# FABRICATION OF SUPERCONDUCTING NIOBIUM RESONATORS AT IUAC

P.N. Potukuchi, K.K. Mistri, S.S.K. Sonti, J. Zacharias, A. Rai, D. Kanjilal, A. Roy
Inter-University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi, India

*Abstract*

The facility for constructing superconducting niobium resonators indigenously was commissioned at the Inter-University Accelerator Centre in 2002. It was primarily setup to fabricate niobium quarter wave resonators for the superconducting booster linac. Starting with a single quarter wave resonator in the first phase, two completely indigenous resonators were successfully built, tested and installed in the cryomodules. Subsequently production of fifteen more resonators for the second and third modules began. Several existing resonators have been successfully reworked and restored from a variety of problems. In addition to 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 Resonator Fabrication Facility (SuRFF) at the Inter-University Accelerator Centre (IUAC) consists of an electron beam welding machine, surface preparation laboratory for electropolishing, high vacuum furnace for heat treatment and annealing and a test cryostat [1]. The facility was primarily setup for constructing and testing niobium quarter wave resonators for the superconducting linear accelerator [2]. After the facility was commissioned a single niobium quarter wave resonator (QWR) was successfully fabricated and tested [3]. Subsequently it was installed in the rebuncher cryostat of the linac. In the second phase two completely indigenous QWRs were fabricated. Unlike the first QWR, all the fabrication for these two QWRs was done using local commercial vendors and the in-house SuRFF facilities. In Fig. 1, one of the resonators along with its niobium slow tuner bellows is shown. In Fig. 2, the performance of one of the indigenous resonator, which has now been installed in the first linac module for beam acceleration [4], is presented. Subsequently production of fifteen more QWRs for the 2nd and 3rd cryomodules began [5]. The resonator production is presently nearing its completion. In addition to the in-house programs IUAC has taken up a project to construct two niobium single spoke resonators for Project-X at Fermi National Accelerator Laboratory (FNAL), USA. More recently IUAC and Raja Ramanna Centre for Advanced Technology, India have jointly started the fabrication of a Tesla-type single cell cavity in niobium.


Figure 1: One of the indigenously built niobium quarter wave resonators along with the slow tuner bellows.

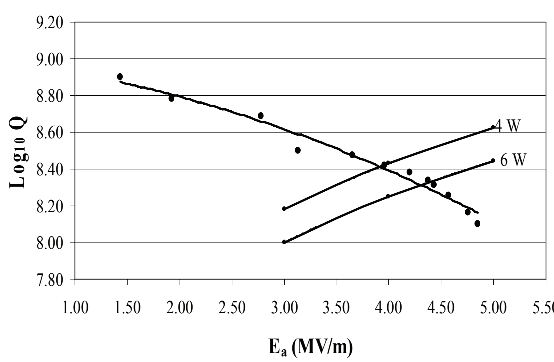


Figure 2: Offline performance of one of the indigenously built QWRs at 4.5 K.

## QWR PRODUCTION

After the successful construction of the first two indigenous resonators, production of fifteen more QWRs for the 2nd and 3rd modules began. During the construction of the first two resonators itself we developed a local commercial vendor for doing the machining, sheet metal forming and fitting of the niobium components and assemblies. The idea was to avoid burdening the in-house workshop during the subsequent resonator production. 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 module, several design changes were incorporated in the production QWRs. The original design had three coupling ports; one each for the drive coupler and RF pickup and a third port for the VCX fast tuner. However, the resonator control module was designed on the dynamic phase feedback control [6] which made the third port redundant. The production resonators therefore have only two coupling ports. In order to improve the cooling at the shorted end of the coaxial line, i.e. at the top end of the resonator where the magnetic field is highest, a separate hemispherical dome was incorporated in the first cryomodule [4]. The dome is attached to the resonator and the helium vessel using indium seals. The production resonators will not have a separate dome, rather the dome will be welded to the outer stainless steel vessel and it will attach to the helium vessel of the cryostat using a CF flange. This will also allow the resonators to be baked to a much higher temperature without breaking the vacuum seal. Two of the resonators built during the QWR production at Argonne National Laboratory (ANL), USA 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 eventual wall thickness depended on the geometrical alignment of the blank and the forming dies. 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 current 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 electron beam welding fixtures were designed, wherever possible, to weld several pieces in a single pump down. Similarly multiple assemblies/parts were electropolished in a single setup to save time and effort. Although most of the tooling was available from the previous constructions, additional tooling and fixtures were made as required, or to replace those which had become unusable from wear and tear. In order to ensure that the QWRs were robust in construction several intermediate checks were incorporated in the process. For example, several electron beam welds, especially on critical components such as Drift Tubes, were radiographed to check porosity and other defects. Although during the welding parameter development we had gone through the procedure quite exhaustively, it was felt that randomly checking of a few components would be prudent. All the coupling and beam port bellows and subsequently, their assemblies were thermally shocked and pressure tested to ensure vacuum leak tightness, once they were installed and welded on the resonators. Leaks from the bellows on several of our existing resonators had been a major problem that prompted us to go through more stringent testing (see details in the following sections). Similarly the work hardened slow tuner bellows (without the Nb-Cu top disc) were stress relieved by vacuum annealing the convolutions at 800 °C.

