T.1: Superconducting RF technology and associated infrastructure development at RRCAT

Purushottam Shrivastava[*,1], **M. Lad**[1], **P. Khare**[1], **V. Prasad**[1], **S. Raghavendra**[1], **V. Jain**[1], **G. V. Kane**[1], **A. Jain**[1], **P. Fatnani**[2] **and V. Kumar**[1,3]

[1]*Proton Accelerator Group, RRCAT, Indore*
[2]*Electron Accelerator Group, RRCAT, Indore*
[3]*Homi Bhabha National Institute, Mumbai*
[*]*Email: purushri@rrcat.gov.in*

Abstract

Raja Ramanna Centre for Advanced Technology (RRCAT) is engaged in setting up of infrastructure for development of superconducting radio-frequency (SCRF) cavities required for high intensity proton accelerators for DAE's long term programme of building pulsed and continuous-wave proton accelerators for various applications, including spallation research, radioisotope production and Accelerator Driven Systems for energy production. Dedicated facilities for forming, machining, electron beam welding, inspection, RF tuning, surface processing, dressing and testing of SCRF cavity have been set up, along with class 100 clean rooms for assembly of the cavities. Two test facilities for RF characterization of cavities at 2 K have been set up: Vertical Test Stand (VTS) for testing bare cavities and Horizontal Test Stand (HTS) for testing dressed cavities. Several SCRF cavities for various frequencies have been developed in collaboration with Fermilab, USA under the framework of Indian Institutions Fermilab Collaboration (IIFC). Development of various sub-systems of cryomodules has been initiated. For testing the cavities in VTS and HTS, dedicated solid state RF systems have been developed and installed.

1. Introduction

RRCAT has taken up R&D activities related to the development of a 1 GeV, 1 MW average power superconducting pulsed H^- linac that will be required to build the Indian facility for Spallation Research (IFSR). The development of a superconducting proton linac for IFSR will also facilitate capacity building for high intensity continuous-wave (CW) superconducting proton linac for Accelerator Driven sub-critical System (ADS). A 1 GeV proton linac would have both the normal conducting structures such as radio-frequency quadrupole (RFQ) and drift tube linac (DTL), as well as superconducting structures, such as spoke resonators and elliptic cavities, to accelerate the charged particle beams. During the last several years, important progress has been made at RRCAT on important aspects of technology development of superconducting elliptic cavities, which is described in this article.

The elliptical SCRF cavities are fabricated by forming half-cells from electrical grade (high residual resistivity ratio) niobium (Nb) sheets. The half-cells are electron beam (EB) welded to first form dumb-bells, and then these are again EB welded to form multi-cell cavities. These cavities require very high-quality interior surface, free from defects or impurities. Even micron size defects can lead to a quench in the cavity, leading to the loss of superconductivity. Hence, after fabrication, cavity needs to go through several steps of processing, in order to conform to the desired surface quality. The first step is to electropolish (EP) the cavity, after which it is cleaned using high pressure, ultra-pure water in a very clean environment (class 100 or better) to remove any particulate contamination. Gases like hydrogen are absorbed during fabrication and polishing of cavity. These are removed by thermal processing of the cavity in a high vacuum furnace.

After the various processing steps, the bare cavity is tested for the required performance at 2 K in Vertical Test Stand (VTS) at low RF power. The VTS qualified cavities are dressed with the titanium helium vessel and a low temperature tuner. The dressed cavity assembled with high power coupler is then tested at high power in Horizontal Test Stand (HTS) facility. The qualified cavities are assembled in a cryomodule, which can be finally integrated in the linac.

Various facilities and infrastructure for forming, machining, electron beam welding, inspection, RF characterization, tuning, processing, clean room assembly, and testing of SCRF cavity, and its final integration in cryomodule have been set up at RRCAT [1]. Few SCRF cavities of 1.3 GHz and 650 MHz have been fabricated and successfully qualified to desired specifications under the Indian Institutions Fermilab Collaboration (IIFC). RRCAT has also developed solid state RF power amplifiers (SSPA) for powering these cavities

2. Infrastructure for fabrication and processing of SCRF cavities

2.1 Material characterization

A material characterization facility has been set up to provide necessary qualification of materials during the SCRF cavity fabrication and processing. This includes a 50 kN universal testing machine for measuring mechanical properties, time of flight secondary ion mass spectrometer (TOF-SIMS) to analyze the impurity distribution after each stage of cavity processing, a 3-D laser scanning confocal microscope (LSCM) for measuring the surface roughness and profile of defect features with height accuracy of 1 nm.

2.2 Cavity forming facility

SCRF cavities are made from high purity fine grain niobium (Nb) sheets of high residual resistivity ratio (~300), which are cut in appropriate donut shapes for forming the half-cells. The cavity half-cells are formed by deep drawing of niobium donut shaped sheets in 120 Ton hydraulic press. Hydraulic press offers advantage of soft and jerk free forming of components. The die and punch used in the process are made from high strength aluminium alloy 7075-T6. In addition to this, the press is used for pull-outs in beam tubes, helium vessel, etc.

2.3 Electron beam welding (EBW) for SCRF cavities

RRCAT has set up an EBW machine dedicated for SCRF cavity welding. The machine has electron beam power of 15 kW and a large vacuum chamber of 3.6 m × 1.6 m × 1.9 m, which can accommodate almost each type of presently designed SCRF cavity (Figure T.1.1).

Fig. T.1.1: 15 kW electron beam welding machine.

Fig. T.1.2: Electron beam welding setup for 5-cell cavity.

This chamber can be evacuated to 1×10^{-6} mbar in less than an hour, using large capacity screw and cryopumps. Single-cell as well as multi-cell cavities of 1.3 GHz and 650 MHz have been welded in this EBW machine.

