RAPID GROWTH OF SRF IN INDIA

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Abstract

The rapid growth of the superconducting radio frequency (SRF) activities at various research centres in India for the development of modern accelerators are summarized. The SRF related activities at Inter-University Accelerator Centre (IUAC) at Delhi, Raja Ramanna Centre for Advanced Technology (RRCAT) at Indore, Bhabha Atomic Research Centre (BARC) and Tata Institute of Fundamental Research (TIFR) both located at Mumbai, and Variable Energy Cyclotron Centre (VECC) at Kolkata are reviewed. The design, fabrication and test facility of niobium quarter wave resonator (QWR) were developed at Inter University Accelerator Centre (IUAC), Delhi at the beginning of this century. The expertise in development of fabrication of niobium cavities, and the availability of fully operational electron beam welding facility along with the various welding parameters developed during more than a decade have been utilized by other laboratories in India and abroad for the development and fabrication of various types of niobium resonators. The SRF related programs at RRCAT, BARC, TIFR and VECC are discussed.

INTRODUCTION

The development of niobium quarter wave resonators (QWRs) was initiated in late ninety eighties by IUAC. Subsequently IUAC developed the collaboration with Argonne National Laboratory (ANL) in early ninety nineties for fabrication and test of initial batch of a new type of bulk 97 MHz two-gap niobium QWRs. The first set of facilities in India for niobium SRF fabrication, surface preparation and tests for the development of superconducting linear accelerator (linac) booster accelerator were developed at the beginning of this century. The superconducting linac booster has been delivering energetic heavy ions regularly for scheduled experiments using the various cavities fabricated at ANL and later at IUAC.

The SRF facility at IUAC became the first fully functional niobium based superconducting resonator design, fabrication and test facility in India. The QWRs developed using these facilities are being used routinely for boosting the energy of the heavy ion beams from the 15 UD Pelletron Tandem Accelerator at required energies to a large number of researchers to carry out scheduled experiments in nuclear physics, materials sciences and atomic physics. The initial batch of QWRs were developed and fabricated in collaboration with Argonne National Laboratory (ANL) in the nineties. Scientists and engineers of IUAC got an excellent opportunity to collaborate with and get trained at ANL. The majority of the niobium resonators of the three superconducting linear accelerator (linac) modules of IUAC were built by the in-house niobium resonator fabrication facilities.

A superconducting lead plated QWR based linac accelerator has been indigenously developed by Tata Institute of Fundamental Research (TIFR) Mumbai and Bhabha Atomic Research Centre (BARC) Mumbail at TIFR to boost the energy of heavy ion beams delivered by the 14 MV Pelletron tandem accelerator. The superconducting booster linac consisting of three accelerating modules in phase I was commissioned in 2002 as first functional superconducting linac in the country. In July 2007, Silicon ions were accelerated using all seven modules. They were transported to the experimental stations in the first user hall. Most of the critical components of the linacbooster have been designed, developed and fabricated indigenously.

There are three major national level projects undertaken in three laboratories of Department of Atomic Energy (DAE). They are: (a) Accelerator Driven sub-critical System (ADS) at Bhaba Atomic Research Centre (BARC), Mumbai; (b) Indian Spallation Neutron Source (ISNS) at Raja Ramanna Centre of Advanced Technology (RRCAT), Indore; and (c) Advanced National facility for Unstable and Rare Isotope Beam (ANURIB) at Variable Energy Cyclotron Centre, Kolkata. In these projects, different types of niobium resonators e.g. half wave, spoke, elliptical resonator in the frequency range of ~ 150 MHz to 1.3 GHz are being developed. Simultaneously the cryostats, power couplers, frequency tuners, RF and, control systems are also being developed.

Fermi National Accelerator Laboratory (FNAL) has proposed the construction of a High Intensity Superconducting Proton Accelerator (HISPA) also known as Proton Improvement Plan (PIP-II). Due to the similar accelerator goal of FNAL, USA and the DAE institutions of India and IUAC Delhi, a collaboration named as Indian Institutes and Fermilab Collaboration (IIFC) has been established to design and develop the superconducting radio frequency accelerators for both the Indian and Fermilab programs [1]. Presently, the R&D activities are going on in Fermilab and Indian institutions including IUAC with the goal of joint preparation towards the construction of the accelerators for the respective domestic programs.

