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HIGHER ORDER MODE COUPLING OPTIONS OF eRHIC CRAB CAVITY*

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Abstract

The eRHIC crab cavity adopts the double quarter wave structure developed at Brookhaven National Lab for the LHC Hi-Lumi upgrade crab cavities. The eRHIC cavity's fundamental (and crabbing) mode is at 338 MHz with the first Higher Order Mode (HOM) more than 190 MHz above that. We investigated the higher order mode distribution up to 2 GHz and considered various locations and geometries of the coupling scheme. The cylindrical outer shell of the cavity allowed various possibilities for coupler port openings on all the walls, which were difficult for the LHC double quarter wave crab cavities due to the proximity of the second beam pipe.

INTRODUCTION

The proposed electron-ion collider at Brookhaven National Laboratory (eRHIC), as shown in Figure 1, is designed for high luminosity in the range from 1032 to 1033 cm^{-2}s^{-1} over a center-of-mass energy range from 30 to 140GeV [1].

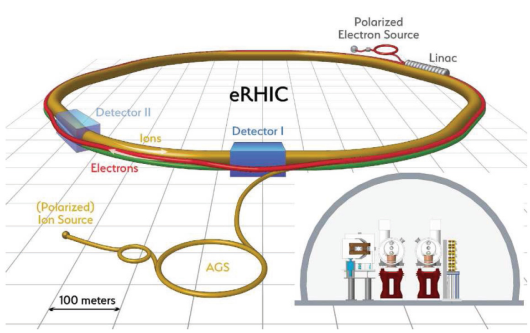

Figure 1: Schematic overview of the eRHIC facility.

To achieve such high luminosity, large crossing angle is adopted in eRHIC design for fast separation between the ion and electron beam lines after the interaction point [2]. Based on the experience from the LHC crab cavity program, a Double Quarter Wave Crab Cavity (DQWCC) has been proven for its RF efficiency, easy fabrication and cleaning, and achievable compact HOM damping system. eRHIC crabbing system requires a frequency of 338 MHz for the proton beam with a bunch length of5- 7 cm at various energies [3]. In order to minimize the design effort and risk of multiple RF systems, the electron beam with shorter bunch length (1.7 – 2.3 mm rms) and much lower energy (5 - 18 GeV) can share the identical cavity design with optimized couplers with proton.

The DQWCC was first designed for the LHC HiLumi upgrade [4], and two of these specific cavities were built and installed in the Super Proton Synchrotron (SPS) for beam test prior production for the LHC upgrade. Those two cavities are designed with careful consideration of HOM damping for the LHC Hi-Lumi scheme. The beam test in SPS will partially validate of the HOM couplers installed with band pass filters. The eRHIC crab cavity also requires same level of HOM damping from each unit, however, the cavity design and damping scheme can be modified due to the relax in spacial limitation compared to the LHC tunnel [5].

CAVITY HOM ANALYSIS

The coaxial-like geometry endowed the DQWCC large separation between its fundamental frequency and the first HOM. In an eRHIC crab cavity, the first HOM is 528 MHz, which is 190 MHz above the fundamental frequency. Due to the boundary settings, the magnetic fields are concentrated on both torus ends, or near the beam pipe openings for all RF modes.

The detailed analysis on the crabbing (fundamental) mode can be found in reference [6]. For various beam patterns proposed in the eRHIC Ring-Ring design [1], a crab cavity will have about 100 HOM modes excited by the proton beam up to 2 GHz. The excited longitudinal HOM will affect the beam momentum in an uncontrollable phase. Therefore, an increased longitudinal emittance or even longitudinal instability is expected. The impedance of the longitudinal HOMs can be written as

$$Z_{\parallel}(\omega) = \frac{1}{2}\sum_{n} \frac{(r/Q)_{\parallel n} Q_n}{1 + iQ_n\left(\frac{\omega_n}{\omega} - \frac{\omega}{\omega_n}\right)}$$

where the subscript n denotes the n-th HOM.

In a crab cavity, the transverse HOM will give the beam unwanted transverse kick in addition to the desired kick for crab crossing. The transverse momentum change due to HOM of the crab cavity may cause transverse instabilities, emittance growth of the proton beam and the resulting luminosity degradation. Due to the non-axial symmetry design of the crab cavity, the impedances of the two transverse directions need to be considered separately:

$$Z_x(\omega) = \frac{1}{2}\sum_{n} \frac{\omega_{n,x}}{c} \frac{(r/Q)_{n,x} Q_{n,x}}{1 + iQ_{n,x}\left(\frac{\omega_{n,x}}{\omega} - \frac{\omega}{\omega_{n,x}}\right)}$$

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$$Z_y(\omega) = \frac{1}{2}\sum_n \frac{\omega_{n,y}}{c} \frac{(r/Q)_{n,y} Q_{n,y}}{1 + iQ_{n,y}\left(\frac{\omega_{n,y}}{\omega} - \frac{\omega}{\omega_{n,y}}\right)}$$

Some samples of the electric and magnetic field distribution of HOMs are shown in Figure 2.