RRCAT has developed expertise in welding 650 MHz five-cell cavities, and so far, six bare cavities have been fabricated using this EBW machine [5]. Figure T.1.2 shows a 650 MHz, five-cell cavity welding setup inside the vacuum chamber of EBW, for the final equator weld. RF measurement of half-cells and dumbbells are done during each step of fabrication for appropriate trimming and machining operation [6]. The cells are also tuned for RF resonating modes. The field flatness measurement of bare cavity is carried out using bead pull setup.

2.4 SCRF cavity inspection facilities

2.4.1 Dimensional inspection facilities

SCRF cavity components are fabricated in very tight tolerances. In order to accurately measure the dimensions, two coordinate measuring machine (CMM) facilities, one portable type, and other fixed type have been set up, as shown in Fig.T.1.3. The fixed CMM is bridge type 3D computer numerically controlled (CNC) high accuracy CMM with ranges in measuring dimensions as X = 1,200 mm, Y = 2,000 mm and Z = 1,000 mm and measuring accuracy of (1.6 + L/400) µm, where L is in mm. A special temperature controlled and dust free enclosure has been built to house the CMM. CMM is equipped with a high precision scanning probe, touch trigger probe, laser-scanning probe, etc. The other CMM is a 7-axes type portable arm CMM, having spherical measuring volumetric length of 2.5 m with volumetric accuracy of ±0.038 mm with single point repeatability of 0.027 mm, using ball probe. Arm CMM has in-built laser scanner which is used for non-contact type measurements. There is a dedicated software for preparing solid models from measured point cloud data.

Fig. T.1.3: Bridge type (left) and portable arm (right) 3D CNC CMM.

2.4.2 Optical Inspection Facility

An optical bench comprising high-resolution camera and illumination system mounted inside a long cylinder has been set up for inspecting the internal surface of SCRF cavities for defects like weld spatters, pits, and scratches, providing resolution up to 40 µm /pixel.

2.5 SCRF cavity processing Facilities

The main objective of surface processing of SCRF cavities is to eliminate surface defects, remove damaged layer (~120 - 150 µm), improve surface smoothness, reduce the adsorbed bulk hydrogen and prevent any particulate contamination or residues inside the RF surface. In order to achieve such stringent surface quality, the SCRF cavity is subjected to various surface treatments, like electropolishing, centrifugal barrel polishing, ultrasonic rinsing, high temperature vacuum degassing, cavity tuning, high pressure rinsing, clean room assembly, evacuation, and low temperature baking. These facilities and the processing recipe must ensure repeatable performance of SCRF cavities in terms of maximum achievable accelerating gradient and quality factor. In this context, dedicated infrastructure for cavity processing is described briefly in the next sub-sections.

2.5.1 Electropolishing setup

Electropolishing is one of the main processes, wherein thin layers of niobium from the RF surface of the cavity are removed via anodic dissolution. In this process, the cavity acts as anode and a hollow coaxial aluminum tube as cathode, which is inserted along the cavity axis and the electrolyte used is a mixture of hydrofluoric (HF – 48%) and sulphuric acid (H_2SO_4 – 98%) in the ratio of 1:9. During EP, the electrolyte is continuously circulated through the cavity in a closed loop manner to avoid any exposure of the acids and the vapors to personnel. After EP process, the cavity is positioned in vertical orientation for draining of acids and subsequent rinsing with ultra-pure water (UPW). The overall setup is shown in Figure T.1.4. This setup has been successfully used to electropolish 5 nos. of 5-cell 650 MHz cavities, and one single-cell 650 MHz cavity[7][8].

Fig. T.1.4: (a) Horizontal electropolishing setup for 5-cell cavity. (b) Setup in vertical orientation for acid draining and UPW rinsing.

2.5.2 Thermal processing facility

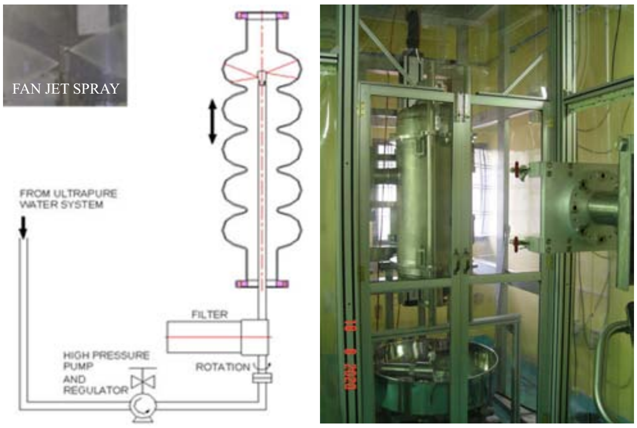
Any mechanical or electrochemical process introduces large amount of hydrogen in bulk Nb, which severely degrades the cavity quality factor. As a result, SCRF cavities are subjected to high temperature and high vacuum treatment to outgas bulk hydrogen absorbed in Nb. The standard treatment involves heating of cavity at 800 °C for 3 hours under high vacuum. Figure T.1.5 shows a dedicated high vacuum annealing furnace facility setup for thermal processing of a variety of superconducting RF cavities, which has a hot zone of diameter of 825 mm and length of 1525 mm, with a maximum operating temperature of 1400 °C ± 5 °C. This setup can also be utilized for nitrogen doping.

Fig. T.1.5: High temperature and high vacuum annealing of 5-cell 650 MHz SCRF cavity.

2.5.3 High pressure rinsing setup

Contamination on the internal surface by a foreign particle of SCRF cavity may cause field emission, which significantly reduces the attainable accelerating gradient. In order to overcome this issue, high pressure rinsing (HPR) of the internal cavity surface is carried out, as a final processing step, by high-pressure jets of ultra-pure water.