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GROWTH IN SRF ACTIVITIES

The design and development of niobium based superconducting linac was initiated at IUAC to augment the energy from 15UD Pelletron tandem accelerator [1]. The linac was designed to have five cryostats, the first one being the Superbuncher (SB) followed by three accelerating modules followed by a Rebuncher (RB) cryostat, to accommodate twenty seven quarter wave resonators (QWR) made of bulk niobium (Figure 1). The design and the fabrication of the prototype resonator [2] were done in collaboration with Argonne National Laboratory (ANL), USA. After the successful completion of the prototype resonator, the collaboration was extended to fabricate twelve more niobium resonators which were carried out by the IUAC personnel by using the facilities at ANL [3]. At the same time, initiative was being taken up to develop the complete fabrication facility at IUAC to accomplish the fabrication job of the remaining niobium resonators of the full linac system [4].

Figure 1: The indigenous niobium QWR successfully fabricated and tested at IUAC.

In 2001, the prototype resonator was installed in the SB cryostat and it was tested with the beam to produce ~ 130 picoseconds beam bunch at the entrance of linac [5]. Subsequently, more resonators and cryostats were added in phases and various modifications, improvements were implemented on the linac facility. From 2008, various ion beams through linac were accelerated for the scheduled experiments [6,7]. By 2011, the second accelerating module (linac-2) was commissioned and energy delivered for scheduled experiments has been increased subsequently. In 2012, the third accelerating module was operational and started accelerating beams for scheduled experiments [8]. The maximum energy gain obtained from SC linac had been measured to be 8.8 MeV/charge state by using all the three accelerating modules along with the Sb and RB cryostats. The beams of ^{12}C, ^{19}F, ^{28}Si, ^{30}Si, ^{35}Cl, ^{37}Cl, ^{48}Ti and ^{107}Ag were accelerated and delivered to the users for the scheduled experiments using these QWRs.

The operation of linac went through different stages of developments to overcome many technical challenges to improve the performance of linac and to make the linac operation more rugged and reliable. A dome structure was added to replace the flat top plate of the initial batch of resonators where the liquid helium bubbles might be trapped thus reducing the cooling efficiency of the top portion of the resonator. This modification had enhanced the power to extract heat load from the critical location of the resonators where the current flow and the magnetic field was the maximum. This modification resulted in an improvement of the accelerating fields in the resonators.

The microphonics coupled to the SC resonator from the ambience is the main cause of the frequency jitter around the central frequency and hence demands more forward RF power to achieve the phase lock. In IUAC's QWR, the vibration picked up by the central conductor contributes mainly to the total amount of the frequency jitter of the SC resonator. To reduce this vibration, optimum number of stainless steel balls having a specific diameter were placed at the end of the central conductor. This mechanism damped the vibration of the central conductor. The forward RF power at the time of phase locking was reduced by a factor of more than 50% [9]. Initially the gas based tuning mechanism adopted from ANL system was implemented in all the QWRs. But a piezo based tuner mechanism which got much faster correction time than the existing gas based tuning mechanism was successfully implemented in all the resonators of the second and third accelerating modules [10]. Due to space limitation, the piezo tuner could not be implemented in the first accelerating modules. Another improved version of the gas tuner called the Pulse Width Modulator (PWM) tuner which is slower than the piezo-tuner but faster than the original gas based tuner, was successfully implemented on the resonators of first accelerating module [11]. The improved methods of phase locking by piezo tuner and the PWM based gas tuner made phase locking much easier with lower RF power.

It was observed that if the central conductor was not perfectly co-axial with respect to the outer cylinder of the niobium resonator, then the vibration of the central conductor gave rise to more frequency jitter. More frequency jitter caused by the non-coaxial central conductor required more RF power from the amplifier for phase locking. To reduce the forward RF power during phase locking, it was required to improve the co-axiality of the central conductor. In the QWR of IUAC, it is not easy to maintain the perfect co-axiality of the central conductor, as the piece was fabricated with half a dozen electron beam weld joints before it was joined to the outer cylinder. So after fabrication was over, the co-axiality of the central conductors was checked and the errors exceeding ±0.5 mm were corrected with a special fixture [8] developed for this purpose. These corrections made the phase locking much easier for the SC resonator with lesser RF power.

