

CRAB CAVITIES FOR eRHIC - A PRELIMINARY DESIGN *

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Abstract

The proposed eRHIC electron ion collider at BNL must use a relatively large crossing angle between the ion and electron beams for various reasons, including the reduction of the long-range beam-beam effects and minimization of synchrotron radiation noise in the detector. To prevent significant loss of the luminosity due to this large crossing angle, the design of the collider requires the use of groups of crab cavities to provide local crabbing for both proton/ion and electron beams. We will base our design for eRHIC crab cavities based on our experience in the design of the 400 MHz double quarter wave crab cavity (DQWCC) for the high luminosity.

eRHIC CRAB CAVITY PROJECT

The high current electron-ion collider (EIC) requires quick separation of the electron and ion beams at the interaction region to prevent beam-beam instabilities. A careful study looked into the possibility of achieving this by a crossing angle of the beams or a separation dipole. The conclusion from the study favoured the crossing angle, because the separation dipole is incompatible with the physics and detector constraints [1]. To prevent significant loss of the luminosity due to large crossing angle, 10mrad or 15mrad for linac-ring or ring-ring scheme respectively, in the future EIC at BNL (eRHIC), there is a demand for crab cavities that deliver high deflecting voltages.

Table 1: Preliminary Basic Beam and Crab Cavity Parameters for Linac-ring Scheme of eRHIC.

| Parameters | Baseline Design | | Ultimate Design | |
|--|-----------------|--------|-----------------|--------|
| | Electron | Proton | Electron | Proton |
| Crossing angle (Full, mrad) | 10 | | 10 | |
| Beam energy (GeV) | 20 | 250 | 20 | 250 |
| Beta function at IP (, cm) | 12.5 | 12.5 | 5 | 5 |
| Transverse beam size at IP (μm) | 15.3 | 15.3 | 7.1 | 7.1 |
| Bunch length (cm) | 0.3 | 15 | 0.3 | 5 |
| Piwinski angle (rad) | 0.98 | 49.0 | 2.14 | 35.7 |
| Beta function at crab cavity (m) | 115 | ~1000 | 270 | 2500 |
| Frequency of fundamental crab cavity (MHz) | 422.2 | 140.7 | 422.2 | 140.7 |
| Total voltage of fundamental crab cavity (MV) | 3 | ~44 | 3 | 38 |
| Frequency of higher harmonic crab cavity (MHz) | N/A | 422.2 | N/A | N/A |
| Total voltage of 3 rd harmonic crab cavity (MV) | N/A | ~2 | N/A | N/A |
| Cavity Aperture [cm] | 10 | 5 | 10 | 5 |

Studies on the crab cavity requirement from beam dynamics are ongoing for both linac-ring and ring-ring schemes for eRHIC [2]. The eRHIC design establishes an asymmetrical collision of 250 GeV protons with 20 GeV electrons. Piwinski angle for horizontal crossing is defined by

$$\varphi = \frac{\theta \sigma_z}{\sigma_x}$$

where θ , σ_z , σ_x are half crossing angle, bunch length, and horizontal beam size. The luminosity deduction ratio

between with and without a crab cavity at the IP is shown in the following equation:

$$R = \frac{1}{\sqrt{1 + \varphi^2}}$$

As shown in Table 1, compared to the 0.6 rad LHC angle, the much larger eRHIC Piwinski angle highly demands a crab cavity system to re-establish the head-on collision at the IP. The eRHIC proton bunches are more than 20 times longer than the KEKB electron bunches, and more than 2 times longer compared to the Hi-Lumi LHC proton bunches, therefore, a low frequency crab cavity is required.

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In comparison to the linac-ring scheme, the ring-ring scheme studies showed similar cavity parameters, see Table 2.

Table 2: Preliminary Basic Beam and Crab Cavity Parameters for Ring-ring Scheme of eRHIC.

| Parameters | Baseline Design | |
|--|-----------------|--------|
| | Electron | Proton |
| Crossing angle (Full, mrad) | 15 | |
| Beam energy (GeV) | 20 | 250 |
| Beta function at IP (cm) | 38 | 216 |
| Transverse beam size at IP (μm) | 143 | 143 |
| Bunch length (cm) | 1 | 20 |
| Piwinski angle (rad) | 0.64 | 10.7 |
| Beta function at crab cavity (m) | N/A | 2400 |
| Frequency of fundamental crab cavity (MHz) | N/A | 168 |
| Total voltage of fundamental crab cavity (MV) | N/A | 20 |
| Frequency of higher harmonic crab cavity (MHz) | N/A | 336 |
| Total voltage of 3rd harmonic crab cavity (MV) | N/A | 2.6 |
| Cavity Aperture [cm] | N/A | 20 |

DOUBLE QUARTER WAVE CRAB CAVITY

Double quarter wave resonators inherited compactness from the coaxial RF structures, compared to elliptical cavities. With two quarter-wave halves heavily capacitive loaded against each other, as shown in Figure 1, the long effective deflection region between the center plates maximizes the deflecting voltage over the cavity length. The comparison of the 400 MHz double quarter wave crab cavity (DQWCC) designed for high luminosity upgrade of LHC [3] and the 509 MHz squashed elliptical crab cavity for KEKB [4] showed the compactness advantage of the DQW structure, Figure 2.

