DEVELOPMENT OF 650 MHz CAVITIES FOR THE GeV PROTON ACCELERATOR IN PROJECT-X

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Abstract

Project X is a GeV range high intensity proton linear accelerator being developed at Fermilab, USA in collaboration with various American and Indian laboratories as well. In stage-1 of the project, the CW linac structures with different velocity factor (beta) accelerate proton up to 3 GeV at an average beam current of 1 mA. For acceleration from 180 MeV to 480 MeV, the development of 650 MHz, beta 0.61, 5-cell elliptical SRF cavities has been taken up by VECC. The EM design and analysis of this cavity, carried out using 2D and 3D codes, will be discussed along with its structural and mechanical modal analysis. This design has been compared with the designs made by JLab and Fermilab. The presence of higher order modes (HOMs), for the said cavity has been thoroughly examined. The multipacting analysis will be presented using 2D code and also 3D CST Particle Studio code with due consideration of Furman model for secondary electron emission comprising of true, elastic and rediffused secondary electrons. The prototype development and low power testing of this cavity will be discussed here. The talk will be concluded with the probable SRF challenges to be faced in the development of the cavity.

INTRODUCTION

A schematic layout of Project X Reference Design Accelerator [1] complex has been shown in Fig. 1 and SRF technology map for CW proton linac of Project X has been shown in Fig. 2. Acceleration of proton beam from the energy of 177 MeV to 3 GeV will be provided by two families of five-cell superconducting RF (SRF) cavities operating at 650 MHz and designed to geometrical β factor (β_G) 0.61 to 0.9. The criterion for the SRF cavity shape optimization is to decrease the field enhancement factors, magnetic and electric, in order to improve the interaction between the beam and the cavities. The cavity aperture needs to be designed to make as small as possible provided the considerations of very good field flatness, minimum beam losses, very good mechanical stability, reliable surface treatment and processing facility for the cavity inside surface are maintained. This paper focuses especially on the low beta cavities (LB650) operating with β=0.61 at the resonant frequency of 650 MHz.

LB650 SRF CAVITY

The working accelerating gradient for LB650 cavity has been chosen as 17 MV/m in order to keep the peak surface magnetic field (B_P) within a limit that allows operation below high-field Q-slope. B_p should be restricted to 70 mT (as shown in Fig. 3) for the operation of the cavity at 650 MHz. Moreover, in order to get rid of the risk of strong electric field emission, the peak surface electric field (E_P) has been restricted to 40–50 MV/m.

According to linear perturbation theory, for a given relative error in the frequencies of the cavity cells, the field flatness is determined by the frequency deviation (δf) between the operating frequency (f_π) in accelerating mode and the frequency of the neighbouring mode.

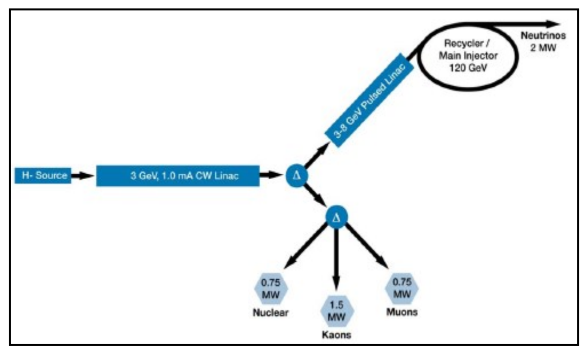

Figure 1: A schematic layout of Project X reference design accelerator complex [1].

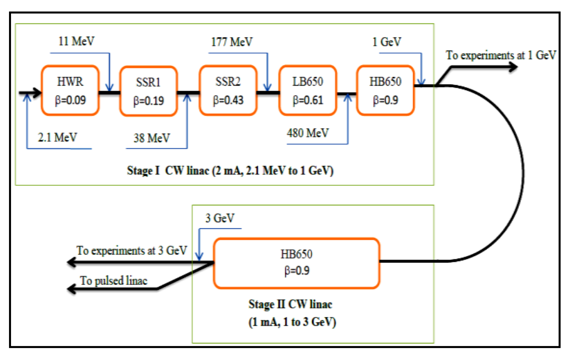

Figure 2: SRF technology map for CW proton linac of Project X [1].