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Indigenous fabrication of resonator [4] facility at UAC has been used for fabrication of various superconducting niobium resonators. Apart from the Test Cryostat facility for testing superconducting niobium resonators at 4K, three major facilities were set up, which are: electron beam welding facility, surface preparation laboratory for electro-polishing, and high vacuum furnace for heat treatment. This infrastructure was used successfully for the construction of niobium quarter wave resonators required for the superconducting heavy ion linac at IUAC. Figure 2 summarizes the performance of some of the indigenously built quarter wave resonators for the superconducting linac at IUAC.

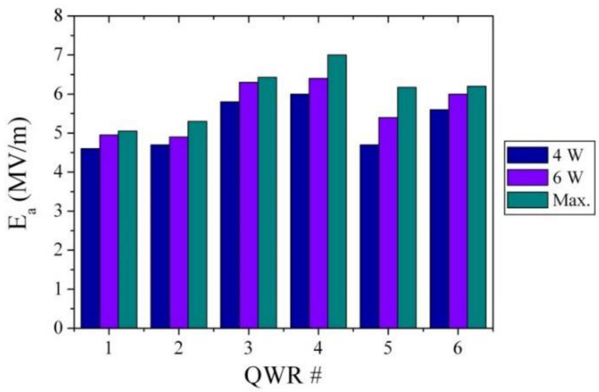

Figure 2: Performance of the indigenously developed niobium quarter wave resonators.

For the proposed high current injector program at IUAC, a prototype low beta niobium quarter wave resonator (β=0.5, f=97 MHz) has been designed and developed [12]. In the initial cold tests performed at 4K, the low beta resonator could easily exceed the nominal design goal of 6 MV/m with less than 2 W RF power, eventually reaching 9.5 MV/m accelerating gradient with 6 W RF power. In Figure 3, the performance of the resonator is shown. The resonator could be easily conditioned through the low level multipacting barriers within 2 hours. We plan to process the resonator and test again since we feel that there is scope for further improvement in its performance, especially in the low and mid gradient regions.

Apart from developing and building niobium resonators for the in-house programs, IUAC has also been involved in a number of collaborations, both with national as well as international laboratories. Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, in collaboration with IUAC has developed single cell and 5-cell TESLA-type 1.3 GHz niobium cavities. The development of the forming dies and subsequent machining of the parts for constructing these cavities was done at RRCAT, while the electron beam welding was performed at IUAC. All the welding fixtures were designed jointly by the two Centers, but they were manufactured at RRCAT. The cavities were sent to Fermilab for processing and testing in VTS. In cold tests, the third and fourth single cell cavities exceeded the ILC design goal of 35 MV/m, with the third cavity reaching 40 MV/m at 1.8K (Figure 4) and the fourth cavity reaching 37.6 MV/m at 2K. The 5-cell TESLA type cavity was also processed and tested at Fermilab. This cavity achieved 42 MV/m at 1.5-1.7K.

After PIP=II (earlier called Project X) design was modified to incorporate elliptical cavities operating at 650 MHz (instead of 1.3 GHz), RRCAT started working on developing the high beta (β=0.9) cavity. In the first instance, a single cell cavity was jointly developed by RRCAT and IUAC. This cavity was again sent to Fermilab for processing and testing. In VTS cold tests it exceeded the design goal and achieved 19.3 MV/m gradient at $Q_0=3\times10^{10}$.

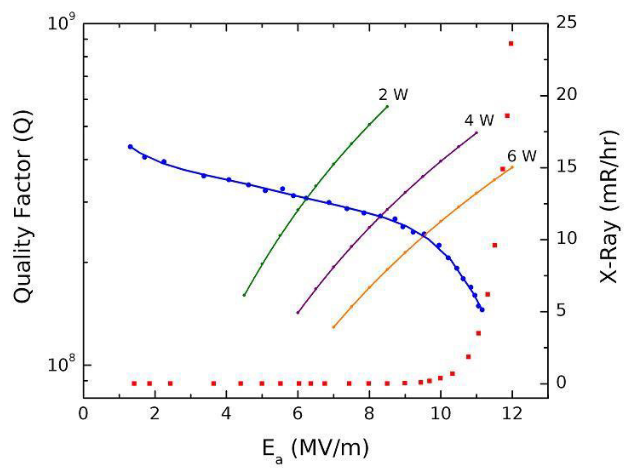

Figure 3: Quality factor Q as a function of accelerating gradient E_a at 4.2 K in the prototype niobium low beta resonator.