The current HPR setup installed in a class 100 clean enclosure, as shown in Figure T.1.6, is capable of rinsing 5-cell, 650 MHz, bare as well as jacketed, cavities [9]. It comprises a wand capable of rotating at 2 to 5 rpm, coaxial with the vertically mounted SCRF cavity that moves up and down at a speed of 5 to 250 mm/min using a motorized actuator.



(a) (b)

Fig. T.1.6: (a) Schematic of HPR. (b) High Pressure rinsing of 650 MHz 5-cell jacketed cavity.

Fan style spray nozzles are attached to the end of the rotating wand and the water jets emerging from spray nozzles scan the entire internal surface of the cavity. A ceramic piston pump is used to produce water jets of 100 bar pressure. Final rinsing of each cavity involves six passes, up and down, which manifests to an overall requirement of ~10,000 liters of ultra-pure water. This demand is met by a dedicated UPW plant of 800 LPH capacity with resistivity of 18 MΩ-cm and total contaminant count of less than 30 ppb.

2.5.4 Clean room facility

Contamination by particulates during assembly and evacuation of the cavity is avoided by working under clean and controlled conditions of environment better than Class 100. A pilot clean room facility of Class 100 is currently available (Figure T.1.7) [5] and clean rooms from Class 10000 to Class 10 are under construction in the SCRF building for future cavities.

Fig. T.1.7: Cleanroom Assembly of SCRF cavity.

2.6 Semi-automatic cavity tuning machine

Frequency tuning of SCRF cavity is an essential process, required during cavity development. Tuning machines for nine-cell, 1.3 GHz and five-cell, 650 MHz SCRF cavities have been designed and developed to achieve the required resonating frequency and field flatness (≥ 90 %) at room temperature [10]. Tuning is performed by providing plastic deformations in cavity cells near stiffener rings.

Semi-automatic tuning machines developed for multi-cell 1.3 GHz and 650 MHz cavities along with control system and tuning algorithms are shown in Figure T.1.8. Figure T.1.9 shows normalized electric field distribution (before, and after tuning). More than five cavities have been successfully tuned using the machine.

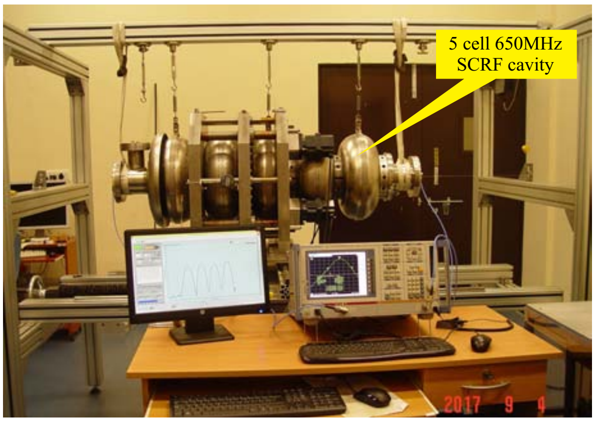


Fig. T.1.8: Semi-automatic cavity tuning machine for five cell 650 MHz SCRF cavity.

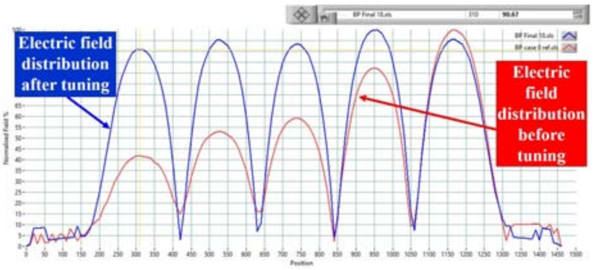


Fig. T.1.9: Normalized electric field distribution (before and after tuning).

3. Cavity dressing infrastructure

Dressing setup consists of 3 major subsystems, an insertion fixture, a rotating mechanism, a glove box along with a frequency warning system. A special assembly fixture known as 'insertion fixture' is designed and developed for insertion of bare cavity over helium vessel, satisfying the precision alignments requirement, as shown in Figure T.1.10. A motorized rotating fixture is developed for welding the cavity inside the glove box in controlled atmosphere.

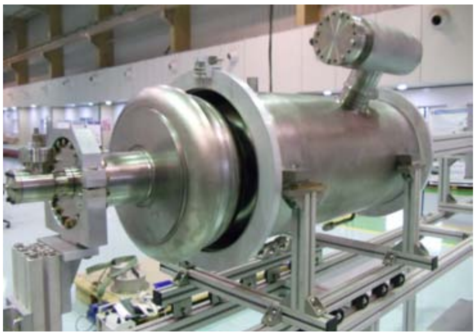


Fig. T.1.10: An insertion fixture for assembly of bare cavity and helium vessel.

Cavity dressing requires an important infrastructure known as environment-controlled welding glove box, which produces the best quality tungsten inert gas welds that meet American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. Figure T.1.11 shows the glove box of size ~ 3.4 m^3 for accommodating dressed cavity assembly for welding.

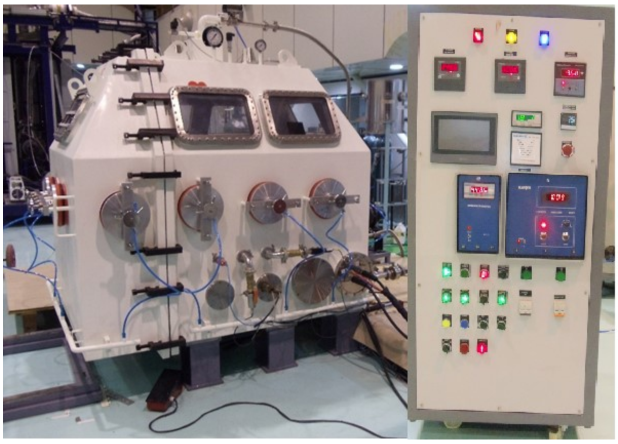


Fig. T.1.11: Environment-controlled glove box for dressing of the cavity and its control panel.