If the number of cells is "N" and the cell-to-cell coupling coefficient is "k_c", the field flatness factor at the operating frequency is, $\frac{f_\pi}{\delta f} \approx \frac{N^2}{k_C}$. Therefore a cavity with a fewer cells shows a smaller coupling coefficient for a given flatness. For the 5-cell elliptical SRF cavity operating at 650 MHz, the value of $\frac{\delta f}{f_\pi} = 5.10^{-4}$ corresponds to k_c=1.25%. The aperture of the cavity is selected considering the trade-off between cell-to-cell coupling and beam loss. The experiences with other

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laboratories determine that these cavities can operate within 100 mm. aperture with tolerable beam loss. So, the aperture of 96 mm. for the LB650 cavity has been adopted.

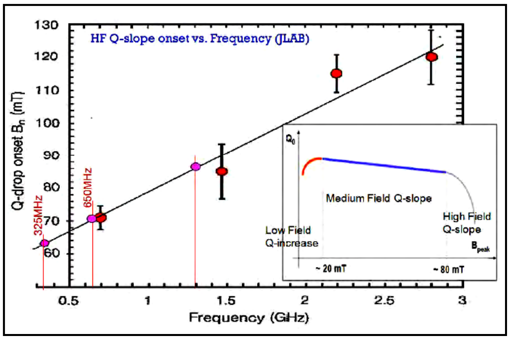

Figure 3: Plot of high field Q-slope vs. Frequency [1].

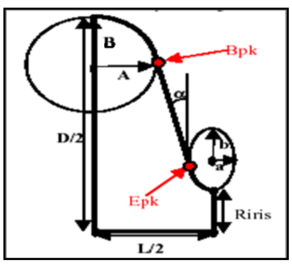

Figure 4: Cavity cell geometry.

Cavity Simulation Results

The 5-cell elliptical shape cavity simulation has been carried out by using 2D SUPERFISH code and also 3D CST MICRWOWAVE STUDIO code and the results are shown in Table 1, where a comparative chart [2] of design parameters of LB650 cavity from various laboratories has been tabulated. The field flatness is very good and the cell-to-cell coupling coefficient is 1.24%. For the mid-cells (as shown in Fig. 4), the equator ellipse aspect ratio, $\frac{A}{B} = \frac{54\ mm.}{58\ mm.}$, the iris ellipse aspect ratio, $\frac{a}{b} = \frac{13.68\ mm.}{30.82\ mm.}$, equator diameter, D=394.8 mm., Iris diameter 96 mm., the cell length, L=140.67 mm. The ratio $\frac{R}{Q}$ =296, which is reasonably good in terms of cryogenic loss is concerned and also the geometrical factor (G=200) is good enough. Two major parameters, electric field enhancement factor ($\frac{E_P}{E_{acc}}$ =3.00) is fairly good value and the magnetic field enhancement factor ($\frac{B_P}{E_{acc}}$ =4.84) is also quite good.

A small cavity wall slope (α) gives more freedom to decrease the field enhancement factor. However, α value is limited by the considerations of surface processing and mechanical stability requirements. In mid-cells, α is chosen as 2.4 degree, in order to maintain low field enhancement factor.

Table 1: Comparative Chart of Design Parameters of 650 MHz, β=0.61 Cavity from various laboratories

Name of the lab designed	$\frac{A}{B}$ (mm./mm.)	$\frac{a}{b}$ (mm./mm.)	Equator radius D/2 (mm.)	Iris radius Riris (mm.)	Half cell length (L/2) (mm.)	$\frac{R}{Q}$ (Ω)	G (=Q.R) (Ω)	E_{acc} (MV/m)	$\frac{E_p}{E_{acc}}$	$\frac{B_p}{E_{acc}}$ (mT/MV/m)	f_π Mode (MHz)	Remarks
Fermilab	$\frac{54}{58}$	$\frac{14}{25}$	194.95	42	70.335	378	191	17.0	2.26	4.21	650	2D SLANS Code L/2=71.385 (endcell) α=2.0deg.(midcell) =2.7deg(endcell) E = 92.7 J
JLab	$\frac{50.46}{45}$	$\frac{15}{22}$	192.10	50	65.456	297	190	17.3	2.71	4.78	650	2D SUPERFISH Equator flat =0.976 (midcell) =0.5047 (endcell) α=0.0deg.(midcell) =0.0deg.(endcell) E = 118.8 J
VECC	$\frac{54}{58}$	$\frac{13.68}{30.82}$	197.40	48	70.335	296	200	17.0	3.00	4.84	650	2D SUPERFISH, 3D CST MWS α=2.4deg.(midcell) =4.5deg(endcell) $\left(\frac{a}{b}\right)_{end-cells} = \frac{10.67}{24.02}$ E = 118.8 J

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Furthermore, end-cell modifications have been carried out to achieve very good field flatness. For end-cells, the iris ellipse aspect ratio has been modified to $\left(\frac{a}{b}\right)_{end-cells} = \frac{10.67}{24.02}$, while the equator ellipse aspect ratio has been kept unchanged. The wall slope angle has been increased to 4.5 degree.

