31st Int. Linear Accel. Conf. LINAC2022, Liverpool, UK JACoW Publishing
ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOJO08

RF DESIGN, OPTIMIZATION AND MULTIPHYSICS STUDY OF A $\beta = 1$, 1.3 GHz SINGLE CELL ACCELERATING CAVITY FOR HIGH-INTENSITY COMPACT SUPERCONDUCTING ELECTRON ACCELERATOR (HICSEA)

Manisha Meena, Abhishek Pathak, Raghava Varma,
Indian Institute of Technology Bombay, Mumbai, India

Abstract

High-energy electron accelerators have been used in water purification for several years. They are very effective for the removal of complex impurities. This study aims to design a superconducting electron beam accelerator with an output energy of 1 MeV and beam power of 40 kW for wastewater treatment. A 1.3 GHz single cell elliptic cavity with $\beta = 1$ was designed and optimized for TM_{010} mode and an accelerating gradient of 15 MV/m. For the optimized cavity, the RF parameters, namely, R/Q, transit time factor and geometry factor (G) were found to be 174.93 Ω, 0.67 and 276 Ω, respectively. Multiphysics studies showed that the value of R/Q for fundamental accelerating mode was 174.93 Ω. It was much higher than that of other modes, thus, HOM coupler is not required for the system. The Lorentz force detuning coefficient after stiffening the cavity iris, and the temperature rise due to the RF surface losses were found to be 0.20 Hz/(MV/m)^2 and 0.085 K, respectively. It is also observed that there is no occurrence of multipacting for the designed accelerating gradient.

INTRODUCTION

Accelerator technology has been proven to be an efficient and sustainable resource for wastewater treatment [1]. Therefore, IIT Bombay proposed to develop a 40 kW superconducting electron accelerator system as shown in Fig. 1 in collaboration with Japanese Universities and Institutes. The proposed accelerator consists of a 1.3 GHz superconducting single cell elliptic cavity to achieve desired beam energy of 1 MeV.

This paper presents detailed RF design and multiphysics optimization studies to maximize RF efficiency, and to obtain an acceptable beam quality at the exit of cavity. The RF design and optimization studies are performed using CST Microwave Studio and Poisson Superfish.

The RF design includes optimization of peak surface electric and magnetic fields since these are the limiting criteria to obtain high accelerating gradient (E_{acc}) and low power loss for SRF cavities. The magnetic field is smoothened out by the appropriate arc at the equator, which lowers the peak surface magnetic field. As with the iris region, smooth curvature lowers the peak surface electric field and solves the issue of field emission. The RF design and optimization have been followed up with multiphysics studies in order to ensure a stable and reliable operation of the cavity. The multipacting studies includes higher order modes (HOMs) analysis, Lorentz force detuning study, multipacting study, and thermal analysis.

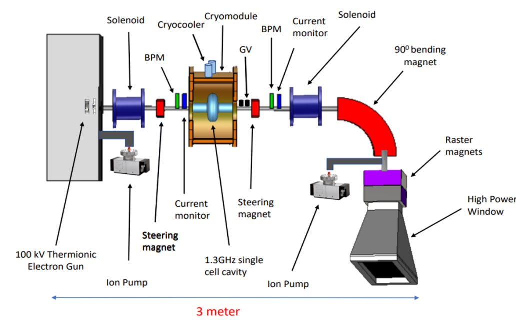

Figure 1: Prototype of the proposed electron accelerator system and its components.

RF CAVITY DESIGN AND OPTIMIZATION

The RF design and simulations are perfomed with cavity symmetry in YZ plane as shown in Fig. 2, where Z is along the cavity length and Y is along the cavity radius. The seven geometry parameters that determine the cavity design include half-cell length (L), iris radius (R_{iris}), iris ellipse radii a and b, equator ellipse radii A and B, and cavity radius (R_{eq}). The wall angle (α) can be derived from these seven parameters. The half-cell length of the cavity for TM_{010} - π mode operation is chosen as $\beta\lambda/4$ to ensure synchronization of the bunch with RF field. The iris radius is chosen to be 3.2 cm, while the cavity radius (R_{eq}) is tuned to achieve the resonant frequency of 1.3 GHz. The wall angle is chosen to be 90° because the product of geometry factor (G) and ratio of shunt impedance to quality factor (R/Q) of the cavity increases with wall angle which which in turn is inversely proportional to the power loss. However, the upper limit for α is limited by manufacturing and cleaning constraints.

