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DESIGN OPTIMIZATION OF SUPERCONDUCTING PARALLEL-BAR CAVITIES*

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Abstract
The parallel-bar structure is a new superconducting geometry whose features and properties may have significant advantages over conventional superconducting deflecting and crabbing cavities for a number of applications. Jefferson Lab is in need for a 499 MHz, 11 GeV rf separator as part of its 12 GeV upgrade program. We report on design optimization studies performed to-date for this and other applications.

INTRODUCTION

The parallel-bar structure introduced in [1,2] is a new structure for both deflecting and crabbing of particle bunches. The structure shown in Fig. 1 consists of two cylindrical parallel bars of λ/2 length, perpendicular to the beam line passing between the bars. The structure length is λ/2 and the width of the parallel-bar structure is adjusted as required upon the application.

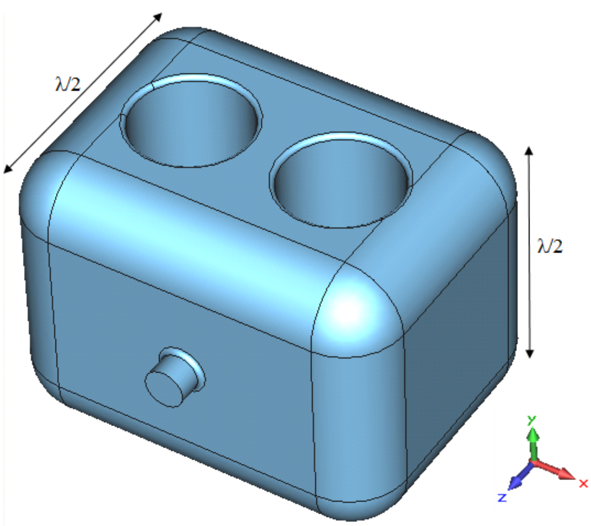

Figure 1: Parallel-bar structure.

The parallel bars operate in TEM mode, generating two fundamental modes. The accelerating mode (0 mode) in which bars operate in phase with a voltage of the same sign. In the deflecting mode (π mode) bars oscillate in opposite phase with a voltage of opposite sign, producing a transverse voltage. The deflecting mode has the lowest frequency, unlike the other deflecting or crabbing cavity structures available at present.

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In the deflecting mode the voltage is maximum between the bars containing the beam aperture generating the maximum deflection. The magnetic field is zero in the mid plane containing the beam aperture and is maximum on the top and bottom surfaces. The electric field is zero on those surfaces and maximum in the mid plane; hence the deflection along the beam line is an effect due to the electric field only.

The optimizations are performed in designing a 11 GeV deflecting cavity for the CEBAF 12 GeV upgrade operating at the frequency, 499 MHz. The other applications considered are the design of a 400 MHz and an 800 MHz crabbing cavity structures for possible use in an LHC upgrade. The current results obtained are presented in detail.

PARAMETERS FOR DESIGN OPTIMIZATION

The key objective in optimizing the design of the parallel-bar structure is to obtain the maximum achievable deflecting voltage between the bars. The deflecting voltage experienced by the particle passing through the beam line is a direct result of the transverse electric field on the beam line. The effective deflecting length in which the particle passes through is also equally essential in supplying a higher deflection to the particle bunch. In a deflecting cavity structure the center of the bunch receives the deflection; in a crabbing structure the head and tail of the beam bunch receive deflections in opposite direction.

The resultant transverse voltage (V_T) seen by a particle on crest is then given by,

$$V_T = \int_{-\infty}^{+\infty} E_x(z) \cos\left(\frac{\omega z}{c}\right) dz \qquad (1)$$

where $E_x(z)$ is the transverse component of the longitudinal electric field, ω is the frequency and c is the speed of light. A small amount of the transverse electric field extends into the beam line at the edge of the cavity; hence the full length is considered in calculating the transverse voltage.

The effective length of the structure along the beam line for a particle travelling in velocity of light is λ/2. The transverse electric field (E_T) is determined considering the effective length along the beam line and is given by,

$$E_T = \frac{V_T}{\lambda/2} \qquad (2)$$

where V_T is the transverse voltage and λ is the wave length.

The design requirement for the CEBAF upgrade is to provide a vertical deflection of 525 μrad for a particle on crest with energy 11.023 GeV. Then the electron beams for the experimental halls (Hall A and Hall C) will receive a deflection of 455 μrad at 30° off crest.