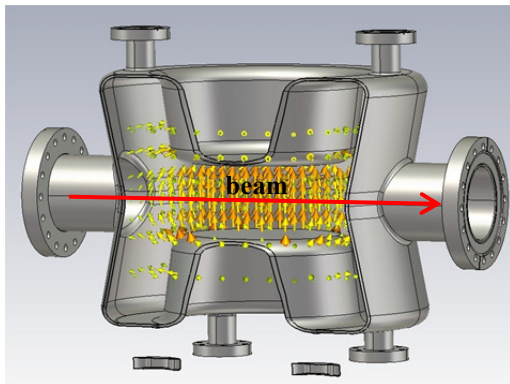
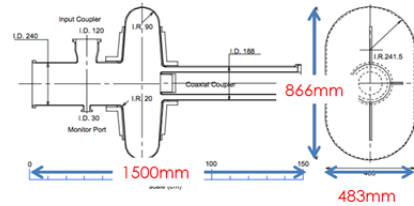


Figure 1: An example of double quarter wave structure and its electric field, with beam axis through the center.

With the successful experience at high luminosity LHC, the proof of principle DQWCC has delivered 4.6 MV deflecting voltage in 2K vertical test at Brookhaven National Laboratory [5]. This result is 35% above the designed value, and with further optimization of the prototype crab cavity, we believe the safety margin can be increased to above 50%.

KEK 509 MHz crab cavity (2.8 MV def voltage at 2.8 K):



DQWCC 400 MHz crab cavity (3.4 MV def voltage at 2 K):

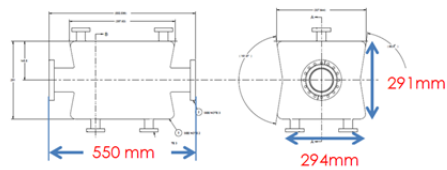


Figure 2: Comparison of elliptical crab cavity for KEK and double quarter wave crab cavity for LHC.

The DQWCC also has the unique property that the lowest higher order mode (HOM) of any sort is significantly separated in frequency from the deflecting fundamental mode, allowing for a simple and efficient damping of these unwanted modes.

PRELIMINARY DESIGN

Based on the frequency and voltage requirements of the eRHIC fundamental crab cavity in linac-ring scheme, and also with fabrication and post processing under consideration, we designed two preliminary DQWCCs, shown in Figure 3.

Cavity basic parameters are shown in Table 3 for both design options. The design shown on top of Figure 3 has lower surface field compared to the bottom design at the same 10 MV deflecting voltage, which is in favour of cavity treatment and operation. However, the bottom version is easier to fabricate due to thinner diameter. The ideal design will be determined with fabrication capability feedbacks from the vendors.

Coupler ports are located on the high magnetic field region for easy coupling of the HOMs. This also demands an efficient coupling and high-pass filter design for the HOM couplers. For both options, the 1st HOM is more than 60 MHz away from the fundamental frequency, which relaxed difficulty of the design of the filter. The top design is again in favour of the physics due to much larger separation between the first two resonant frequencies.

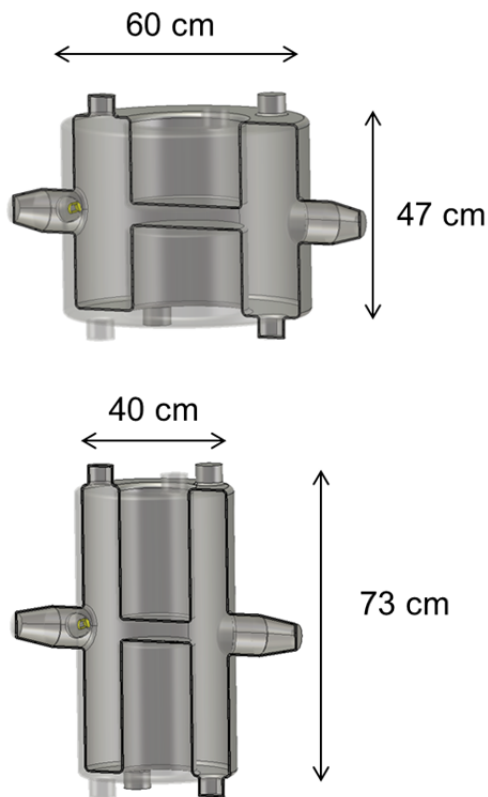


Figure 3: Preliminary design options for eRHIC crab cavity for linac-ring scheme.

SUMMARY

Crab cavity is an essential device for eRHIC, or any high current EIC. With longer bunches in eRHIC compared to previous colliders with crabbing scheme at the interaction region, low frequency crab cavity is required. The DQWCC is an ideal structure to deliver high deflecting voltage with a compact size for high efficient momentum kick and lower the cost of the entire system. Two design options were studied for the preliminary cavity parameters, and the final version will be chosen with compromise between cavity performance and fabrication capabilities.

Table 3: DQWCC Design Options for eRHIC Linac-ring Scheme. All Field Values are Obtained for 10MV Deflecting Voltage.

| | Top | Bottom |
|---------------------------------|-------|--------|
| Frequency [MHz] | 140.7 | 140.7 |
| 1 st HOM [MHz] | 322 | 206 |
| Total height [cm] | 47 | 73 |
| Total length [cm] | 93 | 78 |
| Total width [cm] | 60 | 40 |
| Total surface [m ²] | 1.974 | 1.7542 |
| Total volume [m ³] | 0.107 | 0.0744 |
| peak surface E field [MV/m] | 43.59 | 67.84 |
| peak surface B field [mT] | 40.76 | 67.37 |
| Geometric factor G [Ohm] | 60 | 42 |
| Q0 | 3e9 | 2e9 |

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