INDIAN CAVITY FABRICATION FACILITY AND TEST RESULTS

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Abstract

The first module of the superconducting linac at the Inter-University Accelerator Centre (IUAC) has been commissioned and several different beams have been accelerated and delivered for experiments. The niobium quarter wave resonators for the first module were constructed in collaboration with Argonne National Lab, USA. For constructing the resonators for the second and third modules a resonator fabrication facility was commissioned at IUAC in 2002. Several resonators have been constructed using this facility. Based on the operational experience with the first linac module, some design modifications have also been done. In addition, several existing resonators have been successfully reworked and restored from a variety of problems. Apart from building resonators for the in-house programs, a project to build two single spoke resonators for Project-X at Fermi Lab, USA has also been taken up. A Tesla-type single cell cavity is also being built in collaboration with RRCAT, Indore. This paper presents details of the fabrication, test results and future plans.

INTRODUCTION

The superconducting linear accelerator at the Inter-University Accelerator Centre (IUAC) consists of three cryomodules, each holding eight niobium quarter wave resonators [1]. The prototype niobium quarter wave resonator (QWR) was designed and developed in collaboration with Argonne National Laboratory (ANL), USA [2]. In addition to the prototype resonator, all the resonators for the first linac module, superbuncher and rebuncher were also built at ANL [3]. This portion of the linac has been commissioned [4] and several beams have been accelerated and delivered for user experiments [5]. For constructing the QWRs for the 2nd and 3rd modules, as well as resonators for future projects, a Superconducting Resonator Fabrication Facility (SuRFF) was setup at IUAC [6]. The facility was commissioned in 2002.

In the first phase, a single QWR was fabricated and tested. Subsequently two completely indigenous QWRs were built and tested. While the first QWR was built using all the in-house facilities, the next two QWRs were built using SuRFF, and the machining and forming facilities at a local vendor keeping future production and fabrications in mind. After the successful testing of the indigenously built QWRs, production of 15 QWRs for the 2nd and 3rd modules began [7]. The production is presently nearing its completion. In addition to the in-house projects, two single spoke resonators for Fermi National Lab, USA, and a Tesla-type single cell cavity in collaboration with RRCAT, Indore, are also being built.

SUPERCONDUCTING RESONATOR FABRICATION FACILITY (SURFF)

For constructing the niobium resonators indigenously, three major facilities were setup at IUAC. An electron beam welding facility (EBW), a surface preparation laboratory (SPL) for electropolishing the niobium resonators and a high vacuum furnace (HVF) for annealing and heat treatment of the resonators and its components. Besides this, a simple test cryostat (STC) was also fabricated and commissioned.

The EBW, procured from M/s Techmeta, France, is a 4-axis CNC controlled machine having maximum beam power of 15 KW (60 kV, 250 mA). The vacuum chamber is 2.5 m × 1.0 m × 1.0 m, which is pumped by two large diffusion pumps having water cooled baffles. The machine is equipped with a rotary fixture with tilting facility. It is programmed and run using the CNC-ICN system through a PC and touch screen. For viewing, a CCD camera is provided which can be used both during the setting up of the job, and also during actual welding. In figure 1, the EBW facility is shown.

Figure 1: Electron beam welding facility at IUAC.

The SPL is set up for electropolishing (EP) the resonators. The EP process, which is well established [8], uses a mixture of sulphuric and hydrofluoric acids in the volumetric ratio 85:15. A constant voltage power supply, typically operating at 18 V DC, is used. The power supply is switched ON for one minute and switched OFF for one to two minutes, which constitutes one cycle. The acid temperature is maintained between 30-35 °C. During the OFF time the acid mixture is re-circulated. Twenty cycles removes approximately 25 µm from the niobium surface. Typically the resonators are polished 150-200 cycles.