The glove box has 12 glove-ports for welding in the middle, 6 viewing windows at top and service ports at the bottom for cables of the welding machine, motor operation cables, RF measurements cable, instrumentation cables and for maintenance. This system can be operated in manual, semi-automatic, as well as automatic mode. The control panel displays oxygen level in PPM and moisture level in % relative humidity (RH). This setup has been tested and commissioned with achieved oxygen level <10 PPM and RH level <2%, which are better than the required level of 20 PPM for oxygen and 15% of RH. An important milestone was achieved when first-ever 650 MHz beta 0.92 five-cell cavity was dressed successfully in this chamber [11]. An online frequency monitoring and alarm system was specially developed to keep a close watch on shift in cavity frequency during welding and cooling cycle (Figure T.1.12).

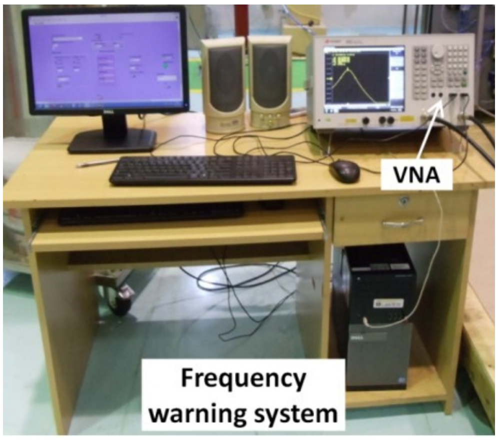


Fig. T.1.12: Online frequency monitoring system.

4. Development of low temperature tuners

SCRF cavity tuners are challenging as resonance bandwidth of an SCRF cavity is very narrow due to high quality factor, and therefore even a subtle deformation caused by Lorentz force or microphonics can detune the cavity significantly. In order to compensate for this detuning, tuning of SCRF cavities needs to be done with precision. Initial adjustment (tuning) of the SCRF cavity is carried out using a slow tuner, which is driven by a stepper motor. Piezo tuners are used as fast tuning mechanism to tune the cavity at resonance frequency during operation.

Three types of tuners are under development at RRCAT as shown in Figure T.1.13

i. Blade tuner (Tesla type design)
ii. Lever tuner (Fermilab design for PIP-II)
iii. X-link tuner (RRCAT design)

RRCAT-designed X-link tuner is capable to perform both slow and fast tuning with low hysteresis and works in both compression and expansion mode. USA, Japan, Europe and India have granted patent on this innovative X-link tuning device.

Tuner Control mechanism: An open loop controller has been developed to drive the stepper motor and piezo-actuators. On the control PC, a GUI using LabView has been developed for selection of motor parameters (such as number of motor rotations, step direction and speed) and piezo waveform parameters (such as amplitude, repetition rate and pulse width). Field programmable gate arrays (FPGA) based tuner controller accepts RS232 signal from PC and generates control signal for driving the motor as well as piezos[12].

Fig. T.1.13: (a) Blade tuner, (b) Lever tuner and (c) X-link tuner.

Tuner testing results: The Blade tuner and X-link tuner were qualified for tuning range (frequency and displacement both), hysteresis, resolution etc. at room temperature and as well as at cryogenic temperature (up to 77K)[13]. Lever tuner is recently tested in HTS at 2K for slow and fast tuning. Slow tuner is tested for its full range (>200 kHz). During the piezo tuner test, 3.5 kHz frequency shift at 100 V was observed at ~ 150K temperature close to the piezo (Figure T.1.14).

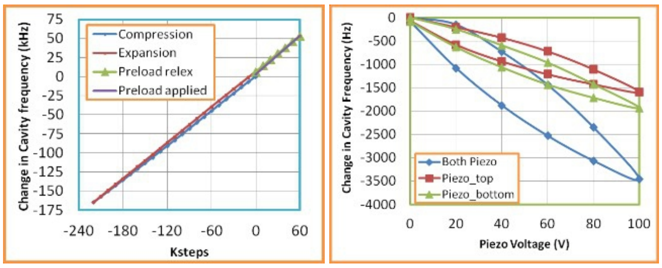


Fig. T.1.14: Tuner results–slow (left) and fast (right).

5. SCRF cavity 2K test facilities

SCRF cavities are required to be qualified for their performance prior to installation in cryomodule of a superconducting linac. The bare cavities are initially tested in a saturated bath of liquid helium at 2K in VTS. After the VTS test, it is dressed with helium vessel, tuner, and power coupler, and then tested in HTS.

5.1 VTS facility

Performance of the cavity is evaluated based on the maximum electric field acceleration gradient (E_{acc}) sustained by cavity before quench, and its intrinsic quality factor (Q_o) and radiation emitted by the cavity, while operating at desired gradient. A dedicated VTS facility for such purpose was made, and is operational at RRCAT since 2014, after its qualification using a single-cell 1.3 GHz SCRF cavity, which was earlier tested at Fermilab [3,14]. The test results obtained at RRCAT facility were similar, thus qualifying the VTS RF system. Since then, it has been regularly used for testing of 1.3 GHz and 650 MHz SRF cavities. The facility comprises the parts described in next sub-sections.

5.1.1 VTS cryostat

The VTS cryostat is designed to support and test superconducting cavities ranging from low β 325 MHz to high β 650 MHz/1.3 GHz cavities at their operating frequencies in a 2K liquid helium (LHe) bath. VTS cryostat assembly comprises an ASME Code stamped stainless steel LHe vessel suitable for 2K liquid helium. The helium vessel and associated tubing are thermally shielded with a LN_2 cooled thermal shield to reduce the cryostat's overall static heat load at 2K. The assembly of LHe vessel and thermal shield is housed in a stainless steel insulating vacuum vessel [14]. The cryostat has an overall diameter of 1370 mm, and length of 5420 mm (Figure. T.1.15).

