T.1: Development of normal conducting RF cavities and their installation in Indus-2

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This complex indigenous technological development of RF cavity for Indus-2 is a collaborative work accomplished by the joint effort of colleagues from RF Systems Division, Design and Manufacturing Technology Division, Ultra High Vacuum Technology Section, Industrial Accelerators Division and working group for development of Indus-2 RF cavity.

Abstract

505.8 MHz normal conducting Indus-2 RF cavity has been designed, developed, installed and commissioned in synchrotron radiation source Indus-2. It consists of bell-shaped oxygen free electronic (OFE) copper shell, input power coupler, higher order modes frequency shifter (HOMFS), tuning system and coolant system. Low power RF and higher order modes (HOM) measurements were performed on the assembled cavity and was further tested and qualified for high vacuum and RF power requirements of Indus-2. The cavity has been installed and commissioned successfully in Indus-2. Presently, this cavity is working in round-the-clock operation of Indus-2.

A broadband kicker RF cavity has been designed for Longitudinal Multi-Bunch Feedback System (LMBFS) to be installed in Indus-2. A test kicker cavity was designed, fabricated and tested for validating the RF parameters. A vacuum compatible kicker RF cavity is in advanced stage of fabrication and will be installed in Indus-2.

1. Introduction

In Indus-2 synchrotron radiation source, electron beam is injected at ~550 MeV from the existing booster synchrotron. After accumulation of beam, the stored beam is accelerated from ~550 MeV to the final energy 2.5 GeV. RF system provides power to accelerate the beam and to compensate for the synchrotron radiation losses.

Indus-2 RF system comprises of four imported RF cavities at 505.8 MHz. To cater to the need of spare RF cavity considering the aging of the present cavities, need of higher RF power for operation of insertion devices and to provide ease of operation, indigenous development of RF cavity was taken up at RRCAT.

The development activity consisted of physics simulation, HOM analysis, thermal-structural analysis, manufacturing and RF testing. High power RF coupler, HOM plunger, coolant system and tuning system were also designed and developed. Indigenous Indus-2 RF cavity has been developed, installed and commissioned successfully in Indus-2. Figure T.1.1 shows the indigenously developed RF cavity, installed in long straight section LS-7 of Indus-2.

Fig. T.1.1: Indigenous RF cavity installed in Indus-2

2. Design of RF cavity

The RF cavity was simulated using electromagnetic codes Superfish and CST Studio. Figure T.1.2 shows the view of the simulated cavity and electric field plot in the cavity.

The resonant frequency, quality factor, shunt impedance and R/Q for fundamental mode and HOMs were estimated. Table T.1.1 shows the main RF parameters of the cavity.

An exhaustive thermal, structural and electromagnetic analysis using ANSYS was carried out to arrive at the mechanical design and tuning behavior of the cavity. The structural simulation has been done to determine the force required to produce deformations in the cavity shape by changing the axial length for the entire tuning range. This force is applied on the end flanges by a tuning mechanism

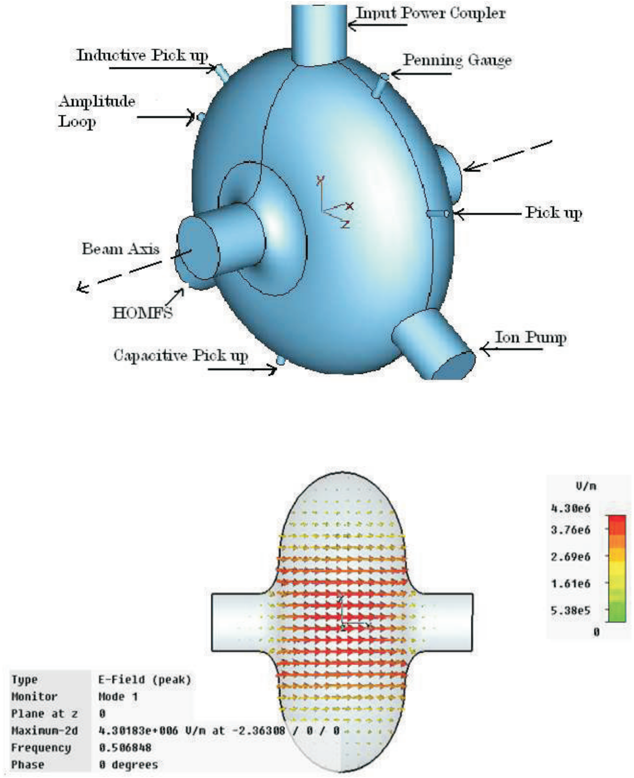


Fig. T.1.2: (a) View of the simulated cavity. (b)Electric field plot in RF cavity

consisting of a gear train of approximately 35000:1 ratio with the servo driven motor. The values of the frequency sensitivity estimated with Eigenmode solver for the entire tuning range for a tuning mechanism with 5 mm pitch ball screw was well within the acceptable limits. Stresses due to tuning/structural deformation were also well within the acceptable limits for OFE copper.

