Design, fabrication, room temperature RF test of 1050 MHz, $\beta = 0.49$ single cell large grain niobium cavity

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Abstract. BARC is developing a technology for the accelerator driven subcritical system (ADSS) that will be mainly utilized for the transmutation of nuclear waste and enrichment of U233. Design and prototyping of a superconducting medium velocity cavity has been taken up as a part of the ADSS project. The cavity design for $\beta =0.49$, $f = 1050$ MHz has been optimized to minimize the peak electric and magnetic fields, with a goal of 5 MV/m of accelerating gradient at a $Q > 5\times10^9$ at 2 K. After the design optimization one single cell cavity was fabricated from large grain (RRR>99) Niobium material. This report presents the design, fabrication, electron beam welding and RF measurements at room temperature before and after electron beam welding.

1. Introduction
In the high energy section (> 100 MeV) of an ADSS accelerator, superconducting elliptical cavities will be used to accelerate protons up to 1 GeV [1]. After the successful completion of the Spallation Neutron Source (SNS) in the USA, the superiority of superconducting (SC) linacs over normal conducting ones is rather well accepted in the accelerator community to efficiently accelerate proton beams with velocity relative to speed of light, $\beta$, of about 0.5 [2]. Short, independently phased SC resonators with large velocity acceptance are also ideal for accelerating efficiently beams with different mass-to-charge ratio. SC cavities are ideal for low current beams, where efficiency is dominated by rf losses. In the high beam loading limit (~100mA), NC and SC linacs have comparable efficiency. Even for low- $\beta$ proton beams SC linacs can be cost effective. In the studies for the EURISOL, 5 mA cw proton driver [3], a comparison between NC and SC option between 5 and 85 MeV was done, showing a similar construction cost.

For this purpose we have studied the RF properties of a $\beta =0.49$, 1050 MHz single cell superconducting elliptical cavity.

Section 2 of this report describes the design of $\beta =0.49$, $f=1050$ MHz single cell elliptic cavity. Section 3 describes the cavity fabrication. Section 4 presents the RF test results before EB welding.
2. Cavity design
RF parameters of 1050 MHz, $\beta = 0.49$ single cell Elliptical cavity has been optimized by means of 2D cavity tuning code SUPERFISH and 3D High Frequency Simulation code CST Microwave Studio for possible use in a High Current Proton Accelerator [4]. The low energy section of the ADS accelerator is being designed for 350 MHz and hence it is decided to build the superconducting accelerator section with the third harmonic of 350 MHz i.e. 1050 MHz.
It was found that $E_{pk}/E_0$ has a minimum at a particular value of the iris-ellipse aspect ratio $a / b$ and around the same point $B_{pk}/E_{pk}$ has a maximum. A drawing of the single-cell cavity of 1050 MHz, $\beta =0.49$ is shown in Figure 1, along with the electric field and magnetic field distribution calculated by SUPERFISH and CST-MWS. Our design is compared with the INFN-TRASCO and RIA design [5]. The INFN-TRASCO design adopts an elliptical iris and an elliptical equator shape where as in our case equator shape is circular and the iris shape is elliptical similar to RIA design.

![Image of cavity design](image)

Fig. 1. (a) Drawing of the 1050 MHz, $\beta=0.49$ cavity, (b) Electrical field distribution in $TM_{010}$ mode, (c) Magnetic field distribution in $TM_{010}$ mode.

The main cavity parameters of our design are summarized in Table-1 and compared with the INFN-TRASCO and RIA design.

| Parameters                  | Present Design | TRASCO Design | RIA Design |
|-----------------------------|----------------|---------------|------------|
| Frequency (MHz)             | 1050           |               |            |
| Geometrical $\beta$         | 0.49           |               |            |
| Iris Radius (cm)            | 3.9            |               |            |
| Cavity Diameter (cm)        | 25.833         |               |            |
| Dome Aspect ratio           | 1              | 1.6           | 1.0        |
| Iris Aspect Ratio           | 1.43           | 1.3           | 1.45       |
| Wall Angle (Deg.)           | 6.5            | 5.5           | 6.5        |
| Wall Distance [mm]          | 7.37           | 7.0           | 8.5        |
| $r/Q$ (Q)                   | 9.19           | 9.46          | 9.04       |
| Geometry Factor G (Q)       | 141.91         | 147.387       | 135.675    |
| $E_{peak}/E_{acc}$          | 4.26           | 4.44          | 3.98       |
| $B_{peak}/B_{acc}$ (mT/(MV/m)) | 8.02          | 7.78          | 8.37       |
The above table shows the design comparison with RIA and TRASCO. Actual RIA design is with frequency 805 MHz and geometrical beta 0.47 and TRASCO is with frequency 704.4 MHz and geometrical beta 0.47. In the above table both the RIA and TRASCO design were scaled for frequency 1050 MHz and geometrical beta 0.49, keeping the iris radius same as our present design i.e. 3.9 cm. The present design which is very close to the design of those other two cavities whose prototypes reached their performance specs and the ratios of the peak fields to $E_{acc}$ in our design is in between the values of the TRASCO cavity, designed to minimize $B_p/E_{acc}$, and the RIA cavity, designed to minimize $E_p/E_{acc}$

3. Fabrication
One prototype single cell Niobium cavity has been fabricated with the designed parameters mentioned in Table 1. The cavity is made from the large grain niobium of RRR $\geq 117$ received from CBMM, Brazil [6]. The disks for the large grain cavity are sliced directly from the ingot by wire electro-discharge machining. A suitable set of dies has been made out of 6061 aluminium to form the cavity half cells from sheet niobium of thickness 4 mm. The schematic and the parts of the different components of the dies are shown in Figure 2.