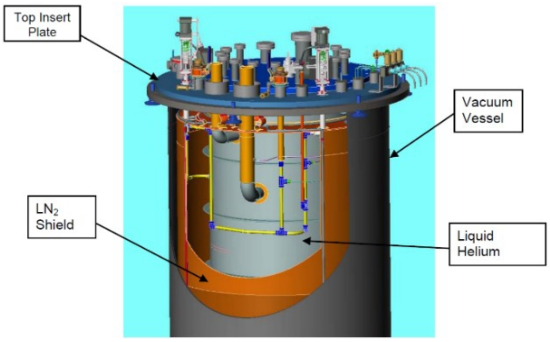


Fig. T.1.15: Schematic of VTS Cryostat Assembly.

The VTS insert assembly supports the cavity in the liquid helium bath during the RF testing and provides penetrations for RF cables, diagnostics, vacuum line etc. It also provides thermal shielding for the liquid helium bath.

5.1.2 Radiation shielding

During RF testing of cavities, field emissions are common due to contamination on the inside surface of the cavity. These field-emitted electrons are accelerated by the cavity field and upon impact with a wall, lead to X-ray radiation. In order to limit the radiation level to within safe limits in working area, radiation shielding comprising 20 cm lead, 10 cm stainless steel and 10 cm borated polythene, is provided above the cavity on insert assembly. Additionally, a movable external radiation shielding, comprising 15 cm steel and 48 cm concrete is provided above the pit.

5.1.3 Cryogenic system

For the VTS, cryogenic transfer lines for liquid helium and liquid nitrogen were fabricated in-house and installed for supply of liquid cryogens. 2K temperature is achieved by evaporative cooling of liquid helium, when the pressure above liquid is reduced and maintained at around 30 mbar. The lowest temperature of 1.65 K for cavity testing has been achieved till date. Cryogenic facilities for cavity test stands are as shown in Figure T.1.16.

Fig T.1.16: Cryogenic facilities for cavity test stands.

5.1.4 RF system of VTS

The RF system consists of low-level RF (LLRF) and high-power RF (HPRF) systems. The phase lock loop (PLL) based LLRF system controls the amplitude and phase of the input RF signal, and tracks the cavity's resonant frequency. Control and data acquisition system for the LLRF provides 32 nos. of 16-bit analog input channels, 04 nos. of 16-bit analog output channels, and up to 48 bits of digital I/O. These input/output channels provide control interfaces for the LLRF system, and accommodate analog input for various test environment parameters, such as Dewar pressure, and radiation level values. The control and DAQ software were originally developed in LabVIEW, and were subsequently upgraded to a PYTHON based version. The software provides a user interface for live monitoring, recording and graphical display of cavity test parameters. The system measures incident, reflected and transmitted power, using power meters, and calculates and displays E_{acc} and Q_o. The HPRF system consists of an in-house developed 350 W CW air cooled SSPA, along with interlocks, and provides the facility to switch to 1 W amplifier for cable calibration purposes. A system of interlocks is used to prevent personnel exposure to ionizing radiation. A set of area radiation monitors, which are located outside of the shielding lid, are used in conjunction with the lid position switches. If any of these monitors detect the presence of radiation above background levels, or if the lid is open, the LLRF output and the SSPA are switched off. Figure T.1.17 shows the two LLRF system and HPRF system installed in the VTS control room.

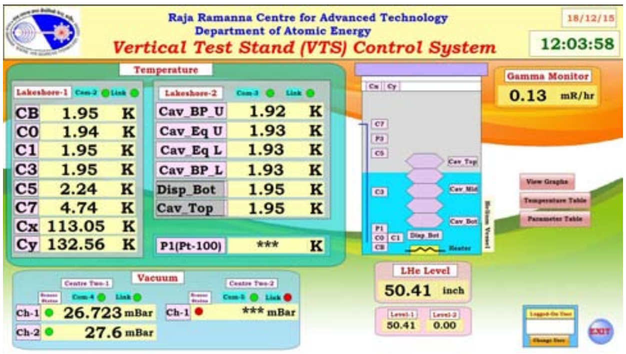
Fig. T.1.17: VTS control room during cavity test.

5.1.5 Data acquisition and control system

Programmable logic controller (PLC) based control system has been developed and deployed for VTS. Some of its main features are as follows.

- Two tier architecture: PC at Layer-1 for GUI & communication and PLC at Layer-2 for Data acquisition, control & interlocks.
- Communication: Ethernet & Serial (RS232)
- No. of Parameters ~ 30
- Interfaced devices: Temperature readout units, pressure transmitters, LHe level meters, radiation monitors etc.

The required PLC functionality has been implemented using ladder logic. WinCC SCADA has been used for GUI (Figure T.1.18).


Raja Ramanna Centre for Advanced Technology
Department of Atomic Energy
Vertical Test Stand (VTS) Control System
18/12/15
12:03:58

Temperature

Lakeshore-1 Com-2 ● Link ●
CB 1.95 K
C0 1.94 K
C1 1.95 K
C3 1.95 K
C5 2.24 K
C7 4.74 K
Cx 113.05 K
Cy 132.56 K

Lakeshore-2 Com-3 ● Link ●
Cav_BP_U 1.92 K
Cav_Eq U 1.93 K
Cav_Eq L 1.93 K
Cav_BP_L 1.93 K
Disp_Bot 1.95 K
Cav_Top 1.95 K
P1(Pt-100) *** K

Gamma Monitor 0.13 mR/hr

Vacuum
Centre Two-1 Com-4 ● Link ●
Ch-1 ● 26.723 mBar
Ch-2 ● 27.6 mBar
Centre Two-2 Com-5 ● Link ●
Ch-1 ● *** mBar

LHe Level 50.41 inch
Level-1 50.41
Level-2 0.00

Fig. T.1.18: WinCC GUI for VTS controls.