Thermal simulations were performed for a heat load of 60 kW, equivalent to 600 kV accelerating gap voltage, on the cavity walls. Forced water cooling through copper tubes in parallel circuits is applied for maintaining the cavity at any fixed temperature between 30 °C to 80 °C. The thermal stress and thermal deformation at different working temperatures were estimated and the thermal stresses were found to be within the acceptable limits. The thermal deformation was further used for determining the shift in the frequency and the frequency sensitivity was approximately -10 kHz/°C. Deformation due to heat load and temperature profile on the cavity wall are shown in Figs. T.1.3 and T.1.4, respectively.

Table T.1.1: RF parameters of the cavity

Description	Parameters	Unit
Resonant Frequency (f)	505.8	MHz
Accelerating voltage (V_{acc})	375	kV
Quality factor	42790	
Transit Time Factor (T)	0.667	
Effective Shunt Impedance	3.55	MΩ
R/Q	79.3	Ω
Power density	< 4	W/cm^2
Power loss (P_c)	19.8	kW
E_{max}/E_{acc}	1.82	

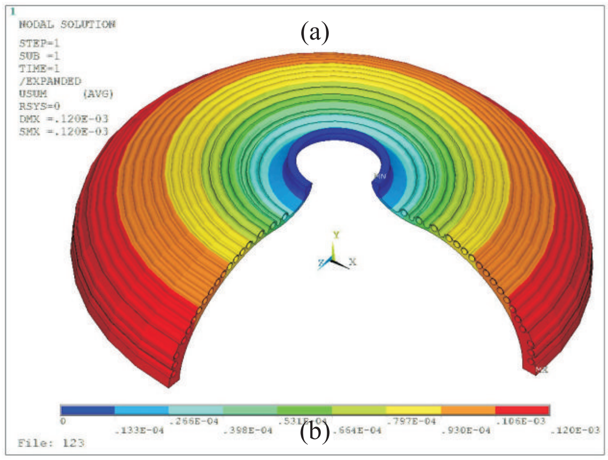


Fig. T.1.3: Deformation due to heat load

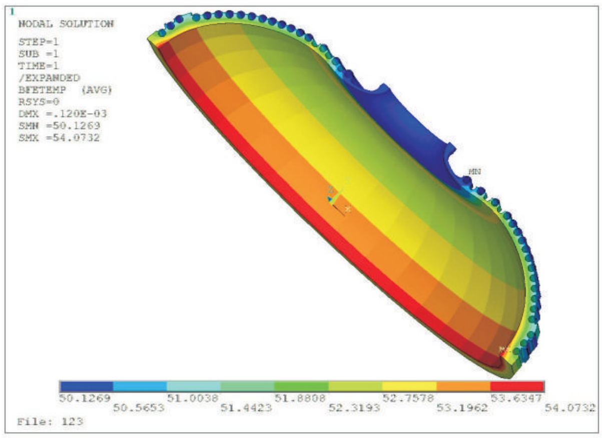


Fig. T.1.4: Temperature profile on the cavity wall

3. Fabrication of RF cavity

For fabrication of this cavity, feasibility study of the various manufacturing processes was carried out to realize the cavity with the existing indigenous facilities and expertise.

3.1 Forming and machining

The cavity body has been fabricated by joining two half cells at mid plane. The half cells were formed with 25 mm thick OFE copper (C10100) plate in a die punch fabricated out of EN-8 alloy. These half cells were stress relieved in vacuum furnace to avoid dimensional instability after machining. Machining of inner and outer profiles were carried out on CNC lathe. Profile accuracy of 0.25 mm on inner surface and flatness of 0.03 mm on equator and iris faces was achieved. Surface finish was improved to 0.35 micron (Ra) by polishing with alumina oxide paper of varying grit sizes up to 1000 grit size followed by polishing with special white pad.

Deep grooves were machined on the external surface of the cavity body for brazing of copper tubes for water cooling of the cavity. The machined two halves of the cavity are kept thin near the beam ports to obtain the required tuning. A special epoxy fixture was developed to provide support to the half-cell during machining of outer cooling grooves as the cells were fragile after profile machining from inside and outside. Various cutting tools were developed for machining of grooves on outer profile of both halves of the cavity. Machined half cells were inspected for its required dimensional and profile accuracy on co-ordinate measuring machine (CMM) and found to be acceptable as shown in Fig. T.1.5. After brazing of the two halves, ports openings were machined on the equatorial plane of the shell using horizontal boring machine. Components of the transition pipes of the ports were machined with precision for the furnace brazing application.

