DESIGN OF SUPERCONDUCTING PARALLEL-BAR CAVITIES FOR DEFLECTING/CRABBING APPLICATIONS*

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Abstract

The superconducting parallel-bar cavity is a deflecting/crabbing cavity with attractive properties, compared to other conventional designs, that is currently being considered for a number of applications. The new parallel-bar design with curved loading elements and circular or elliptical outer conductors have improved properties compared to the designs with rectangular outer conductors. We present the designs proposed as the deflecting cavities for the Jefferson Lab 12 GeV upgrade and for Project-X and crabbing cavities for the proposed LHC luminosity upgrade and electron-ion collider at Jefferson Lab.

INTRODUCTION

A variety of superconducting parallel-bar cavity [1] geometries with rectangular, cylindrical and elliptical outer conductors and straight, curved bars have been analyzed [2, 3]. The geometry with a cylindrical outer conductor and trapezoidal shaped bars is proven to have better properties compared to other geometries in terms of lower and balanced surface fields and higher shunt impedance. The fundamental deflecting mode in the parallel-bar cavity which is used to deflect and crab the beam has a transverse electric field between the bars with magnetic field at top and bottom of the cavity as shown in Fig. 1.

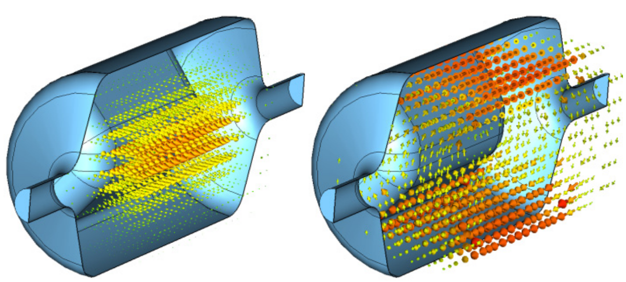

Figure 1: Electric field profile (left) and magnetic field profile (right) of the parallel-bar cavity.

This field orientation gives rise to surface electric fields on the bar surfaces and surface magnetic fields at top and bottom surfaces of the cylindrical outer conductor as shown in Fig 2. The trapezoidal shaped geometry of the bars allows reducing both surface electric field and magnetic field independently by varying the inner bar height and the slope of the bars connecting to the outer conductor.

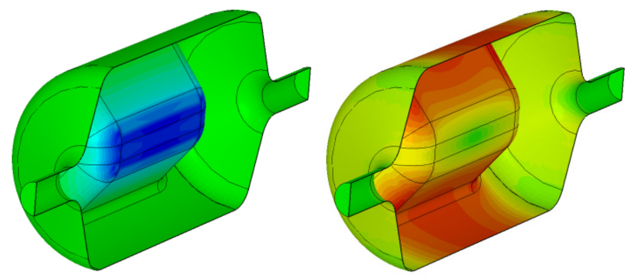

Figure 2: Surface electric field (left) and surface magnetic field (right) of the parallel-bar cavity.

Also this geometry has the fundamental deflecting mode as the lowest frequency mode. The parallel-bar cavity with trapezoidal shaped bars has wider mode separation in the higher order modes (HOMs) spectrum [3] making this geometry very attractive in HOM damping, especially in high current applications.

Currently the parallel-bar cavity is considered for two deflecting cavity and another two crabbing cavity applications. The major applications of the superconducting parallel-bar cavity are the 499 MHz deflecting cavity for the Jefferson Lab 12 GeV upgrade and the crabbing cavity for the proposed LHC luminosity upgrade operating at 400 MHz. These two designs are being optimized to meet the requirements and are in the initial phase of prototype fabrication. The parallel-bar cavity is also being considered for the 750 MHz crabbing cavity for medium energy electron ion collider (MEIC) at Jefferson Lab and the 365.625 MHz deflecting cavity for Project-X.

The parallel-bar designs for all the above mentioned applications are presented in this paper with detailed optimization and cavity properties.