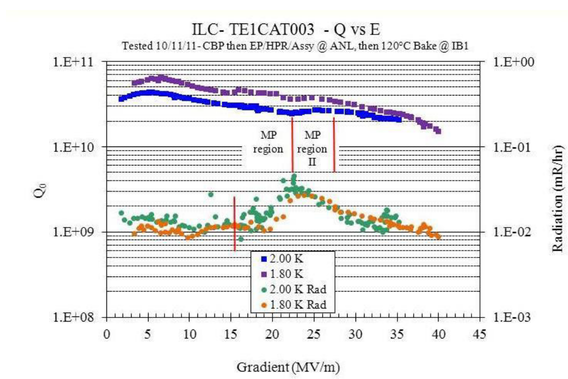

Figure 4: VTS performance of the a single cell TESLA-type niobium cavities developed by RRCAT and IUAC.

In addition to national collaborations, IUAC has also been involved in international collaborations for developing superconducting niobium cavities. IUAC recently completed developing two niobium single spoke resonators for PXIE accelerator as part of PIP-II project of Fermilab. All the niobium material for the two resonators was supplied by Fermilab. All the dies, -machining, welding and electro-polishing fixtures - were designed & developed at a vendor in New Delhi who has

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been working with IUAC in developing superconducting niobium resonators. The electron beam welding and electro-polishing was done at IUAC. Substantial amount of effort was put in the development and validation of the various processes required for manufacturing the cavities. In Figure 5, the two resonators built by IUAC are shown.

Figure 5: The two niobium single spoke resonators (SSR1) developed and built at IUAC for FNAL.

The resonators were sent to Fermilab for processing and testing [13]. At 2K, the first of the resonators tested exceeded the PIP-II design specification to produce 12 MV/m accelerating gradient at $Q_0=1.3\times10^{10}$ (PIP-II design spec 12 MV/m at $Q_0=5\times10^9$), eventually reaching a maximum gradient of 18 MV/m, before quenching.

At Tata Institute of Fundamental Research (TIFR) an electron beam welding facility is installed and associated SRF systems are being developed for fabrication of niobium quarter wave resonators (150 Mhz) for upgrading the existing superconducting linac system.

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 for research in the areas of condensed matter physics, materials science, chemistry, biology and engineering. The major sub-systems of the spallation neutron source would comprise of a 1 GeV high power superconducting pulsed H-linac, an accumulator ring, spallation target and beam lines. The first step towards realizing these long term objectives is to develop capabilities to build superconducting linac that can reliably and efficiently deliver a high intensity H-/ proton beam of 1 GeV energy. RRCAT has taken up R&D activities for the development of a 1 GeV superconducting pulsed H- linac for Indian spallation neutron source (ISNS).

A program for setting-up of a infrastructure facility for development of SCRF cavity at RRCAT was approved. The facilities comprising of SCRF cavity forming, machining, electron beam welding, RF characterization, cavity tuning and cavity processing has been set up at RRCAT. The cavity processing includes centrifugal barrel polishing, electro-polishing, thermal processing and high pressure rinsing. A dedicated building has been constructed to house this infrastructure and clean rooms for assembly and testing of cavities. A few 1.3 GHz and 650 MHz cavities have been fabricated and tested, showing excellent performance. A prototype blade tuner mechanism for 1.3 GHz niobium cavity has also been developed. A vertical test stand (VTS) has been commissioned.

A dedicated 120 Ton hydraulic press has been installed for forming of cells of SCRF cavity from high RRR niobium sheets. High strength aluminium alloy 7075-T6 is used for fabricating deep drawing die-n-punch, tooling and fixtures for trim machining of cavity halves. The cavity halves are welded together using an electron beam welding (EBW) in high vacuum. An EBW machine of 15 kW beam power has been procured and installed (Figure 6). The EBW machine has a large size vacuum chamber which is capable of welding from low to high beta SCRF cavities required for the high intensity proton linac.