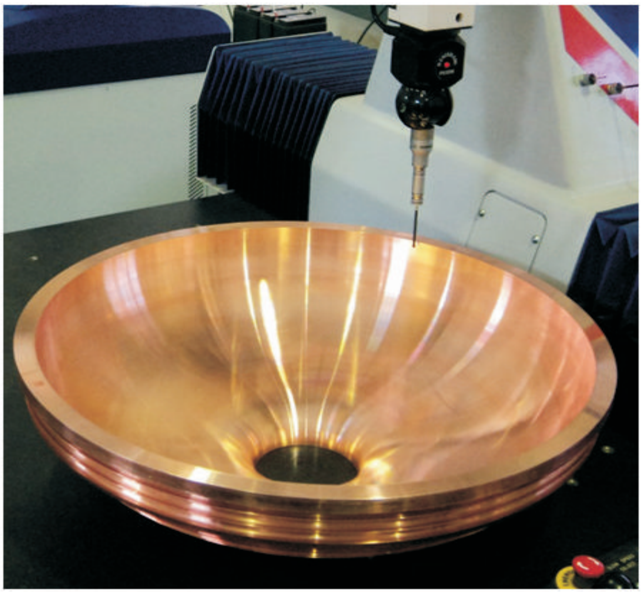


Fig. T.1.5: Inspection of half-cell on CMM

3.2 Vacuum brazing

The realization of RF cavity along with all the ports and cooling tubes was achieved in four stages of vacuum furnace brazing. In order to fulfil requirements of the brazed joints, which were in different planes, orientation and at various locations, special precision fixtures were designed and developed.

In the first stage two half cells were brazed at the equator to realize the elliptical shell. Palcusil5 (5% palladium and Cu-Ag) was used in foil preform with brazing temperature of about 850 °C. The copper to SS transition joints for ports were also done with similar alloy. In the second stage eight ports on equatorial plane and two axial ports were brazed to the cavity shell with Ag-Cu eutectic alloy foils and wires in some places at 800 °C. Figure T.1.6 shows pre-brazing assembly of all the ten ports with the cavity shell and its loading in the brazing fixture.

Fig. T.1.6: Pre-brazing assembly of ports with the cavity shell and its loading in the brazing fixture

In the third stage cooling tubes in the one half machined grooves were brazed using 14.5% Incusil foils at 725 °C. The temperature was ramped quickly through the solidus-liquidus range to avoid separation of the alloy. In the fourth stage, cooling tubes in the other half and 2 tubes per port were brazed with the same alloy keeping the braze temperature little above the liquidus 708 °C with a lesser soaking time. Figure T.1.7 shows the cavity as brazed in the final stage on the furnace hearth.

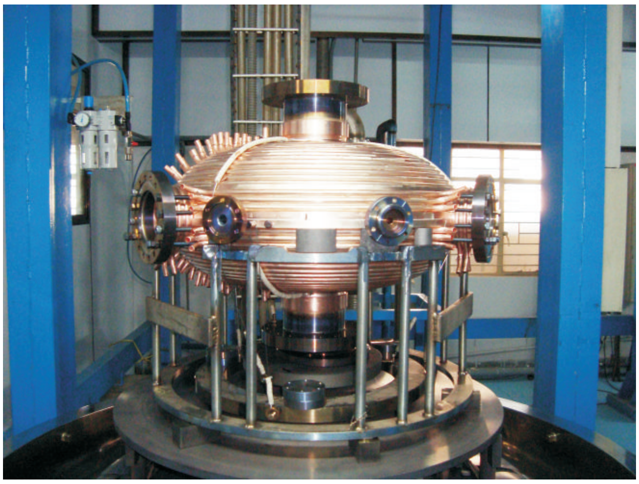


Fig. T.1.7: Cavity as brazed in the final stage on the furnace hearth with all cooling tubes

Complex fixtures were developed for each stage in a way to maintain the optimal brazing gaps at all the joints at higher temperature. Annealed molybdenum wires were used to restrict the uncontrolled expansion of copper parts at elevated temperature. Chemical processing was carried before each of the brazing cycle. Vacuum leak test of brazed joints were performed at each stage of brazing for the leak rate better than $1x10^{-10}$ tor-l/s.

3.3 Tuner system

A cage type tuner system was designed and fabricated for tuning the RF cavity to the desired frequency by mechanically compressing or stretching the cavity in axial direction. It has a mechanism consisting of ball-screws, linear guideways and precision gearboxes having overall gear ratio of ~35000 with a resolution of 1micron. The cavity is integrated to the tuner system by its beam port flanges bolted with the two stiffened brackets movable on linear guideways.

3.4 HOMFS system

In order to shift the HOM frequencies a plunger is inserted into the cavity volume. The mechanism consists of linear guideway, bellow, plunger cooling channel, linear motion system. Figure T.1.8 shows RF cavity integrated with tuner and HOMFS.