PARALLEL-BAR CAVITY DESIGNS

499 MHz Deflecting Cavity

The 499 MHz deflecting cavity for the Jefferson Lab 12 GeV upgrade is required to separate the 5^{th} pass beam of 11.025 GeV in to 3 beams, in order to deliver the maximum energy beam to the 3 experimental halls simultaneously. The required net deflection of a peak transverse voltage of 5.6 MV is applied to the bunches in the beam with a phase offset of $\pm 120^0$ to separate the beam to halls A and C, where the beam for hall B passes without any deflection. The dimensional constraints for

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the 499 MHz deflecting cavity are the vertical separation between the 4th pass and 5th pass beam lines of 450 mm and the 300 mm horizontal separation from the beam axis.

The geometry with the trapezoidal shaped bars is optimized to meet the requirements of the deflecting cavity, with lower and balanced surface fields and high shunt impedance. The cavity length, bar length and the shape of the bar given by inner bar height and angle of the trapezoidal shaped bar as shown in Fig. 3 are the major parameters that have been optimized in this geometry.

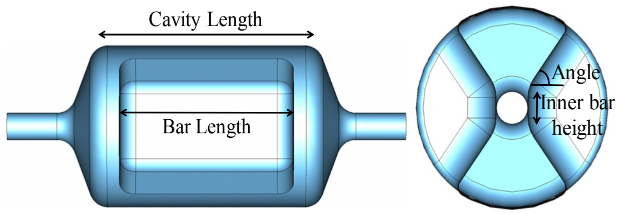

Figure 3: Main cavity parameters of optimization.

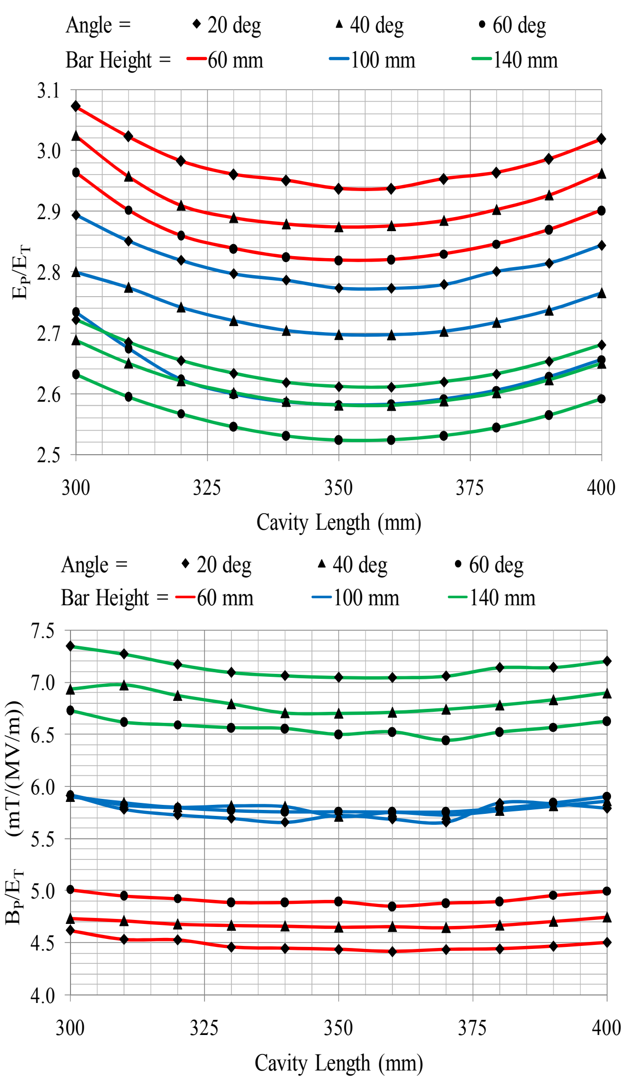

Figure 4: Ratios of peak surface electric field (E_P) and magnetic field (B_P) to the transverse electric field (E_T) with varying cavity length for different bar shapes.

The cavity length and bar length is changed simultaneously for different bar shapes to determine the optimum cavity length and bar length that minimizes the surface fields as shown in Fig. 4. The peak surface electric fields (E_P) decrease with increasing inner bar height due to the increase in the surface area of the higher surface fields. However this increases the peak surface magnetic fields (B_P) as the magnetic field gets stronger at top and bottom of the cavity. Peak surface electric field is higher for smaller angles while the peak surface magnetic fields are lower. The dependence of cavity length and the bar length on the peak surface fields are similar for different bar shapes. However the change in peak surface electric field is higher than that of peak surface magnetic field.

