ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOGE03

DESIGN & MULTIPHYSICS ANALYSIS OF THREE-CELL, 1.3 GHZ SUPERCONDUCTING RF CAVITY FOR ELECTRON BEAM ACCELERATOR TO TREAT WASTEWATER

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Abstract

To treat industrial effluents including contaminants of emerging concern (CECs), Irradiation treatment by electron beam accelerator has shown promising results. Our aim is to design and develop a superconducting linear electron accelerator. A 1.3 GHz, three cell conduction cooled, TM class superconducting cavity has been proposed to accelerate a 100 mA electron beam from 100 keV to 4.5 MeV. The main aim of the design is to optimize the cavity for low heat loss and high accelerating gradient. The optimized ratio of peak surface electric and magnetic field to accelerating field for cavity are E_{pk}/E_{acc} = 2.72 and H_{pk}/E_{acc} = 4.11 mT/(MV/m). The optimized Geometry factor (G) and R/Q values for this cavity are 246.7 and 306.4 ohms respectively. Here we also addressed other multiphysics issues such as Lorentz force detuning (LFD), Higher order modes (HOMs) and Multipacting. The multiphysics analysis helps to estimate the degree of these challenges. The final Lorentz detuning factor of the cavity has been reduced to 0.12 Hz/(MV/m)^2, HOMs of 2.18 and 2.9 GHz modes are dominating except the main mode and Multipacting phenomena is not found at 15 MV/m of accelerating gradient.

INTRODUCTION

A 450 kW, 100 mA, 4.5 MeV High-Intensity Compact Superconducting Electron Accelerator (HICSEA) is proposed by IIT Bombay as a sustainable alternative to treat wastewater. Figure 1 shows the schematic and different components of the proposed accelerator.

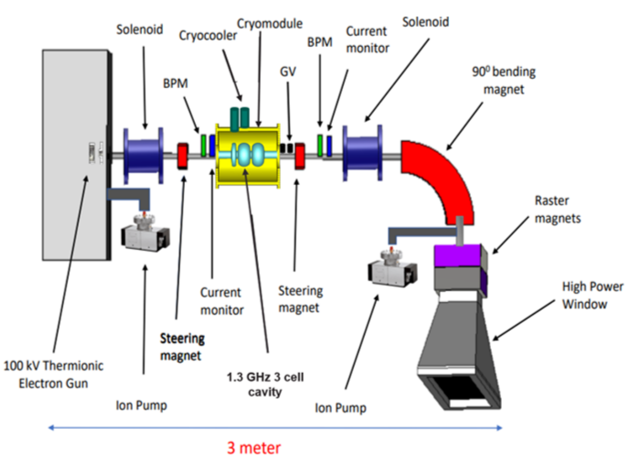

Figure 1: A Schematic figure of proposed accelerator structure.

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This paper discusses the RF design, optimization, and multiphysics analysis of a 1.3 GHz, three-cell Superconducting RF cavity that will be used to accelerate the beam to a final energy of 4.5 MeV. The main aim is to optimize the cavity for low power loss and high energy gain while transmitting a high-intensity beam of 100 mA with minimum emittance growth and energy spread. To meet these requirements, the cavities must be tuned for low peak surface electric (E_{pk}) and magnetic (H_{pk}) fields, allowing us to raise the accelerating gradient and a high GR/Q value with a large beam pipe radius, allowing the beam to gain maximum energy and pass with minimal disruption. The simulation and optimization are done using the 3D electromagnetic simulating code CST Microwave Studio for high-frequency components.

This superconducting cavity also has certain technological hurdles that must be solved for efficient acceleration. These concerns include cavity deformation due to radiation pressure, beam instability induced by High order modes (HOMs), and multipacting of electrons through the cavity's surface. These faults are generated by the cavity's inadequate geometry optimization, resulting in increased power loss and beam instability.