Figure 6: 15 kW electron beam welding machine.

A material characterization facility has been set up to support the SCRF cavity development. This includes a 50 kN universal testing machine capable of measuring mechanical properties of samples of cavity materials and stiffness of multi-cell SCRF cavity. A time of flight secondary ion mass spectrometer (TOF-SIMS) has been installed, to analyze the impurity distribution in high purity niobium at different processing steps. A 3-D laser scanning confocal microscope with 1 nm depth resolution, capable of measuring the surface roughness and profile of various defects has been set up. Metallographic facilities comprising of a polishing machine, a mounting press, a precision cutting machine, and a micro-hardness tester are also set up.

Major sub-systems of cavity processing facilities installed are centrifugal barrel polishing (CBP) machine (Figure 7), electro-polishing setup, high pressure rinsing (HPR) setup, horizontal high vacuum annealing furnace for thermal processing etc. 1.3 GHz single-cell SCRF cavities have been polished and processed using the facility [14].

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Figure 7: Centrifugal barrel polishing (CBP) machine.

A larger CBP machine to accommodate up to five-cell 650 MHz cavity is under fabrication. A horizontal continuous electro-polishing setup is developed for electro-polishing of the niobium cavities (Figure 8). EP process testing has been carried out on a single-cell 1.3 GHz and 650 MHz cavity using this facility. A HPR set-up has been developed. It comprises of a linear motion system, a rotary mechanism to rotate the water jets at 2 to 20 rpm, coming out from fine nozzle tips fitted at the end of a vertical pipe. A high pressure pump is used to produce water jets of 100 bar pressure.

Figure 8: Electro-polishing setup.

A dedicated high vacuum annealing furnace has been commissioned for thermal processing of SRF cavities. Thermal processing of cavities at 800°C for 2-3 hours or 600°C for 6-10 hours is necessary to reduce the hydrogen concentration to a few atomic ppm in the bulk and in the surface layer. 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.

Construction of a cavity fabrication and processing building at RRCAT has been completed for housing infrastructure facilities for cavity fabrication, chemical processing and assembly. Construction of new Cryogenics building has also been completed for housing cavity test facilities (VTS and HTS) and related infrastructure.

Stage-wise development of SRF cavity manufacturing technology has been carried out, starting from single-cell cavity to multi-cell cavities. Design and development of various tooling and fixtures for forming, machining, welding and RF testing were carried out. The electron beam welding was carried out at Inter university accelerator centre (IUAC), New Delhi and at industries. The cavity processing and testing at 2 K was carried out at Fermilab and Argonne National Laboratory (ANL), USA under Indian Institutions and Fermilab Collaboration (IIFC). The cavities achieved an accelerating gradient > 37 MV/m with the quality factor > 2.1×10^{10} during testing at 2 K. [15]

A single-cell 650 MHz, beta=0.9 SCRF cavity was fabricated at RRCAT and EB welding was carried out at IUAC, New Delhi facility. The processing and 2 K testing was done at Fermilab under IIFC for performance evaluation [16]. The cavity achieved the accelerating gradient (Eacc) of 19.3 MV/m with excellent quality factor Q_0 7×10^{10} at 2.1K during VTS testing. The cavity performance exceeded the rated specification of acceleration gradient (Eacc) of 17 MV/m with quality factor $Q_0 > 2.0\times10^{10}$ (Figure 9). The cavity was free from field emission and multipacting.

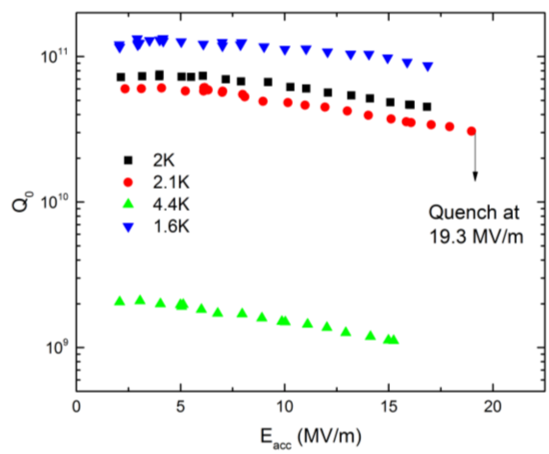

Figure 9: The Q_0 vs E plot.