The major niobium sub-assemblies of the QWR, i.e. the central conductor of the coaxial line, the outer cylindrical housing and the top flange (which joins together the other two sub-assemblies) 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 data 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. After all the electropolishing was completed each resonator was heat treated to 1100 °C in vacuum $< 5 \times 10^{-6}$ mbar. In Fig. 3(a), the bare niobium resonators with the Nb-SS flange welded at the open end and ready for the outer stainless steel jacketing are shown. In Fig. 3(b), the niobium slow tuner bellows are shown.

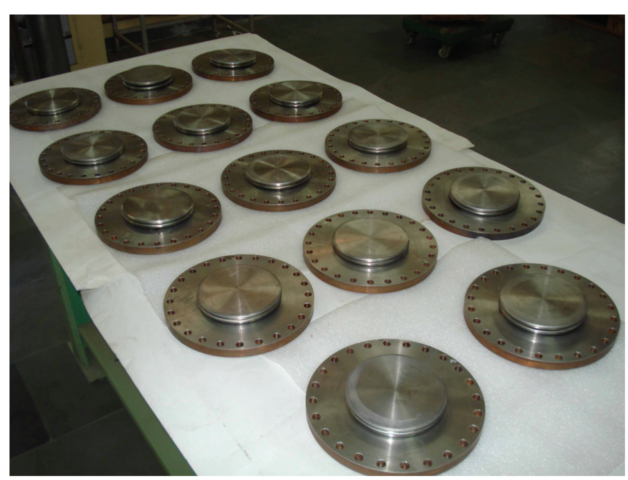

Figure 3: (a) Top-Bare niobium QWRs ready for the outer stainless steel jacketing. (b) Bottom-Slow tuner bellows.

## RESONATOR REPAIRS

In addition to constructing new resonators for the linac, a variety of repairs on the existing QWRs have been successfully carried out. Two of the resonators built during the QWR production at ANL [7], got punctured at the upper cap on the central conductor of the coaxial line (Fig. 4). The upper cap is located where the capacitive drift tube joins the inductive loading arm. The resonators were cut open from the shorted end. All the formed components on the IUAC-QWR are made out of 1.6 mm or 3.2 mm thick niobium (except the slow tuner bellows). On the ANL built QWRs the upper caps had been formed out of 1.6 mm thick niobium. To avoid problems in future, we decided to form the upper cap as well as the end caps (located at the drift tube end) with 3.2 mm thick material. The punctured upper caps were cut and removed from the coaxial line, and 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 drift tube and loading arm were electropolished to remove 100 µm from the surface, and the entire 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 < $5 \times 10^{-6}$ mbar. The central conductor and outer housing (along with its stainless steel jacket) of a resonator after the repair, but before the closure welding, are shown in Fig. 5. After the repair was over both the resonators were lightly electropolished to remove 5 µm before the cold test. Since the resonators had been heavily electropolished in the past, we did not want to risk puncturing the original closure weld and decided for only light electropolishing. In cold tests at 4.5 K one of the resonators (QWR-6) performed as shown in Fig. 6. We believe that the slightly inferior performance of the resonator, as compared to the past [8], could be due to the very light final electropolishing.

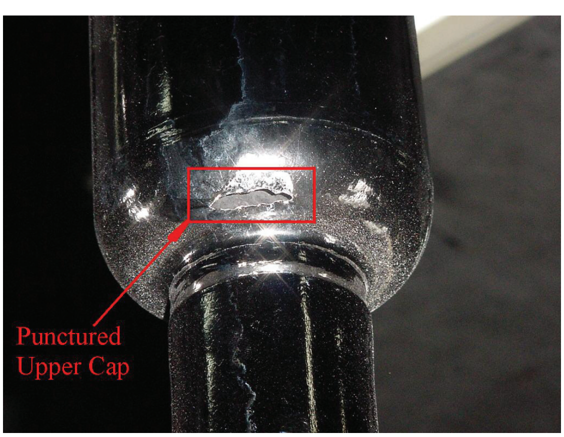


Figure 4: Punctured upper cap on the central conductor of the coaxial line.

