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TEST RESULT OF 650 MHz, BETA0.61, SINGLE CELL NIOBIUM CAVITY

Sudeshna Seth[1*], Sumit Som[1], Surajit Ghosh[1], Pranab Bhattacharyya[1], Aditya Mandal[1], Sundeep Ghosh[1], Anjan Dutta Gupta[1], P. Prakash[2], Kishore Kumar Mistri[2], Thomas H. Nicol[3], Allan Rowe[3], Anna Grassellino[3], Timergali N. Khabiboulline[3],Dmitri A. Sergatskov[3], Oleksandr Stepanovych Melnychuk[3], Shekhar Mishra[3], Michael Kelly[4], Thomas Reid[4]
[1] Variable Energy Cyclotron Centre (VECC), Kolkata, India
[2] Inter University Accelerator Centre (IUAC), New Delhi, India
[3] Fermi National Accelerator Laboratory, Illinois, USA
[4]Argonne National Accelerator Laboratory, Illinois, USA

Abstract

VECC has been involved in the design, analysis and development of 650 MHz, beta 0.61 (LB650), elliptical Superconducting RF linac cavity, as part of research and development activities on SRF cavities and associated technologies under Indian Institutions Fermilab Collaboration (IIFC). A single-cell niobium cavity has been indigenously designed and developed at VECC, with the help of Electron Beam Welding (EBW) facility at IUAC, New Delhi. Various measurements, processing and testing at 2K in Vertical Test Stand (VTS) of the single-cell cavity were carried out at ANL and Fermilab, USA, with active participation of VECC engineers. It achieved a maximum accelerating gradient (Eacc) of 34.5 MV/m with Quality Factor of 2E+09 and 30 MV/m with Q_0 of 1.5E+10. This is the highest accelerating gradient achieved so far in the world for LB650 cavities. This paper describes the design, fabrication and measurement of the single cell niobium cavity. Cavity processing and test results of Vertical Test of the single-cell niobium cavity are also presented.

CAVITY DESIGN

A 650 MHz 5-cell elliptical cavities with geometric β_G = 0.61 has been designed to optimize acceleration efficiency to operate in superfluid helium at a temperature2.0K, with gradient (Eacc) of 17 MV/m.The cell shape has been designed to minimize the peak surface magnetic and electric fields, Hpeak and Epeak, to achieve the required gradient and minimize field emission, and to minimize multipacting and to maximize R/Q and G to have less RF power dissipation in cavity wall and smaller heat load on the cryogenic system [1]. RF design of the 5-cell cavity has been carried out using 2-D Superfish and 3-D CST Microwave Studio [2]. EM design parameters of the optimized geometry of 5 cell, LB650 cavity are summarized in Table 1 [1] and electric field lines for accelerating mode (π-mode) of the cavity have been shown in Figure 1. Geometry of end cell of the cavity is optimized to have good field flatness over the five cells. Also a single cell elliptical cavity, which has the same dimensions as that of the mid-cell of 5-cell LB650 cavity, has been simulated in both Superfish and CST Microwave Studio. Frequency of single-cell niobium cavity with beampipe is found to be 645.2 MHz. Electric field lines in single cell niobium cavity have been shown in Figure 2.

Table 1: Cavity EM Parameters of 5-Cell Cavity

	Values
Frequency	650MHz
Shape, No of Cells	Elliptical, 5
Geometric beta(β_G)	0.61
Effective Length = 5*($\beta g \lambda/2$)	703.4mm
Iris Aperture	96mm
Wall angle for midcell	2.4∘
Wall angle for endcell	4.5∘
Epeak /E_{acc}	3
Bpeak /E_{acc}	4.84
R/Q	296
G	200
Cell to cell coupling K_{cc}	1.24%

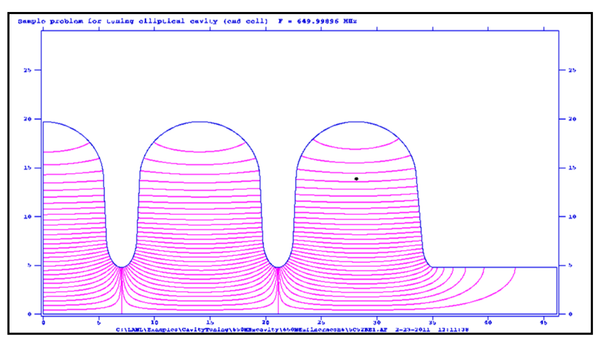

Figure 1: Accelerating mode at 649.99896MHz.