Cavity Shrinkage

The cavity is designed at room temperature and it will be operated at 2 K. The niobium cavity will shrink due to thermal contraction of the material. It is necessary to adjust the dimensions of the cavity by taking into account the 150 µm of material removal (t_{BCP}) due to buffered chemical polish (BCP) and thermal shrinkage from room temperature (293 K) to 2 K. The aperture and equator radius is decreased by 150 µm. The ellipse centres and half cell length do not change appreciably. Half axis in Iris area are increased by 150 µm, while that in equator area are decreased by the same quantity. Although the thermal expansion/contraction coefficient (α_{Nb}) of niobium is actually non-linear (as shown in Fig. 5) with respect to temperature (in K), the linear approximation gives, α_{Nb}= 142 x 10^{-5} / K. If the inside dimension of the cavity under cold and warm condition are L_{COLD} and L_{WARM}, the relation between them is established as follows.

$$L_{COLD} = \frac{(L_{WARM} + t_{BCP})}{(1 + \alpha_{Nb})}$$

The cold and warm dimensions of the cavity are tabulated in Table 2.

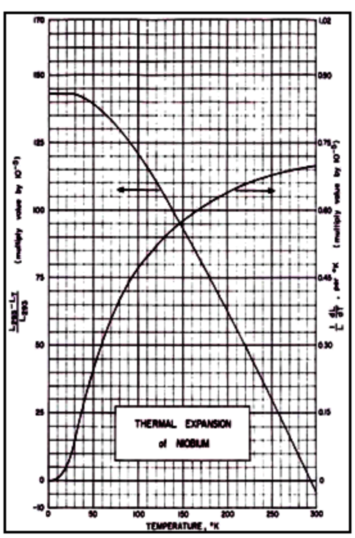

Figure 5: Thermal expansion of niobium.

Higher Order Modes (HOMs)

The existence of transverse and longitudinal HOMs of the cavity has been investigated using CST Microwave Studio code. However, it is observed (from Fig. 6 & Fig. 7) that there is no trapped mode (transverse or longitudinal) with high effective impedance. Hence, HOM dampers are not necessary for the cavity operating at the beam current of around 2 mA.

Table 2: Cold and Warm Dimensions of Cavity

Dimensional Parameters	COLD Dimension (inside) (Designed) (mm.)	COLD Dimension Pre- BCP treatment of 150 µm (mm.)	WARM Dimension inside (Fabricated) (mm.)
Equator radius	197.400	197.250	197.53
Iris radius	48.000	47.850	47.92
A	54.000	53.850	53.93
B	58.000	57.850	57.93
a	13.680	13.830	13.85
b	30.820	30.970	31.01
a (for end cell)	10.670	10.820	10.84
b (for end cell)	24.020	24.170	24.21
Half cell length (L/2)	70.335	70.335	70.44

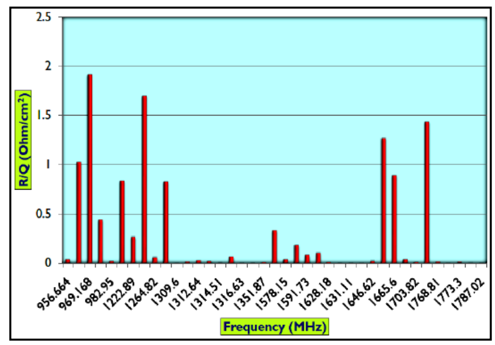

Figure 6: Effective impedance for transverse HOMs.

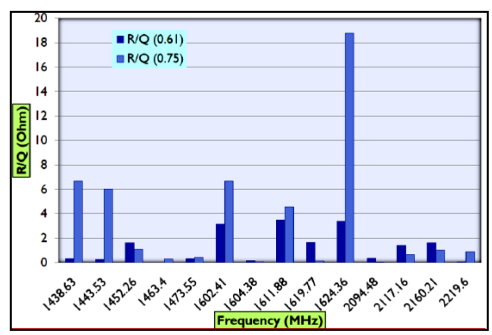

Figure 7: Effective impedance for longitudinal HOMs.