5.2 HTS facility

The HTS facility is used in testing and validation of the complete integrated SCRF cavity with coupler and tuner. The setup consists of horizontal cryostat, cryogenic distribution system, LLRF and RF protection system, high power RF amplifier system, control system etc. The cryostat is designed for testing of two nos. of 650 MHz SCRF cavities in one testing cycle.

5.2.1 HTS cryostat

HTS cryostat consists of vacuum vessel, cavity support system, liquid nitrogen cooled thermal shield, and other sub-systems, such as cryogenic distribution system and safety systems. The vacuum vessel is of diameter 1.29 m and length 4.3 m and is designed as per ASME codes. The cryostat installed in the shielded vault with cryogenic transfer lines is shown in Figure T.1.19.

Fig. T.1.19: HTS Cryostat integrated with sub-systems

5.2.2 Cryogenic system

The cryogenic infrastructure for VTS facility has been extended and upgraded for operation of HTS with an in-house liquid helium supply transfer line, liquid nitrogen pumping line, gas return lines and 2K pumping line (see Figure T.1.20).

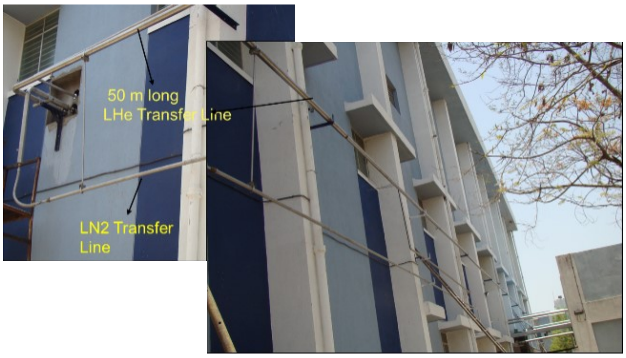


Fig. T.1.20: Cryogenic transfer lines for HTS.

Suitable safety provisions and instrumentation have been incorporated in the cryogenic distribution system. The 2K pumping system has been upgraded with addition of three pumping stations. Helium was transferred into the helium vessel of cavity in the liquid mode, as well as in the supercritical mode. In the supercritical mode, gaseous helium was transferred in supercritical state and expanded to liquid directly in the helium vessel of cavity by using Joule-Thompson (J-T) valve. The cryogenic distribution system has been commissioned, and 2K temperature has been obtained in the first dressed cavity, which has been tested at low power in the HTS facility.

5.2.3 HTS control system

HTS control system caters to about 250 signals coming from cryostat, dressed cavity, and RF coupler. Using this system, cryostat cooldown has been successfully performed several times, with parameters monitored and controlled from the control room. Instruments that have been interfaced with control system include temperature readout units (for Cernox & PT100), liquid He level meters, mass flow meters, area radiation monitors, radiation rate meter, oxygen monitor, electro-pneumatic valve actuators, pressure sensors, vacuum gauges, power supplies, RF amplifier etc. The major sub-systems of HTS control system are as follows.

VERSA-Module Eurocard (VME) based DAQ system: The system parameters that need to be monitored and controlled are handled by a VME based system. This system has a capacity of 180 analog and digital signals (Figure T.1.21). Isolation has been provided for all the signals. The real-time OS based programs for data acquisition and communication run on a CPU board.

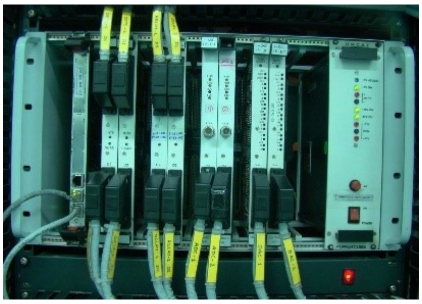


Fig. T.1.21: VME based DAQ system for HTS.

Control software and GUI: The software presents a comprehensive graphical view of read back parameters and setting of control parameters (Figure T.1.22).

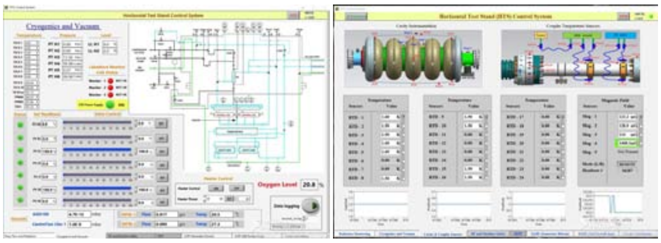


Fig. T.1.22: GUI for HTS cryostat operation.

It also logs the data at user selectable rate. It communicates with VME station over TCP. About 50 parameters from various instruments are acquired over data communication links like RS232, RS485, and UDP. The software has facilities for performing cryostat operation, calorimetric measurement, and calculations for cavity characterization.

HTS machine protection system: This system takes signals that are critical for machine safety, e.g., oxygen level, radiation levels, He vessel pressure, LHe level etc. In addition, it generates safety permit signal that goes to other sub-systems. Machine operation is allowed only if the parameters are in safe state. The system is shown in Figure T.1.23.

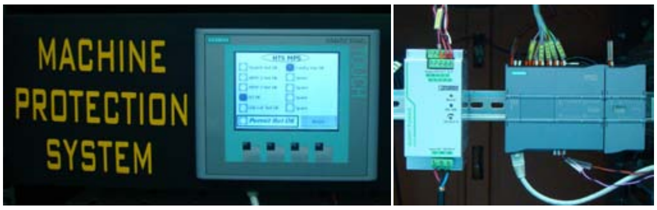


Fig. T.1.23: PLC based Machine Protection System.