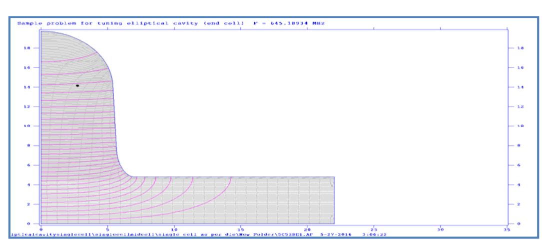

Figure 2: Fundamental mode of the Single-cell at 645.19 MHz.

* sseth@vecc.gov.in

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SINGLE CELL CAVITY FABRICATION AND MEASUREMENT

A prototype single cell aluminium cavity has been fabricated using die-punch assembly (Fig. 3) designed for fabrication of elliptical mid half-cells (Fig. 4) to check the procedures for forming and to make sure the desired frequency could be obtained.

Figure 3: Die Punch Assembly.

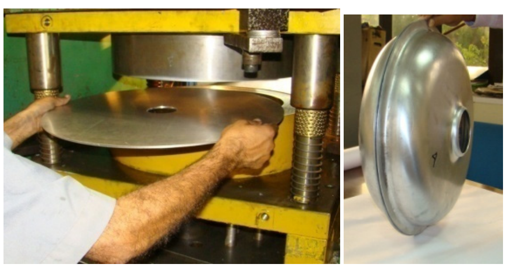

Figure 4: Forming of elliptical half cells.

Single Cell Aluminium Prototype

Single cell Aluminium prototype has been fabricated using mid-cell dimensions and fundamental mode frequency of the prototype is measured as 645.86 MHz and quality factor 20700 (Fig. 5). Simulated value for single cell prototype, obtained from 2-D Superfish is 645.2 MHz.

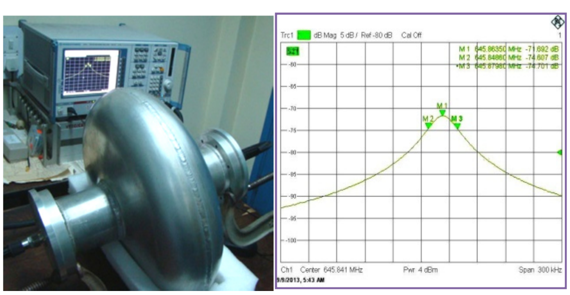

Figure 5: Single cell Aluminium prototype cavity-VNA measurement.

Single Cell Niobium Cavity

The fabrication of a single-cell niobium cavity was carried out indigenously and with the help of Electron Beam Welding (EBW) facility at IUAC, New Delhi (see Figs. 6 to 8). The half cells have been fabricated from 600 mm x 600 mm x 4 mm thick niobium sheet (RRR≥300), using die-punch assembly designed for elliptical half-cells and beam pipes are also rolled from 4 mm thick niobium sheet. Flanges are fabricated using Nb-55Ti alloy .The dimensional measurement of the half cells has been carried out using Coordinate Measurement Machine (CMM) (Fig. 9) andRF measurement of two half cells(shown in Figure 10) and a full-cell has been done using vector network analyser (VNA). The fundamental resonant modes(π-mode) of the two niobium half cells are measured as 634.3 MHz and 636.8 MHz. After electron beam welding of the two half cells, fundamental resonant frequency of the full-cell cavity, fitted with the beam tube (though not welded), is measured as 640.84 MHz.

Figure 6: Niobium half cells and beam pipes with fixtures developed for Electron Beam Welding.

Figure 7: Cavity half cells being put inside EBW machine for equator welding at IUAC, New Delhi.

