A NOVEL DESIGN AND DEVELOPMENT OF 650 MHZ, β=0.61, 5-CELL SRF CAVITY FOR HIGH INTENSITY PROTON LINAC

Sumit Som*, Sudeshna Seth, Pranab Bhattacharyya, Aditya Mandal, Surajit Ghosh, Anjan Duttagupta, Variable Energy Cyclotron Centre (VECC), Kolkata, India

Abstract

DAE labs in India are involved in R&D activities on SRF cavity technology for the proposed high intensity proton linacs for ISNS/IADS and also FERMILAB PIP-II program under IIFC. VECC is responsible for design, analysis and development of a 650 MHz, β=0.61, 5-cell, elliptical cavity. This paper describes the novel design of the cavity, with different aperture and wall angle, having better field flatness and mechanical stability, reliable surface processing facility and less beam loss. The cavity geometry has been optimized to get acceptable values of field enhancement factors, R/Q, Geometric factor, cell-to-cell coupling etc. The effective impedance of transverse and longitudinal HOMs are low enough to get rid of HOM damper for low beam current. 2-D analysis shows no possibility of multipacting. However, 3-D analysis using CST Particle Studio code confirms its presence and it can be suppressed by introducing a small convexity in the equator region. Two niobium half cells and beam pipes for the single cell cavity have been fabricated. Measurement and RF characterisation of half cells, prototype 1-cell and 5-cell and also 1-cell niobium cavities have been carried out.

CAVITY DESIGN

The 650 MHz 5-cell elliptical cavities with geometric velocity factors $\beta_G = 0.61$ have been designed to optimize acceleration efficiency. The cavities are required to operate in superfluid helium at a temperature of around 2K, with accelerating gradient (E_{acc}) of 17 MV/m. The cell shape has been designed to minimize the peak surface magnetic (B_{peak}) and peak surface electric field (E_{peak}), to achieve the required gradient and minimum field emission, and also to minimize the effect of multipacting and to maximize R/Q and geometric factor (G) to have less RF power dissipation in the cavity wall and smaller heat load on the cryogenic system. RF design of the cavity has been carried out using 2-D Superfish and 3-D CST Microwave Studio [1]. Multipacting analysis of the cavity has been carried out for 650 MHz, β=0.61, superconducting elliptical cavity using 2-D code MultiPac2.1 [2] and 3-D CST particle studio code[1].

RF Design

The electromagnetic (EM) design parameters [3] of the optimized cavity geometry at 2K are summarized in Table 1 and electric field lines for five fundamental modes of the cavity have been shown in Figure 1 to Figure 3. The geometry of end cell of the cavity is optimized to have good field flatness over the five cells.

*E-mail: ssom@vecc.gov.in

Table 1: Cavity EM Parameters

Parameters	Values
Frequency	650 MHz
Shape, No. of Cells	Elliptical, 5
Geometric beta (β_G)	0.61
Effective Length = 5*(βg.λ/2)	703.4 mm.
Iris Aperture	96 mm.
Wall angle for midcell	2.4^0
Wall angle for endcell	4.5^0
E_{peak}/E_{acc}	3
B_{peak}/E_{acc}	4.84
R/Q	296
G	200
Cell-to-cell coupling, K_{cc}	1.24%

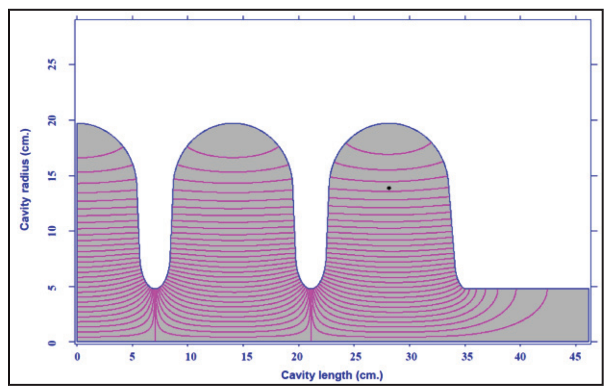

Figure 1: Accelerating mode (π-mode) at 649.99896MHz.

The 5-cell cavity structure has been analysed for transverse and longitudinal higher order modes and their effective impedances have been obtained as very low. No trapped modes with high effective impedance (as shown in Figure 4 and Figure 5) is observed for beam current up to a few mA.