The bar shape was optimized for different inner bar heights and angles to further minimize the peak surface fields with a balanced field ratio (B_P/E_P). The B_P/E_P decreases for smaller inner bar heights and larger angles as shown in Fig. 5. However the bar height cannot be reduced less than 50 mm as it is limited by the beam aperture diameter of 40 mm to maintain the field uniformity across the beam aperture. The shape of the bar is optimized to achieve a field balancing ratio of B_P/E_P=1.5 mT/(MV/m) for the 499 MHz deflecting cavity.

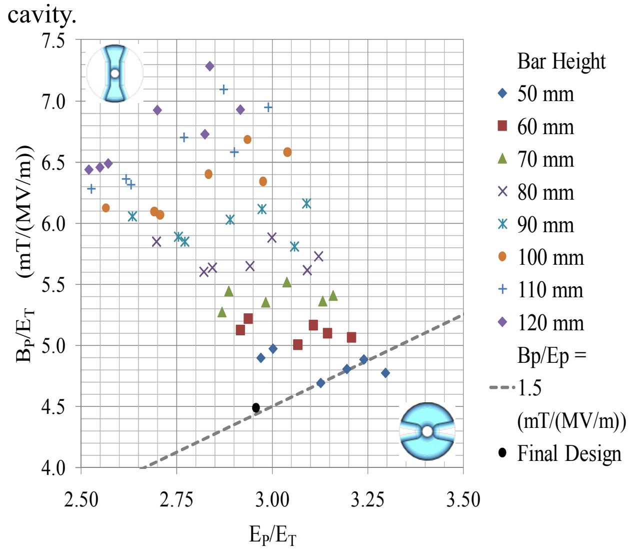

Figure 5: Dependence of the inner bar height on peak surface field ratios of (E_P/E_T) and (B_P/E_T) for different angles of the bar shape for the 499 MHz deflecting cavity.

The optimized final design for the 499 MHz deflecting cavity is shown in Fig. 6 and the final properties of the cavity are shown in Table 1. With peak surface field ratios of E_P/E_T=2.96 and B_P/E_T=4.49 mT/(MV/m) the cavity can generate a transverse voltage of 3.0 MV per cavity at operating peak surface fields of E_P=30 MV/m and B_P=45 mT. Hence the transverse voltage requirement of 5.6 MV can be achieved by 2 deflecting cavities. The low operating peak surface magnetic field is a very attractive feature of the design where the 30 MV/m of peak surface electric field can be easily achieved by chemically processing and cleaning the cavity surface.

Table 1: Properties of the 499 MHz, 365.6 MHz deflecting cavity designs and 400 MHz, 750 MHz crabbing cavity designs.

Parameter	499 MHz	400 MHz	750 MHz	365.6 MHz	Units
Frequency of π mode	499.0	400.0	750.0	365.625	MHz
λ/2 of π mode	300.4	375.0	199.9	410.0	mm
Frequency of 0 mode	1035.9	729.5	1314.4	659.7	MHz
Frequency of near neighbour mode	771.2	593.4	1143.1	571.9	MHz
Cavity length	440.0	520.0	300.0	530.0	mm
Cavity diameter	241.9	339.8	193.0	388.4	mm
Bars length	260.0	345.0	185.0	350.0	mm
Bars inner height	50.0	80.0	57.5	85.0	mm
Angle	50.0	50.0	36.2	55.0	deg
Aperture diameter	40.0	84.0	60.0	84.0	mm
Deflecting voltage (V_T^*)	0.3	0.375	0.2	0.41	MV
Peak electric field (E_P^*)	2.96	3.82	4.95	3.61	MV/m
Peak magnetic field (B_P^*)	4.49	7.09	8.74	6.41	mT
B_P^* / E_P^*	1.52	1.86	1.77	1.77	mT/(MV/m)
Energy content (U^*)	0.029	0.19	0.056	0.19	J
Geometrical factor	105.6	119.7	136.9	115.9	Ω
$[R/Q]_T$	982.2	312.2	152.9	378.5	Ω
$R_T R_S$	1.04×10^5	3.7×10^4	2.1×10^4	4.4×10^4	Ω^2

At $E_T^* = 1$ MV/m

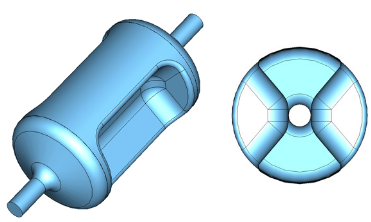

Figure 6: Final design geometry (left) and the cross section (right) for the 499 MHz deflecting cavity.