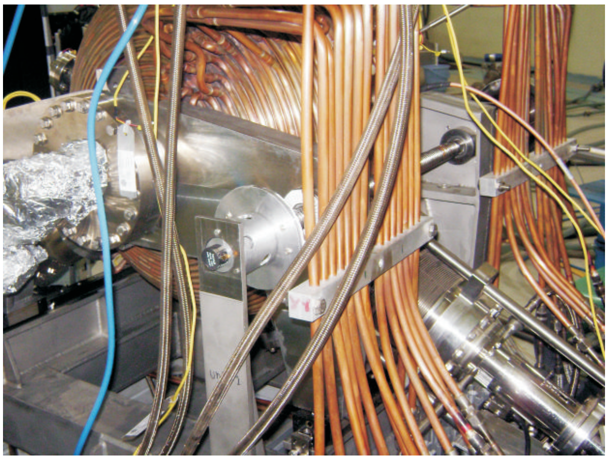


Fig. T.1.8: Cavity integrated with tuner and HOMFS

3.5 Input power Coupler

In order to feed RF power into the RF cavity, a high power RF coupler was designed and fabricated. The inductive loop and the central conductor are provided with complex coolant channels. It consists of a 97% pure alumina ceramic disc as a vacuum barrier that is cooled from outside by forced air. Parts were machined at RRCAT and brazing was carried out at CEERI, Pilani.

4. Baking, RF conditioning and high power testing

After chemical processing, the cavity was assembled with RF power and sensing couplers, vacuum gauge and pump. The input power coupler was adjusted for a coupling coefficient of 1.2 for limiting the power reflection to below 1%. The RF frequency of the cavity was measured to be 505.5 MHz. Figure T.1.9 shows the view of the RF cavity along with VNA during coupling coefficient adjustment.

All joints were leak tested up to vacuum level of $5x10^{-11}$ mbar-litre/sec. Baking of the cavity was performed by flowing hot water at 150 °C at 6 bar pressure through all the copper tubes meant for cooling of the cavity during normal operation. Heating tapes were used to heat all the CF flanges in tandem with the cavity. A slow heating and cooling rate of 12 °C per 20 minutes and 8 °C per 20 minutes respectively was chosen to avoid any thermal stress issues in the ceramic and metallic parts of the cavity, keeping a flat top period of about 36 hours at 150 °C. After cool down a vacuum level of $4x10^{-10}$ mbar in the cavity was achieved.

After baking, vacuum system, coolant system, RF power station, coaxial transmission line system, window air cooling system and LLRF interlock system were made functional for carrying RF conditioning. Air cooling for RF window and LCW cooling for cavity body and coupler with flow diagnostics were fitted. A LLRF interlock system to control the whole process with all important trip signals was used.

Fig. T.1.9: Coupling coefficient adjustment of RF cavity

RF power was delivered through a 6-1/8 inch transmission line from high power Solid State Power Amplifier (SSPA) via circulator. Figure T.1.10 shows the view of the test set-up consisting of RF cavity, high power input coupler, sensing couplers, vacuum pump and gauge, 6-1/8 inch coaxial transmission line, high power circulator and RF stations.

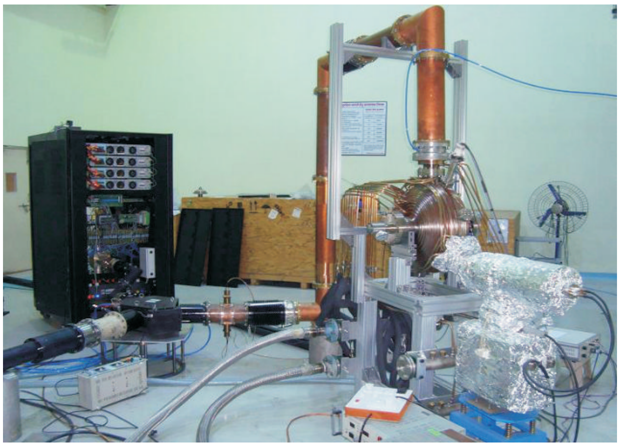


Fig. T.1.10: Set-up for RF conditioning and high power RF testing of the cavity

After the test set-up was in order, high power testing and RF conditioning of RF cavity was started. RF conditioning was started by feeding low power in pulse mode with Pulse Repetition Frequency (PRF) of 25 Hz and pulse width of 100 µs i.e. duty factor 0.25%. After this, with same duty factor, RF power level was increased to 33 kW. Then, PRF and pulse width were increased slowly to take duty factor 100% so that CW operation was reached. Net RF power of 33 kW (CW) was delivered to the cavity successfully meeting the consistent operational requirements of Indus-2.