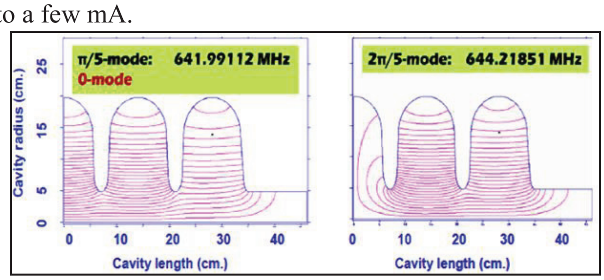

Figure 2: E-Field Profile at π/5-mode and 2π/5-mode.

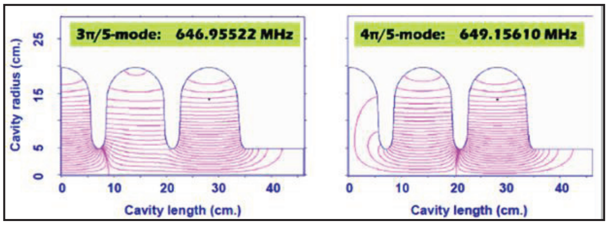

Figure 3: E-Field Profile at 3π/5-mode and 4π/5-mode.

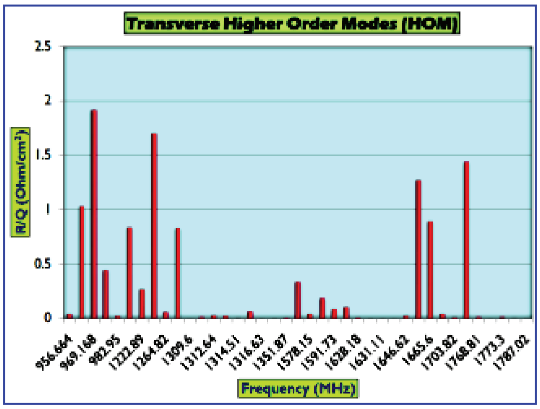

Figure 4*:* Effective Impedance of transverse HOMs.

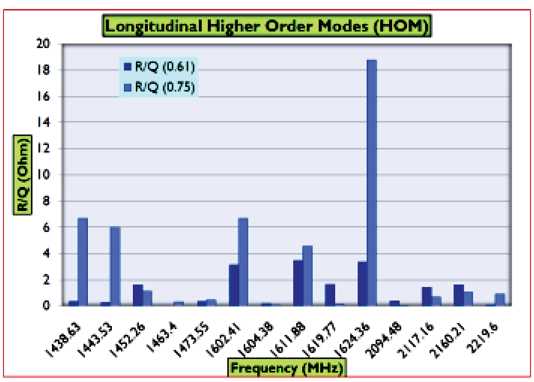

Figure 5*:* Effective Impedance of longitudinal HOMs.

MULTIPACTING STUDY

Multipacting analysis has been carried out for 650 MHz, β=0.61, superconducting elliptical cavity using 2D MultiPac2.1 code [3] and also using 3D CST particle studio code. The 2D multipacting analysis for both mid cell and end cell of 650 MHz elliptical cavity shows no multipacting up to the accelerating electric field of 20 MV/m. Figure 6 shows secondary electron yield for niobium as provided in 2D MultiPac code. Figure 7 and Figure 8 show electron counter, average impact energy of electron and relative enhanced electron counter after 30 impacts, for mid-cell and end cell respectively. Based on 2D analysis, we can conclude that there is no possibility of multipacting as the relative enhanced electron counter is less than 1 for whole range. However, 3D analysis using CST particle studio shows different result.

Unlike 2D code, the 3D CST Particle Studio code is based on Furman model, which besides true secondary electrons, also takes care of two other secondary electrons, back scattered and rediffused. For MP simulation, niobium is used from CST material library. In

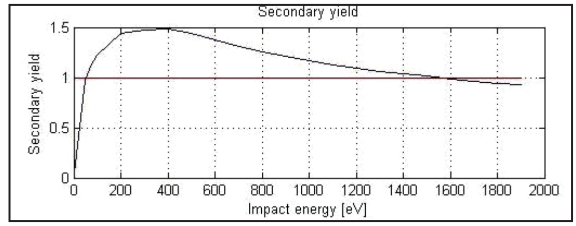

Figure 6: Secondary electron yield for niobium.

the equator region, 30 mm along the equator diameter has been simulated in CST particle studio and mesh cell dimensions minimum 0.37 mm and maximum 0.74 mm have been used for good convergence. Multipacting has been found between accelerating gradients 5.8 MV/m and 11.5 MV/m. The maximum rate of multipacting has been predicted around accelerating gradient 6.8 MV/m (as shown in Figure 9 and Figure 10).