The other parameters of interest are transverse shunt impedance (R_T) and the geometrical factor (G) are given by,

$$R_T = \frac{V_T^2}{P} \tag{3}$$

$$G = QR_s \tag{4}$$

$$\left[\frac{R}{Q}\right]_T = \frac{V_T^2}{\omega U} \tag{5}$$

where P is the power loss through walls, Q is the quality factor, R_s is the surface resistance of the material and U is the stored energy. The requirement for a normal conducting structure is to maximize the transverse shunt impedance while for a superconducting structure is to minimize the surface fields.

The analytical model of the parallel-bar structure proposed in [1,2] has degenerated frequencies in the two fundamental modes. With the inclusion of the beam aperture the degeneracy is reduced slightly. Further optimization steps are taken by curving the edges of the cavity to separate the modes with a least minimum of 6 MHz of mode separation.

SIMULATION RESULTS

Currently CEBAF is using a 499 MHz 2-cell normal conducting rf separator cavity [3] in separating the particle beam that is sent to the 3 experimental halls. The CEBAF 12 GeV upgrade requires 8 rf separator cavities to vertically separate the beam for the increased energy. A single cell 499 MHz deflecting cavity for the CEBAF 12 GeV upgrade is an alternative proposed to the existing rf separator cavity currently used, due to its reduced size and rf power requirements.

Four design structures shown in Fig. 2 were analysed in achieving an optimized deflecting parallel-bar structure. In each structure the parallel-bars are appropriately curved to reduce the field concentration near the edges. The initial design length and height of the cavity was 375 mm, width was 400 mm and the beam aperture diameter was 40 mm.

The effective deflecting length along the beam line is the smallest in the structure (a) with the circular shaped parallel bars; hence the net deflecting voltage seen by the beam is low. The deflecting voltage is higher in the parallel bar structure (d) with race track shaped parallel bars due to length of the parallel bars along the beam line. Therefore the structure can be optimized to have a larger effective deflecting length with low surface fields on the parallel bars. Hence the ratio of peak surface fields (E_P & B_P) to the deflecting electric field (E_T) is minimised to achieve the above requirement.

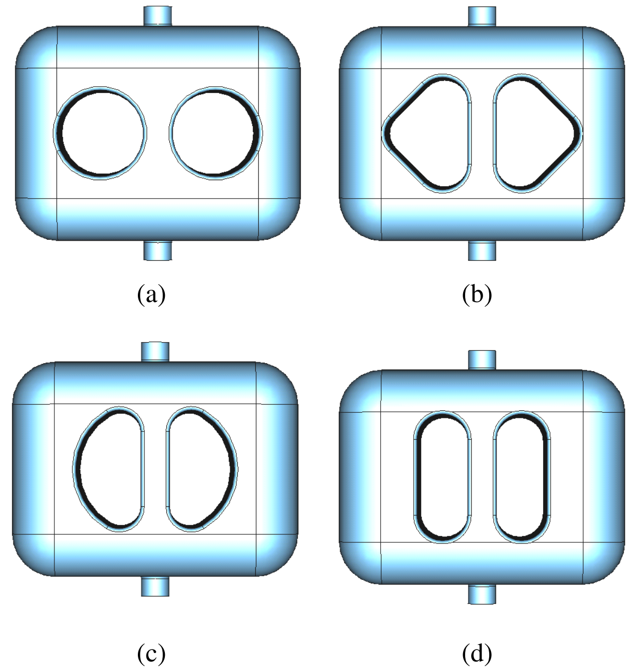


Figure 2: Design structures for CEBAF 499 MHz deflecting cavity with (a) circular, (b) triangular, (c) half circular and (d) race track shaped parallel bars.

The peak surface electric and magnetic field values for the four structures are shown in Table 1. As expected the structure with race track shaped parallel bars has the lowest peak surface fields for a higher deflecting voltage.

