T.2 RF system for Indus-2

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Indus-2, 2.5 GeV, 300 mA synchrotron radiation source (SRS), is fully assembled and ready for trial injection. RF System, which is important and crucial for operation of SRS, has been developed indigenously. It has to serve two purposes, namely, to compensate energy losses suffered by the circulating electrons through bending magnets and insertion devices due to synchrotron radiation and to boost the electron injection energy from ~550 MeV to 2.5 GeV. The system has been designed to generate an accelerating voltage of 1.5 MV at 505.812 MHz that gives sufficiently high quantum and Touschek lifetime.

Introduction

The system employs four normal conducting cavities each fed independently by 64 kW RF source that is built using multibeam klystron. RF power from the klystron is transmitted to the cavity through 6 1/8'' co-axial transmission line. Lab-View based supervisory system has been used for monitoring various parameters of the RF sub-systems. It has been designed to facilitate detection of any component malfunctioning before it fails, reducing system downtime. Indigenously developed synthesized signal generator provides synchronized RF drive signals for Indus-2 as well as for booster synchrotron. All the RF stations have been operated upto 30kW power level, feeding RF power to cavities and qualifying all the associated subsystems. Required amplitude stability of (1%) and phase stability (0.5°) of cavity voltage against variation in different parameters of klystron amplifier and high voltage power supply, has been achieved. Modular design approach is followed to have flexibility during operation. Each RF module comprises of a 64 kW klystron amplifier, 20 kV cathode bias power supply, 10 W solid-state driver amplifier, low level RF control loops and supervisory system. These sub-systems are described below.

RF cavity

Four number of Bell shaped copper cavities have been installed at S-8 straight section of Indus-2 ring. The use of 505 MHz RF System has resulted in the smaller cavity size**,** which implies less number of higher order modes (HOMs) for the beam pipe diameter of 100 mm. The cavities have been provided with two independent mechanisms to tune away the HOMs. One mechanism is the precision temperature control system and another, the Higher Order Mode Frequency Shifter (HOMFS). A precision temperature control system allows setting the temperature of individual cavities anywhere from 35 to 85 °C within ±0.05°C of the set value. A combination of HOMFS and temperature control system is used to cure the coupled bunch instabilities (CBI) in the machine. The resonant frequencies, loaded and unloaded Q factors for all RF cavities have been tested for their fundamental and HOM characteristics. Longitudinal and transverse coupling impedances were measured for most of the HOMs. There are eight monopole and 21 dipole modes below beam pipe cutoff frequencies. The measured shift in resonant frequencies of fundamental and HOMs as a function of cavity temperature on cavity is shown in fig. T.2.1. The cavities have been baked for several hours using pressurized water at 150 °C. Vacuum of $1x10^{-9}$ Torr has been achieved. RF conditioning carried out by operating the amplifiers both in pulsed and continuous mode.

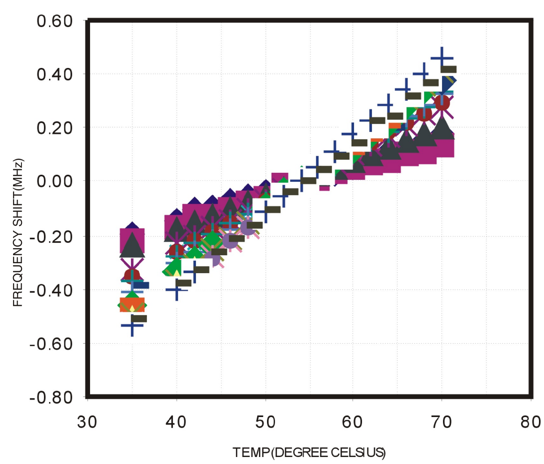

Fig. T.2.1 *Frequency shift- monopole modes*

RF transmitter

The RF amplifiers (fig. T.2.2) are based on 64 kW multi-beam, integral-cavity type klystrons KY-400. The auxiliary power supplies for its filament, ion pump and modulating-anode are floating at beam supply voltage of 20 kV. The current and voltage signals floating at beam voltage are monitored through optical fiber interface. The RF power transmission system is realized using $6^1/_8$" EIA lines and coaxial-line components, which operate at normal atmospheric pressure. The transmission line gives maximum VSWR of 1.07 and insertion loss less than 0.4dB at the