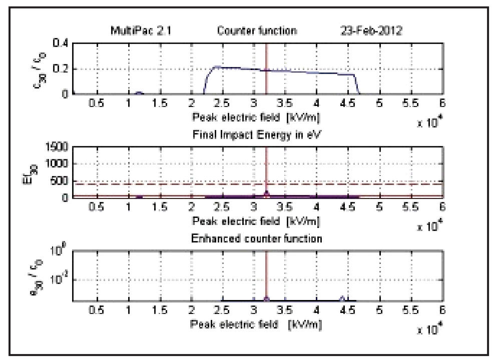

Figure 7: Results for mid cell of the cavity.

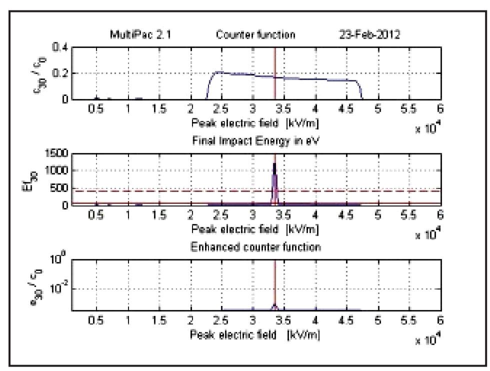

Figure 8: Results for end cell of the cavity.

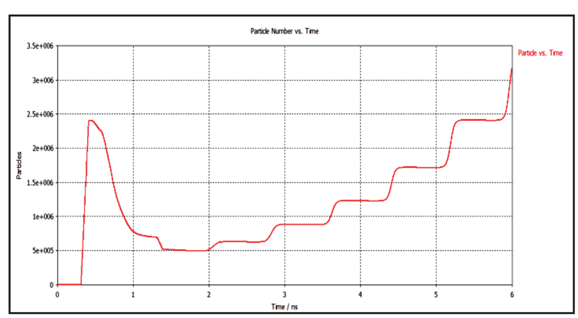

Figure 9: Particle number vs. time (ns) at 6.8 MV/m.

A small convexity in the equator region suppresses the multipacting significantly. However, the convexity does not change the cavity parameters, like, peak surface

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fields, quality factor, R/Q etc. Practically, this small convexity gets introduced automatically during electron beam welding, which in turn may become beneficial.

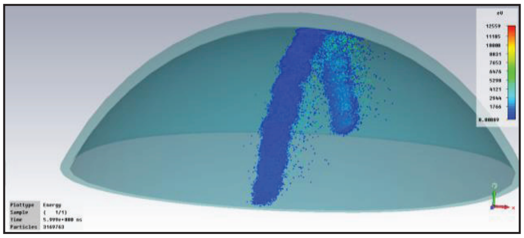

Figure 10: Particle after 6ns at 6.8 MV/m.

PROTOTYPE CAVITY FABRICATION AND MEASUREMENT

A prototype 1-cell aluminium cavity and a prototype 5-cell copper cavity have been fabricated using die-punch assembly (as shown in Figure 11) designed for fabrication of elliptical half-cells to check the procedures for forming and to make sure the desired frequency and field flatness could be obtained. RF characterisation has been carried out for both the prototypes using Vector Network Analyser and Bead pull measurement set up [4].

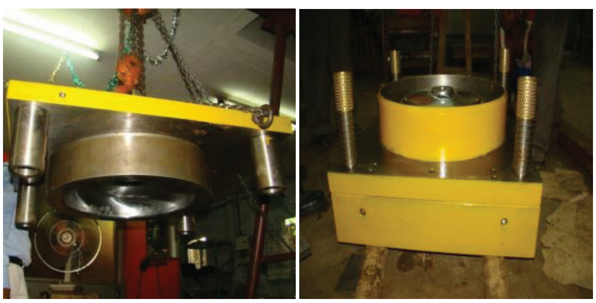

Figure 11: Die Punch Assembly for the cavity.

Single Cell Prototype Cavity

A Single cell aluminium prototype cavity (as shown in Figure 12) has been fabricated using mid-cell dimensions and fundamental mode frequency and the quality factor of the prototype cavity are measured (as shown in Figure 13) as 645.86 MHz and 20700 respectively. The simulated value for the geometry of fabricated single cell prototype, obtained from 2D Superfish code is 645.3 MHz.

Figure 12: Single cell Aluminium prototype cavity.

