NOVEL DEFLECTING CAVITY DESIGN FOR eRHIC*

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Abstract
To prevent significant loss of the luminosity due to large crossing angle in the future ERL based Electron Ion Collider at BNL (eRHIC), there is a demand for crab cavities. In this article, we will present a novel design of the deflecting/crabbing 181 MHz superconducting RF cavity that will fulfil the requirements of eRHIC. The quarter-wave resonator structure of the new cavity possesses many advantages, such as compact size, high R_t/Q, the absence of the same order mode and lower order mode, and easy higher order mode damping. We will present the properties and characteristics of the new cavity in detail.

INTRODUCTION

In the past few years, the application of deflecting cavities has extended to a wide range of projects and facilities [1, 2, 3]. As the accelerator systems grow in complexity, developing compact and efficient deflecting cavities is of great interest [4]. Such cavities will benefit situations where the beam line space is limited.

The future linac-ring type electron-ion collider requires implementation of a crab-crossing scheme for both beams at the interaction region. The ion beam has a long bunches and high rigidity. Therefore, it requires a low frequency, large kicking angle deflector. The frequency of the deflecting mode for the current collider design is 181 MHz, and the deflecting angle is ~5 mrad for each beam.

At such low frequency, the previous designs of the crab cavities will have very large dimensions, and also will be confronted by typical problems of damping the Lower Order Mode (LOM), the Same Order Mode (SOM), and as usual, the Higher Order Modes (HOM).

In this paper we describe how one can use the concept of a quarter-wave (QW) resonator for a deflecting/crabbing cavity, and use its fundamental mode to deflect the beam. The simplicity of the cavity geometry and the large separation between its fundamental mode and the first HOM make it very attractive.

CRAB CAVITY CONCEPT

The QW crab cavity concept is shown in Figure 1. As the major drawback of a simple QW crab cavity is residual acceleration, the idea in the proposed design is to add a coaxial stub opposite to the main coaxial line to symmetrize the longitudinal field on beam axis and thus eliminate acceleration.

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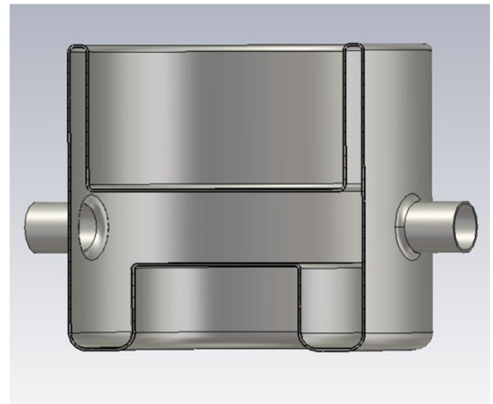

Figure 1: Concept model of QW crab cavity.

Figure 2 shows the electric field of the fundamental (deflecting) mode in the cavity symmetry plane. As the beam passes the cavity, the deflecting field in the gap interacts with the particles as a pair of parallel plates. The longitudinal electric field have large non-zero components near the beam pipes while the center of the cavity is dominated by transverse electric field.

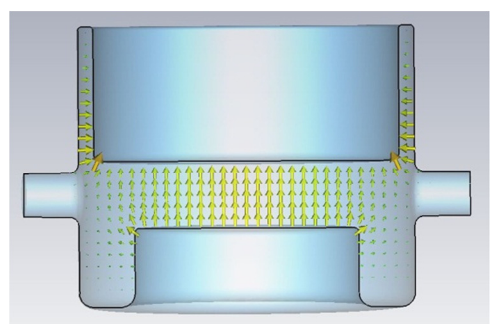

Figure 2: Electric field of the fundamental mode in the symmetric plane.

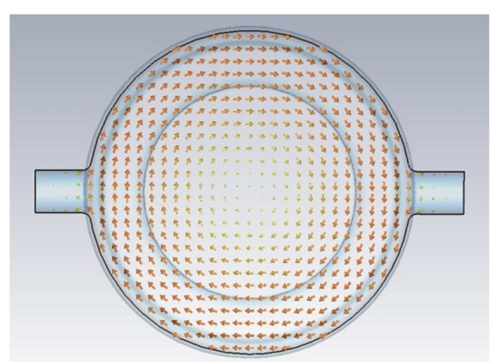

Figure 3: Magnetic field of the fundamental mode in the top view.

