Development of Infrastructure Facilities for Superconducting RF Cavity Fabrication, Processing and 2 K Characterization at RRCAT

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Abstract. An extensive infrastructure facility is being established at Raja Ramanna Centre for Advanced Technology (RRCAT) for a proposed 1 GeV, high intensity superconducting proton linac for Indian Spallation Neutron Source. The proton linac will comprise of a large number of superconducting Radio Frequency (SCRF) cavities ranging from low beta spoke resonators to medium and high beta multi-cell elliptical cavities at different RF frequencies. Infrastructure facilities for SCRF cavity fabrication, processing and performance characterization at 2 K are setup to take-up manufacturing of large number of cavities required for future projects of Department of Atomic Energy (DAE). RRCAT is also participating in a DAE’s approved mega project on “Physics and Advanced technology for High intensity Proton Accelerators” under Indian Institutions- Fermilab Collaboration (IIFC). In the R&D phase of IIFC program, a number of high beta, fully dressed multi-cell elliptical SCRF cavities will be developed in collaboration with Fermilab. A dedicated facility for SCRF cavity fabrication, tuning and processing is set up. SCRF cavities developed will be characterized at 2K using a vertical test stand facility, which is already commissioned. A Horizontal Test Stand facility has also been designed and under development for testing a dressed multi-cell SCRF cavity at 2K. The paper presents the infrastructure facilities setup at RRCAT for SCRF cavity fabrication, processing and testing at 2K.

1. Introduction
Raja Ramanna Centre for Advanced Technology (RRCAT) has taken up a program on R&D activities of a 1 GeV, high intensity superconducting proton linac for a spallation neutron source, which will provide high flux pulse neutrons for research in the areas of condensed matter physics, materials science, chemistry, biology and engineering. This will complement the existing synchrotron light source facility, INDUS-2 at RRCAT and reactor based neutron facilities at BARC. RRCAT is also participating in approved mega project on “Physics and Advanced Technology for High Intensity Proton Accelerator” to support activities of Indian Institutions – Fermilab Collaboration (IIFC). The SNS facility will be based on 1 GeV accumulator ring and a 1 GeV superconducting proton linac as injector. The superconducting proton linac will require a large number of superconducting Radio Frequency (SCRF) cavities ranging from low beta spoke resonators to medium and high beta multi-cell elliptical cavities at different RF frequencies. An extensive infrastructure setup with stringent quality requirement is being
established and scientific and technical expertise is being developed for fabrication, processing and testing of the SCRF cavities for efficient production [1].

A dedicated facility for SCRF cavity fabrication, material characterization, tuning, processing and testing has been set up for this purpose. The cavity fabrication facility include a facility for deep drawing of components, precision machining facility and fixtures, 15 kW electron beam welding machine for SCRF cavity. The electron beam welding machine has a large size vacuum chamber capable of welding multi-cell SCRF cavities. A novel technique of laser-welding of superconducting niobium cavities has also been developed and world's first single-cell 1.3 GHz SCRF cavity has been fabricated and successfully tested. Cavity inspection facility has been set up which include a CNC 3-D Coordinate Measuring Machine, optical inspection bench for inspection of internal surface of cavity etc. A material characterization facility has been set up which includes a 50 kN universal testing machine, a time of flight secondary ion mass spectrometer (TOF-SIMS), a 3-D laser scanning confocal microscope etc. Facility for measurement of RRR of niobium material has been setup to inspect the material procured for cavity. RF measurement and testing facility has been developed for RF inspection and characterization of cavity components and full-length cavity. A cavity tuning machine has been developed for frequency and field tuning of multi-cell cavities. A prototype blade tuner has been fabricated for nine-cell 1.3 GHz cavity for correcting the resonance frequency after cool down to 2 K. The cavities are tested at 2 K in the Vertical Test Stand (VTS). A vertical Test Stand (VTS) is a facility for qualifying bare SRF cavities for their required performance by measuring quality factor and cavity accelerating gradient at a cryogenic temperature of 2K. The VTS cryostat has been designed for a large testing aperture for testing variety of SRF cavities including 325 MHz Spoke resonators, 650 MHz and 1.3 GHz multi-cell SRF cavities [2].

