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DESIGN OF ELECTRON AND ION CRABBING CAVITIES FOR AN ELECTRON-ION COLLIDER*

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Abstract

Beyond the 12 GeV upgrade at the Jefferson Lab a Medium Energy Electron-Ion Collider (MEIC) is being considered. In order to achieve the desired high luminosities at the Interaction Points (IP), the use of crabbing cavities is under study. In this work, we will present up to date designs of superconducting cavities, considered for crabbing both ion and electron bunches. A discussion of properties such as peak surface fields and Higher Order Modes (HOMs) separation will be presented.

INTRODUCTION

The superconducting parallel-bar cavities have been introduced as attractive deflecting/crabbing radio frequency structures [1, 2] for applications such as the LHC luminosity upgrade and the MEIC at the Jefferson Lab. In this case a modification on the geometry of the parallel bars is analyzed for the MEIC electron's and proton's crabbing systems at 750 MHz.

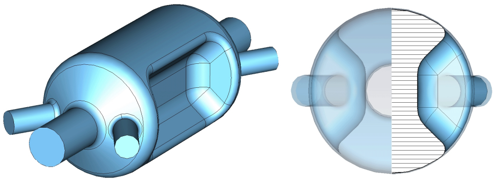

Figure 1: 750 MHz cylindrical cavity with trapezoidal carved parallel-elements (left) and vertical cross section (right), including coupler ports for HOM damping.

The parallel external conductors have been removed from the original parallel-bar design [2] to eliminate fields trapped in the outer sections of the cavity and favours circulating modes around the trapezoidal loading carved sections on the side walls of the cavity (as shown in Fig. 1). This feature introduces a vertical magnetic field with a small but not negligible contribution. The particles are crabbed by the transverse electric field generated between the parallel sections, which oscillate in opposite phase. The carved trapezoidal just like the usual parallel-bar geometry has two degenerate modes [3], the first is a deflecting/crabbing mode and the other an accelerating mode in which the parallel sections oscillate in phase.

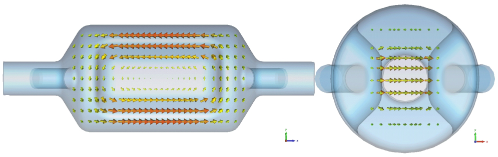

Figure 2: Magnetic (left) and electric (right) field profiles for the trapezoidal parallel-bar cavity.

The field orientation in the cavity in Fig. 2 shows the generated transverse electric field between the parallel sections and the magnetic field looping around the parallel sections. The length of the parallel sections are of the order of $\lambda/2$ and the design is optimized to meet the requirements of the 750 MHz crabbing system for both proton (60 GeV) and electron (5 GeV) beams at the MEIC under study at the Jefferson Lab. Due to that the considerable separation between the two fundamental modes in this compact design, it is suitable for higher current applications. For tolerable operating peak surface fields of $E_P = 35.6$ MV/m and $B_P = 75.5$ mT the field balancing ratio (B_P/E_P) is 2.09 mT/(MV/m).

PARALLEL-BAR DESIGN

In a parallel-bar cavity, the main contribution to the crabbing kick is given by the transverse electric field. The present design has low peak surface electric field with higher peak surface magnetic field. The properties for this design are listed in Table 1 in comparison with the KEK squashed elliptical design.

HOM Properties

There are different parasitic modes other than the fundamental operating mode inside a resonant cavity, activated by wake fields generated due to interactions with the charged particles of the beam. This modes spread over a range of frequencies with different field orientations and can be grouped according to their frequency as Similar Order Modes (SOMs), Lower Order Modes (LOMs, with frequency under the fundamental) or HOMs. While according to the field orientation they can be grouped as shown in Table 2. In this case it is not practical to identify the HOMs

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Table 1: Properties of Parallel-Bar Structures