Fig. 2. (a) Schematic of the forming die for the 1050 MHz, 4mm thick cavity, (b) Different parts of the forming die.

The half cells are deep drawn and then the required machining at the equator and the iris region are carried out. All the defects, machine marks are removed by mechanical buffing followed by ultrasonic degreasing and buffered chemical polishing (BCP) ($HF:HNO_3:H_3PO_4 = 1:1:1$ (by volume)) to remove about 30$\mu$m from the inner surface of the cavity half cells. The beam tubes for both cavities are fabricated from a fine grain Niobium sheet of low RRR by rolling and electron beam welding (EBW) along the length of the tube. Then the half cells are EB welded with the respective beam tubes. No difficulties observed in welding of fine grain beam tubes with the large grain half cells. Finally equator welding is carried out to form the single cell. All the welded joints are leak tested by MSLD. In all the EB welded joints have shown a leak rate better than $1\times10^{-9}$ std. cc/sec. The EB welded niobium large grain cavity is shown in Figure 3.
360° view of the EBW from inside of the Nb large grain cavity at the equator region is shown in Figure 4. Each picture shows about 40° sections in linear scale. The picture shows full penetration weld around the equator line except some regions. There is a clear evidence of grain growth in the welding heat affected zone.

Fig. 3. $f = 1050$ MHz, $\beta = 0.49$ EB welded Niobium Large Grain cavity.

4. Results and discussions

4.1. Measurement of resonant frequency and $Q_0$

To measure the resonant frequency and unloaded $Q_0$ of the cavity, the coupling coefficient $\beta$ due to the input probe is taken into account where as the coupling coefficient of the transmitted probe is negligible. The coupling coefficient of the input probe was 0.22. The measured frequency before EBW was 1026 MHz. The frequency bandwidth at 3-dB points was 2 MHz. Thus loaded $Q$, $Q_L$ was 376. Therefore, $Q_0 = Q_L(1+\beta) = 459$. After initial test it is found that the contact between the half cells are not proper and then the equator region is pressed with indium wire to have better RF contact. With the indium contact the measured frequency was 1048 MHz, $Q_0$ was 6832.
The measured $f_0$ and $Q_0$ after EBW were 1036.507 and 8076. Table 2 shows the details of the measurement results.

4.2. Measurement of geometrical shunt impedance, $R/Q$

Any object placed inside the cavity volume will disturb the field inside the cavity that will change the resonant frequency of the cavity. Experimentally $R/Q$ can be evaluated by measuring the frequency shift due to perturbing object. The final relationship of $R/Q$ with the frequency shift is given by,

$$R/Q = \left( d s \sum_{i=1}^{n} \Delta f_i \right) / \pi \varepsilon k \Delta v f_0^2$$

Where, $ds$ — bead displacement, $\Delta v$ — volume of bead, $k = 1$ (assumed as bead is much smaller than the cavity dimensions), $\Delta f$ — frequency shift, $f_0$ — resonant frequency, $\varepsilon = \varepsilon_0 (\varepsilon_r - 1/\varepsilon_r + 1)$, $\varepsilon_0$ — permittivity of free space, $\varepsilon_r$ — dielectric constant ($= 2:1$ for teflon and tends to infinity for metallic bead). A teflon bead of radius 5mm and length 5mm is made to pass through the central axis of the cavity, a change in resonant frequency is noted at the various positions of the bead with a step ($=ds$) of 10 mm. Figure 5 and 6 shows the measured axial electric field with theoretical on axis field before and after EBW. Table 2 shows the measured and theoretical values of shunt impedance and $R/Q$ values.
Table 2: RF measurements of the cavity before EB welding and after EB welding with Vector network analyzer

| Parameters     | Simulated value without Beam tube | Measured value before EBW without beam tube | Simulated value with Beam tube | Measured value after EBW with Beam tube |
|----------------|-----------------------------------|--------------------------------------------|--------------------------------|----------------------------------------|
| Frequency [MHz] | 1050                              | 1048                                       | 1036.856                       | 1036.507                               |
| Q Value        | 17000                             | 459                                        | 17032                          | 8076 (not cleaned after EBW)           |
| R/Q [Ω]        | 9.225                             | 8.59                                       | 9.675                          | 9.0                                    |

5. Conclusion

A single cell large grain niobium cavity indigenously developed and tested at room temperature. The initial results are encouraging and matches with the simulated value within 5%. Soon the cavity will be tested at 2K and subsequent results will be reported.

References

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