2. SCRF cavity fabrication facilities

The cavities are made using blanks cut from high purity fine grain rolled niobium sheets. The cavity half-cells are formed by deep drawing niobium sheets using special die-n-punch on a dedicated 120 Ton hydraulic press (Fig. 1). High strength alloy of aluminum 7075-T6 is used for fabricating deep drawing die-n-punch, tooling and fixtures for trim machining of cavity halves. The cavity halves are joined together using an electron beam welding (EBW) machine in high vacuum to minimize contamination during welding. An EBW machine (Fig. 2) of 15 kW beam power has been procured and installed. The EBW machine has a large size vacuum chamber which is capable of welding low and high beta SCRF cavities required for the high intensity proton linac.
Laser-welding of 1.3 GHz SCRF niobium cavities
An innovative technique to fabricate SCRF niobium cavities by laser welding has been developed. The idea was conceptualized and developed for the first time at RRCAT. An international patent has been filed with title "Niobium based superconducting radio frequency cavities comprising niobium components joined by laser welding, method and apparatus for manufacturing such cavities".

The laser welding setup developed for the purpose is shown in Fig. 3. A 10 kW fiber coupled Nd:YAG laser developed at RRCAT has been used. The laser welding experiments were carried out on more than 150 samples for parameter optimization and the world’s first laser-welded 1.3 GHz SCRF cavity was developed. This cavity was also tested at Fermilab, USA. It reached an acceleration gradient of 31.6 MV/m with a quality factor of $1.0 \times 10^{10}$ at 2 K. The results are shown in Fig. 4.

![Laser-welding setup](image1)

![Test results of laser-welded single-cell cavity.](image2)

3. Material characterization facilities
A material characterization facility has been setup to analyse the issues related to cavity development. The facility includes –

a) 50kN Universal Testing Machine capable of measuring mechanical properties of tensile samples along with plastic strain ratio and stiffness of nine-cell 1.3 GHz cavity

b) A Time of Flight Secondary Ion Mass Spectrometer (TOF-SIMS) (Fig. 5) capable of analysing the impurity distribution in high purity niobium samples after different processing steps. Depth profiles of the sample was obtained by alternately bombarding the surface with a pulsed Bismuth ion gun for analysis and Cesium ion gun for sputtering.

![Secondary ion mass spectrometer](image3)

![3D Laser scanning confocal microscope](image4)
c) 3D Laser Scanning Confocal Microscope (LSM) (Fig. 6) with 1 nano-meter depth resolution capable of measuring the surface roughness and profile of various defects like pits, dents, scratches etc. It also finds application in measuring the depth of craters created during depth profiling of niobium samples using TOF SIMS.

4. Cavity inspection facilities
Facilities for inspection of various components of cavity and the cavity is developed and installed. The facilities include:

a) A CNC 3D co-ordinate measuring machine (Fig. 7) is procured for assessing the form accuracy of the cavity parts. The CMM can handle jobs up to 2000mm x 1200mm x 1000mm & measure with a resolution of 0.1 microns and accuracy of 1.6+L/400 microns.

b) A system is developed to optically inspect the internal surface of 1.3 GHz and 650 MHz SCRF cavities (Fig. 8). The system will be useful to study the relation between achieved field gradient and defects on the internal surface of SCRF cavities. A high resolution camera and illumination system is used to obtain high resolution images. The system provides a resolution up to 40µm/pixel. The smallest measurable feature size is 10 microns.