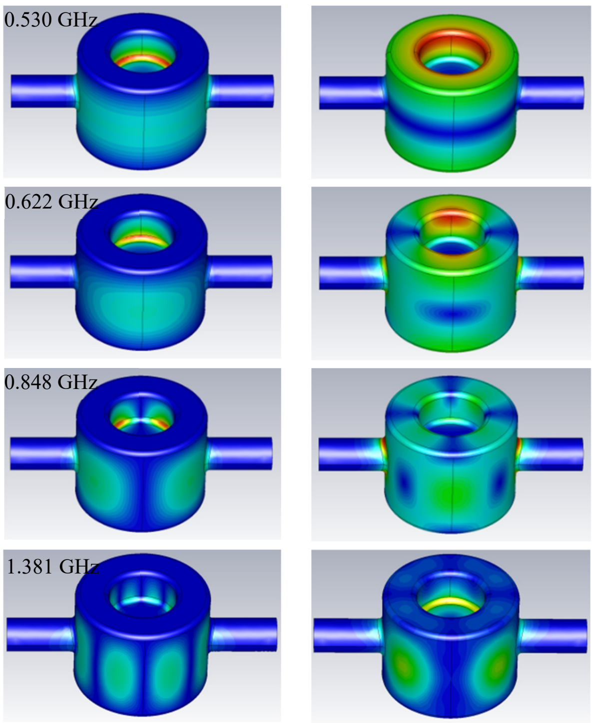

Figure 2: Typical HOM field distributions of the DQWCC with electric field on the left, and magnetic field on the right.

The HOM damping scheme is based on the field distribution with consideration of fabrication, surface treatment, installation accessibility, and tolerance studies.

HOM DAMPING OPTIONS

In the eRHIC DQWCC, we currently investigate two types of HOM damping scheme, electric and magnetic as shown in Figure 3.

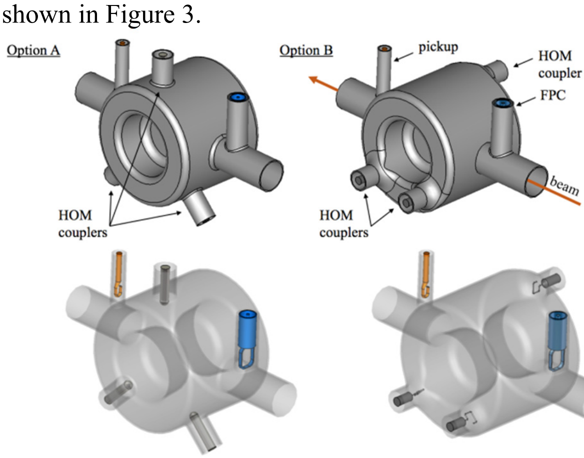

Figure 3: Electric (left) and magnetic (right) coupling of the HOMs.

The magnetic couplers are similar to what we have designed for the LHC crab cavity, in which a hook couples into most of the HOMs which have magnetic fields concentrated at the end of the cavity. In current studies, three hook type couplers, 2.4 cm by 3.4 cm, are inserted from both ends of the cavity. However, there still remain high impedances from some HOMs above 1 GHz indicating these couplers alone cannot provide sufficient damping.