5.2.4 RF system

The RF system, which includes solid state amplifier, low-level RF (LLRF), RF protection interface (RFPI), circulator etc. are operated continuously for couple of days in pulse and CW mode, during the testing.

Fig. T.1.24: 32 kW RF SSPA along with circulator.

The LLRF system will control amplitude (cavity gap voltage), phase and tuner system of SCRF cavity under specific requirement in both self-excited loop (SEL) and generator driven mode. RF protection system will provide protection against interlock in different sub-systems of HTS, e.g., cryogenics, RF system, vacuum system, machine protection, and personal safety. A 32 kW, 650 MHz solid-state RF amplifier has been installed and commissioned, along with high power circulator, transmission line system, dedicated cooling system, and RF interlock system. All sub-systems are tested in remote operation mode, and are ready for operation during HTS operation. The 32 kW RF amplifier is shown in Figure T.1.24.

5.3 Cryomodule development

5.3.1 Development path

Cryomodules have to be developed for maintaining SCRF cavities at a temperature of 2K. These are large sized complex systems (diameter: 1.2 m and length 9.5 m). It was decided to first design and develop a horizontal test cryostat, which is akin to a two-cavity cryomodule, and would be used to test dressed SCRF cavities. It was envisaged that the design and development of cryomodules will be taken up in the next step, and in parallel, infrastructure will be created for assembly of cryomodules.

5.3.2 Six Ton capacity lifting tool (part of cryomodule assembly station)

As a part of cryomodule assembly infrastructure, the first assembly station for 650 MHz cryomodule was designed, fabricated in an Indian industry, and installed at RRCAT. The lifting tool is shown in Figure T.1.25.

Fig. T.1.25: Lifting tool installed at New Cryomodule Building will be used as first assembly station of 650 MHz cryomodule.

5.3.3 Design of major sub-systems for high-beta 650 MHz cryomodule under Indian Institutions Fermilab Collaboration

Design of major sub-systems like vacuum vessel, 50 K thermal shield, lower cold mass assembly for 650 MHz, β =0.92 cryomodule has been carried out. This is based on latest inputs available from Fermilab. The 3D model is shown in Figure T.1.26.

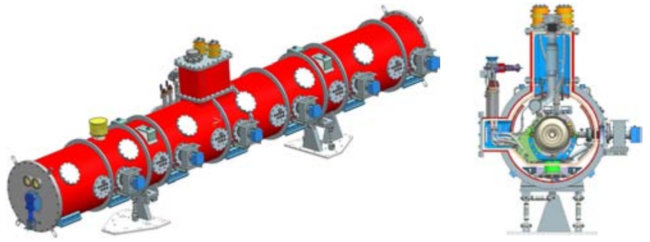


Fig. T.1.26: 3D Model of 650 MHz Cryomodule

6. SCRF cavity development and qualification

The development of SCRF cavity manufacturing technology has been done in stages, starting from single-cell cavities, and then moving towards multi-cell cavities. Initially 4 nos. of prototype 1.3 GHz, single-cell cavities were developed, which included fabrication at RRCAT, followed by electron beam welding at Inter University Accelerator Centre (IUAC), New Delhi, and industries. The cavity was thereafter processed and tested at 2K at Fermilab under IIFC. Two of these cavities exhibited an accelerating gradient > 35 MV/m with a $Q_o > 2\times10^{10}$. In the next stage, manufacturing of five-cell 1.3 GHz cavity, and single-cell 650 MHz cavity was carried out indigenously, while processing and testing was carried out at Fermilab.

After gaining experience from the prototype development, 05 nos. of five-cell, 650 MHz SCRF cavities were indigenously manufactured, processed, and tested at RRCAT[5]. These cavities have been processed with baseline recipe of electropolishing (bulk and light), high temperature annealing, ultrasonic rinsing, high-pressure rinsing, low temperature baking etc. R&D efforts with centrifugal barrel polishing and nitrogen doping in few single-cell and multi-cell cavities were also attempted. Few of those five-cell 650 MHz SCRF cavities are shown in Figure T.1.27. Two of these five-cell $\beta=0.92$ 650 MHz cavities (HB504 and HB505) demonstrated accelerating gradient greater than 21 MV/m and low field quality factor exceeding 4×10^{10}. The best result obtained was for HB505, which demonstrated $E_{acc} > 29$ MV/m and $Q_o \sim 3.3\times10^{10}$ at 20 MV/m (Figure T.1.28).

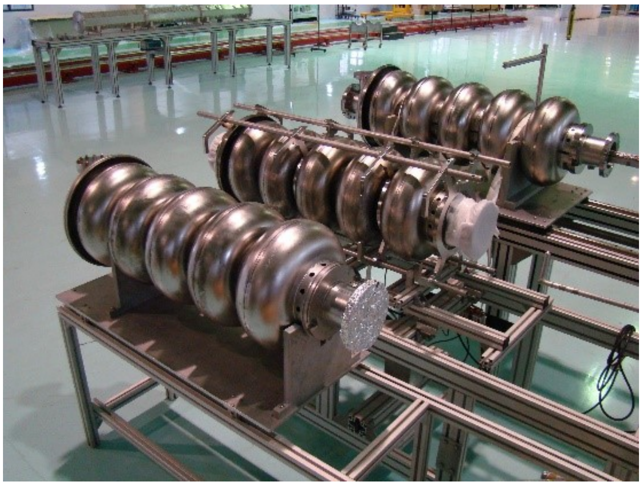


Fig. T.1.27: Five-cell 650 MHz SCRF cavities.