The SPL has all the facilities of a chemical lab suitable for electropolishing, e.g. large fume hood, sink, 0-20 V, 1000 A power supply, water chiller for maintaining the acid temperature, acid handling pumps, large ultrasonic cleaner, safety shower, storage refrigerator etc. A separate clean room area has been built for assembling and storing of the resonators. Although a high pressure rinsing system has been installed, it has not been commissioned and used for rinsing resonators. The entire EP process is monitored and controlled through a computer.

The HVF, procured from M/s Hind High Vacuum, India, is a bottom loading type furnace which can operate upto a maximum temperature of 1300 °C. The furnace is pumped by a 6000 l/s oil free turbo pump, which maintains the vacuum at $< 5 \times 10^{-6}$ mbar. The furnace can be programmed & monitored, both manually, as well as through a PC. A niobium cylindrical chamber of size ϕ600 mm × 1000 mm (size of the hot zone) is used for enclosing the resonator. In figure 2, the furnace is shown.

Figure 2: High vacuum furnace at IUAC.

RESONATOR FABRICATION

1st QWR

After the SuRFF was commissioned and the various facilities had been calibrated, tested, and in the case of EBW the welding parameters were developed, fabrication of a single QWR was taken up in the first phase. During the resonator production at ANL several additional niobium parts, as spares, were made. We decided to use them in order to fabricate the first QWR so that all the facilities are checked. Some components, such as the niobium housing, top flange, ports etc. were made using the in-house workshop. However, most of the critical electron beam welds, electropolishing and heat treatment were done using the SuRFF facilities, and it provided us the opportunity to fine tune the systems. In figure 3 the offline performance of the 1st QWR is shown.

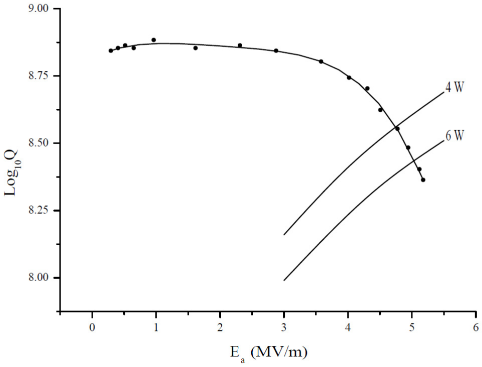

Figure 3: Offline performance of the first QWR as a function of the accelerating electric field E_a at 4.5 K.

Completely Indigenous QWRs

In the second phase of construction, two more QWRs were built. Unlike for the first QWR, all components for these two resonators were indigenously built. The niobium machining and forming was done at a local commercial vendor, while the electron beam welding, electropolishing and heat treatment was done at IUAC using the SuRFF facility. The commercial vendor was developed keeping in mind the QWR production for the 2nd & 3rd cryomodules, and future projects. Considerable effort was put in training the vendor's manpower for niobium machining, sheet metal forming, handling and in assembling the resonator components. In figure 4, an indigenously built QWR along with its niobium slow tuner bellows is shown.

Figure 4: A completely indigenously fabricated QWR along with its slow tuner bellows.

In offline test at 4.5 K one of the QWRs that was tested, indicated a low field Q of ~ 1.5×10^9. The resonator was pulse conditioned for just 10 minutes and it could easily perform at 3.5 MV/m accelerating electric field with 3.5 W input power, very close to the nominal design goal of 4 MV/m accelerating electric field at 6 W rf power. Due to shortage of time the full performance of the resonator was not achieved at that time.

The second indigenous resonator performed at 4.4 MV/m accelerating electric field at 6 W rf power, exceeding the nominal design goal. In figure 5, the offline performance of the resonator is shown.

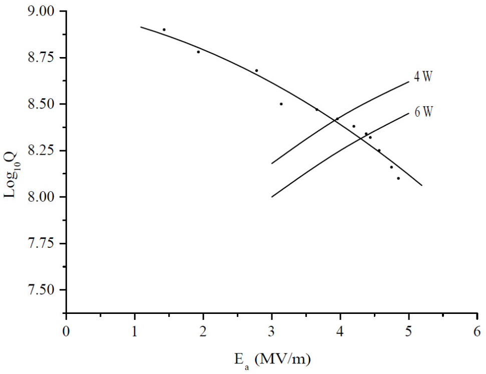

Figure 5: Offline performance of the indigenous QWR as a function of the accelerating electric field E_a at 4.5 K.