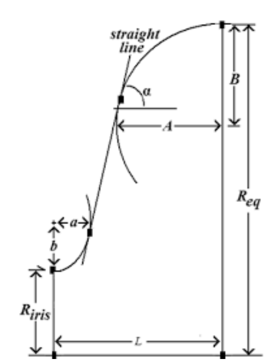

Figure 2: Schematic design and geometry parameters of the half-cell cavity [2].

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOJO08

The RF requirements of the proposed system are to achieve maximum R/Q and G, minimal power loss, and minimum peak surface fields for the accelerating gradient of 15 MV/m. Therefore, optimization of a $\beta = 1$ single cell superconducting cavity operating at 1.3 GHz is performed by the 2D software Poisson Superfish, and this optimized cavity shape is further simulated using the 3D software CST Studio Suite.

The peak surface magnetic field (B_{pk}) must be less than the critical magnetic field of niobium (≈ 180 mT) for superconducting operation, and the peak surface electric field (E_{pk}) should be below the critical value (93 MV/m) since it can lead to field emission [3]. In this work, the geometry is optimized to reduce the value of B_{pk}/E_{acc} for a certain value of E_{pk}/E_{acc} in order to attain maximum E_{acc}.

The cavity frequency is tuned to operate at 1.3 GHz. Hence, there are now only four independent parameters for optimizing the RF efficiency: a, b, A, and B. We kept $E_{pk}/E_{acc} \leq 1.6$ as the target value since it is the value for pill-box cavity [4], and we performed the calculations by assuming that a/b = A/B = 1. Thereafter, we only have one independent parameter, which is taken to be B with the initial value equal to L/2. It can be seen from Fig. 3 that B_{pk}/E_{acc} continuously decreases with B, but E_{pk}/E_{acc} starts to rise noticeably after B = 4.1 cm, hence by adhering to the constraint $E_{pk}/E_{acc} \leq 1.6$, the value of B is set at 4.1 cm for subsequent simulations.

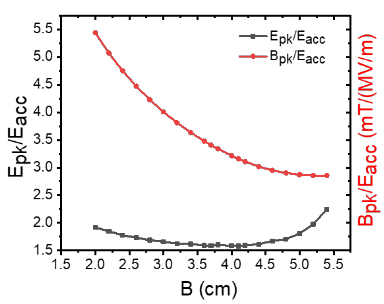

Figure 3: Variation of E_{pk}/E_{acc} and B_{pk}/E_{acc} as a function of B by keeping a/b = A/B = 1.

The ratios E_{pk}/E_{acc} and B_{pk}/E_{acc} are plotted as a function of A for various a/b ratios in order to optimize the value of A as shown in Fig. 4. It is observed that E_{pk}/E_{acc} increases with A, whereas B_{pk}/E_{acc} keeps monotonically decreasing with A because the peak magnetic field falls as the equatorial volume rises. Six data points (A, B, C, D, E, and F) are obtained that match the criterion $E_{pk}/E_{acc} \leq 1.6$. By considering these six data points, the B_{pk}/E_{acc} is found to be at its lowest with an optimal value of A = 4.73 cm and a/b = 0.73.

The RF characteristics of the optimized cavity are listed in data Table 1. The transit time factor (TTF) for β=1 is 0.67 for the cavity.

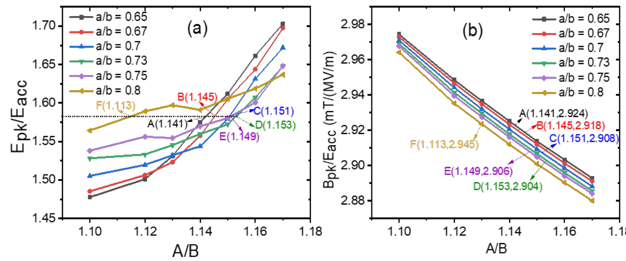

Figure 4: Variation of (a) E_{pk}/E_{acc}, and (b) B_{pk}/E_{acc} as a function of A for different a/b ratios.