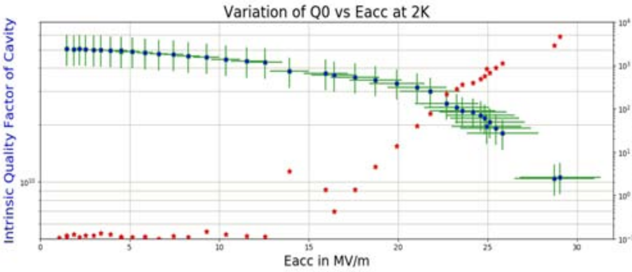


Fig. T.1.28: Test curve of Q_o vs E_{acc} for cavity HB505.

One of these cavities, HB501, has been successfully dressed at RRCAT. On the other hand, 3 nos. of five-cell HB650 SCRF cavities viz., RRCAT-HB502, HB504, and HB506 have been developed and sent to Fermilab as in-kind contribution in the R&D phase of IIFC collaboration, which shall be further processed, tested, and dressed at Fermilab.

Acknowledgements

The reported work represents contributions from a large number of colleagues from various divisions and sections of Proton Accelerator Group as well as Electron Accelerator Group and Technology Development and Support Group. We sincerely acknowledge their contribution.

References

[1] S. C. Joshi, S. Raghavendra, V. K. Jain, A. Puntambekar, P. Khare, J. Dwivedi, G. Mundra, P. K. Kush, P. Shrivastava, S. B. Roy, P. R. Hannurkar and P. D. Gupta, "Development of Superconducting Cavities and Related Infrastructure for High Intensity Proton Linac for Spallation Neutron Source," in 27th LINAC, Geneva, 2014.

[2] S. C. Joshi, S. Raghavendra, V. Jain, A. Puntambekar, P. Khare, J. Dwivedi, G. Mundra, P. K. Kush, P. Shrivastava, M. Lad and P. D. Gupta, "Development of Infrastructure Facilities for Superconducting RF Cavity Fabrication, Processing and 2 K Characterization at RRCAT," Materials Science and Engineering, vol. 171, p. 012114, 2017.

[3] S. C. Joshi, S. Raghavendra, S. K. Suhane, M. Kumar, P. Mohania, A. Chauhan, P. Fatnani, P. Shrivastava, P. K. Kush and P. D. Gupta, "Commissioning of Vertical Test Stand Facility for 2 K Testing of Superconducting Cavities at RRCAT," in 27th LINAC, Geneva, 2014.

[4] M. Bagre, T. Maurya, A. Yedle, S. Moulali, V. Kumar, A. K. Singh, V. Yadav, V. K. Srivastava, A. Puntambekar and S. C. Joshi, "Development of process parameters for Electron Beam Welding of various parts of a 650 MHz five cell SCRF cavities," in InPAC, Indore, 2018.

[5] A. Puntambekar, M. Bagre, R. S. Sandha, P. Shrivastava, G. Mundra, P. Ramsankar and S. C. Joshi, "Indigenous development of first five-cell 650 MHz SCRF cavity and series manufacturing plans," in InPAC, Indore, 2018.

[6] S. Moulali, V. Jain, M. Bagre, V. Kumar, A. Singh, A. Yadav, A. Puntambekar and V. Namdeo, "FE analysis of SCRF cavity weld joints and its experimental verification," in InPAC, Kolkata, 2013.

[7] S. Raghavendra, K. K. Das, A. Singh, S. V. Kokil, S. K. Chauhan, A. Bose, P. S. Ram, S. K. Suhane, D. S. Rajpoot, A. P. Singh, M. Hussain, K. Prasad, A. Sahu and S. C. Joshi, "Electropolishing of five-Cell 650 MHz (β=0.92) Superconducting RF Cavity," in InPAC, Indore, 2018.

[8] S. Raghavendra, S. K. Suhane, P. S. Ram, A. P. Singh, A. Singh, K. K. Das, S. K. Chauhan, S. V. Kokil, D. S. Rajpoot and S. C. Joshi, "Electropolishing of Superconducting RF Cavities," in 32nd DAE Safety & Occupational Health Professionals Meet, Indore, 2015.

[9] S. K. Suhane, S. K. Chauhan, K. K. Das, A. Chaturvedi, S. V. Kokil, D. S. Rajpoot, B. Oraon, M. A. Hussain, S. Raghavendra and S. C. Joshi, "High Pressure Rinsing facility for elliptical shaped niobium superconducting cavities," in InPAC, Indore, 2018.

[10] N. K. Sharma, G. V. Kane, N. Nigam, S. V. Kokil, S. K. Chauhan, B. Oraon, P. Kumar, A. Sahu, A. Chaturvedi and S. C. Joshi, "Indigenous development of a tuning machine for five-cell 650 MHz SCRF cavities," in InPAC, Indore, 2018.

[11] V. K. Jain, C. Grimm, I. V. Gonin, T. N. Khabiboulline, A. Rowe, T. Nicol and V. P. Yakovlev, "Progress of HB650 Cavities for PIP-II Project at Fermilab," in InPAC, Indore, 2018.

[12] K. K. Singh, V. Jain, S. V. Kokil and S. C. Joshi, "Development and testing of an open loop control system for coaxial blade tuner," in National Symposium on Instrumentation-38, Hubli, 2013.

[13] K. K. Singh, A. Yedle, S. Mandle, V. K. Jain and S. C. Joshi, "HB650 Tuner Testing Scheme with Single-cell SCRF Cavity," in *InPAC*, Indore, 2018.

[14] S. Raghavendra, S. K. Suhane, N. K. Sharma, S. K. Chauhan and S. C. Joshi, "Fabrication and testing of 2K Cryostat for Vertical Test Facility at RRCAT," Indian Journal of Cryogenics, vol. 39, no. 1, p. 13, 2014.