QWR Production

After the successful construction of the indigenous resonators, production of fifteen QWRs for the 2nd and 3rd modules began in the third phase. All the niobium machining & forming work has been done at the local commercial vendor and the electron beam welding, electropolishing and heat treatment were done at IUAC using the SuRFF facilities.

Based on the operational experience with the existing resonators in the first linac module, several design modifications were incorporated in the production resonators as described in the following. The original resonator design had three coupling ports [2]; one each for the drive coupler and RF pickup and a third port for the VCX fast tuner. However, the resonator control module for the IUAC linac was designed using the dynamic phase feedback control [9], which made the third port redundant. The production resonators therefore have only two coupling ports.

During the operation of the resonators in the first linac module it was found that their performance was substantially lower than in the test cryostat [4]. The possible reduction in the performance in the linac cryostat was thought to be due to trapping of helium gas bubbles between the niobium top flange (where the rf current reaches its maximum) and the stainless steel flat flange of the connection to the helium vessel, whereas in the test cryostat a large diameter SS connection was used. When the attachments in the linac cryostat were suitably modified into a hemispherical dome, the performance of the QWRs improved and reached close to the values obtained in the test cryostat. In the production resonators the hemispherical dome has been welded to the outer SS jacket, making it an integral part of the resonator. The dome would attach to the helium vessel through a CF flange. This design has the added advantage that the resonators can be baked to a higher temperature, which is known to improve its performance [10].

Two of the resonators built during the resonator production at ANL got punctured at the upper cap on the coaxial line (see details in the following section). The upper cap, which is formed in two steps, was made out of 1.6 mm thick niobium and the uniformity of the final wall thickness depended on the geometrical alignment of the cap with respect to the forming die. Subsequent heavy electropolishing further compromised with the wall thickness, which finally resulted in the puncture at the thinnest region. In order to avoid this problem on the production resonators the upper caps (and end caps) on the drift tube of the coaxial line are made out of 3.2 mm thick niobium.

For the production work the EBW fixtures were designed, wherever possible, to weld several parts in a single pump down. Similarly multiple assemblies were electropolished in a single setup to save time and effort. Although most of the tooling was available from previous constructions, additional tooling and fixtures were made, as required, to replace those which had become unusable from wear and tear. Several intermediate steps were incorporated in the fabrication process to make the resonators more reliable in construction. All the coupling and beam port bellows, and subsequently their assemblies, were thermally shocked and pressure tested to ensure vacuum leak tightness. Leaks from the coupling port bellows on several of our existing resonators had been a major problem which prompted us to go through more stringent testing (see details in the following section). The work hardened niobium slow tuner bellows (without the Nb-Cu top disc) were stress relieved by vacuum annealing the convolutions at 800 °C. Some critical electron beam welds on the drift tubes were radiographed to check porosity and other defects. Although during the welding parameter development we had gone through the procedure quite exhaustively, we felt that it would be prudent to check some welds.

The major niobium sub-assemblies of the QWR were individually electropolished to remove 150 µm from the surface. The resonators were then frequency tuned and the sub-assemblies were welded together to complete the bare niobium resonator. Based on the frequency values of the resonators they were electropolished in two different ways. Those resonators whose frequency was below or near the design value were fully electropolished to remove 50-100 µm from the surface depending on how far away their frequency was. The remaining resonators, whose frequency was higher than the design value, were first preferentially electropolished in the inductive region of the coaxial line to drop the frequency, followed by electropolishing of the full resonator to remove ~50 µm. The amount of preferential electropolishing was decided by how far away the frequency was compared to the design value. This approach ensured that most of the resonators were within ±20 kHz of the design frequency at that point of fabrication. After all the electropolishing was completed each resonator was heat treated to 1100 °C in vacuum <5 × 10^{-6} mbar. The resonators were then jacketed with the outer stainless steel vessel. At present twelve, of the fifteen, resonators and fourteen, out of the fifteen, slow tuners are ready. In Figure 6a, the production QWRs are shown. In Figure 6b, the niobium slow tuner bellows are shown. Cold testing of the resonators will begin soon.