Thus, a multiphysics analysis of this cavity is required to eliminate these kinds of cavity issues. The CST microwave studio is used to perform: (1) Lorentz Force Detuning (LFD), (2) HOMs analysis, and (3) Multipacting analysis. All of these simulations are performed for an accelerating gradient of 15 MV/m.

RF CAVITY DESIGN AND OPTIMIZATION

The designed cavity has three cells from which We have designed the inner and end cells individually to optimize the geometric parameters of the cavity due to the coupling of the beam tube pipe with the end cell. [1]. The second and third cells are tuned for minimum heat loss and a strong accelerating gradient which is constrained by the peak electric and magnetic fields. The power dissipation in the cavity is also influenced by the Geometry factor and the R/Q value. Therefore, both cells are tuned to reduce E_{pk}/E_{acc} and B_{pk}/E_{acc} while increasing the Geometry factor (G) and R/Q value for fundamental mode (F = 1.3 GHz). Both cells have a half-cell length of 5.77 cm (L = $\beta\lambda/4$), where (β = 1) is the ratio of electron velocity to light velocity, and λ is the wavelength of the fundamental mode. The iris radius of R_i = 3.2 cm is chosen to maximize the cell-to-cell coupling (K_{cc}) as well as R/Q. The cavity's initial cell design is critical because the electron entering the cavity has a low velocity (v = 0.4c to 0.6c). The synchronous electron must be able to see the cor-

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rect phase. To match the phase of the incoming electron with the RF field, the length of this cell (half-length $L_f = \beta\lambda/4$ = 2.5 cm, where $\beta = 0.5$) is reduced. To get an improved mechanical characteristic with minimal field emission, this first cell is adjusted further, and a wall angle (θ) of 8^o is inserted in the first half cell near the cavity's entrance to avoid field emission.

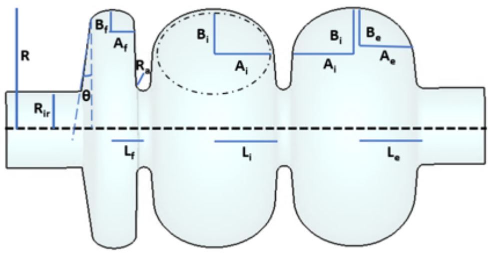

Figure 2: Three cell elliptical cavity and its tunable parameters.

Optimization and RF Parameters

The proposed three-cell niobium cavity is optimized by varying the cavity's parameters (see Fig. 2) while considering geometrical restrictions into account. The peak surface electric and magnetic fields are reduced by adjusting the iris elliptical radii (a and b) and equatorial elliptical radii (A and B) as shown in the Fig. 4. The peak surface fields

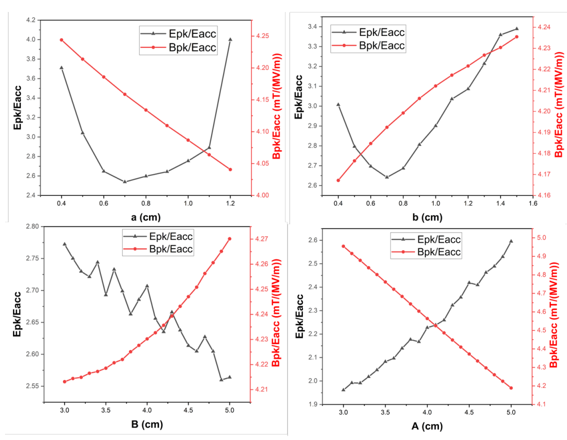

Figure 3: Variation of E_{pk}/E_{acc} and H_{pk}/E_{acc} with respect to a,b and B,A.

are constrained by the cavity wall material, which is niobium (Nb). For single crystal niobium, the highest critical magnetic field (Bc) is 180 mT and the maximum electric field is 93 MV/m. [2]. Other parameters, primarily R/Q and G value, have also been optimized for the cavity's last two cells, which are essentially intended as LL shape cavities for ILC [2]. The final RF parameters of the optimized cavity are shown in the Table 1 .

