MULTI-CELL RF-DIPOLE DEFLECTING AND CRABBING CAVITY*

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Abstract
Single cell superconducting rf-dipole cavities operating at 400 MHz, 499 MHz and 750 MHz have been designed, fabricated and successfully tested at cryogenic temperatures. These cavities have been shown to have attractive rf properties: high deflecting gradients, low electric and magnetic peak surface fields, and high shunt impedance. The single cell rf-dipole geometry has no lower order modes and has widely separated higher order mode spectrum. In this study we are investigating a multi-cell superconducting rf-dipole cavity operating at 952.6 MHz intended for the Jefferson Lab Energy Electron-Ion Collider. The analysis investigates the dependence of beam aperture variation and other cavity parameters on rf properties including cavity gradient, surface fields, shunt impedance and higher order mode separation.

INTRODUCTION

The Jefferson Lab Electron Ion Collider (JLEIC) consists of two figure-8 rings; one electron and the other for protons [1]. There are two interaction points as shown in Fig. 1. The ranges of energies of the different species are as follows:

- Electrons - 3 to 10 GeV
- Protons - 20 to 100 GeV
- Ions - Up to 40 GeV per nucleon

Ion species of interest include polarized protons, deuterons, and helium-3. The range of energies of different species hence gives a range of 15-65 GeV in the center of mass of the collider. The electrons are accelerated using the existing CEBAF machine and the ions are accelerated at the linac booster ring (Fig. 1).

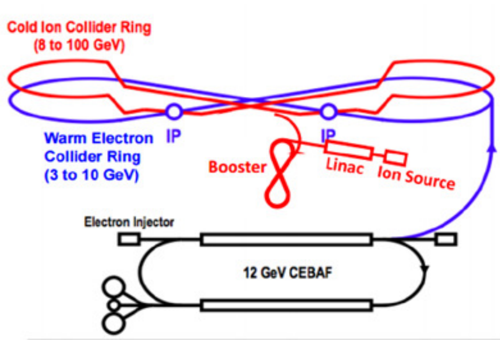

Figure 1: JLEIC electron and ion collider rings.

The luminosity goal of the JLEIC is in the range of low-to-mid 10^{33} $cm^{-2}sec^{-1}$ per interaction point over a broad energy range. A set of local crabbing cavities will be installed at each interaction point to enforce the head-on collision of incoming bunches, hence increasing the luminosity by increasing the number of interactions. The corresponding net transverse voltage for local crabbing crossing system is given by

$$V_t = \frac{cE_b \tan\left(\frac{\varphi_{crab}}{2}\right)}{2\pi f_{rf}\sqrt{\beta_x^* \beta_x^c}} \quad (1)$$

where c is the speed of light, E_b is the beam energy, φ_{crab} is the crossing angle, β_x^* is the betatron function at the interaction point, β_c^* is the betatron function at the location of the crabbing cavity. The crab crossing design parameters for both electron and proton beams are listed in Table 1.

Table 1: JLEIC crab crossing design parameters.

Parameter	Electron	Proton	Units
Beam energy	10	100	GeV
Beam current	0.72	5.0	A
Bunch frequency	952.6		MHz
Crab crossing angle	50		mrad
Betatron function at IP	10		cm
Betatron function at crab cavity	200	750	m
Integrated transverse voltage	2.8	18.4	MV

The first stage of the JLEIC is the medium energy EIC operating at 476.3 MHz followed by the upgrade operating at 952.6 MHz; hence, the crabbing cavities are designed to operate at 952.6 MHz. Due to the proton beam parameters the cavity design requires a large beam aperture, also favourable in HOM damping. However, the large aperture degrades the cavity rf properties increasing the number of cavities required to achieve the crab crossing. This paper presents the study of identical multi-cell rf-dipole cavity design for both electron and proton beams with varying beam aperture.

MULTI-CELL RF-DIPOLE CAVITY GEOMETRY

Single cell proof-of-principle rf-dipole cavities have been successfully demonstrated at several frequencies [2-4] and a 400 MHz prototype is currently being implemented into a crabbing system for the LHC HiLumi Upgrade [5]. The multi-cell rf-dipole cavity concept was first proposed in Ref. [6]. A 952.6 MHz 3-cell rf-dipole cavity design shown in Fig. 2 was analysed with varying

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beam aperture with improved rf properties by minimizing the peak surface fields (E_p/E_t) and (B_p/E_t) and maximizing the transverse shunt impedance ($R_tR_s = G*[R/Q]_t$ where G is the geometrical factor and transverse $[R/Q]_t$). The effective cavity length of the 3-cell cavity is $3\lambda/2$ with transverse voltage given by

$$V_t = \int_{-\infty}^{\infty} \left[E_x \cos\left(\frac{\omega z}{c}\right) \quad cH_y \sin\left(\frac{\omega z}{c}\right) \right] dz \qquad (2)$$

where E_x and H_y are the on-axis transverse electric and magnetic field components.