Fig. T.2.2 *505.8 MHz RF Transmitters*

operating frequency. At one end, the transmission line system connects the cavity located in the Indus-2 ring and at other end it connects to the klystron placed in the RF equipment area. The transmission line layout is realized by using 90º and 45º bends, keeping the length of line minimum. 50dB loop type dual directional coupler is incorporated at the output of the klystron to facilitate through-line measurement of forward and reflected power. Disc-loaded coaxial line harmonic filter has been incorporated in the line to reduce the harmonic and non-harmonic component in the klystron output below –60dBc. A $6^{1}/_{8}$" coaxial flexible line section has been inserted between the directional coupler and the klystron output window to take care of thermal expansion in the line. A breakaway line section has been realized using $6^{1}/_{8}$" coaxial line, which facilitates assembly of transmission line components. Y-junction temperature compensated coaxial circulator has been used to protect the klystron from reflected power from cavity. It provides insertion loss less than 0.1dB and isolation of 25dB at 505.8MHz. The circulator is terminated at port-3 with 80 kW coaxial water load to absorb the reflected power from the cavity.

Transmission line components

Various transmission line components have been indigenously developed. They are described below:

(a) Dual directional coupler : Loop type dual directional coupler is developed for measurement of forward and reflected RF power. It is designed to give adjustable coupling factor of 30-50 dB with isolation of 30 dB (fig. T.2.3).

(b) Harmonic filter: The Klystron output has harmonic distortion of about -35 dBc. It is desired to have harmonic and non-harmonic distortion less than -60 dBc. In order to get distortion less than -60 dBc, a low pass filter is developed in the form of disc-loaded $6^{1}/_{8}$" line. It has 0.1 dB-band-edge frequency of 650MHz and insertion-loss less than 0.05 dB.

(c) Coaxial line bend: For desired optimum placement of the transmission line system, 90º and 45º bends have been used, at various locations of transmission system. These bends show VSWR better than 1.05. The center conductor of these coaxial bends is mitered at its corner to required depth, for minimizing the effect of the discontinuity and achieving insertion loss less than 0.05 dB (fig. T.2.4). These joints are optimized using HFSS software.