Figure 6: (a) Top-Production QWRs ready with the outer stainless steel jackets. (b) Bottom-Slow tuner bellows.

RESONATOR REPAIRS

Puncturing of the Central Conductor

Two of the resonators built during the QWR production at ANL [3], got punctured at the upper cap on the central conductor of the coaxial line (figure 7). The upper cap is located where the capacitive drift tube joins the inductive loading arm. The resonators were cut open from the shorted end and the punctured upper caps were cut and removed from the coaxial line. After adjusting the drift tube length the new caps were welded in place. The length of the inductive loading arm also had to be adjusted in order to retain the overall length of the central conductor, thereby maintaining the rf frequency. The niobium outer housing length was also adjusted so that the beam ports on the central conductor could match the housing. The freshly inserted niobium parts on the drift tube and loading arm were electropolished to remove 100 µm from the surface, and the complete drift tube and loading arm assemblies were further electropolished to remove ~50 µm. They were then welded together and heat treated at 800 °C in vacuum < 5 × 10^{-6} mbar. After the repair, the resonators were lightly electropolished to remove ~5 µm before the cold test. Since the resonators had been heavily electropolished, before they had punctured, we did not want to risk puncturing the original closure weld and decided to only lightly electropolish them. In cold test at 4.5 K one of the resonators performed as shown in figure 8. The inferior performance of the resonator as compared to its performance before it punctured [11], as shown in the figure, could possibly be due to the very light final electropolishing done before the cold test. However, the performance is still at an acceptable level that it could be used in the rebuncher cryostat of the superconducting linac, where the accelerating electric field required is lower than the linac module.

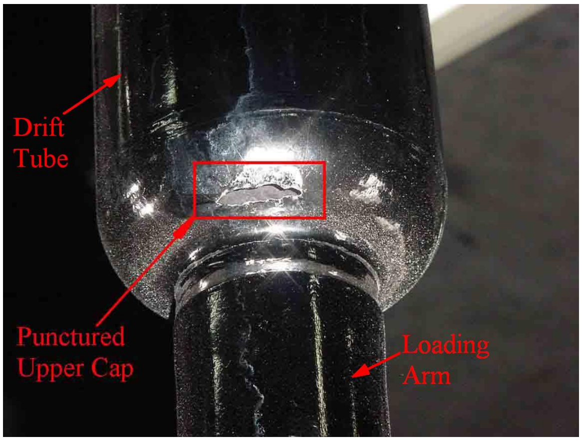

Figure 7: Punctured upper cap on the central conductor of the coaxial line.

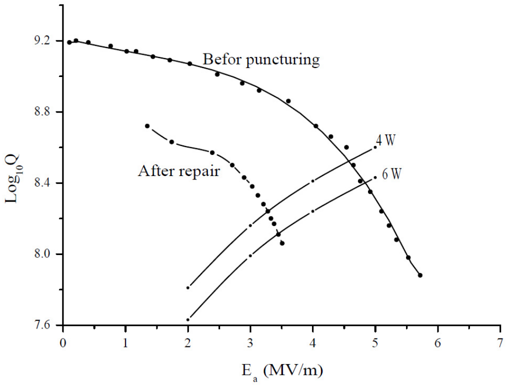

Figure 8: Offline performance of a repaired resonator at 4.5 K after the repair and before puncturing.

Vacuum Leaks from the Coupler Ports

Several QWRs in the first cryomodule had developed vacuum leaks through the coupling port transition flange bellows assembly. They were replaced with the new design as and when they occurred. Since the resonator and cryostat vacuums are common this affected the linac operation. Recently we decided to replace all the assemblies on all the resonators regardless of any leak.