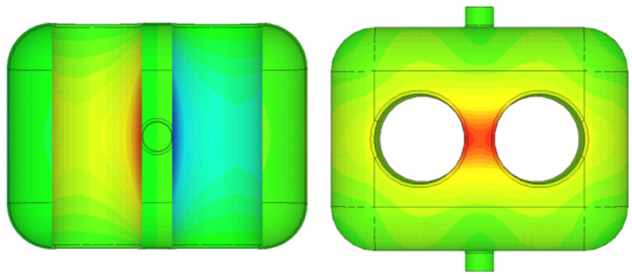
Table 1: Peak surface electric and magnetic fields for the four design structures

Design structure	E_P / E_T^* (MV/m)	B_P / E_T^* (mT)
(a)	3.45	8.86
(b)	2.47	6.60
(c)	2.30	6.15
(d)	2.28	5.94

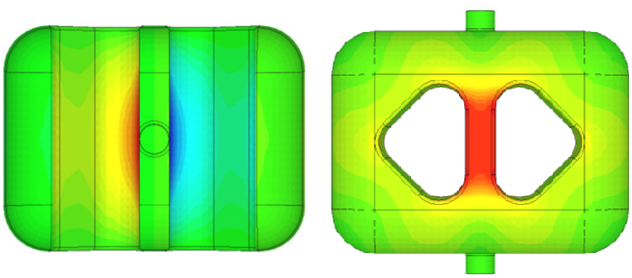
At $E_T^* = 1$ MV/m

The surface electric field between the parallel bars (left) and the surface magnetic field (right) on the top surface are shown in Fig. 3. Curving the edges of the parallel bars reduce the field concentration at the edges.

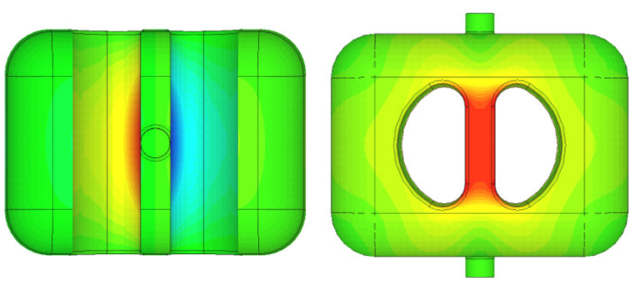
Comparing the four structures, the last three have a larger surface area on the between the bars increasing the surface field on the surface facing the beam line. The main idea of the different shapes is to obtain a more uniform field between the bars and low surface fields on the remaining area on the surface. In the structure (d) with the optimized width of the parallel bars the surface fields are controlled to be between the bars, preventing it spreading beyond the bars. The optimized width also eliminates any field concentration at the edges of the parallel bars.



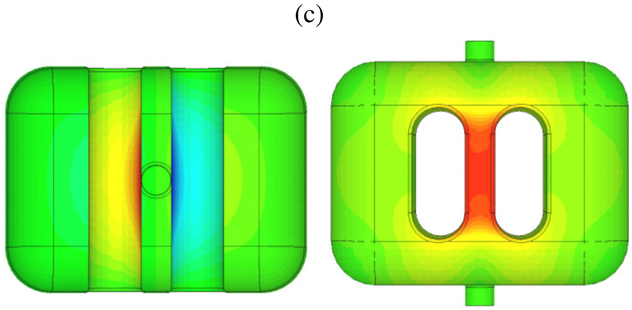
(a)



(b)



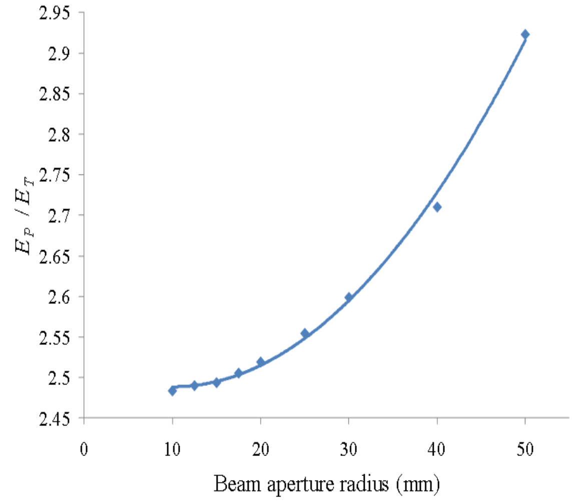
(c)