Figure 8: Single cell elliptical cavity after EBW.

Decrease in frequency from simulated results is due to the fact that iris radius of the half cells and length of the cavity were less than the designed dimension. These deviations, during forming and machining, finally led to decrease in fundamental mode frequency [3].

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Figure 9: CMM measurement of halfcell.

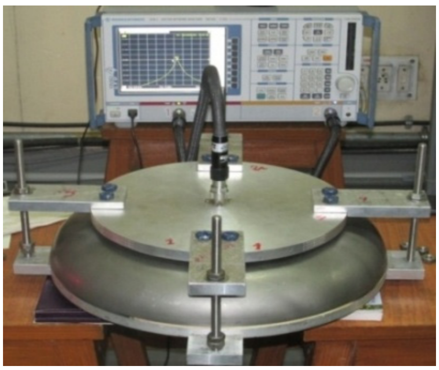

Figure 10: VNA measurement of Niobium Half cell.

After welding of the beampipes and iris region, the frequency and the quality factor of the final single cell niobium cavity are measured to be 636 MHz and 9880 respectively(Shown in Figure 11). This further decrease in frequency after iris welding is due to unanticipatedshrinkage and deformation at iris region caused by problem of blow through atiris jointalthoughblow throughis successfully taken care ofby machining to a regular shape and fixing a niobium button[3].

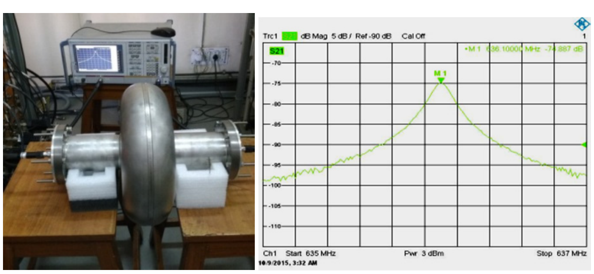

Figure 11: VNA measurement of final single cell cavity.

CAVITY PROCESSING

After RF measurement at low power, finally the cavity was shipped to Fermilab, USA for cavity processing followed by testing in VTS (Vertical Test System) in a test cryostat at 2K temperature for unloaded quality factor and accelerating gradient measurement (Fig. 12).

The cavity surface processing is the most crucial aspect for achieving high Q and high gradient in SRF cavities. Considering the fact that it is the first cavity developed by VECC, it was decided to push the cavity towards higher

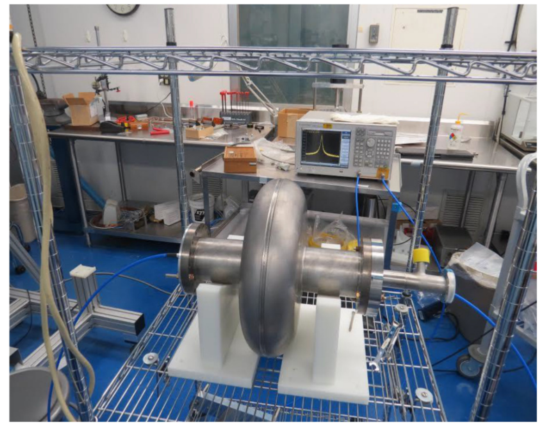

Figure 12: RF Measurement at Fermilab.

gradient rather than higher Q. The treatment procedures were decided on that basis. The cavity went through optical inspection (Fig. 13), bulk Electro polishing (Fig. 14), Annealing, light Electro polishing and finally high pressure rinsing serially. Initially the weld joints were scanned using high resolution camera for defects and scratches. The cavity goes to next step if there is no major defect on cavity surface.

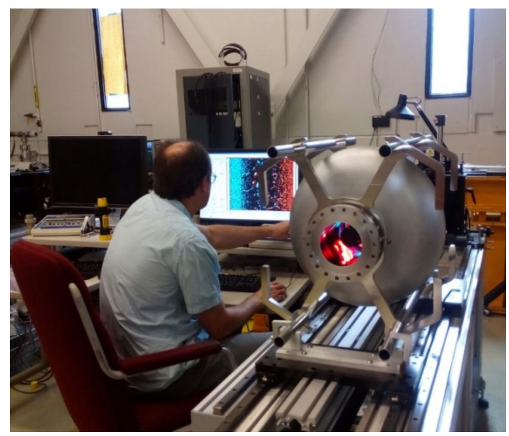

Figure 13: Optical inspection.