The original design had used niobium-stainless steel explosively bonded flange and welded SS bellows to provide the transition from niobium to stainless steel. An alternate assembly was designed using formed SS bellows, but retaining all the other features of the original assembly [12]. The formed bellows were commercially procured with appropriate end fittings and the Nb-SS flange was electron beam welded to it. Prior to welding to the flange, the bellows were thermally shocked from 300 to 77 K atleast half a dozen times and then pressure tested. After the bellows were welded to the flange, the assemblies were again thermally shocked and then pressure tested, before welding them to the resonators. This procedure, which was also adapted on the production resonators, ensured that the resonators were leak tight. The resonators were individually pressure tested in the test cryostat, lightly electropolished and tuned, before mounting in the cryomodule. This entire effort has resulted in the cryostat vacuum improving from low 10^{-7} to high 10^{-9} mbar. In the recent linac run the cryomodule turbo pump could be isolated without degrading the cryostat vacuum level.

COLLABORATIONS

Single Spoke Resonators

Apart from constructing resonators for the in-house programs, IUAC has also taken up a project to build two niobium single spoke resonators for Project-X at Fermi National Accelerator Laboratory (FNAL), USA [13]. An exploded view of the resonator, designed for β=0.22 operating at 325 MHz, is shown in figure 9.

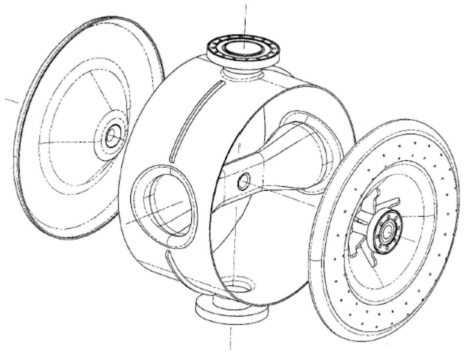

Figure 9: 325 MHz, β=0.22 single spoke resonator. The outer shell diameter is 498 mm.

The single spoke resonator has three major sub-assemblies, namely the outer cylindrical shell, the spoke - which is formed in two halves and welded together, and the end walls with its beam port and stiffening ribs. The outer stainless steel jacketing of the resonator would be done at FNAL. Apart from the smaller dies required for forming the spoke to shell collar and the coupler port pullout, the major dies required are for forming the half spoke and the end wall, both of which are non-trivial to make. Most of the initial effort went into making these two large dies.

Just like the QWRs, the spoke resonators are also being fabricated using the in-house SuRFF facilities and the local commercial vendor developed for the niobium work. The dies for forming the half spoke and end wall have been developed and several trials were done on copper sheets. The half spoke is formed in two steps; first the central flat is formed followed by the loft and the circular ends. In figure 10a, a half spoke formed in copper is shown after machining the edge. The end wall is formed in three steps; the nose is formed in two steps using two different punches. This is followed by forming of the end radius (where the shell meets the end wall). In figure 10b, an end wall formed in copper is shown. The edge has not been machined. In addition, the die for forming the spoke to shell collar has been developed and several trial pieces in copper have been formed. Development of the coupler port pull out die is also nearing completion. Apart from fabricating the dies, several machining fixtures have also been designed and built. The brazed beam ports and coupler ports will be supplied by FNAL. For the coupler ports, a niobium tube has been rolled, welded, sliced and sent to FNAL for brazing. At present the two outer shells have been rolled in niobium and they are being readied for the seam welding. The electron beam welding and electropolishing fixtures are also under fabrication. We expect the resonators to be ready by the middle of next year.

Figure 10: (a) Left – Half spoke formed in copper and after machining the edges & ends. (b) Right – End wall formed in copper. The edge has not been machined.