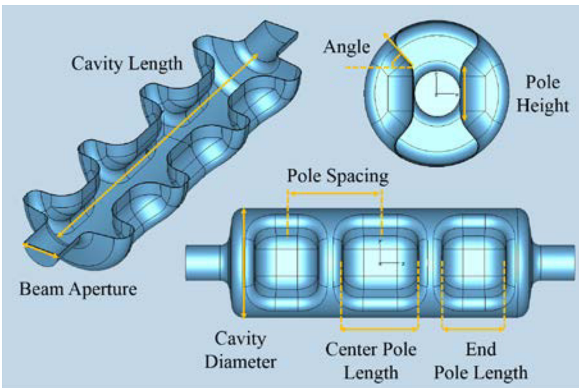

Figure 2: 952.6 MHz multi-cell rf-dipole cavity.

Figure 3 shows the electromagnetic field profile and surface fields of the multi-cell cavity. The multi-cell cavity has two lower same-order-modes (LOMs) and the 3rd mode is the deflecting mode of operation.

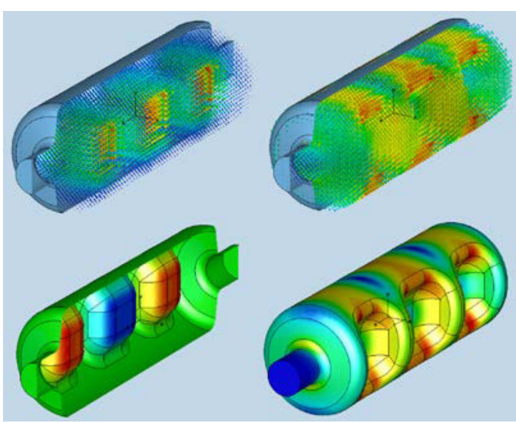

Figure 3: Electric field (top left), magnetic field (top right), surface electric field (bottom left), and surface magnetic field (bottom right) of 952.6 MHz multi-cell rf-dipole cavity.

DESIGN OPTIMIZATION

The important dimensional parameters of the multi-cell cavity are related to the poles as listed in Fig. 2. These parameters are optimized to reduce the peak surface fields and increase the transverse shunt impedance of the cavity.

Pole Spacing

The optimum separation between the poles is $\lambda/2$ (157.4 mm) that gives minimum peak surface field ratios and maximizes the R_tR_s with varying beam aperture.

Pole Length

The three poles in the multi-cell cavity do not have identical lengths where the length of center pole is longer compared to the length of the end poles. Figure 4 shows the rf properties dependence on the ratio of center pole length to end pole length.

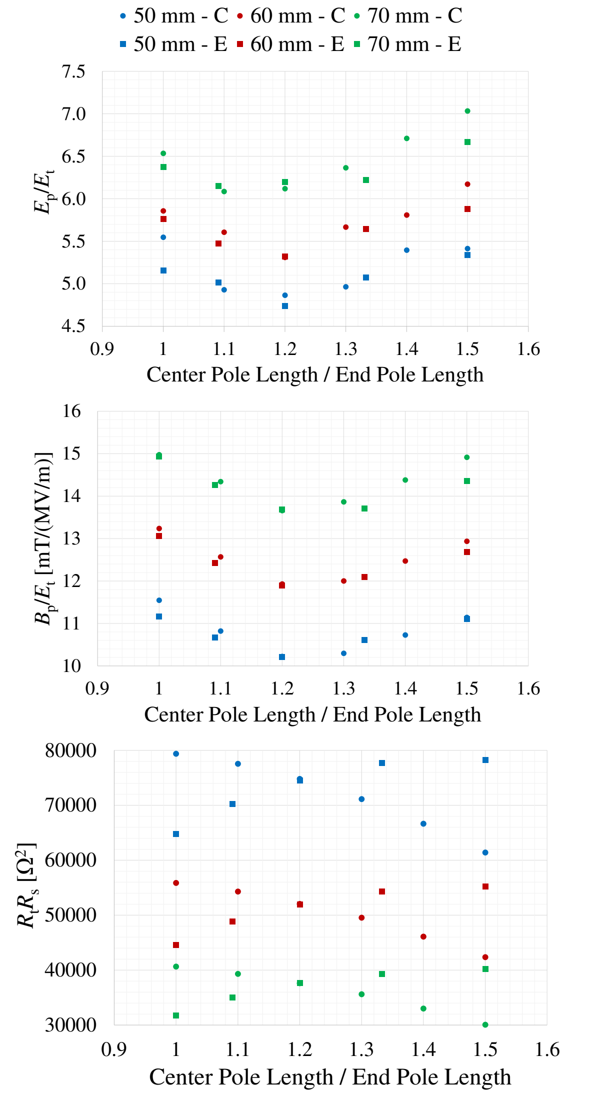

Figure 4: E_p/E_t (top), B_p/E_t (middle), and R_tR_s (bottom) dependence on ratio of center pole length to end pole length.