MULTI-PHYSICS ANALYSIS

As previously noted, multiphysics studies are critical for the stability of the designed cavity to eliminate drawbacks

Table 1: Final RF Parameters of the Cavity

Parameters	Value
Frequency (GHz)	1.3
Accelerating Gradient (MV/m)	15
E_{pk}/E_{acc}	2.72
B_{pk}/E_{acc} (mT/(MV/m))	4.11
Q	4.6×10^{10}
G (Ω)	246.7
R/Q (Ω)	306.4
G x R/Q (Ω-Ω)	75 619
K_{cc} (%)	1.86

in the cavity when it is functioning. Lorentz Force Detuning (LFD) studies, multipacting analysis, and Higher Order Modes (HOMs) analysis are conducted for the optimized RF design to ensure a smooth and reliable operation.

Lorentz Force Detuning (LFD)

The Structural Mechanics solver from CST was employed for this study, and the Lorentz force was imported from the eigenmode solver for LFD calculation. Initially, the LFD coefficient of an optimized cavity was calculated to be -3421 Hz/$(\mathrm{MV/m})^2$ at an accelerating gradient of 15 MV/m. As a result, the operating frequency is reduced by 769.7 KHz for the same gradient. This detuning is reduced by applying mechanical stiffness by placing stiffening rings around the cavity at the equator, as shown in Fig. 4. The displacement of these stiffening rings is kept at zero in all directions during the computation. The final LFD coefficient is 0.12 Hz/$(\mathrm{MV/m})^2$, resulting in a nominal detuning of 27 Hz.

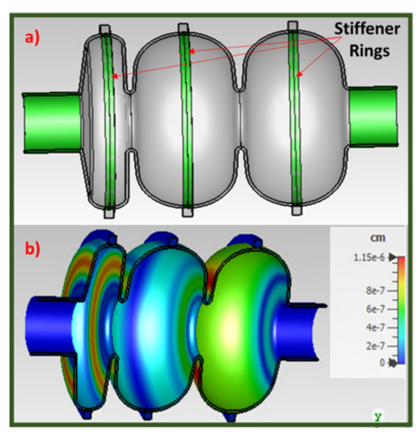

Figure 4: Three cell elliptical cavity LFD analysis, a) Locations of stiffener rings with boundary conditions of $\Delta X = \Delta Y = \Delta Z = 0$ cm (green colour) and, b) Cavity deformation (in cm) after adding stiffener rings.

Higher Order Modes (HOMs) Analysis

Other than the fundamental mode i.e. 1.3 GHz, Higher order modes can be also present in the cavity, including

31st Int. Linear Accel. Conf. LINAC2022, Liverpool, UK JACoW Publishing
ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-THPOGE03

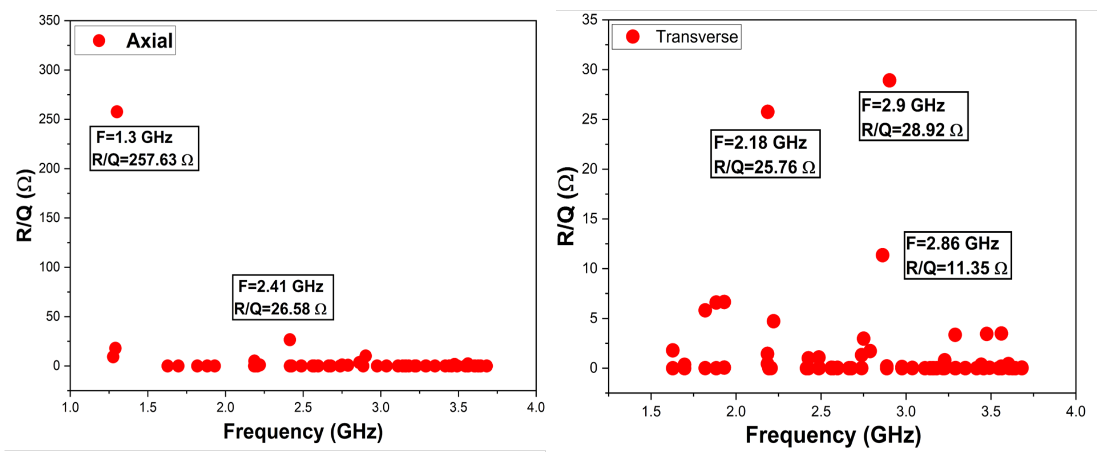

Figure 5: R/Q parameter vs Frequency graph for optimized cavity, a) for longitudinal (monopole mode), b) for transverse mode.