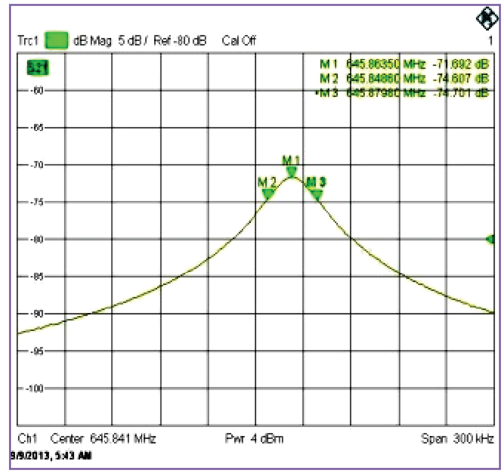

Figure 13: VNA measurement of 1-cell prototype cavity.

Five Cell Prototype Cavity

A five-cell Copper prototype (as shown in Figure 14) has been fabricated using the mid-cell dimensions and frequencies of five fundamental modes have been measured (as shown in Figure 15 to Figure 19) using a bead-pull measurement set up[4] already developed at VECC. The electric field profile along the axis of the cavity has been obtained for five fundamental modes. The highest mode is the accelerating mode or π- mode.

The resonant frequency of π-mode deviates from its simulated frequency by 2 MHz and field profile of copper prototype measured by perturbation technique using bead pull measurement set-up is found to be non-uniform. As the copper prototype has been fabricated using mid-cell dimensions only, field at end cells is lower than inner cells. Also formed copper half cells were not identical in dimension, with a deviation on the order of 0.6 mm. This is another reason for non-uniform field profile.

SINGLE CELL NIOBIUM CAVITY FABRICATION AND MEASUREMENT

The fabrication of a single-cell niobium cavity has been carried out indigenously and with the help of Electron Beam Welding (EBW) facility at IUAC, New Delhi. The half cell (as shown in Figure 20) has 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. The beam pipes are rolled from 4 mm thick niobium sheet. The dimensional measurement (as shown in Figure 21) of the half cells has been carried out using Coordinate Measurement Machine (CMM) to find out the deviation of the geometry of the half-cell from the designed value. RF measurement of two half cells and a full-cell has been done using vector network analyser (VNA) to find out the deviation from the designed frequency in order to improve further. EB welding of Nb-55Ti alloy flange to beam pipes (as shown in Figure 22) has been completed. Two half cells are joined at the equator region by electron beam welding (as shown in Figure 23) and also rolled beam pipes are electron beam welded. Electron beam welding of the joint between the beam pipe and iris has been done to build single cell cavity (as shown in Figure 24).

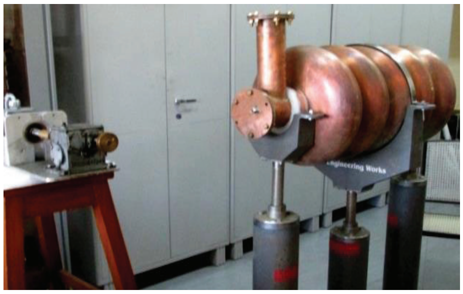

Figure 14: 5-cell copper prototype cavity.

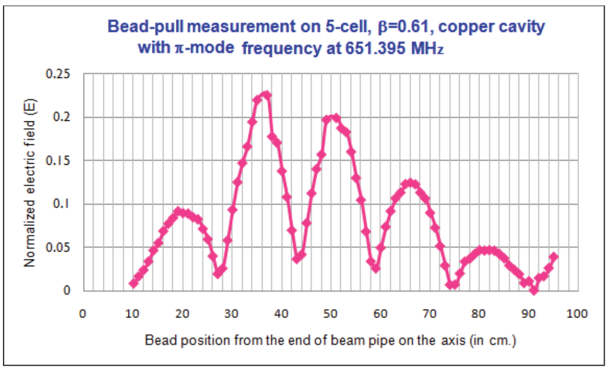

Figure 15: Measured E-field profile for π-mode.

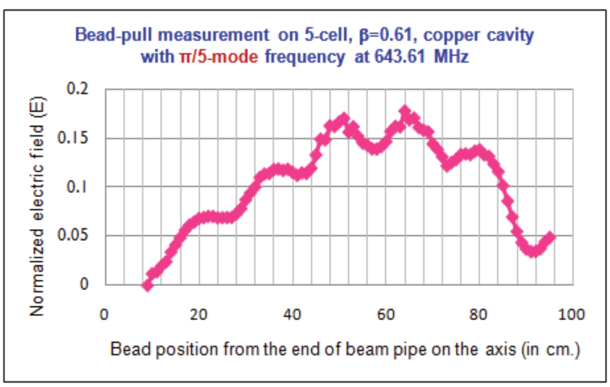

Figure 16: Measured E-field profile for π/5-mode.