Table 1: RF Parameters of the Optimized Cavity

RF Parameter	Value	Unit
E_{acc}	15	MV/m
Q_0	5.17×10^{10}	-
R/Q_0	174.93	Ω
G	275.98	Ω
B_{pk}/E_{acc}	2.90	mT/(MV/m)
E_{pk}/E_{acc}	1.59	-

MULTIPHYSICS STUDY

Prior to manufacture, multiphysics studies are conducted to validate and improve the cavity design. Therefore, various multiphysics studies for the optimized cavity are performed including higher order modes, Lorentz force detuning, and multipacting.

Higher Order Modes (HOMs) Analysis

Small R/Q values for the HOMs and high R/Q value for the accelerating mode are preferred since the performance of the cavity is constrained by the power dissipation, cryogenic load, and beam instabilities caused by the HOMs [4]. Figure 5 depicts the R/Q values for monopole, dipole, and quadrupole modes for the optimized cavity under various symmetry conditions (i.e., $E_{tangential} = 0$ and $H_{tangential} = 0$) in XY, YZ, and XZ planes. It is noted that the maximum value of R/Q for the TM_{010} mode is 174.9 Ω, while it is 28.6 Ω and 0.1 Ω for dipoles and quadruple modes respectively.

Lorentz Force Detuning (LFD)

The electromagnetic and structural solvers of the finite element code are used to calculate LFD for 3 mm of cavity wall thickness. Before stiffening the cavity iris for E_{acc} of 15 MV/m, the displacement of the cavity caused by the Lorentz force density is 0.0129 cm. The displacement, frequency detuning, and LFD coefficient [5] ($K_L = -\Delta f/ E_{acc}^2$) are 5.67×10^{-7} cm, -44.68 Hz, and 0.20 Hz/(MV/m)^2 after stiffening the cavity iris, respectively. As shown in Fig. 6, the resonant frequency detuning increases with E_{acc}.

Multipacting (MP)

Multipacting is a phenomenon in which electron avalanche takes place. Due to considerable RF power ab-

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-MOPOJO08

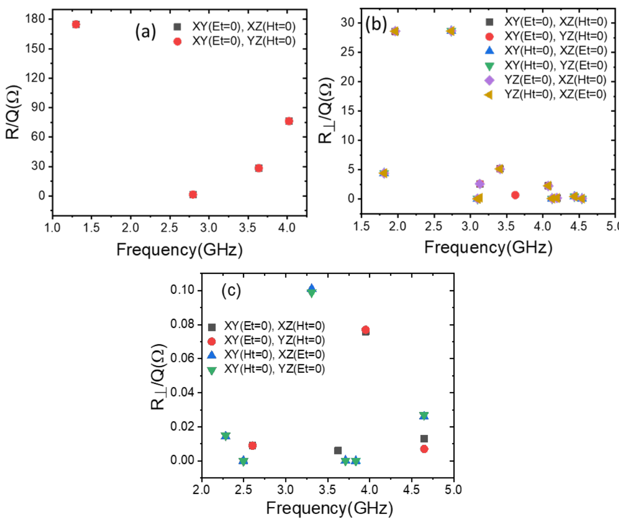

Figure 5: R/Q with respect to frequency of, (a) monopole mode, (b) dipole mode, and (c) quadrupole mode for the optimized cavity.

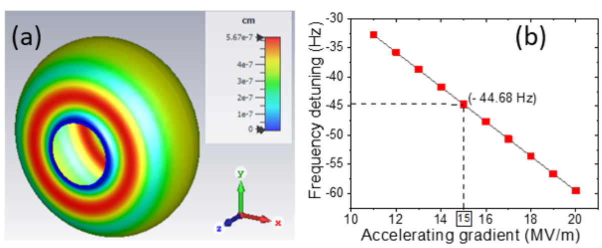

Figure 6: (a) Displacement of cavity after fixing the cavity iris for E_{acc} = 15 MV/m, (b) Resonant frequency detuning for different accelerating gradient.

sorption by the unwanted electrons, the cavity operation is affected.