During the process of RF conditioning, important parameters like cavity vacuum level, forward and reflected RF power values, cavity gap voltage sensing signal, cavity temperature were observed for any abnormality. Some abrupt vacuum deterioration at certain power levels (8 kW, 16 kW and 23 kW) were noticed, but no signatures of multipacting, severe arcing or oscillations in cavity were observed. The vacuum trip limit was set at pressure level of 5×10^{-8} mbar. To compensate for the frequency shift due to thermal effects, RF generator frequency was varied as tuning system and precision chiller for cooling was unavailable at the time. Radiation was monitored and adequate precautionary measures were taken throughout the cavity conditioning.

5. RF and HOM measurements of the RF cavity

Low power RF measurements and analysis were performed to determine physical parameters such as frequency, quality factor, coupling coefficient, coupling of HOMs, coupling of sensing couplers. The resonant frequency of fundamental mode of the as fabricated cavity was measured to be 505.488 MHz and unloaded quality factor was estimated to be 39,900. The coupling between input coupler and two inductive couplers was measured and the values are -46 dB and -44 dB respectively. Figure T.1.11 shows the snapshot of low power RF measurement.

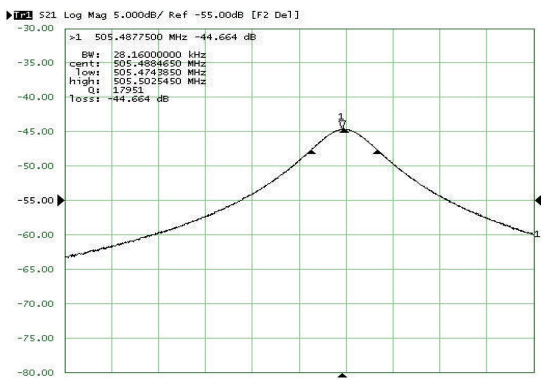


Fig. T.1.11: Snapshot of low power RF measurement

Bead-pull measurements were performed to determine R/Q and shunt impedance values of the fundamental as well as HOMs below beam-pipe cut-off frequency. The bead was moved by using stepper motor which was controlled in fine steps. The frequencies, unloaded quality factors of HOMs were measured and analysis was performed. The fundamental mode R/Q value was ~85 Ω which was close to the expected value.

In the Indus-2 RF cavities, instabilities due to HOMs are suppressed by varying the temperature of precision chiller of cavity and HOMFS position. The tuning system and HOMFS were assembled with the cavity. HOMs measurements were performed by varying the tuner position and HOMFS position were estimated. Tuner coefficient i.e. variation in frequency of each HOM w.r.t. variation in frequency of fundamental mode was calculated. Table T.1.2 shows the tuner coefficients of important longitudinal and dipole modes.

Table T.1.2: Tuner coefficients of important HOMs

Mode	Frequency (MHz)	Tuner Coeff.
L1	950.5	0.78
L2	1072.7	-0.11
L3	1434.5	-2.24
L4	1518.5	0.08
L5	1626.4	-3.37
L7	1961.1	-2.34
D1a	747.2	-2.99
D1b	747.5	-2.70

Measurements of HOMs with variation in cavity body temperature were also performed. Temperature coefficient i.e. variation in frequency of each HOM w.r.t. variation in cavity body temperature was calculated. Table T.1.3 shows the temperature coefficients of important longitudinal and dipole modes.

Table T.1.3: Temperature coefficients of important HOMs

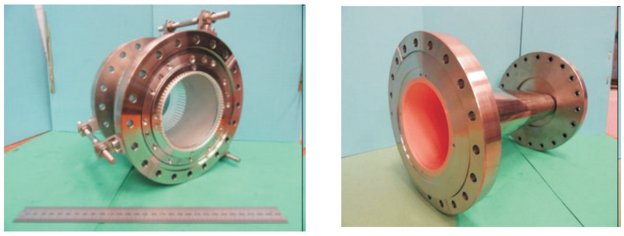
Mode	Frequency (MHz)	Temp Coeff. (kHz/°C)
L0	505.8	-9.56
L1	950.5	-16.65
L2	1072.7	-17.80
L3	1434.5	-21.94
L4	1518.5	-26.06
L5	1626.4	-23.97
D1a	747.2	-9.68
D1b	747.5	-9.28

These coefficients were within tolerable limits. The data was used for estimating the initial settings of temperature and HOMFS position for beam operation in Indus-2.

6. Installation of RF cavity in Indus-2

After low power RF measurements and high power RF testing of the cavity, it was safely transported to Indus-2 complex for the installation. Vacuum chamber of long straight section LS-7 of Indus-2 was vented and necessary modifications in the vacuum chamber were done to integrate the new RF cavity. Final alignment of RF cavity was done w.r.t. best-fit beam path (magnetic axis) of the section within 0.2 mm in transverse plane. Figure T.1.12 shows photographs of RF-shielded bellows and tapered vacuum chambers. The RF cavity was installed with a vacuum system comprising 270 lps sputter ion pump, 1000 lps titanium sublimation pump, and a Bayard-Alpert gauge. Figure T.1.13 shows the upgraded LS-7 with indigenous RF cavity and vacuum system.