400 MHz Crabbing Cavity

The 400 MHz crabbing system for the proposed luminosity upgrade of LHC is required to deliver a net peak transverse voltage of 10 MV per beam at each side of the two interaction points (IP1 and IP5).

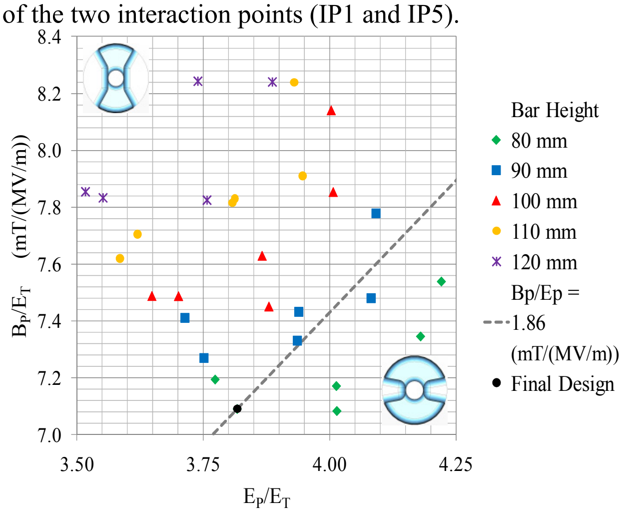

Figure 7: Dependence of the inner bar height on peak surface field ratios of (E_P/E_T) and (B_P/E_T) for different angles of the bar shape for the 400 MHz crabbing cavity.

The crabbing cavity is also optimized following the similar procedure as in the 499 MHz deflecting cavity. The shape of the bar is optimized as shown in Fig. 7, after optimizing the cavity and bar lengths. The inner bar height is kept at a minimum of 80 mm in order to have uniform fields across the beam aperture. The larger beam aperture gives high surface fields.

The final design is shown in Fig. 8 with the cavity properties listed in Table 1.

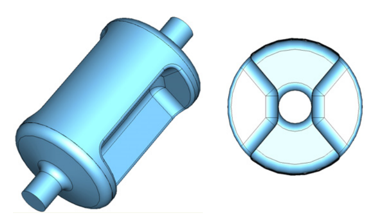

Figure 8: Final design geometry (left) and the cross section (right) for the 400 MHz crabbing cavity.

The design is optimized for a field balancing ratio of B_P/E_P=1.86 mT/(MV/m) in which a transverse voltage of 3.4 MV can be achieved with peak surface fields of E_P=35 MV/m and B_P=65 mT. Three crabbing cavities are required to achieve the net transverse voltage requirement of 10 MV.

750 MHz Crabbing Cavity

The medium energy electron ion collider (MEIC) at Jefferson Lab is in the need of a crabbing system for the proton beam in order to have a head on collision between the 60 GeV proton beam and the 12 GeV electron beam. The design shown in Fig. 9 is obtained by a preliminary optimization with the cavity properties given in Table 1. The cavity design is very compact with less than 200 mm diameter due to the higher frequency and as a result has comparatively high peak surface fields.

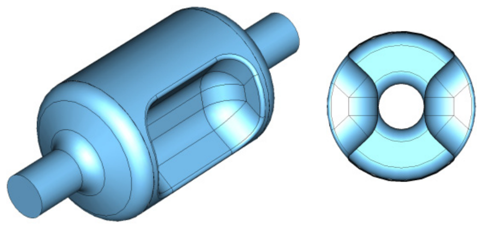

Figure 9: Final design geometry (left) and the cross section (right) for the 750 MHz crabbing cavity.