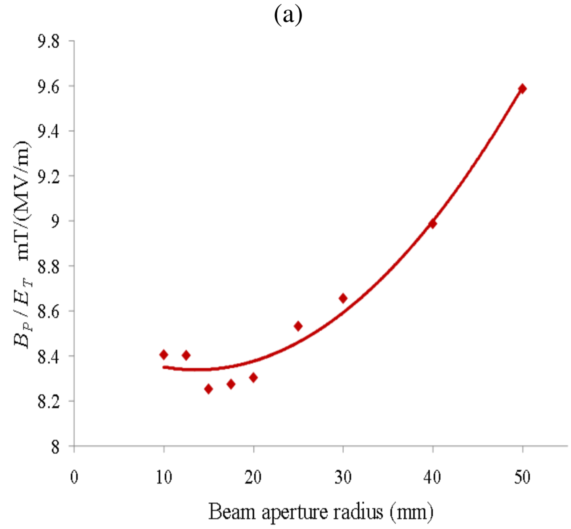
(d)

Figure 3: Surface electric field between the bars (left) and surface magnetic field on the top surface (right) of (a) circular, (b) triangular, (c) half circular and (d) race track shaped parallel-bar structures.

The above structures were optimized for the 499 MHz CEBAF deflecting cavity by varying the beam aperture diameter, width and length of the parallel bars. Figs. 4(a) & (b) show the variation of the peak surface electric field and magnetic field respectively due to change in the beam aperture radius. The other parameters of length, width and height are kept the same and the beam aperture is increased. The resultant ratios of peak surface fields to the deflecting electric field increase as the beam aperture is increased. This is a direct result of the drop in the deflecting voltage as separation increases between the parallel bars. Hence the beam aperture has to be minimized to achieve a higher deflecting voltage also providing the sufficient gap in the beam aperture for the deflection of the beam.



(a)

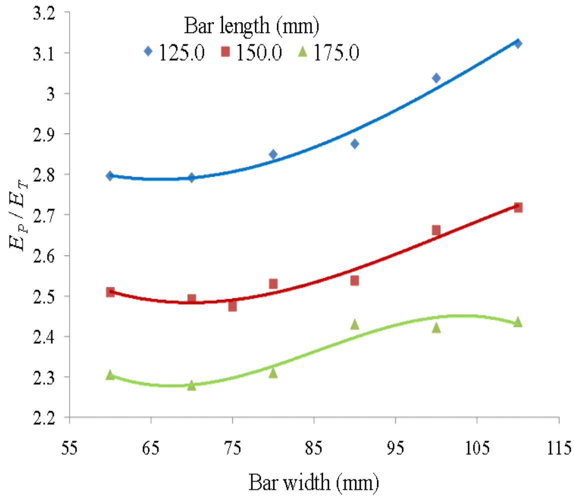


(b)

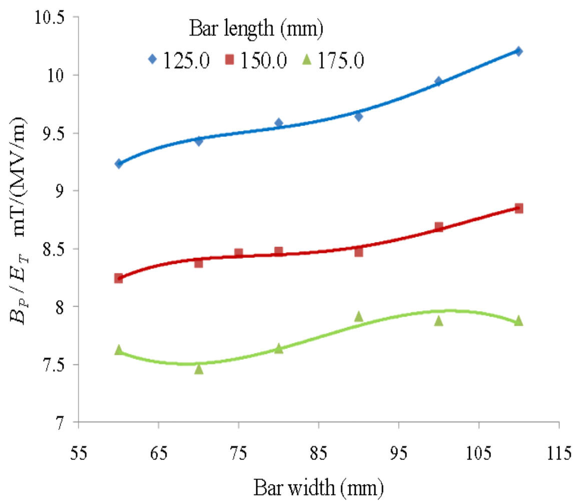
Figure 4: Change in peak surface (a) electric field and (b) magnetic field due to the change in beam aperture radius.

Figs. 5(a) & (b) show the peak surface electric and magnetic field variation due to change in bar width and length. Different bar lengths were analyzed with increasing bar widths. As the bar length is increased it increases the effective deflecting length; hence a maximum deflection is achieved with low surface fields. However the bar width is needed to be kept optimized as very thin bars produce a higher surface field on the curved edges of the parallel bars. The transverse shunt impedance also decreases as the beam aperture radius increased.

The optimized results up to date were obtained from the race track shaped parallel bars. Another proposed design given in [4] is to use curved parallel bars as a substitute of the straight bars. However this restricts the ability to reduce the vertical height as required by the CEBAF 12 GeV upgrade.