Tesla-type Single Cell Cavity

Raja Ramanna Centre for Advanced Technology (RRCAT), India, in collaboration with IUAC is fabricating a Tesla-type single cell cavity in niobium. In figure 11, a picture of the cavity being built is shown. All the dies, tooling and fixtures required for the fabrication have been developed and built by RRCAT. IUAC is extending its fabrication facilities and expertise and several fixtures have been designed based on its input.

The first half cell has been fabricated, which is shown in figure 12. The second half cell is also nearing completion. For developing the e-beam welding parameter for the equator joint some trials are being performed. Once the parameter has been optimized the two halves would be welded together. We plan to complete the fabrication of the single cell cavity by October this year.

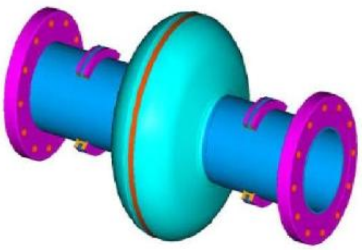

Figure 11: Tesla-type single cell cavity. The overall length is 392 mm.

Figure 12: Half cell of the Tesla-type single cell cavity.

FUTURE PLANS

A high current injector (HCI) system is being developed at IUAC for injection of highly charged ions having higher beam current (than currently available from the existing 15 UD Pelletron) into the superconducting linac. The HCI would consist of a high temperature superconducting ECR ion source [14] which will inject the beam of A/q=6 at ~8 keV/n into a room temperature radio frequency quadrupole (RFQ) [15]. The RFQ will accelerate the beam to ~180 keV/n and feed into the drift tube linacs (DTL) [16]. The DTL section would accelerate the beam to ~1.8 MeV/n for injection into the superconducting linac. In order to provide flexibility in the HCI system, as well as for increasing the mass range that could be injected into the superconducting linac from the Pelletron accelerator, a superconducting low beta module is also being planned. Figure 13 shows a schematic of the proposed system. The low beta niobium resonators in this module would be optimized for β=0.05, which is the average velocity for heavier ions from the Pelletron accelerator. The preliminary design and modelling work on the resonator has started. We expect the prototype resonator to be ready for tests in the second half of next year.

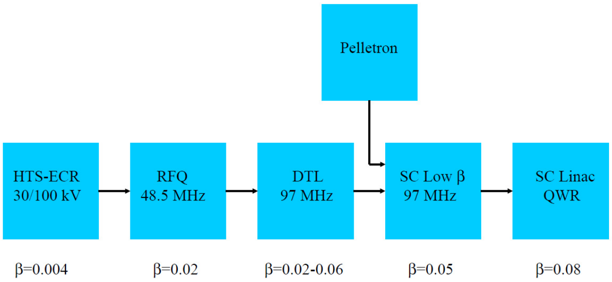

Figure 13: Proposed high current injector system at IUAC.

CONCLUSIONS

The Superconducting Resonator Fabrication Facility at IUAC has been fully operational since July 2002. Presently this is the only facility in India for constructing superconducting niobium resonant cavities. The facility is primarily being used for constructing niobium quarter wave resonators for the linac project. IUAC has successfully fabricated quarter wave resonators which have been installed in the first cryomodule of the superconducting linac. Production of fifteen resonators for the second and third modules is almost complete. The second and third cryomodules will be commissioned by the middle of next year. IUAC has also developed expertise in carrying out a variety of critical and challenging repairs on existing resonators. Two resonators have been successfully restored by repairing the punctured central coaxial line. While their present performance is inferior to their performance before they got punctured, it is still at an acceptable level. Several resonators have been repaired to fix recurring vacuum leaks from the coupling port bellows using an indigenously developed design. It has resulted in achieving better vacuum in the first linac module. In addition to building resonators for the in-house projects, construction of two single spoke resonators for Fermi Lab, USA has been taken up. Although this project has got slightly delayed, considerable progress has been made in the last ten months in developing the tooling. RRCAT, India in collaboration with IUAC is fabricating a Tesla-type single cell cavity in niobium, which would be ready for cold tests by next month.

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