The cavity went through bulk material removal of 120 micron using electro-polishing method at Argonne National Laboratory. The electro polishing process took 4 hours and 5.2 hours in two consecutive days for removing 55 µm+65 µm respectively (Figs. 15 and 16).

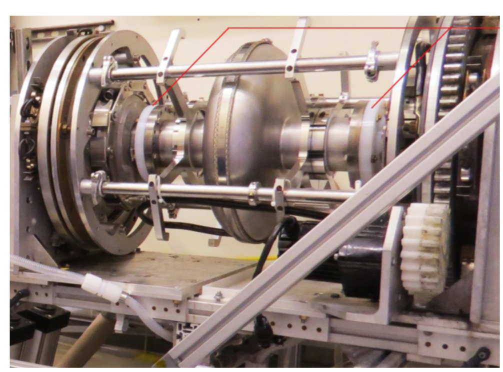

Figure 14: Cavity Installed Electro-polishing machine.

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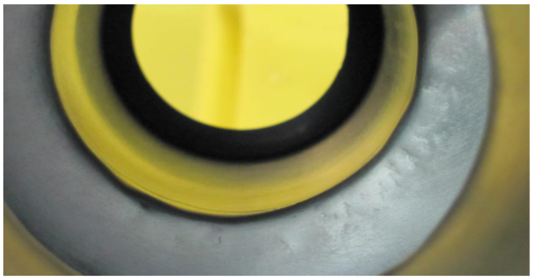

Figure 15: Cavity surface before EP.

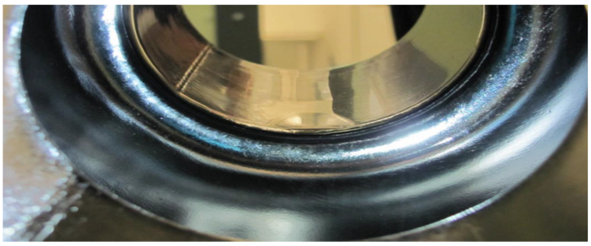

Figure 16: Cavity surface before EP.

The thermal processing of SCRF cavity i.e. annealing at 800°C for 3 hours is an important step. This annealing aims at achieving higher Q by removal of hydrogen gas from the RF surface which got absorbed at different stages of surface processing. Hydrogen absorption takes place in Nb surface due to chemical process. Baking of the cavity at 800°C for 3 hours at vacuum furnace reduces the hydrogen concentration (Fig. 17). Typical pressure inside vacuum furnace is kept around ~1E-7 torr to 1E-8 torr.

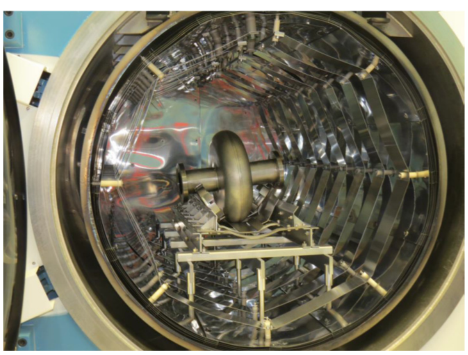

Figure 17: Furnace baking at 800 C (Annealing).

Figure 18: High Pressure Rinsing (HPR).

The same procedure of electro polishing repeated for 20 micron material removal from Nb surface as final processing steps. The process parameters were kept same like bulk EP. Final HPR (High Pressure Rinsing) was performed on the cavity for 24 hours(Fig. 18)and finally couplers were assembled in a clean room to test the cavity in VTS.