The magnetic field has simple configuration in the horizontal beam axis plane as one expects from a coaxial structure of the cavity. As shown in Figure 3, the magnetic field is null at the center of the cavity, and maximized near the outer wall. Connections with the beam pipes break the uniformity, but not significantly.

The fundamental mode is a single TEM resonance mode of the double coaxial structure. The deflection is produced by interaction with both electric and magnetic field.

ELECTROMAGNETIC ANALYSIS

The crabbing application requires the reference particle in a bunch to have a net deflection of zero after passing the cavity, while the head and tail of the bunch experience maximum kick in opposite directions. In this case, the phase of the cavity field with respect to the beam is important.

For QW crab cavity, the electric field symmetry plane is at the center of the cavity and perpendicular to the beam axis, while the magnetic field has opposite sign on both sides of this plane. If the reference particle in a bunch arrives at the center of the cavity with zero electric field, the deflection from the electric field would cancel as the direction of the electric field flips in its first and second half of travel. The deflection from the magnetic field would also cancel due to the field structure.

The deflection can be derived from the Panofsky-Wenzel Theorem:

$$\frac{\partial}{\partial z} p_{\perp} = \nabla_{\perp} p_z$$

where z is the direction of the beam axis.

If we define that the bunch is deflected in y direction, the deflection voltage would be:

$$V_y = \left| \left(\frac{c}{\omega}\right) \int_{-L/2}^{L/2} (-i) \nabla_y E_z \, dz \right|$$

In the above equation, L is the length of the cavity; c is the speed of light; ω is the frequency of the fundamental mode; E_z is the electric field long z direction on beam axis.

The traditional QW resonator structures have the same inner conductor diameters, i.e. $a = b$ in Figure 4, and one of the lines much shorter than the other, i.e. $d \ll c$ in Figure 4. The length of the longer line then determines the frequency. The direct usage of such a structure will result in large beam acceleration. For example, for a 200 MHz QW resonator, the accelerating voltage would be in the range of hundreds of kV. Despite potentially causing beam instabilities, this would lead to heavy beam loading and demand for high RF power. Our novel QW crab cavity design has eliminated the accelerating voltage.

The accelerating voltage provided to the reference particle by the cavity is

$$V_{acc} = \left| \int_{-L/2}^{L/2} E_z(r = 0, z)\, \mathrm{e}^{-\mathrm{i}kz} dz \right|$$

where r is the distance to the beam axis, and k is the wave number of the fundamental mode.

As the phase of the cavity with respect to the bunch has been set for crabbing, the longitudinal momentum imparted to the reference particle is

$$p_z = \left(\frac{\mathrm{e}}{c}\right) \int_{-L/2}^{L/2} E_{z0}(y, z) sin(\omega t)\, dz$$

The pattern of the E field along the beam axis is critical in this case.

DETAILED MODEL

The QW crab cavity inherited its characteristics from quarter-wave resonators. One of these characteristics is the compact size, which is very important for low frequencies.

Table 1 shows parameters of the QW crab cavity calculated using MicroWave Studio, and several dimensions as indicated in Figure 4. The length of the cavity is the diameter of the outer shell. The current design for 181 MHz only consumes approximately 75 cm of the beam line space, and can provide 6 MV deflecting voltage.

Table 1: Properties of QW crab cavity by MicroWave Studio simulation.

Parameter	**Unit**	**QW crab cavity**
Crab mode frequency	MHz	181
Nearest other mode frequency	MHz	251
Cavity length	cm	75.2
Cavity width	cm	38.1/25.1
Diameter of large electrode (a)	cm	68.6
Diameter of small electrode (b)	cm	50.2
Height of large electrode (c)	cm	30.6
Height of small electrode (d)	cm	17.6
Deflecting voltage*	MV	6.1
Peak surface electric field*	MV/m	39
Stored energy*	J	100
R_t/Q	Ω	291
Accelerating voltage*	MV	0**

*: Normalized to 100 mT peak magnetic field.

**: For beam pipe radius of 5 cm.

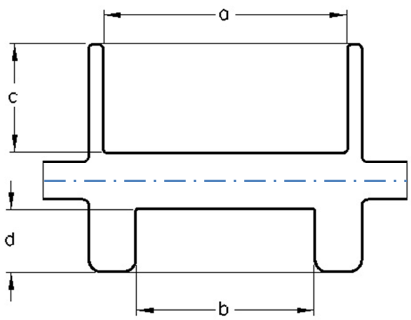

Figure 4: Cavity dimensions referred to in Table 1. The blue line shows the beam axis.