transverse and axial modes that may affect beam quality and extra power loss in the cavity. The R/Q value for a particular mode indicates how successfully the energy held in the cavity can be transferred to the beam. So HOMs must have low R/Q to prevent the influence on particles. The axial and transverse R/Q values can be calculated as [3],

$$(R/Q)_{\|,n} = \frac{|\int_{-\infty}^{+\infty} E_{n,z}(r=0,z)e^{i\omega_n \frac{z}{\beta c}}dz|^2}{\omega_n U_n} \quad (1)$$

$$(R/Q)_{\perp,n} = \frac{|i\frac{c}{\omega_n a}\displaystyle\int_{-\infty}^{+\infty} E_{n,z}(r=a)e^{i\omega_n \frac{z}{\beta c}}dz|^2}{\omega_n U_n} \quad (2)$$

where $E_{n,z}$ is the axial electric field of n-mode inside the cavity at a distance r from the cavity axis, a is radius of beam tube, β is the relativistic factor, ω_n and U_n are the frequency and stored energy corresponding to the n-th mode. The R/Q values for axial (monopole), and transverse modes are given for different mode frequencies in Fig. 5. This figure shows that the dominated axial and transverse frequency other than the main frequency are 2.41, 2.18 & 2.9 GHz with R/Q of 26.58, 25.78 & 28.92 Ω respectively.

Multipacting Analysis

Multipacing is a phenomena caused by resonating electrons in the cavity with RF fields. At certain point, parasitic discharge occurs through the conducting wall of the cavity, resulting in a large number of electrons inside the cavity. These electrons decreases the cavity's performance by draining its RF energy (Q-value and maximal accelerating gradient E_{acc}) and destroying the superconductivity through cavity wall heating. For numerical simulations, Particle-in-Cell (PIC) solver from CST-Microwave studio was used. Because of its high precision, the Furman model was chosen for secondary particle emission from the niobium cavity wall [4]. We only consider 1/4th part of the cavity for simulations to decrease simulation time and to limit particle loss the cavity is covered by a material sheet with 100 % reflectivity and zero secondary electron yield. The simulation results show that there is no multipacting found up to the accelerating gradient of 15 MV/m (operating gradient). For higher accelerating gradients, the multipacting is found in the equatorial region, which can be cured by adding some bumps inside the equator region. This bumps can break any synchronization between the RF field and secondary electrons.

CONCLUSION

A three-cell cavity is designed for high intensity with energy gain of 4.5 MeV. In this structure, first cell is tuned for phase synchronization of low energy particles with minimal field emission, while the last two cells are optimized for low power loss and high accelerating gradient. For an accelerating gradient of 15 MV/m, the maximum peak surface electric and magnetic fields are 41.4 MV/m and 62.25 mT, respectively, which are less than the critical limit 93 MV/m and 180 mT for niobium respectively .
The LFD analysis was performed to treat cavity detuning by applying stiffener around the equator, which reduced the LFD coefficient (K_L) from 3421 to 0.12 Hz/(MV/m)^2 and frequency detuning from 769.7 to 27 Hz. According to the HOMs analysis, two HOMs, f=1.81 GHz and f=2.22 GHz, are dominated in cavities other than the operating mode (f=1.3 GHz), which are far from operating frequency.Finally, multipacting analyses show that no multipacting phenomena were observed at E_{acc} of 15 MV/m in the equatorial region.

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