(a)

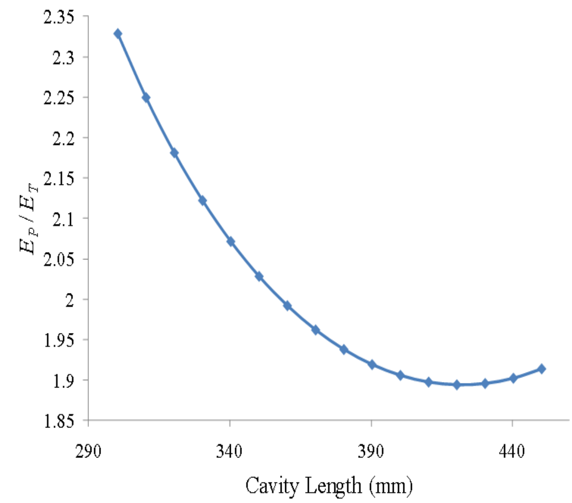


(b)

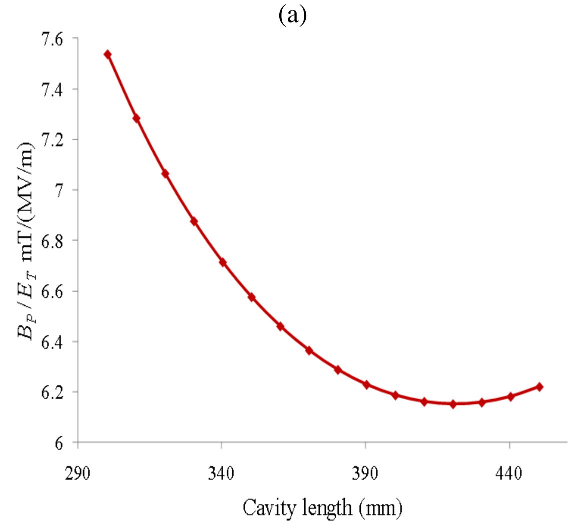
Figure 5: Change in peak surface (a) electric field and (b) magnetic field due to the change in bar width and length

Then the cavity length along the beam line was increased over the standard length of λ/2, also increasing the length of the parallel bars proportionately. This increases the deflecting electric field seen by the particle. However a certain fraction of the deflecting electric field extends into the beam aperture. As the length is increased beyond the optimal length the losses due to the electric field extension into the beam line are dominant than the increase in the transverse electric field. Therefore there exists a minimum of the peak surface fields that gives the optimum length of the deflecting cavity. The change in peak surface electric field and magnetic field are shown in Fig. 7.

The list of properties of the parallel bar structure in comparison with the existing normal conducting rf separator cavity used in CEBAF at present are shown in Table 2. Low surface fields are achieved for a higher deflection with high $[R/Q]_T$. A mode separation of 20 MHz is achieved in separating the deflecting mode with the fundamental mode.



(a)



(b)

Figure 6: Change in peak surface (a) electric field and (b) magnetic field due to the change in cavity length.

Table 2: Properties of parallel-bar structure (d) of Fig. 3 and comparison with existing CEBAF's separator cavity

Parameter	**Structure (d)**	**CEBAF**	**Units**
Freq. of π mode	499	499	MHz
λ/2 of π mode	300.4	300.4	mm
Freq. of 0 mode	521.9	~537	MHz
Cavity length	420.4	~300	Mm
Cavity width	320	292	Mm
Bars height	305.5	20	Mm
Bars width	70	20	Mm
Bars length	295	135	Mm
Aperture diameter	40	15	Mm
Deflecting voltage (V_T*)	0.3	0.3	MV
Peak electric field (E_P*)	1.9	3.39	MV/m
Peak magnetic field (B_P*)	4.9	8.87	mT
Energy content (U*)	0.028	0.0012	J
Geometrical factor	69.4	34.9	Ω
$[R/Q]_T$	1045.3	24921	Ω

At $E_T^* = 1$ MV/m

Crabbing Cavity Structures

In considering other applications two crabbing cavity structures of frequencies 400 MHz and 800 MHz for possible use in an LHC upgrade were analyzed. The cavity structures are shown in Fig. 7 and Fig. 8.