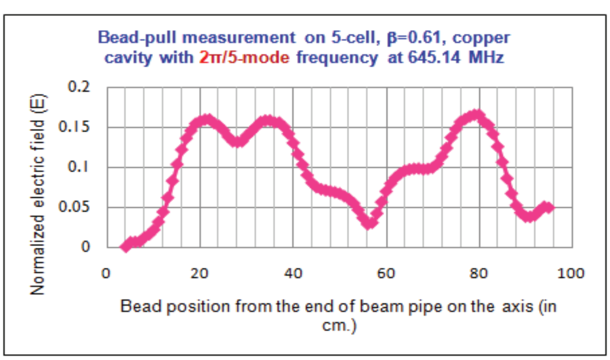

Figure 17: Measured E-Field Profile for 2π/5-mode.

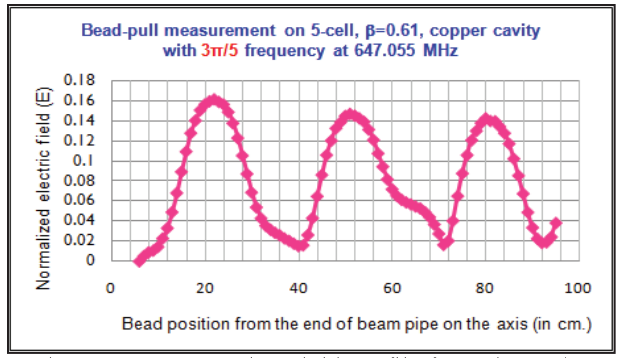

Figure 18: Measured E-Field Profile for 3π/5-mode.

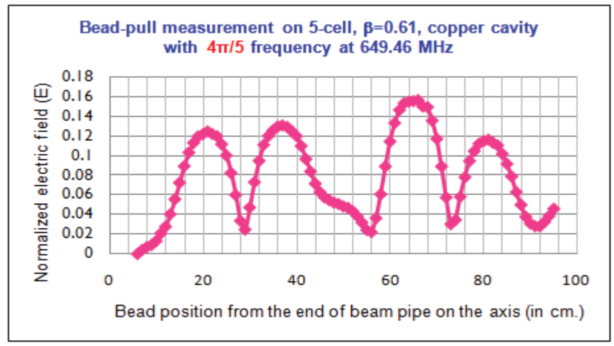

Figure 19: Measured E-Field Profile for 4π/5-mode.

The fundamental resonant modes (π-mode) of the two niobium half cells are measured (shown in Figure 25) as 634.3 MHz and 636.8 MHz respectively though simulated value for half-cell is 641.13 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 640.84MHz. The simulated frequency of single-cell cavity along with two beam pipes is 645.3 MHz. This deviation of frequency from simulated results conforms to the CMM measurement of the niobium half cells. From CMM measurement it is found that deviation of the iris radius of the half cells from the designed dimension is 0.8 mm and 2 mm respectively. Also the cell length is less than the designed value by around 3.3 mm. These deviations, during forming and machining, finally led to decrease in fundamental mode frequency.

Figure 20: Niobium half-cell.

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Figure 21: CMM measurement of half-cell.

Figure 22: Niobium half cells and beam pipes with fixtures developed for Electron Beam Welding.

Figure 23: Cavity half cells being put inside EBW machine for equator welding at IUAC, New Delhi.

Figure 24: Single cell elliptical cavity after EBW.

CONCLUSION

The present design of Low beta, 650MHz elliptical cavity (LB650 cavity) is different from the other two designs of LB650 cavity done by Femilab and JLab. The aperture is 96 mm and wall slope angle is 2.4^0 (for mid-cell) and 4.5^0 (for end-cell) as compared to aperture 84 mm and wall slope angle 2^0 (for mid-cell) and 2.7^0 (for end-cell) by Fermilab and aperture 100 mm and wall slope angle is 0^0 (for mid-cell and end-cell) by JLab. Larger aperture radius will give better cell-to-cell coupling (%K_{cc}) and better field flatness factor. Multi-cell field profile will be less sensitive to the frequency errors of an individual cell for accelerating π-mode. Also large aperture leads to less beam loss and higher beam current. The wall slope angle (greater than zero) provides the scope for reliable surface processing and better mechanical stability. Though the aluminium single cell prototype cavity does not deviate much from the design dimension, deviation of the niobium half cells from design is significantly high. So our fabrication process is being modified according to the experience gained from the first niobium cavity and the fabrication of another single cell niobium cavity is under process.

Figure 25: VNA measurement of niobium half-cell.

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