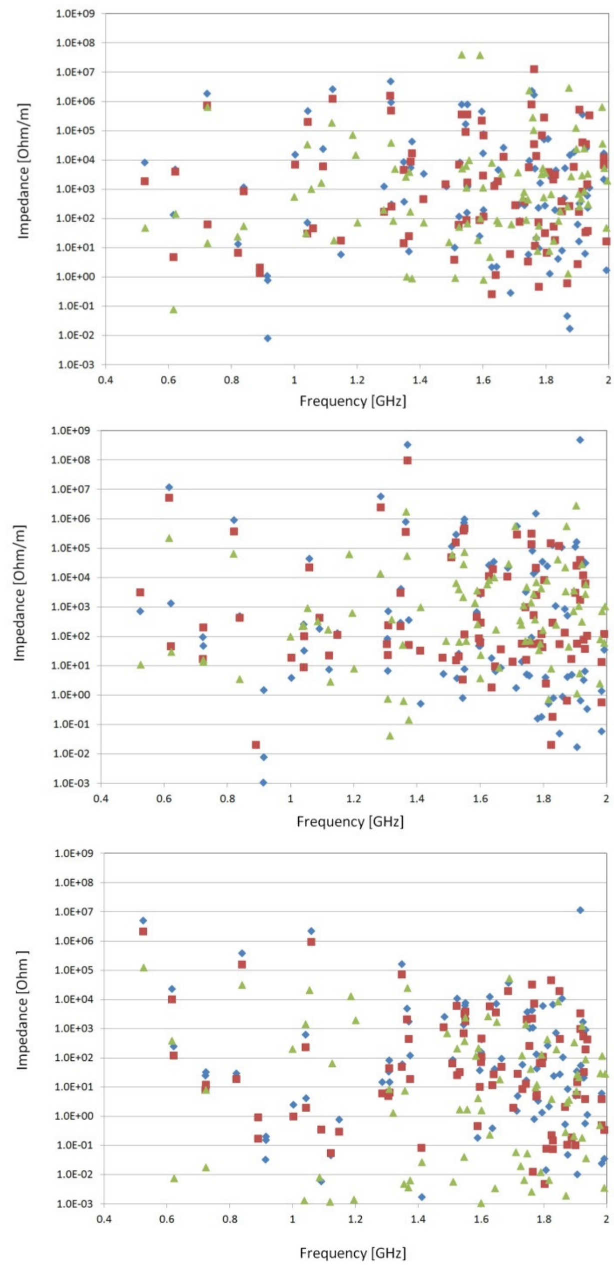

Figure 4: Comparison of deflection (top), vertical (middle), and longitudinal (bottom) impedance with different damping schemes. Each plot has magnetic couplers tip at port opening (blue diamond), 10 mm penetrated into cavity (red square), and electric couplers 10 mm penetrated into cavity (green triangle).

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From the experience in the LHC crab cavities, these weakly coupled modes have their magnetic field concentrated in the middle of the cavity near the circumference of the cavity body. One example would be the 1.381 GHz mode shown in Figure 2. Therefore, extra damping on the beam pipe opening is needed, as the multi-function pick-up coupler designed for the LHC crab cavity [7].

Figure 4 plotted impedances for the two magnetic coupling options. The impedance from hook couplers that have the tip of the hook at the same level of the coupler port opening (blue diamond) is no more than two times of the impedance from the hook with 10 mm penetration into the cavity. Therefore, having the couplers penetrating further into strong fundamental field does not significantly increase the HOM damping effect.

Compared to the magnetic couplers, the electric coupling option involves three 2.75 cm diameter antenna couplers on the side of the cavity from different angles. The three couplers are in the same plane but with an 8 cm offset from the symmetry plane of the cavity. The offset is chosen for TEmn (n>0) with weak electric field along the beam axis. Impedance analysis show the overall impedance with electric coupler is much lower, with a few exceptions.

With very similar thermal loss on the two types of couplers as shown in Figure 5, electrical coupling shows more efficient damping of most of the HOMs. The few modes with insufficient damping, especially the two deflecting modes at 1.533 GHz and 1.591 GHz requires further study with additional dampers, such as beam pipe absorbers or use of the pickup. Optimization of the coupler configuration would also improve the damping of these modes. With simpler geometry and accessibility, the electrical coupler is easy to adopt active cooling channels to keep the temperature of the coupler tip at a cryogenic level. Along with consideration of the chemical treatment for these couplers, electrical coupling performs better in all these aspects.

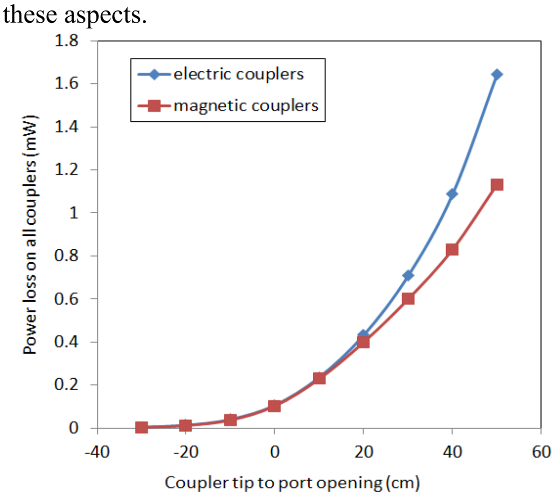

Figure 5: Comparison of power loss on all couplers at various penetrations between electric and magnetic coupling. Positive distance defined as couplers penetrate into cavity.

HOM POWER

At the highest design collision energy of eRHIC (275 GeV), using electrical couplers, the total HOM power coupled through all three antennas is 1.44 KW in the proton ring with 330 bunches of 5 cm bunch length each. The beam average current is 0.81 A.

Table 1: HOMs with Less Than 2 MHz From Beam Spectrum Line

Freq. [MHz]	Qext	Design Power [W]	Distance from closest beam resonance [MHz]
616	514	20.3	0.76
1042	544	87.7	1.28
1185	6854	0.8	0.37
1551	2169	0.7	0.568
1690	2868	0.9	0.845

The power extracted from each port is less than 500 W, which is not challenging for mechanical and thermal connections when considering that the LHC crab cavity HOM couplers are designed with 1 kW RF power transfer. However, the modes listed in Table **1** are dangerous frequencies close to proton beam spectrum lines. Their frequencies may shift due to fabrication error or tuning, and cause significant HOM power increase. These modes may need modifications to the cavity design to intentionally move their frequencies away from the resonance lines.

CONCLUSION

The eRHIC crab cavity HOM analysis predicted electrical coupling has more efficiency compared to magnetic couplers, with additional advantages in fabrication, chemical treatment, and cooling. A few modes are with 2 MHz from the beam spectrum line indicating further changes in their frequencies are needed. The coupler design will combine with the design of a high pass filter to reflect the actual HOM damping effectiveness.

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