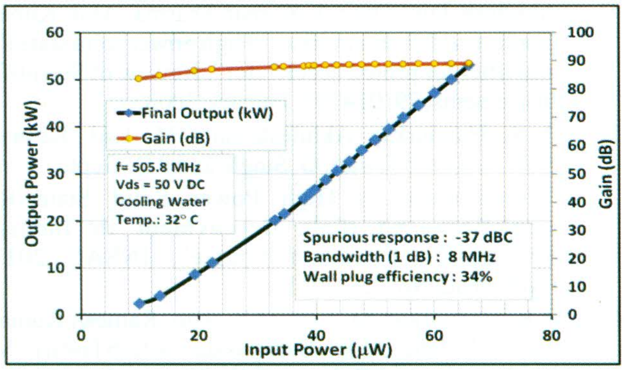

Fig.T.1.10: Measured power transfer characteristics of 50 kW SSPA at 505.8 MHz

Commissioning with Indus-2

Two 50 kW amplifiers were developed and coupled to RF cavity # 1 and # 3 using the existing 6-1/8" co-axial transmission line and high power circulator. High power directional coupler was incorporated in the transmission line for monitoring of forward and reflected power fed to the cavity. In situ calibration of the directional coupler was performed using standard RF test instruments. With the support of these amplifiers, Indus-2 beam energy could be increased up to 2.5 GeV at 100 mA.

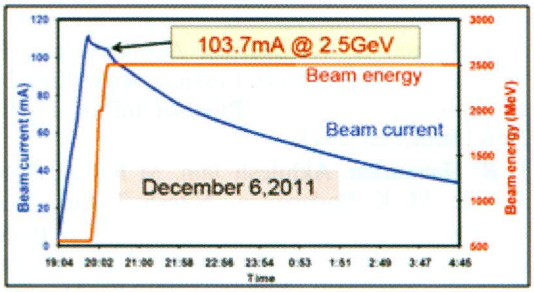

Fig.T.1.11: Indus-2 operation at 2.5 GeV 100 mA

Development at 31.6 MHz for Booster Synchrotron and Indus-1

The high power RF amplifiers of Booster Synchrotron and Indus1 RF Systems at 31.6 MHz were earlier designed using vacuum tube devices. Due to non availability of Vacuum tetrode tubes from M/S BEL India, development of solid state RF amplifiers at 31.6 MHz was taken up. 1kW Solid State RF Power amplifier for 550 MeV Booster Synchrotron and 2 kW Solid State RF Power amplifier for 450 MeV Indus-1 storage ring were developed, tested and commissioned. The deployment of solid state RF power amplifiers has resulted in improved performance with elimination of the high voltage problems, higher efficiency and less maintenance.

In Booster RF System 800 watts RF power at 31.6 MHz is required for 10 mA beam power and generating 20 kV accelerating gap voltage in RF cavity. Similarly in Indus1 RF System 1400 watts RF power at 31.6 MHz is required for 150 mA stored beam current with 22 kV accelerating gap voltage in the RF cavity. Hence, 1 kW Solid State RF Power amplifier for Booster RF system and 2 kW Solid State RF Power amplifier for Indus1 RF system were designed. The basic building block in both the amplifier systems is MRF 141 G MOSFET based 300 watts RF power module. Output of four and eight such modules is combined together using Wilkinson type power combiner to get 1 kW and 2 kW RF power respectively for Booster synchrotron and Indus-1 SRS. At low frequency of 31.6 MHz circulators are not easily available for protection of individual modules. Hence, high power combiners are designed to absorb the reflected power coming from mismatched load and protect the amplifier modules. All the components like Pre-driver amplifier, Driver amplifier, Lumped power splitters , RF filters, Lumped power combiners and a 4:1 Coaxial line high power combinerused in these amplifiers, were developed in-house. These components were tested, characterized and assembled in 19" sub racks along with RF interlock unit. The installation of the 1 kW solid state RF amplifier system in Booster Synchrotron ring was accomplished in March 2010 and 2 kW Solid State RF Power amplifier for Indus1 RF system in March 2012. Since their inception both the systems are running successfully with better performance and having less down time.

Schematic diagram of 31.6 MHz 2 kW RF power amplifier is shown in Fig. T.1.12. Low Level RF input signal is amplified by different stages of driver amplifiers. The output from the driver amplifier is split using lumped power splitter in stages to provide input drive signal for eight RF power modules. Output power from eight 300 watts amplifier modules is combined using two port lumped power combiner and four port coaxial high power combiner.

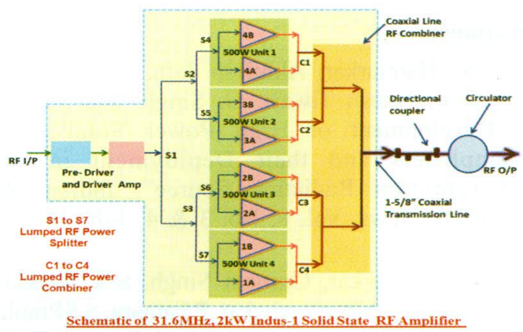

Fig. T.1.12: 31.6 MHz amplifier Schematic

Amplitude and phase matching of all RF power modules is done to improve the combining efficiency. Interlock unit is also developed for the protection of the high power solid state RF amplifier along with the other subsystems of the Indus-1 RF system. The RF amplifier modules and combiners are water cooled to have efficient cooling and hence higher output power. This will also increase the life of the amplifier by reducing failure rate of the MOSFET devices. Proper shielding was done to ensure radiation safety and RF radiation measurements were done at different stages of the development and installation of the RF amplifier.

Fig. T.1.13: Solid state RF amplifier installed in Indus-1 hall

2 kW solid state RF amplifier (Fig. T.1.13) was installed with Indus-1 RF system in March 2012, since then Indus-1 is being regularly operated at 450 MeV/120 mA with this amplifier in round the clock shift operation. Installation and commissioning of solid state RF amplifier for Indus-1 has improved the RF system performance and resulted in reduction of noise level in Indus-1 experimental hall.

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