Fig. 7: 3D CNC Co-ordinate Measuring Machine

Fig. 8: Optical inspection bench

5. SCRF cavity processing facilities
It is a challenging task to produce SCRF cavities with high accelerating gradient. To achieve a reliable production of high performance cavities one needs to couple processing and performance tests in a tight-loop program to observe the variation in the performance of the cavity. The cavity processing includes centrifugal barrel polishing (CBP) and electro-polishing (EP) to produce smooth RF surfaces, high pressure rinse (HPR) stations to remove particulates from cavity surfaces, and vacuum furnace to remove hydrogen. Major cavity processing facilities are briefly described below:

5.1. Centrifugal barrel polishing machine (CBP)
The top surface layer in a SCRF cavity up to 100-150 microns is removed by mass finishing operations (CBP & EP). A surface finish of a few tens of nanometer is obtained using barrel polishing. Two CBP machines have been developed with the help of an Indian industry. Fig. 9 shows a centrifugal barrel polishing machine to accommodate two single-cell 1.3 GHz SCRF cavities. The rotational speed can be varied from 0 to 200 rpm independently for barrel and turret of the machine. This was a prototype machine which helped in developing an understanding of the process. Based on the experience from this machine, a machine for polishing five-cell 650 MHz cavities was developed. Fig. 10 shows a centrifugal barrel polishing machine to accommodate four five-cell 650 MHz SCRF cavities.
5.2. Electropolishing set-up
Electro polishing (EP) is an electro-chemical method of removing thin layers of niobium from the cavity surface by anodic dissolution. In the basic electro-polishing set-up, the cavity is the anode and a hollow coaxial aluminum tube is the cathode which is placed along the cavity axis.

The electrolyte is a mixture of hydrofluoric (HF) and sulphuric acid ($\text{H}_2\text{SO}_4$). Two horizontal continuous electro-polishing setup is developed for electro-polishing of the 1.3 GHz and 650 MHz niobium cavities (Fig. 11 and Fig. 12).

5.3. High pressure rinsing set-up
High pressure rinsing (HPR) is a super-cleaning process for the surface preparation of superconducting cavities. In this process high pressure jets of ultra-pure water dislodge surface contaminants from the cavity surfaces that is normally difficult to remove with conventional rinsing procedures. Cavities treated finally with HPR leads to a substantial reduction in the field emission and better performance. An HPR set-up has been developed. It comprises of a linear motion system capable of moving SCRF cavity, vertically up and down and a rotary mechanism to rotate the water jets. The water jet comes out from fine nozzle tips fitted at the end of a vertical pipe. Fi. 13 shows the HPR setup.

5.4. Thermal processing facility
During EP, hydrogen bubbles come in direct contact with the Nb surface which increase absorption of hydrogen. With more than 100 atomic ppm hydrogen dissolved in Nb surface / bulk, there is a possibility of niobium hydride precipitation during cool-down (at around 100 K). This results in reducing the quality factor of the cavity at high accelerating gradient.
A furnace treatment at 800°C for 3 hours or 600°C for 10 hours reduces the hydrogen concentration to a few atomic ppm in the bulk and in the surface layer. For thermal processing of niobium superconducting RF cavities, a dedicated high vacuum annealing furnace (Fig. 14) is procured. The furnace has a hot zone of diameter 825 mm and 1525 mm length with a maximum temperature of 1400°C and a temperature stability of ±5°C.

6. SCRF cavity tuner development

Tuner is an essential part of an SCRF cavity, which corrects the resonance frequency after cool down to 2 K. It also controls the resonating frequency instabilities (Lorentz detuning, microphonics etc.) during operation. A prototype blade tuner has been fabricated along with a prototype nine-cell 1.3 GHz cavity (in copper) for qualifying the tuner. The tuner sensitivity, stiffness, hysteresis, resolution and precise control of the tuner was tested at liquid nitrogen temperature. The tuner is also tested with piezo actuators, which are required for fast tuning control of the cavity frequency.

7. SCRF cavity test stand facility

All Superconducting radio frequency (SCRF) cavities of superconducting linear accelerators have to be qualified in two test facilities prior to installation in cryomodules of a superconducting linac. First, the bare cavities are tested in a saturated bath of liquid helium at a temperature of 2 K in the Vertical Test Stand (VTS). Cavities, qualified in VTS are then dressed with their auxiliary equipments, like helium vessel, HOM couplers, cold tuner and main coupler. These dressed cavities are then tested in a Horizontal Test Stand (HTS), under the same conditions as it will see during operation in a cryomodule, but without beam.