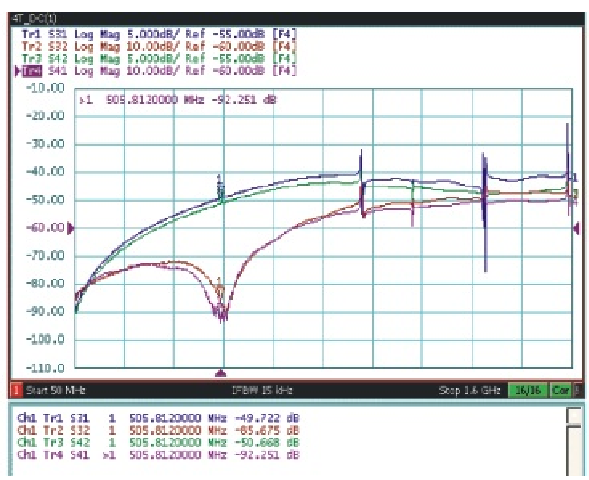

Fig. T.2.3 *Directional Coupler Test Results*

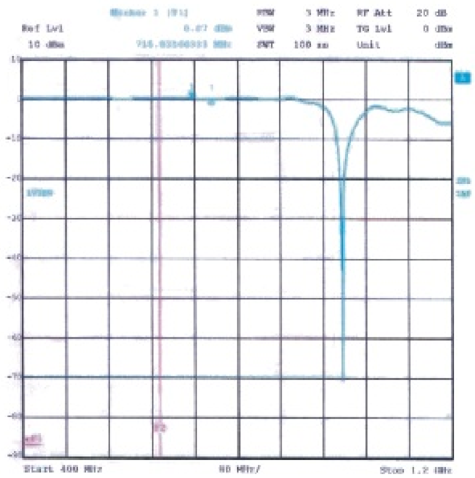

Fig. T.2.4 *Insertion loss of 90º bend*

(d) 80 kW coaxial load: As RF system has to operate in a narrow bandwidth centered at 505.812MHz, a narrow band load is developed. It provides matching of –30 dB at the operating frequency with reasonably good bandwidth of ± 5 MHz. This load is realized by employing lossy coaxial lines, in which a thick film tubular 50ΩDC resistor of 2 feet length and 1" diameter is used as center conductor. The outer conductor is made of Aluminium. The heat generated by dissipation of RF power in tubular resistor is removed by de-mineralized water flowing over the resistor element. A Teflon tube concentric to the resistor element is located between the resistor and the outer conductor to confine the cooling water flow between resistive element and the Teflon tube. The measured VSWR is 1.04 in frequency band of 505.8 ± 5 MHz (fig.T.2.5). These loads have been tested upto 60 kW RF power and performance was satisfactory.

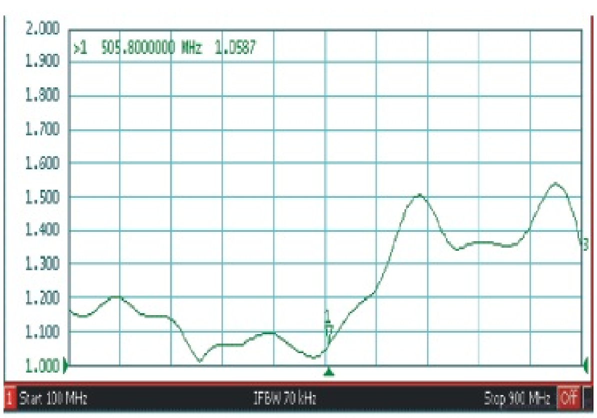

Fig. T.2.5 *Frequency response of the coaxial load*

(e) Break-away line section: Breakaway sections are provided to facilitate assembly of rigid coaxial line components between cavity and klystron tube. In this design a coaxial line is sliding over another fixed coaxial line, both separated by thin layer of PTFE. This arrangement forms a low impedance line of $\lambda/4$ length open at one end and providing virtual short at sliding end. This sliding contact is further equipped with a physical short made of Cu-Be finger contact to improve the RF shielding. Insertion loss of this line is less than 0.04 dB at operating frequency.

20 kV Klystron bias power supply

There are four numbers of 20 kV, 5.5 Amp high voltage DC power supplies that provide cathode bias to klystron amplifiers. To cater to the widely varying input conditions, these power supplies are controlled through six SCRs in three phase-AC regulator schemes. Different primary control schemes were analyzed and the main transformer configuration, having either delta connected primary or star connected primary without neutral, were chosen. A three phase linear inductor is kept at the primary side of each power supply unit to reduce the fault current level, higher order harmonics. The fault current in primary side is limited to about three times with this limiting inductor, which otherwise would have gone up to seventeen times. This inductor also limits the temperature at any point of the main transformer windings well within its hotspot limit, under fault conditions. Suitable L-C ripple filter is incorporated in each power supply to keep the output ripple within the desired limit. Turns ratio of main transformer windings are decided to take care of possible input mains variations. As the starting load to the A-C Regulator is inductive, a resistive bleeder network is put just at the output terminals of AC regulator, which allows SCRs to catch their latching currents. Phase control IC UAA-145 is used for firing SCRs at appropriate instant and allowing automatic voltage control. Various protection circuits like over voltage circuit, over current circuit, klystron shunt trip, phase failure/reversal circuit, spark control circuit, transformer oil top, bottom float (level), SCR temperature high and oil temperature high etc, are incorporated.

Four numbers of line harmonic filters are employed, one for each supply unit, to keep the input power factor near unity and the line harmonics within the limit as specified by IEEE Standard-519, 1992. The filter components are tuned to 228 Hz, to avoid parallel resonance with the source. Several protection features like over load, reactor core temperature high etc. are incorporated to disconnect these filter bunches, in case of resonance conditions.