Multipacting Analysis

The possibility of cavity multipacting has been investigated initially by using 2D MultiPac 2.1 code. The impact energy (as shown in Fig. 8) is less than 50 eV for all peak electric fields except a small region between 30 to 35 MV/m, where it is around 200 eV. For mid-cells and end-cells, even after 30 impacts of electrons at the equator region (at the radius 197 mm) of the cavity, the final impact energy is 28.4364 eV, which is well below 50 eV. Based on 2D analysis, it is unlikely to cross secondary electron emission yield for producing multipacting, as the relative enhanced electron counter function is less than unity for the whole range of peak electric field up to 60 MV/m.

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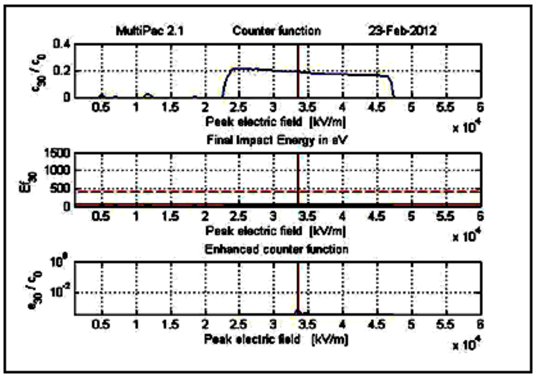


Figure 8: Results for end-cell cavity.

The 3D analysis for the same cavity has been carried out extensively for further investigation using CST Particle Studio code that takes into account Furman Model [3] for three types of secondary electron emission, true secondary, back scattered and rediffused electrons. Here, 30 mm. of equator region has been simulated with a minimum mesh size of 0.37 mm. Multipacting takes place at electric field between 5.8 MV/m and 11.5 MV/m and the rate is very fast at 6.8 MV/m (shown in Fig. 9 & Fig. 10). At 11.5 MV/m, the rate of increase in particle due to multipacting is very low. There is no occurrence of multipacting below 4.5 MV/m and beyond 22.5 MV/m.

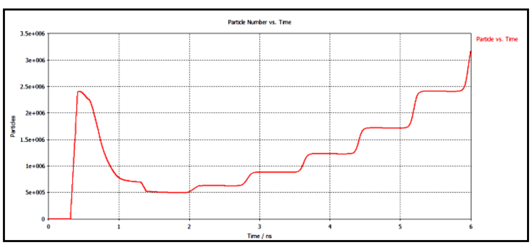


Figure 9: Particle vs. time (ns) at 6.8 MV/m.

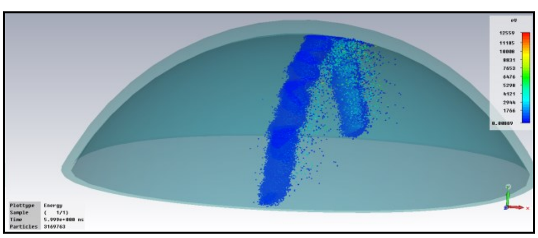
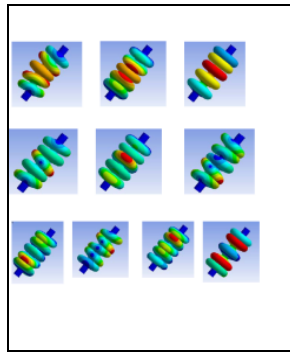


Figure 10: Particle after 6 ns at 6.8 MV/m.

Mechanical Modal Analysis

The mechanical modal analysis (as shown in Fig. 11) of the cavity determines that the frequencies of mechanical modes without stiffener are below 100 Hz, which is not desirable for operation. However, with stiffener, the frequencies are increased beyond 100 Hz. The stiffener needs to be placed at the radius of 133 mm. (as shown in Fig. 12) in order to raise the mechanical mode above 100 Hz.



Mode	Frequency [Hz]
1.	3.0625
2.	5.9953
3.	8.6136
4.	10.776
5.	11.161
6.	24.688
7.	26.005
8.	27.449
9.	28.538
10.	57.485

Figure11: Mechanical modes without stiffener.

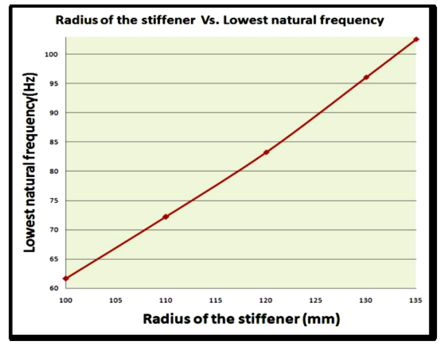


Figure 12: Mechanical modes vs. Stiffener position.