The coupling coefficient of the cavity was set for optimum RF power transfer considering the effect of beam loading during operation. Couplings of other ports were also measured. Figure T.1.14 shows the snapshot of input power coupler coefficient measurement.



(a) (b)

Fig. T.1.12: (a) RF-shielded bellow. (b) Tapered chamber

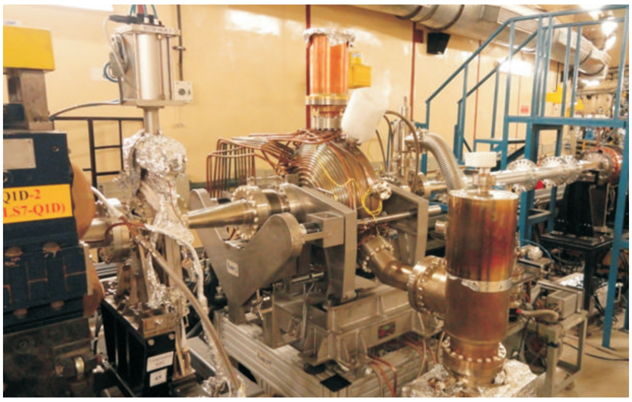


Fig. T.1.13: Upgraded LS-7 with indigenous RF cavity and vacuum system

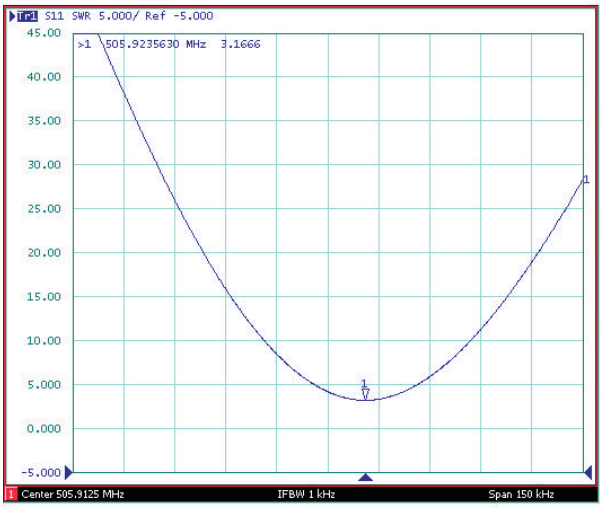


Fig. T.1.14: Snapshot of input power coupler coupling coefficient measurement

The RF cavity was evacuated and baked for 36 hours with circulating hot water at 150 °C for 24 hours flat top and vacuum of ~$4x10^{-10}$ mbar was achieved after cool down. The cavity was then connected with cooling water line from the precision chiller. Coolant circuit connections to high power coupler, HOMFS and bracket cooling were made. Precision chiller coolant supply was calibrated on a dummy load for the required operating temperature. Window air cooling connection with flow switch, temperature measuring sensor and filters was made and flow was set. Several thermocouples were pasted with special potting compounds on different parts of the body for temperature mapping of the cavity.

New RF station comprising 60 kW solid state RF amplifier system, RF interlock system, digital low level RF control system, higher order mode frequency shifter control unit, frequency tuner control system, and RF cavity signal distribution unit was installed. RF cavity was connected to the RF station outside the tunnel at the other end through a fabricated 6-1/8 inch transmission line system consisting of several line sections, bends, flexible sections, directional couplers, RF circulator, water cooled RF load etc. Figure T.1.15 shows the view of SSPA with transmission line system.

All the necessary interlocks for RF cavity window air, cavity vacuum, RF cavity water, RF amplifiers, RF powers, RF cavity gap voltage, tuning limits, tuner and HOMFS motor driver etc. were implemented. Online frequency tuning range necessary to compensate for beam loading was adjusted and limit switches were fixed and enabled.

Fig. T.1.15: View of SSPA with transmission line system

RF cavity was conditioned and tested in CW mode up to full RF power. Digital low level RF control system was optimized at full RF power range for keeping RF amplitude and phase constant within allowable range. Finally RF cavity was tested with frequency tuning loop in auto mode from low to high RF power.

7. Commissioning of RF cavity in Indus-2

Beam trials were performed on this RF cavity in operation along with previously installed four imported RF cavities. The important parameters like cavity gap voltage, relative phase, synchrotron frequency, forward RF power, reflected RF power, vacuum level, tuning position, cavity temperature etc. were observed and optimized during initial experiments with beam. During regular operation, cavity vacuum kept on improving with increase in RF power and after a few weeks beam current of 150 mA at 2.5 GeV was attained in Indus-2. Experiments to store high beam current (up to 200 mA) were performed. During experiments L3 mode (~1434 MHz) was observed to be higher at injection energy (~550 MeV) and was causing beam saturation. The harmful mode L3 was avoided by optimizing the HOMFS position of the RF cavity, keeping all the other modes within safe limits. At the optimized RF and HOM settings (cavity temperature and HOMFS position), more than 200 mA at 2.5 GeV beam operation was attained in Indus-2.