7.1. Vertical Test Stand

The vertical test stand consists of a large size liquid helium cryostat, an RF power supply and control system, and a liquid helium (LHe) and liquid nitrogen (LN2) piping system. The SCRF cavity is tested for the quality factor (Q) and accelerating gradient (E) at 4.2 K and 2 K. The test stand consists of a large LHe cryostat, high power RF system and low level RF control system.

A liquid helium cryostat assembly comprises of an ASME Code stamped stainless steel helium vessel, process tubing for flow of helium. These are thermally shielded with a liquid nitrogen cooled thermal shield. The assembly of LHe vessel and thermal shield is housed in a stainless steel insulating vacuum vessel wrapped in multilayer super-insulation for reducing heat leak. The cryostat has an overall dimension of diameter 1370 mm and length of 5420 mm. The VTS is equipped with two magnetic
shields. The external shield covers the outer vacuum vessel and internal magnetic shield is located inside the LHe vessel covering the SCRF cavity under test. The cryostat assembly is installed below the ground level in a pit. The pit will be covered with a movable radiation shielding lid during testing of SCRF cavities. The cryostat is shown in Fig. 15 and cavity testing in the cryostat is shown in Fig. 16 [3][4].

![Fig. 15 : VTS cryostat assembly](image1)

![Fig. 16 : Cavity under test in VTS](image2)

The 1.3 GHz nine-cell SCRF cavities require ~250 W of CW power to produce accelerating gradient in excess of 35 MV/m. Keeping in view the maximum field gradient to be achieved in the cavities and the margins for other losses, a 1.3 GHz, 500 W CW solid state power amplifier system has been designed and developed. The amplifier operates with a bandwidth of 1270-1310 MHz. The amplifier consists of a water-cooled high power stage driven by an air-cooled 50 W amplifier. The low level RF (LLRF) system tracks the cavity frequency using a phase locked loop (PLL) which maintains the frequency of the RF source equal to the cavity resonance frequency. The amplitude and phase of RF power going to the cavity is controlled with a modulator. The LabView based data acquisition and control software provides the complete control of phase in 0-360° and amplitude in 0-40 dB range. The incident, reflected and transmitted power from the cavity is measured using power meters in CW mode and diode detectors in pulsed mode. The power meter, generator and counter are connected via a GPIB to the data acquisition software which records the data and facilitates real-time plotting of quality factor ($Q_0$) v/s accelerating gradient (E) and calculates errors associated with all measured and calculated quantities.

Performance of SCRF cavities is limited by power dissipated either by the field emission, multipacting or thermal breakdown. These loss mechanisms present the major snag in achieving high gradient cavities. To improve the understanding of cavities limited performance, the powerful combination of Thermometry and microscopy is being used as a universal tool by international laboratories for extensive study of quench mechanism. A temperature mapping system has been designed and developed for identifying the quench location during vertical testing of cavity. This system is suitable for thermal mapping of key region of the single cell SCRF cavity (equator region). This system is generally deployed almost every time while testing single cell cavities. The prototype system has been successfully applied during the VTS runs of the cavity.

7.2. Horizontal Test Stand
A horizontal test stand (HTS) has been designed. This system will facilitate testing two 5-cell 650 MHz SCRF cavities at a time. It can be used for testing SCRF cavities in both CW and pulse mode at operating temperature of 2 K. The fabrication of the cryostat for the facility is under process.

For testing of 650 MHz superconducting RF cavity, high power solid-state RF amplifiers with RF output of 30-40 kW range is being developed. Based on the experience of development of 505.8 MHz
300 kW solid state RF amplifier, a 30 kW (average) solid-state amplifier has been developed at 650 MHz. The RF amplifier consists of 500 W power amplifier modules, 2-way power combiner, 40-way power dividers and combiners, and high power directional couplers. The 30 kW RF amplifier is realized with two amplifier racks each of 15 kW, housed in a single euro rack with 40 nos. of RF amplifier modules, DC power supplied, power dividers and combiners. The final power of 30 kW is obtained in 6 inch coaxial line with two 15 kW racks combined.

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