Another very attractive aspect of the cavity is the large separation between the deflecting mode and the nearest other mode, as listed in the same table. The simple QW resonator has the lowest HOM at 3 times the fundamental mode frequency. In our 181 MHz crab cavity design, this feature is weakened by the presence of a large coaxial stub, but still leaving a 70 MHz gap between the fundamental mode for deflection and the first HOM. This frequency difference scales with the fundamental frequency. For example, the gap will increase to 150 MHz for a 400 MHz QW crab cavity. This allows for very simple damping of all unwanted modes [5].

The electric and magnetic field distributions along the beam axis in the cavity are shown in Figure 5-Figure **7**.

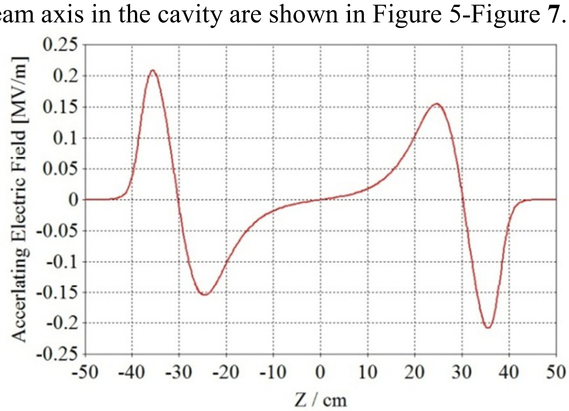

Figure 5: $\boldsymbol{E_z}$ along the beam axis.

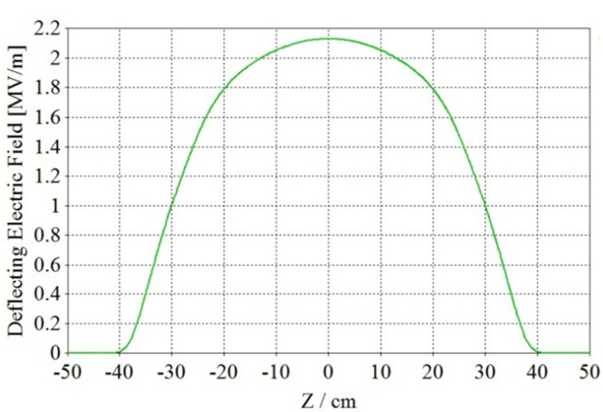

Figure 6: Deflecting electric field along the beam axis.

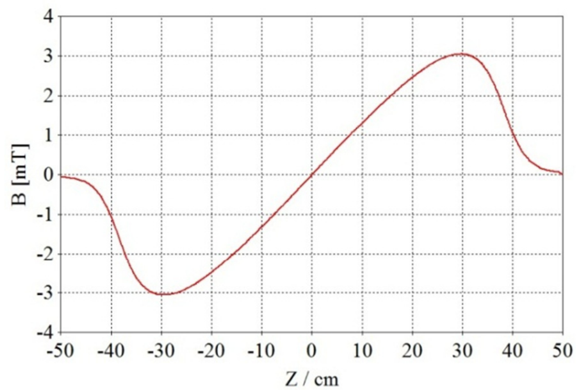

Figure 7: Magnetic field along the beam axis.

With a null accelerating voltage, the maximum deflecting voltage of a 181 MHz QW crab cavity is 6.1 MV. This is calculated with the normalization on 100 mT peak surface magnetic field in the cavity.

The deflection angle provided to the bunch is

$$\theta = \frac{eR_{12}\int_{-L/2}^{L/2} \nabla_y E_{z0}(y,z) sin(\omega\, z/c)\, dz}{E_{beam}}$$

where R_{12} is the transfer matrix element, e is the charge of an electron, E_{beam} is the reference particle energy. For an IP lattice design with $R_{12} = 10$ m, seven QW crab cavities are needed to deflect the bunch for 5 mrad.

Along with all other advantages of the QW cavity, the deflection and acceleration voltage for the design are not sensitive to the beam pipe radius.

FURTHER OPTIMIZATION

The deflecting voltage of the QW crab cavity design discussed above is limited by the peak magnetic field. Further optimization can be done by changing the geometry around the top and bottom of the cavity where the surface magnetic field reaches its maximum. The width of the cavity can also be decreased by changing the gap between the electrodes.

The current design of the QW crab cavity allows us a relatively large room of geometry modification, but still maintains its simplicity for manufacturing.

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