Figure T.1.16 shows the snapshot of beam injection, ramping and storage with five cavities including indigenously developed RF cavity. Presently, the RF cavity is working in round-the-clock mode operation in Indus-2.

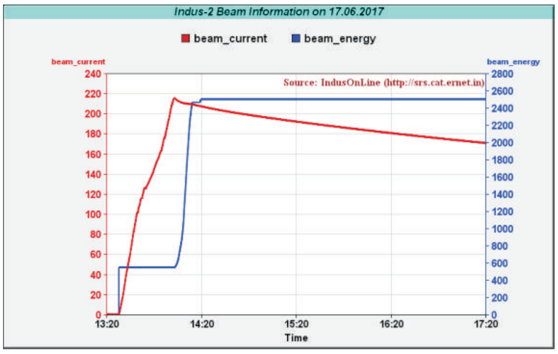


Fig. T.1.16: Indus-2 operation at 200 mA and 2.5 GeV

8. LMBFS kicker cavity

It is envisaged to install LMBF system for suppressing the longitudinal multi-bunch instabilities in Indus-2. So, LMFB system is an active mechanism that senses the oscillation generated due to instabilities and applies a corrective RF kick by using a cavity type kicker. The bandwidth of RF kicker cavity is half of the Indus-2 operating frequency i.e. ~ 253 MHz. The kicker cavity operation band was chosen as lower sideband ($3f_{RF} - f_{RF}/2$) of third harmonic (f_{RF} = 505.808 MHz). The central frequency of the kicker cavity is 1391 MHz with bandwidth of 253 MHz. The loaded quality factor of this type of cavity is ~5.5. To obtain low *Q*-factor, four input and four output ports including a ridge waveguide geometry was inserted in pillbox cavity. Simulations have been carried out with the help of computer code Superfish and 3D-CST Studio Suite and important RF parameters of the cavity were worked out. Simulated electric field plots for the fundamental mode is shown in Fig. T.1.17.

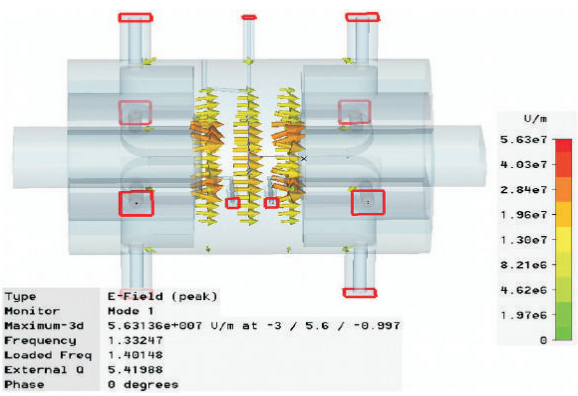


Fig. T.1.17: Simulated electric field for fundamental mode

One test kicker RF cavity in Aluminum alloy AA6061T6 was fabricated to test the RF parameters. Cavity internal shape and all four ridged waveguides of each shell were machined from a solid bar using CNC wire cut and CNC ball end mill. Some dimensional allowances were kept for final tuning of the cavity. Eight feedthroughs were also designed, fabricated and mounted on the cavity. Machined parts are shown in Fig. T.1.18.

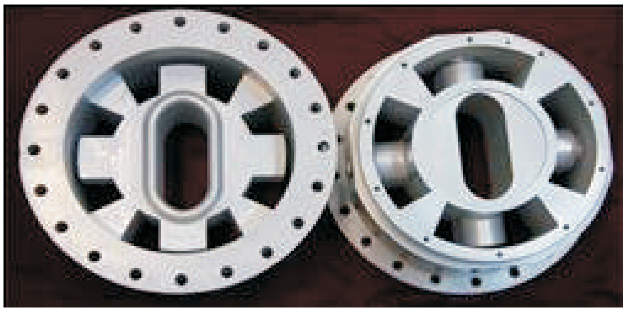


Fig. T.1.18: Machined parts of Kicker RF cavity

Kicker cavity was assembled with all the eight feed through and end flanges. RF characterization has been carried out using a broadband two four-way splitters, eight cables of identical length and 50 Ω matched loads. The resonant frequency was attained in steps by taking a cut on the lip of the two shells. The couplings of ports were also measured and the measured S11 and S22 parameters of the cavity were -30.6 dB and -31 dB respectively. The HOM frequencies of the broadband cavity were also measured and the approx. HOM frequencies are: 2526.6 MHz, 3375.0 MHz, 3757.9 MHz, 3997.8 MHz, 4261.6 MHz, and 4357.1 MHz. To supress a few unsolicited HOMs, three new inductive damping couplers were designed, fabricated and assembled with the cavity.