Figure 5: Central conductor and outer housing, along with its stainless steel jacket, of the resonator after the repair.

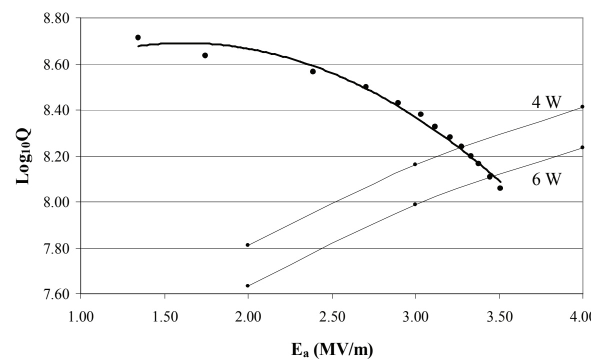


Figure 6: Offline performance of one of the repaired resonator QWR-6 at 4.5 K.

Several QWRs in the first cryomodule developed vacuum leaks through the coupling port transition flange bellows assembly. On all the resonators the leaking assemblies have been machined out and replaced with a newly designed assembly. The original design 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 [3]. The formed bellows are commercially procured with appropriate end fittings and the Nb-SS flange is electron beam welded to it. Prior to welding to the flange, the bellows were thermally shocked from 300 to 77 K several times and pressure tested. After the bellows were welded to the flange, the assembly was again thermally shocked and pressure tested before welding to the resonator. The resonators were individually pressure tested and then lightly electropolished before mounting in the cryomodule. This entire effort has resulted in the cryostat vacuum improving from low $10^{-7}$ to high $10^{-9}$ mbar.

## SINGLE SPOKE RESONATORS

Apart from constructing resonators for the in-house programs IUAC has taken up a project to build two niobium single spoke resonators designed for β=0.22 operating at 325 MHz, for Project-X at Fermi National Accelerator Laboratory (FNAL), USA [9]. An exploded view of the resonator is shown in Fig. 7.

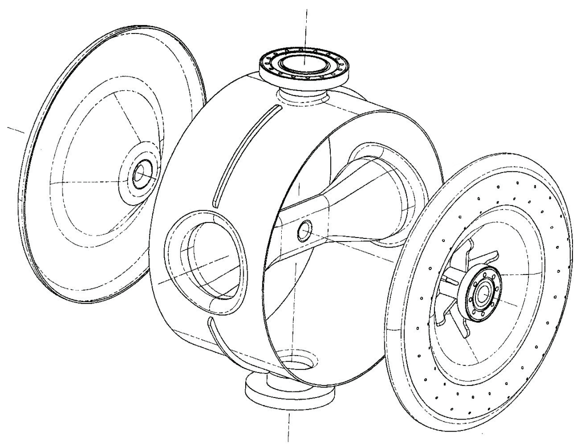

Figure 7: 325 MHz, β=0.22 Single Spoke Resonator. The outer shell diameter is 498 mm.

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, stiffening ribs and donut rib. 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. Therefore most of the initial effort was put into making these two large dies.

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 Fig. 8(a), a half spoke formed in copper and after the edge machining is shown. 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 Fig. 8(b), 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. The coupler port pull out die is presently being developed. 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. 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 being designed. We plan to complete the fabrication by the end of this year.

Figure 8: (a) Left – Half Spoke formed in copper and after machining the edges and ends. (b) Right – End Wall formed in copper. The edge has not been machined.

## TESLA TYPE SINGLE CELL CAVITY

IUAC in collaboration with Raja Ramanna Centre for Advanced Technology (RRCAT), India is fabricating a Tesla-type single cell cavity in niobium. In Fig. 9, 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 that has been fabricated is shown in Fig. 10. We plan to complete the full single cell cavity in the next couple of months.

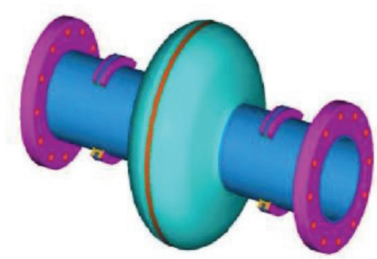

Figure 9: Tesla-type Single Cell cavity. The overall length is 392 mm.

Figure 10: Half cell of the Tesla-type single cell cavity.

## CONCLUSIONS

The Superconducting Resonator Fabrication Facility at IUAC has been fully operational since July 2002. The facility is being primarily used for indigenously 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 more resonators for the second and third modules is nearing completion. These two cryomodules will be commissioned by the end of this 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 the past, i.e. 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 six months in developing the tooling. IUAC in collaboration with RRCAT, India is also fabricating a Tesla-type single cell cavity in niobium, which should be ready for cold tests in the next few months.

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