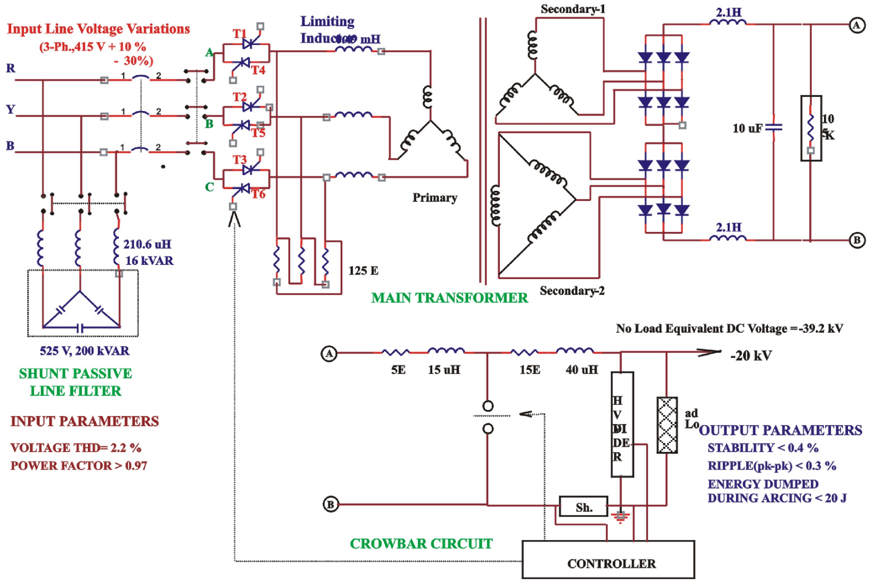

Fig. T.2.6 *Schematic of 20 kV, 5.5 A, HVPS along with Crowbar and Detuned Filter*

Klystron tubes are highly sensitive to arcing, hence crowbar protection is provided, which operates within few microseconds under arcing conditions. In the event of arcing of the klystron, the energy dissipated in the klystron is limited below 20 Joules by using crowbar. A crowbar current limiting resistor is kept between DC filter capacitor bank and crowbar unit, to limit capacitor peak current. Resistor is also kept between crowbar and load, to provide necessary header voltage for operation of the crowbar, even under load short circuit condition. Under klystron arcing, the fault current is sensed and used to fire the crowbar. The detailed schematic of high voltage power supply (HVPS) along with detuned filter and crowbar is shown in fig. T.2.6.

Solid-state driver amplifier

10-Watts solid-state amplifiers, operating at 505 MHz, have been developed to drive the klystron amplifier. It provides gain of 40 dB with spurious and harmonics distortion below 40 dBc. The amplifier chain consists of various low power (1W) and high power (10W) amplifier modules in cascade. Each module has its own supply-regulation, protection and interlock circuit. Matching circuit of each stage encompasses transmission line transformers and micro strip line based network. Distributed negative feedback is employed to make the amplifier stable for full range of VSWR. For reducing downtime, hot swappable redundant configuration has been used. Hot swapping, gain control, transfer of amplifier status over serial bus and other supervisory functions are executed by an FPGA based card. The main protections incorporated are over current fold back, cooling fan failure and over temperature. RF switch is provided to divert input RF signal to a matched load, in case amplifier is off or any fault occurs. All amplifier modules, controller, RF switch and a power supply are enclosed in an EMI shielded 19" 4U sub-rack.

Low level RF control

Low level RF (LLRF) control system has been developed to keep cavity voltage, phase & frequency stable during various phases of machine operations like injection, ramping, and beam storage. The cavity gap voltage requirement is 75 kV for injection and 375 kV at 2.5 GeV, correspondingly the wasted power on the cavity surfaces is 900 watts and 22 kW respectively. The power transferred to the beam is of the order of 50 kW per cavity at full beam current. Hence the operation of the RF stations is strongly influenced by the loading due to the circulating beam. LLRF system maintains cavity amplitude and phase stable within 1% and 0.5^{o} respectively under heavy beam loading condition. Three feedback loops namely tuning loop, an amplitude loop and a phase loop are installed. A mechanical frequency tuning loop and an amplitude loop compensate for the beam loading effects, while phase loop maintains phase of RF cavity. Synthesized RF source is used to drive four RF stations. The reference signal from synthesizer is amplified by 1 Watt solid state amplifier & it is then split into 8 channels by 8 port micro-stripline based power splitter. Four of them are used to drive RF stations, and remaining channels are used as reference and monitoring signals. Distribution system provides 505.8 MHz, 10 mW phase & amplitude controlled drive input to the power amplifier chain.