Structural Analysis

The structural analysis [4] of the cavity has been carried out using 3D ANSYS code, assuming operating temperature at 2K and external pressure of 3 atm, with boundary conditions of both ends being fixed. Various stress plots indicate that they are within allowable limit. The stress integral (as shown in Fig. 13), comprising of primary membrane, bending and secondary stress, of 4 mm. thick niobium sheet has been obtained as 131 MPa, which is well within the allowable limit of 309 MPa, as per ASME code.

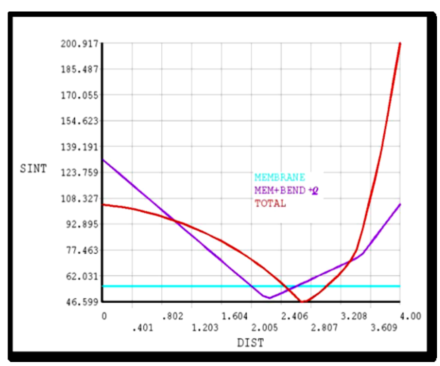


Figure 13: Plot of stress vs. thickness of the cavity wall.

Prototype Cavity Fabrication and Testing

The half cells of the prototype aluminium LB650 cavity has been fabricated after the design and development of the necessary die-punch assembly. The inside dimensions of the half-cell has been measured using Laser Faro

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Coordinate measuring machine (CMM) and the maximum deviation of the order of 0.4 mm is found and further improvement is being tried. Two half cells have been joined to fabricate a single cell cavity as shown in Fig. 14. The low power RF test has been carried out using Vector Network Analyzer (VNA) on this cavity. The transmission scattering parameter (S_{21}) measurement (as shown in Fig. 15) shows that the resonant frequency of the cavity is f_0 = 645.86350 MHz and -3dB frequencies are, f_1 = 645.84860 MHz and f_2 = 645.87980 MHz. The half-power (-3dB) bandwidth of the single cell cavity is $\Delta f = f_2 - f_1 = 31.2\,kHz$. The quality factor is calculated as $Q = \frac{f_0}{\Delta f}$ =20700. The electric field gradient on the axis of the cavity is being carried out using bead-pull measurement set up [5] already developed at VECC.

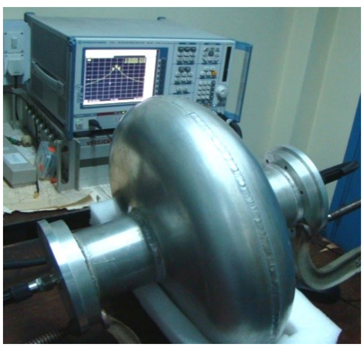

Figure 14: VNA Measurement of single cell cavity.

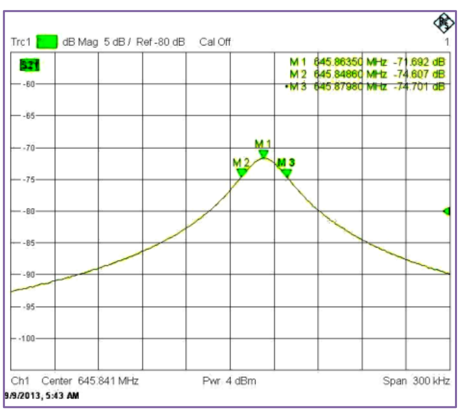

Figure 15: S_{21} measurement of single cell cavity.

CONCLUSION

The LB650 cavity development activity has been carrying out by VECC in collaboration with Fermilab, USA and the funding has been provided by the DAE, Government of India. The electromagnetic design of the 5-cell cavity has been done with 96 mm. aperture and aimed at accelerating gradient of 17 MV/m. The end-cell modification incorporated in the design to achieve very good field flatness. The problem of HOMs is not anticipated in this cavity operating at around 1 mA of beam current. The extensive analysis using Furman Model indicates that strong multipacting is likely to occur in the cavity at the field between 5.8 MV and 11.5 MV. The stiffener is required at the appropriate position to keep mechanical modes above the safe value of 100 Hz. The cavity structure appears to be failsafe with stress values well within the allowable limits for 4 mm. wall thickness. A prototype single cell aluminium cavity has been fabricated with dimensional accuracy of around ±0.4 mm. as measured with laser Faro CMM. The low power RF test with VNA shows fairly good results with resonant frequency around 646 MHz under warm condition. The measurement of electric field gradient on the cavity axis is being carried out using Bead=pull set up. Better dimensional accuracy (±0.2 mm.) is being tried in actual niobium cavity, where many other challenges on fabrication and surface treatment etc. are involved.

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