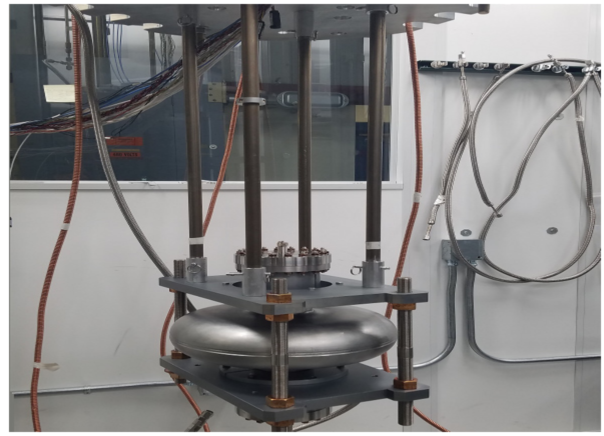

Figure 19: VTS insert assembly.

VERTICAL TEST RESULT

The cavity was mounted on VTS insert assembly(Fig. 19) on 4th July 2016. Temperature sensors, RF cables etc were connected and cavity was inserted finally in VTS 3 at FNAL for cool down. After cool-down to 2K the frequency of cavity was measured as 639.1 MHz. The cables used for VTS were calibrated following the standard procedure.

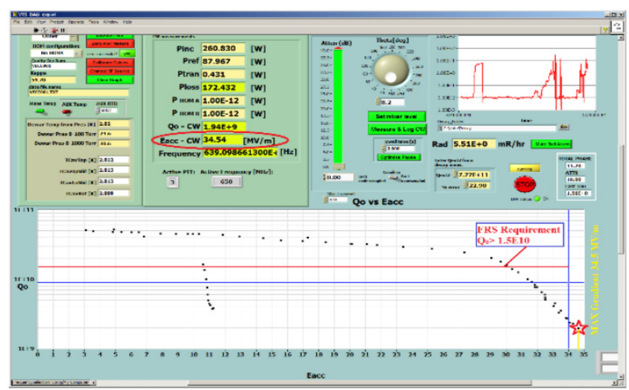

Figure 20: Vertical test of the cavity.

One next day, the cavity reached upto 34.5 MV/m at maximum power(~200W) with no quench even though some amount of multipacting was seen around 11 MV/m (Figure 20).

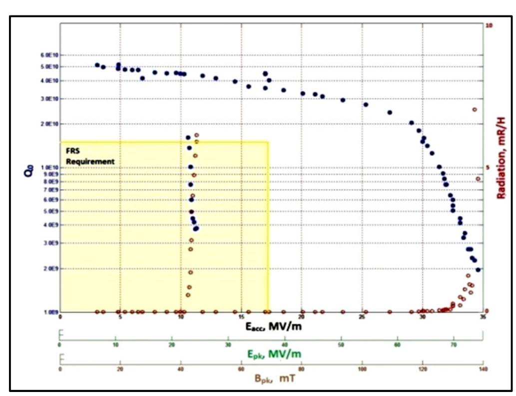

Figure 21: Plot of Q vs Eacc.

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The unloaded quality factor Q_0 was 1.5E+10 at 30 MV/m gradient.Cavity could sustain 74MV/m Peak Electric Field (E_{pk}) and 137 mT Peak Magnetic Field (B_{pk}), with accelerating gradient of 34.5 MV/m @ 2K (-271°C). Figure 21 shows the plot of Quality factor with Accelerating Gradient, Peak surface electric field and Peak surface magnetic field.

CONCLUSION

Design, development and testing of 650 MHz, low beta single-cell niobium cavity is a successful collaborative effort of VECC/DAE, IUAC and FNAL/ANL. The accelerating gradient achieved by first single cell niobium cavity developed by VECC, is the highest accelerating gradient so far in the world for 650 MHz, low beta cavities. It is well above the operating accelerating gradient of 17 MV/m. Quality factor at operating gradient is also higher than the required value. Though the frequency of aluminium single cell prototype cavity is very close to the design frequency, frequency of the niobium cavity deviates from the design value. This change in frequency is mainly due to deviation during machining of niobium half-cells and unanticipated shrinkage during iris-beampipe welding. These issues will be taken care of during the fabrication of our next single cell and 5-cell LB650 cavities.

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