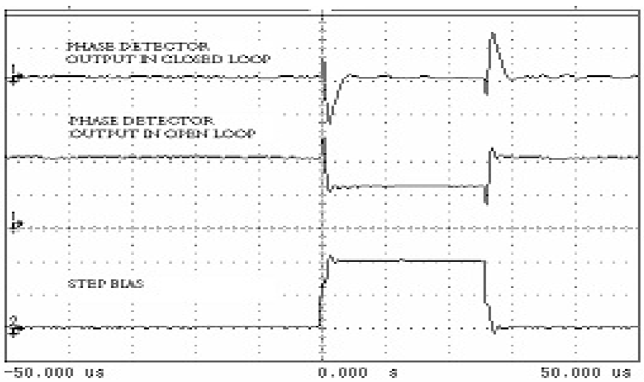

Fig. T.2.7 *Phase control loop test response*

A station phase shifter is provided to set phase of each RF station to required value. A micro strip line based fast phase shifter is designed using drop-in circulator & varacter diodes. It provides response time better than 0.2 μsec. The fast electronic phase shifter is basic building block of phase loop. The phase loop incorporates phase shifter; phase detector and PI control circuits. Testing of RF stations with phase loop has been performed. With the loop closed, phase stability better than 0.1º was measured for phase error of 80º at correction speed of 5 μsec (fig.T.2.7). An amplitude loop comprising of RF-DC detectors, RF attenuator and control circuit is incorporated. It maintains the cavity gap voltage constant at 1% within 10 μsec. Provision has been made to operate the RF system in pulsed mode as required during conditioning of cavity.

The tuning loop keeps the cavity tuned by compensating for stationary beam loading and temperature effects. It comprises of limiting amplifiers, phase detector, logic generator, protection and interlock unit and DC motor driver. The tuning loop compares the phases of the cavity feed port signal and cavity sensing loop signal and produces proportional dc error voltage. The error signal is used to generate appropriate logic for the motor to move it in CW / CCW direction for restoring resonance frequency. The tuning is achieved by an axial elastic deformation of the RF cavities.

RF power-monitoring unit at 505.8 MHz has been developed to monitor forward and reflected power at three places in the RF amplifier chain, namely, solid state driver amplifier output, klystron output and cavity input. It also provides RF trip signal in case of excess RF power at these locations. Sampled RF signals are converted to DC with RF detector and linearized using lookup tables. A fast RF on/off control & interlock is incorporated to switch off RF in case of faults like poor vacuum, excess forward or reflected power, cavity tuner out of range, HOMFS out of range, no cooling water and air, arc in circulator/klystron or malfunctioning of HVDC power supply or klystron amplifier. In the event of fault condition, RF input to amplifier chain is disabled within 4 μsec. RF signal distribution unit is designed to distribute RF signals at cavity sensing loop and feed port. This unit consists of band pass filters, Wilkinson type in phase RF power splitters and signal conditioning amplifiers.

Supervisory system

PC based distributed supervisory system has been developed for monitoring various parameters of entire RF system. The physical distance involved between various RF equipments is sufficiently large; hence distributed architecture is selected for data acquisition, processing and presentation. Various types of signal conditioning and isolation cards were developed for analog and digital input and output signals. The software environment chosen was LabVIEW running on Microsoft Windows 2000. Modular design approach is followed for the hardware and software development so that reconfiguration and debugging becomes easier.

The software developed has four-layer architecture namely physical layer, device interface layer, supervisory layer and presentation layer. The layering gives the advantage of using readily available software tools and the benefits of modularity. The software developed is based around a data transport and database management engine named as "tag engine". At the device interface layer the device servers provide data to the tag engine. The acquired data and the historical database are then presented under various software panels. All the supervisory units are networked together using 1000 Mbps copper and fiber LAN.

Conclusions

505.8 MHz modular RF system based on multibeam klystron is developed for Indus-2. The system is designed to generate 1.5 MV across four cavities. Assembly and installation is completed. High power RF testing with cavities has been carried out. Performance of various sub systems during this testing was satisfactory.