RF measurements and bead-pull measurements were performed to test the HOM parameters. It was found that these HOMs were dampened to an acceptable level. Figure T.1.19 shows the RF measurement set up with assembled cavity. Designed and measured RF parameters of RF cavity is given in Table T.1.4.

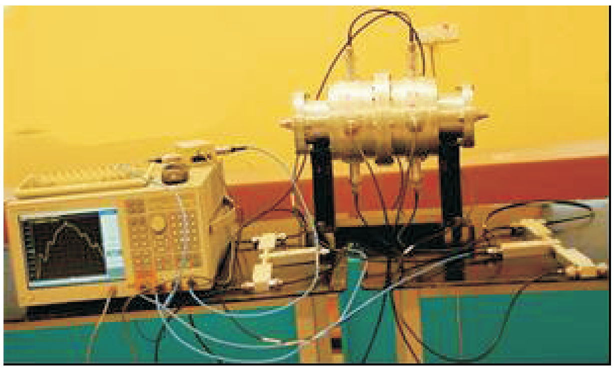


Fig. T.1.19: RF measurement set up with assembled cavity

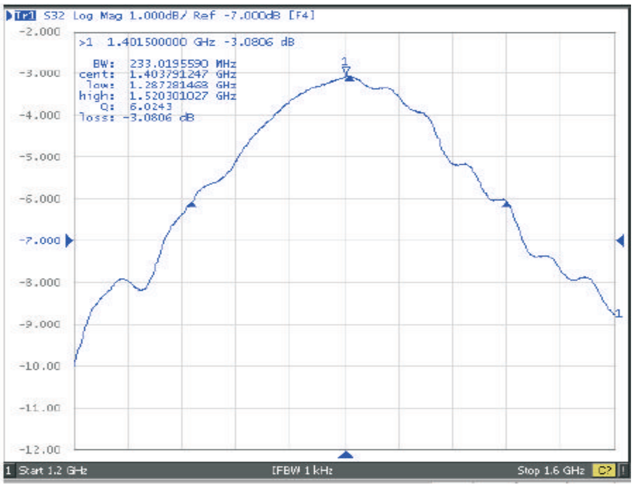


Fig. T.1.20: Snapshot of kicker cavity measurement

Table T.1.4: Simulated and measured parameters of Kicker cavity with HOM dampers

Parameter	Simulated	Measured	Unit
Central Frequency	1401.5	1401.5	MHz
Bandwidth	258	233	MHz
Loaded Quality Factor	5.42	6.02	
Shunt Impedance	1540	1580	Ohm
RF Couplers	8	8	No.

Further to this, whole cavity was redesigned in stainless steel 316L with fully welded joints and ultra high vacuum compatible coupling insertions. Alumina ceramic discs of two sizes with metallization over braze-able surfaces are used for realization of eleven number of RF couplers. As the internal geometry of the cavity involves complicated shapes (four ridges per side), a 4 axis ball end machining followed by die sinking with electro discharge machine to remove extra material at corners, is being pursued. Since the cavity is fully welded type, machining is carried out in stages to achieve good surface finish and geometrical accuracies. Fabrication of the cavity and associated components is in advanced stage. After fabrication and testing, RF broadband kicker cavity will be installed in Indus-2.

Related Publications

[1] Ramesh Kumar, M. Prasad, A.K. Tiwari, A.K. Gupta, N. Kumar, Rajiv K. Arora, A.K. Jain, M.K. Badapanda, R.M. Pandey, V.G. Sathe, M. Lad, "High power test of indigenously developed RF cavity and RF power coupler of Indus-2", Indian Particle Accelerator Conference InPAC-2015, TIFR Mumbai, 21-24, Dec-2015.

[2] G. Mundra, S. D. Sharma, Ramesh Kumar, V. K. Bhatnagar, V. G. Sathe, R. K. Gupta, T. Veerbhadraiah, S. Sharma, K. N. Yedle, B. Sisodia, P. Ramsankar, A. K. Tiwari, M. Prasad, M.Lad, "Manufacturing of indigenous RF cavity for Indus-2", Indian Particle Accelerator Conference InPAC-2015, TIFR Mumbai, 21-24, Dec-2015.

[3] M. Prasad, Ramesh Kumar, Rajiv Kumar Arora, M. Lad, "Design, fabrication and RF characterization of broadband prototype kicker RF cavity for longitudinal multi bunch feedback system for Indus-2", Indian Particle Accelerator Conference InPAC-2015, TIFR Mumbai, 21-24, Dec-2015.