Varying the center pole length with constant end pole length and vice versa has similar effect on peak surface field ratios. However, increasing the center pole length increases the R_tR_s while decreasing the end pole length reduces it, independent of beam aperture. Therefore, the selected optimum center pole length is 120 mm and end pole length is 100 mm.

Pole Height and Angle

The pole cross-section parameters of inner pole height and angle as shown in Fig. 2 are the key parameters that give low and balanced peak surface field ratios.

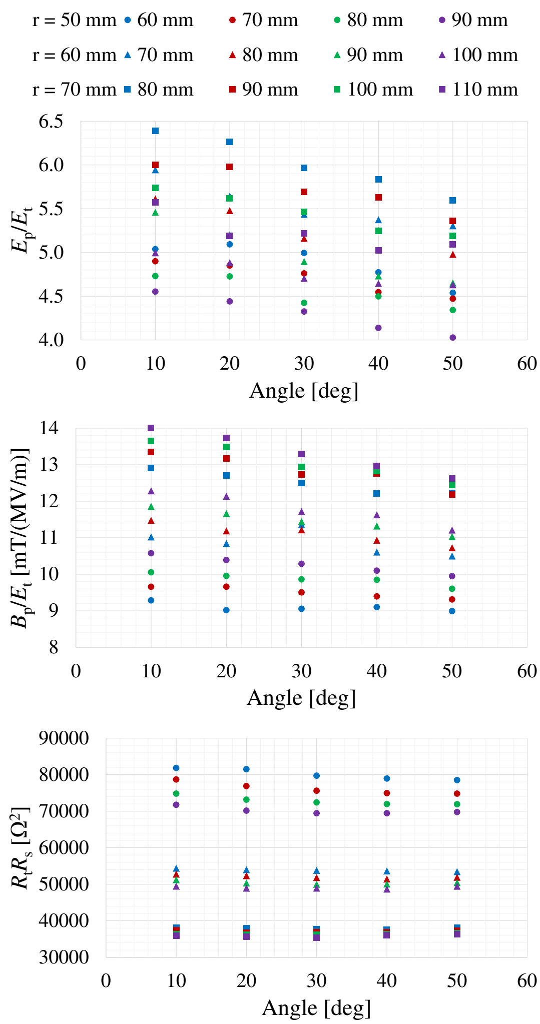

Figure 5: E_p/E_t (top), B_p/E_t (middle), and R_tR_s (bottom) dependence on pole height and angle.

As shown in Fig. 5 increasing the angle reduces the peak surface electric and magnetic field ratios and subsequently reduces R_tR_s as well. Similarly, increasing the inner pole height reduces E_p/E_t but has opposite effect on B_p/E_t. This also reduces R_tR_s where smaller pole heights and smaller angle are preferred to have higher R_tR_s. This reduces B_p/E_t with larger magnetic field volume but increases the E_p/E_t due to small pole surface area. Therefore, smaller pole height is selected with larger angle to further reduce E_p/E_t. The optimum pole height and angle are listed in Table 2.

A smaller pole height increases the field non-uniformity across between the poles. This effect can be reduced by curving the poles outward beam aperture [5]. The final parameters of the three designs are shown in Table 2.

CONCLUSION

This study investigates a multi-cell rf-dipole crabbing cavity for the JLEIC operating at 952.6 MHz. The analysis includes the variation of beam aperture of the geometry and dependence on rf properties as an input to further beam physics studies.

Table 2: RF properties of 952.6 MHz multi-cell rf-dipole cavities with varying beam aperture diameters.

Parameter	**(A)**	**(B)**	**(C)**	**Units**
Aperture diameter	50	60	70	mm
Cavity length	510	505	500	mm
Cavity diameter	174.7	185.3	195.5	mm
Pole height	60	70	80	mm
Angle	50	50	50	deg
LOMs	790, 879	773, 870	757, 862	MHz
Nearest HOM	1409	1383	1335	MHz
Deflecting voltage (V_t*)		0.472		MV
Peak electric field (E_p*)	4.72	5.14	5.56	MV/m
Peak magnetic field (B_p*)	8.69	10.03	11.4	mT
B_p* / E_p*	1.84	1.95	2.05	mT/ (MV/m)
Geometrical factor (G)	160.9	170.2	178.9	Ω
$[R/Q]_t$	494.4	323.1	218.8	Ω
$R_t R_s$	8.0×10^4	5.5×10^4	3.9×10^4	Ω^2
At E_t* = 1 MV/m				
V_t per cavity	3.3	3.0	2.8	MV
E_p	33	33	33	MV/m
B_p	61	64	68	mT
No. of cavities (e/p) per side	1 / 6	1 / 7	1 / 7	

A large beam aperture cavity would be needed in crabbing the proton beam while the aperture of the crabbing cavity for electron beam may be smaller. The analysis shows that as the beam aperture is increased the rf performance of the cavity degrades. The advantage of multi-cell cavities is that it reduces the requirement on number of cavities, however this geometry has lower order modes that requires damping. Further analysis is required to determine HOM and multipole specifications.

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