An innovative technique to fabricate SCRF niobium cavities by laser welding has been developed at RRCAT. The idea was conceptualized and developed for the first time. 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 Figure 10. 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. The world's first laser-welded 1.3 GHz SCRF cavity was developed at RRCAT. This cavity was processed and tested at

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Fermilab, USA. It reached an acceleration gradient of 31.6 MV/m with a quality factor of 1.0 x 1010 at 2 K [17].
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Figure 10: Laser-welding setup.

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.

SRF cavities have to be qualified for their performance prior to installation in a cryomodule 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 equipment, like helium vessel, HOM couplers, cold tuner and main coupler. These dressed cavities are then tested in a Horizontal Test Stand (HTS).

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 (LN_2) piping system. The SCRF cavity is tested for the quality factor (Q) and accelerating gradient (E) at 4.2 K and 2 K. The facility has been commissioned and benchmarked by testing a single-cell 1.3 GHz SCRF cavity tested earlier at Fermilab, USA. The details of development and commissioning of VTS facility has been reported [18].

Bhabha Atomic Research Centre (BARC) is one of the leading large Development and Research centre having extensive infrastructural support to develop various systems for SRF activities. In addition to the co-ordination of IIFC collaboration it is involved in the developments most of the systems as well as those not taken up by other centres. It is involved in the design and development of Single Spoke Resonators (SSR2) and other SRF cavities, high power RF couplers, Feed Box, Transfer Lines, Feed Cap and End Cap of cryo-module test facility, high power solid state 325 MHz RF amplifiers, magnets The expertise developed and the systems fabricated will be very useful for the IIFC, ISNS and the 1GeV high intensity superconducting proton accelerator for ADS [19].

Variable Enery Cyclotron Centre (VECC) Kolkata has been constructing a new facility called ANURIB (Advanced National facility for Unstable and Rare Isotope Beams) at their upcoming new campus in Kolkata [20]. To be built in phases starting from low energy of 1.5 keV/A in phase-I to a final energy of 100 MeV/u in the next phase, ANURIB will be a combined ISOL and PFS type facility. Two primary accelerators are planned aimed at producing both neutron-rich and proton-rich beams. First one, a 50 MeV 100 kW superconducting electron linac (e-Linac) photo-fission driver, is being developed in collaboration with TRIUMF Canada. The project has received funding for phase-1 in 2013 for constructing the electron accelerator (till 30 MeV), electron target module and low energy experimental facility (LEEF) along with the phase-1 building.

In the e-Linac, electron beam from a thermionic gun having energy of 300 keV will be accelerated first to 10 MeV in an Injector Cryo-Module (ICM) housing one 1.3 GHz 9-cell cavity to be operated at 2K. Thereafter the beam would be further accelerated to 50 MeV in two Accelerator Cryo-Modules (ACM), each housing two 9-cell cavities. Last year in a test run at TRIUMF, successful beam acceleration to 23 MeV using ICM and one nine cell cavity inside ACM1 has been demonstrated. A second ICM meant for VECC is presently under construction at TRIUMF (Figure 11). It will be tested at TRIUMF in early 2016 and thereafter shipped to VECC where an e-Linac test area has been set-up at the existing campus for initial R&D and beam tests.

Figure 11: Injector Cryo Module at TRIUMF for the VECC superconducting Electron Linac (e-Linac).

Recently a single cell 650 MHz low beta (β=0.6) niobium cavity has been developed by Variable Energy Cyclotron Centre (VECC), Kolkata, and IUAC. Similar to RRCAT and IUAC collaboration, VECC designed &

developed the forming tools. The welding fixtures were jointly designed by IUAC and VECC. They were, however, manufactured by VECC. The single cell cavity is shown in Figure 12. It will be sent to Fermilab for processing and testing.

Figure 12: Single cell 650 MHz, β=0.6 niobium cavity developed by VECC and IUAC.

CONCLUSION AND OUTLOOK

The SRF activities initiated in a few research laboratories in the later part of nineteen nineties mainly to develop heavy ion accelerators for basic research purposes have shown a fast growth in India during last decade due to large accelerator and associated developmental activities taken up by different leading laboratories in the country.

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