An argon discharge cleaned niobium cavity shelled model with 3 mm thickness was used for the MP simulations. The entire interior surface of the cavity has been chosen as the particle source. The Gauss emission model is adopted, with the electron as the preferred particles.

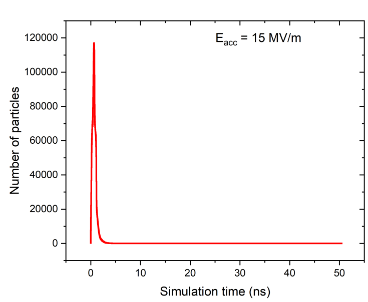

Figure 7: Number of particles as a function of time for E_{acc} 15 MV/m.

The particles are dissipating over time for E_{acc} 15 MV/m as shown in Fig. 7, hence there is no multipacting. It is also observed that within 13.33 % variation from the 15 MV/m E_{acc}, multipacting does not occur.

Thermal Analysis

The increase in temperature caused by RF fields only is modelled here. There are two type of losses due to EM fields, one is the volume losses within the cavity, and the other is the surface losses because of resistivity of the cavity wall. In the optimized cavity, the surface losses are 0.16 W and the volume losses are zero due to RF fields. The optimized cavity shows a temperature increase of 0.085 K for the designed gradient of 15 MV/m. The temperature rise profile is given in Fig. 8, and it can be seen that the temperature rise is highest at equatorial region where the magnetic field is maximum.

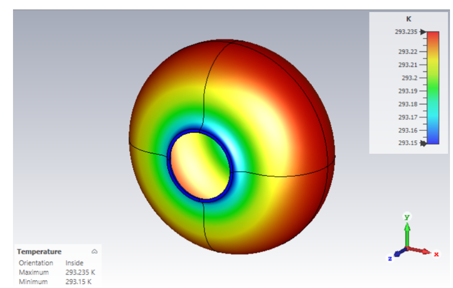

Figure 8: Temperature rise profile due to RF losses at ambient temperature 293.15 K.

CONCLUSION

The E_{pk} is 23.85 MV/m and B_{pk} is 48.45 mT for the optimized cavity, which are smaller than the allowed limits of 93 MV/m and 180 mT for niobium (Nb) cavity, respectively. Multiphysics studies show that HOM couplers are not necessary because the R/Q values of HOMs are sufficiently low (≈six times) in comparison to the R/Q of the accelerating mode. LFD coefficient (0.20 Hz/(MV/m)^2) and temperature rise (0.085 K) values are negligible. The operational gradient does not show multipacting. Thus, the cavity is perfectly tuned for the designed E_{acc} of 15 MV/m.

REFERENCES

[1] B. Han *et al.*, "Industrial Wastewater Treatment with Electron Beam", JAERI, 2001. doi:JAERI-Conf2001-005.

[2] Jana et al., "Electromagnetic Design of a β_g= 0.9 650-MHz Superconducting Radio-Frequency Cavity", in *IEEE Transactions on Applied Superconductivity*, vol. 23, p. 4, 2013. doi:10.1109/TASC.2013.2256356

[3] J. S. Sekutowicz *et al.*, "Design of a Low Loss SRF Cavity for the ILC", in *Proc. PAC'05*, Knoxville, TN, USA, May 2005, paper TPPT056, pp. 3342-3344.

[4] Padamsee, Hasan, Ja Knobloch and T. Hays, "RF Superconductivity for Accelerators", John Wiley and Sons Inc., New York 199 (1998).

[5] P. Sekalsky, C. Albrecht, S. Simrock, and L. Lilje, "Lorentz force detuning compensation system for accelerating field gradients up to 35 Mv/M for superconducting XFEL and TESLA nine-cell cavities", 2004. doi:CARE-CONF-04-001-SRF.