365.625 MHz Deflecting Cavity

The Project-X 365.625 MHz deflecting cavity is required to separate the 3 GeV proton beam into 3 beams similar to Jefferson Lab deflecting cavity with phase offsets of $\pm 90^0$. With low operating peak surface fields of E_P=30 MV/m and B_P=53.5 mT the cavity can generate a transverse voltage of 3.4 VM per cavity, where 3 deflecting cavities are required to deliver the full deflection of 10 MV The design shown in Fig. 10 and the cavity properties listed in Table 1 are obtained after a preliminary optimization.

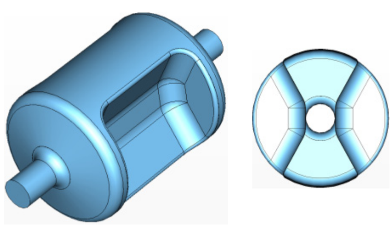

Figure 10: Final design geometry (left) and the cross section (right) for the 365.625 MHz deflecting cavity.

ANALYSIS OF FIELD NON-LINEARITY

A field non-linearity analysis is carried out for all the designs, evaluating the field across the beam aperture as show in Fig. 11 to determine the change in transverse voltage for both horizontal and vertical directions. The 750 MHz crabbing cavity has the largest change in the transverse voltage compared to other designs.

If needed, the non-linearity can be reduced by increasing the inner bar height (see Fig. 3) and/or by giving it a curvature.

CONCLUSION

The parallel-bar geometry with the cylindrical outer conductor and trapezoidal shaped bars has proven to have improved properties compared to other parallel-bar geometries, therefore have been considered for a number of deflecting/crabbing cavity applications. This geometry is capable of delivering lower and well balanced peak surface fields with higher shunt impedance. Another attractive feature is the fact that this geometry has no lower-order mode and the nearest higher-order mode is far removed from the fundamental mode [3]. The shape of the bars connecting to the outer conductor with sloped end plates adds rigidity to the design in terms of mechanical deformations [4].

The parallel-bar geometry for the applications of the 499MHz and 365.625 MHz deflecting cavities and 400 MHz crabbing cavities have shown very attractive properties in meeting the requirements. The 499 MHz deflecting and 400 MHz crabbing cavities are in the stage of prototype fabrication.

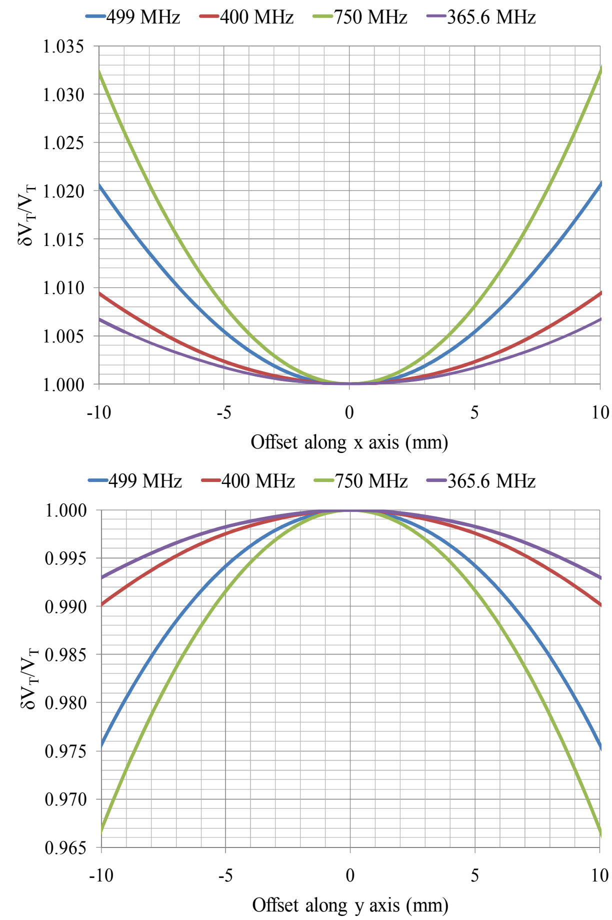

Figure 11: Normalized transverse deflecting voltage in horizontal (offset along x asis) and vertical (offset along y axis) directions.

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