Parameter	750 MHz	KEK [4] Cavity	Units
Freq. of π mode	750.1	501.7	MHz
$\lambda/2$ of π mode	200.0	299.8	mm
Freq. of 0 mode	1350.6	~700.0	MHz
Freq. of nearest mode	1055.9	410.0	MHz
Freq. of lower order mode	-	410.0	MHz
Cavity length	300.0	299.8	mm
Cavity width	190.1	866.0	mm
Cavity height	190.1	483.0	mm
Bars length	200.0	-	mm
Angle	45	-	deg
Aperture diameter	60.0	130.0	mm
Deflecting Voltage (V_T^*)	0.200	0.300	MV
Peak electric field (E_P^*)	4.45	4.36	MV/m
Peak magnetic field (B_P^*)	9.31	12.45	mT
Geometrical factor	131.4	220	Ω
$[R/Q]_T$	124.15	46.70	Ω
$R_T R_S$	1.65	1.03	$\times 10^4 \Omega^2$

At E_T^*= 1 MV/m

as multipoles as is conventional for cavities with circular symmetry.

Table 2: Types of HOMs

Field on Beam Axis	Type of Mode
E_X, H_Y	Deflecting
E_Z	Accelerating
E_Y, H_X	Deflecting
H_Z	It does not couple to the beam

The intensity of each of these modes is determined by either the longitudinal or transverse $[R/Q]$ (depending on whether it is an accelerating or deflecting mode respectively) and the natural decay time $\tau = Q_{0,n}/\omega_n$, function of the frequency of each mode ω_n and its intrinsic quality factor $Q_{0,n}$. The $[R/Q]$ values for HOMs calculated up to 2.5 GHz using CST Microwave Studio are shown in Fig. 3.

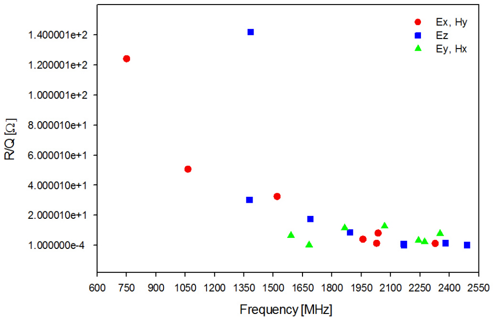

Figure 3: $[R/Q]$ values for the MEIC 750 MHz cavity.

Another important factors to highlight for this design is the abscence of any LOMs and SOMs, along with a wide frequency separation between the HOMs and the fundamental mode as shown in the Fig. 3.

Analysis of Field Profiles

The beam-induced voltage on the cavity can not be neglected since it is meant to work at average currents of 3 A for the electron beam and 500 mA for the proton beam. Therefore the effects of the HOMs play an important role on the operation of this design and need to be analyzed carefully for their proper damping. The modes with highest $[R/Q]_S$ identified for our design are shown in Table 3.

Table 3: Modes with highest $[R/Q]$

Mode Type	Frequency [MHz]	[R/Q] [Ω]
E_X, H_Y	750.10	124.294
E_Z	1384.03	141.959
E_Y, H_X	1589.31	6.51428

The transverse $[R/Q]$ calculated using direct integration method and Panofsky Wenzel method [5] are in agreement within $< 2\%$ and the longitudinal $[R/Q]$ values for the deflecting modes were found to be negligible. The net deflection due to the magnetic field is $V_T^* = 0.211$ MV and due to the electric field is $V_T^* = 0.412$ MV (* normalized to $E_T = 1.0$ MV/m). There is considerable competition between both contributions, which act against each other. This is due to the fact that, for this application, the ratio of beam aperture diameter (separation between the bars) and wavelength (or cavity diameter) is quite large. The electric and magnetic field orientations for the fundamental deflecting mode are shown in Fig. 4.

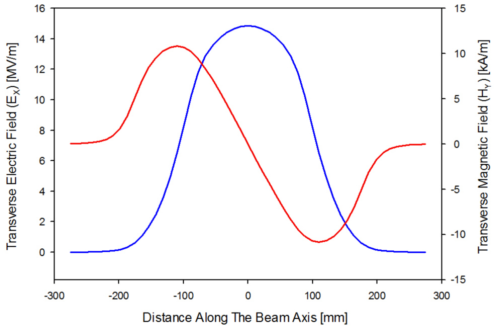

Figure 4: The fundamental deflecting mode transverse magnetic (red) and electric (blue) fields along the beam axis in the cavity.

For the accelerating mode, the field orientations are presented in Fig. 5, which also is the mode with higher $[R/Q]$.