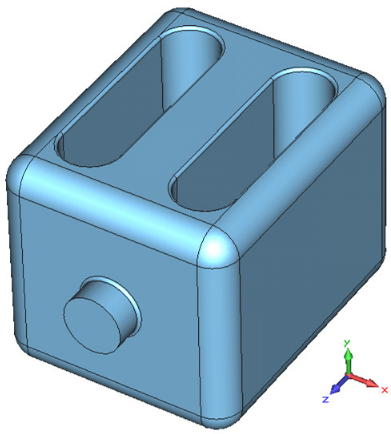


Figure 7: 400 MHz crabbing cavity.

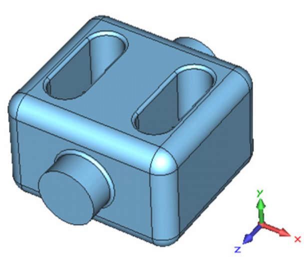
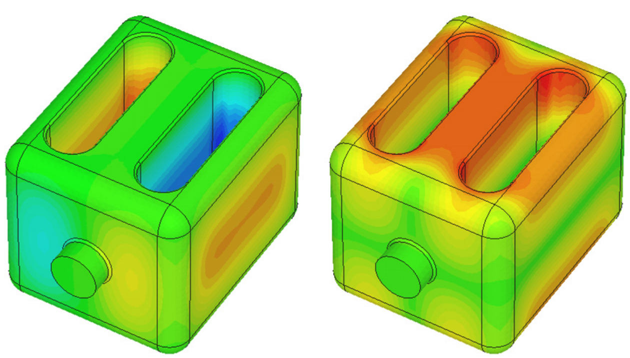
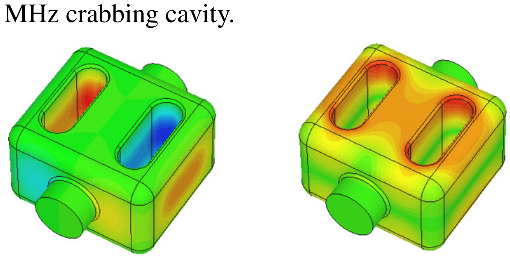


Figure 8: 800 MHz crabbing cavity.



(a) (b)

Figure 9: Surface (a) electric and (b) magnetic field of 400 MHz crabbing cavity.



(a) (b)

Figure 10: Surface (a) electric and (b) magnetic field of 800 MHz crabbing cavity.

The same parameters were optimized using the same procedure as followed in the 499 MHz deflecting cavity. The surface electric and magnetic fields of the crabbing cavities are shown in Fig. 9 and Fig. 10. The cavity properties are given in Table 3.

Table 3: Properties of 400 MHz and 800 MHz crabbing cavity structures for LHC

Parameter	**Fig. 7**	**Fig. 8**	**Units**
Freq. of π mode	400	800	MHz
$\lambda/2$ of π mode	374.7	187.4	Mm
Freq. of 0 mode	407.1	815.3	MHz
Cavity length	494.7	267.4	Mm
Cavity width	400	300	Mm
Bars height	382.2	191.8	Mm
Bars width	100	60	Mm
Bars length	370	170	Mm
Aperture diameter	100	100	Mm
Deflecting voltage (V_T*)	0.375	0.187	MV
Peak electric field (E_P*)	2.16	2.79	MV/m
Peak magnetic field (B_P*)	7.05	9.78	mT
Energy content (U*)	0.175	0.062	J
Geometrical factor	81.37	112.3	Ω
$[R/Q]_T$	319.13	113.55	Ω
R_TR_S	2.6×10^4	1.3×10^4	Ω^2

At E_T^* = 1 MV/m

CONCLUSION

The parallel-bar structure has been optimized for the applications of CEBAF upgrade and potential luminosity upgrade of LHC. The race track shaped parallel-bar structure is the optimized design obtained from the simulations performed up to date. In addition the design has a reduced transverse dimension and extended length along the beam line. This design allows high deflecting voltage for low surface fields with high shunt impedance. The cavity design was further optimized to achieve low frequencies of operation due to its compact size. One other advantage of this design, compared to the conventional superconducting deflecting and crabbing structures is that the deflecting mode has the lowest frequency; hence HOM damping requires only damping of all the higher order frequencies. Further analysis requires the study of the effects of multipacting and HOM damping of the parallel-bar structure.

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