For the vertical deflecting mode (which is the degenerated mode of our fundamental 750 MHz mode), the field profiles along the beam axis are shown in Fig. 6.

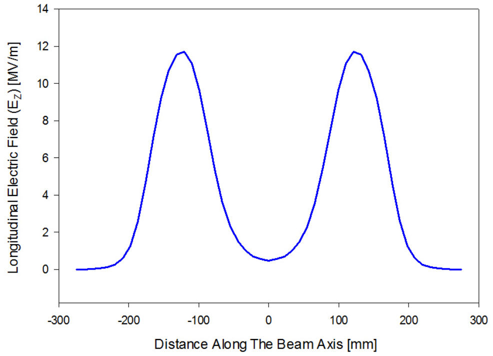

Figure 5: Longitudinal electric field along the fundamental accelerating mode (highest $[R/Q]$).

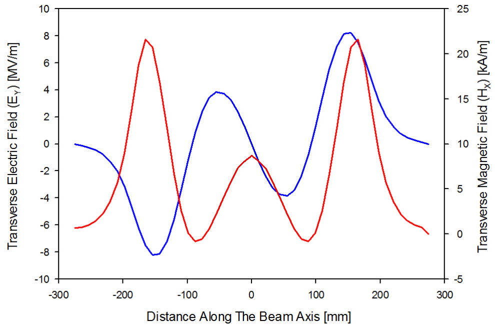

Figure 6: Transverse magnetic (red) and electric (blue) fields along the beam axis for the degenerated vertical deflecting mode in the cavity.

Field Non-uniformity Analysis

In Fig. 7 the variation of the transverse deflection in terms of an offset from the beam axis along the horizontal (x) and the vertical (y) directions across the entire beam aperture is presented. It can be appreciated from Fig. 7 that the normalized transverse voltage is uniform very close to the beam axis, but changes considerably as the offset increments. This change is fairly similar in both directions. This non-uniformity can be reduced substantially by shaping (curving) the bars in the beam aperture region [6].

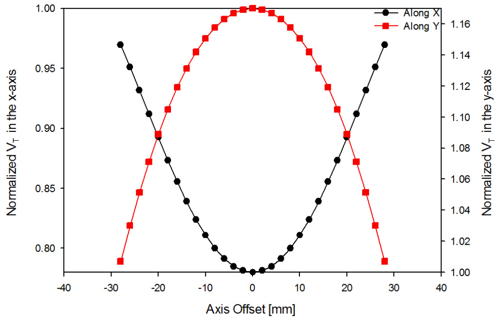

Figure 7: The normalized transverse deflecting voltage variations across the beam aperture both in x and y directions inside the cavity.

PROTOTYPE FABRICATION

As a result of the extensive study realized over this cavity design, a mechanical scheme was developed by Niowave Inc. using our parameters as shown in Fig. 8 (courtesy of Niowave Inc.). This crab cavity prototype for the MEIC is now under construction.

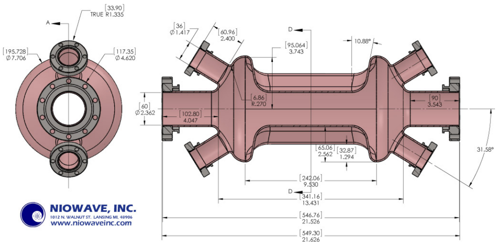

Figure 8: Mechanical design and construction specifications for the 750 MHz MEIC crab cavity, developed by Niowave Inc., construction undergoing.

CONCLUSIONS

The 750 MHz crab cavity design with parallel-trapezoidal carved element is analysed in detail, identifying its improved properties. This design is compact and presents attractive properties as a crabbing system, its balanced surface fields allow the operation at high deflecting voltages and due to the wide separation for the fundamental modes it is suitable for high-current applications. A study of the HOM properties is presented in terms of frequency separation, $[R/Q]$, and field profiles. The characteristics of the transverse voltage properties are presented as a function of offsets along the x and y directions. The absence of LOMs and fewer HOMs with wider separations, makes the damping of parasitic modes efficient. The construction of this design is currently undergoing at Niowave Inc.

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