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CAVITY DESIGN FOR THE UPDATED eRHIC CRABBING SYSTEM *

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Abstract

The electron-ion collider eRHIC proposed by Brookhaven National Laboratory includes a crabbing system to reestablish head-on collisions for a maximum geometric overlap of the colliding bunches. Since the last cavity design, the crossing angle has increased from 22 to 25 mrad to relax the field strength requirement in one of the IR magnets – increasing the deflecting kick required to collider the bunches head on – and one of the considered options is to have both proton and electron crab cavities work at 200 MHz. The present paper discusses the RF design of the 200 MHz crab cavities for the electron and hadron beams of eRHIC.

INTRODUCTION

The construction of an Electron-Ion Collider (EIC) would enable to further investigations on gluons and quarks, and deepen our understanding of fundamental properties of matter like the origin of the nucleons mass [1]. The EIC proposed by Brookhaven National Laboratory (BNL) receives the name of eRHIC: electron Relativistic Heavy Ion Collider.

The eRHIC consists of two storage rings as depicted in Fig. 1, one for electrons and another one for hadrons [2]. The baseline design of eRHIC includes a crabbing system for each ring to enable the so-called crab crossing in the horizontal plane. Crab crossing in eRHIC will maximize the geometric overlap of the colliding bunches and becomes essential to reach the luminosity levels required for studying rare processes.

Since our last report [3], some eRHIC design parameters relevant to the crabbing system were updated. The number of bunches has changed to 290 for the 275 GeV proton and 18 GeV electron collisions with base harmonic number of 315. For other high-luminosity scenarios, the number of bunches is 1160 (4×290), requiring a factor of 4 times the base harmonic number [4,5]. In addition, the crossing angle has been increased from 22 mrad to 25 mrad to relax the field strength requirement in one of the Interaction Region (IR) magnets. This work discusses the RF characteristics of the crab cavities for the electron and hadron rings of the latest eRHIC design.

THE eRHIC CRAB CAVITY DESIGN

The choice of the crab cavity frequency impacts the cavity size and necessary kick voltage. It also has an effect on power and tuning requirements. The final frequency has to consider possible space constraints and non linear kicks to long bunches.

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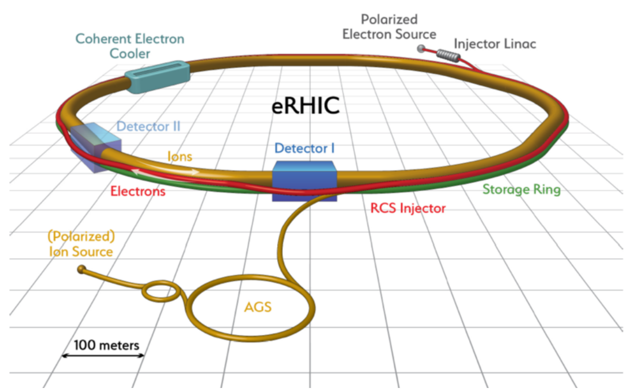

Figure 1: Conceptual layout of eRHIC.

RF Frequency Choice

The operational frequency of the eRHIC crab cavities needs to be a multiple of the base harmonic number (h) times the revolution frequency (f_r). The revolution frequency is given by $f_r = \beta_r c_0/\mathscr{C}$, where v is the particle velocity, β_r is the relativistic particle velocity, c_0 is the speed of light in vacuum and $\mathscr{C}$ is the accelerator circumference. The eRHIC will occupy the tunnel currently hosting the Relativistic Heavy Ion Collider (RHIC). The nominal eRHIC circumference is 3833.845 m [6], so the revolution frequency is approximately 78.25 kHz (it varies with the beam energy). Another factor 2 is additionally required to allow the shared luminosity scheme between the two Interaction Points (IP) [7].

Here we investigate a low-frequency crab cavity option for eRHIC working at 197.19 MHz ($2 \times 4 \times 315 \times f_r$), close to the frequency of the RHIC copper storage cavities. This low frequency is preferred to ensure that the eRHIC proton bunches, with 5–7.5 cm rms bunch length, receive a linear kick (the half wavelength of 197 MHz is about a factor 10 larger than the bunch length). The non-linearities introduced by a higher frequency cavity could be corrected with the addition of higher harmonics, but this would increase the complexity of the crabbing system. First beam-beam emittance growth studies do not find significant differences between multi-harmonic or 200 MHz systems [8].

Kick Voltage

The transverse kick voltage ($V_\perp$) provided by a crab cavity is given by:

$$V_\perp = \frac{c_0 E_0 \theta_C}{2\omega\sqrt{\beta^* \beta_C}} \tag{1}$$

where E_0 is the beam energy, θ_C is the crossing angle, ω is the angular RF frequency of the crabbing mode, β^* is the

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betatron function in the IP and β_C is the betatron function at the crab location.

The necessary kick voltage depends on the RF frequency of the crab cavity, with lower frequency cavities requiring higher voltages. A 200 MHz crab cavity system should provide a kick of 22.3 MV to fully crab the bunches of the 275 GeV proton beam.

RF Cavity Geometry

The eRHIC crab cavities are based on the Double-Quarter Wave (DQW) cavity developed for the High-Luminosity upgrade of the Large Hadron Collider (HL-LHC). The DQW crab cavity concept was validated in a series of tests. Vertical tests of bare DQW prototypes fabricated by industry demonstrated operation at significantly high peak surface magnetic and electric fields, 125 mT and 65 MV/m, respectively. The surface of the cavities was treated following a standard recipe of bulk Buffered-Chemical Polishing (BCP), 600° degassing, light BCP and 120° baking [9]. The tests of a cavity with its HOM filter, while reaching lower voltages, were also satisfactory [10]. More recently, in 2018, two DQW cavities successfully crabbed proton bunches in the Super Proton Synchrotron [11].

The DQW cavity is specially suited when requiring low-frequency deflecting kicks but available space is an issue. The DQW is a compact crab cavity which fundamental mode provides a deflecting kick [12]. Roughly, the DQW width is proportional to half the wavelength, that is, about 0.75 meters for 200 MHz (the width can be reduced by enlarging the magnetic region by other means). For comparison, a KEK-B-type crab cavity delivering a deflecting kick at 200 MHz would be more than double the width and would require Fundamental Order Mode and Same Order Mode dampers in addition to the Higher Order Mode (HOM) damper.

The deflecting kick provided by a DQW cavity is approximately proportional to the product of the capacitive plate diameter times the voltage sustained between the plates [13]. For the eRHIC crabbing system, the DQW cavity adopts an elliptical profile, as shown in Fig. 2, with the major axis parallel to the beamline. The longer kick path traveled by the bunch translates into a higher transverse geometric shunt impedance $(R/Q)_\perp$ than the value obtained for a circular-cylinder DQW cavity. The higher kick efficiency of this cavity design allows operating at lower peak surface fields. The ellipticity cannot be indefinitely increased. The highest magnetic field is located in the two narrower sides of the ellipse, and increases its value with the ellipticity.

Table 1 compares the performances of circular and elliptical DQW cavities calculated with CST Microwave Studio [14]. The beam aperture is 100 mm diameter. Both cavities are tuned to present their fundamental (crabbing) mode at 200 MHz. The ratio of maximum magnetic field over deflecting voltage ($B_p^{max}/V_\perp$) considerably low.

Assuming that operation of Superconducting Radio-Frequency (SRF) niobium cavities is limited to 120 mT, the eRHIC crabbing system would require about 3 cavities to fully crab the bunches of the eRHIC 275 GeV proton beam (about 8.2 MV per cavity). In a more conservative approach, we assume that reliable operation is limited to 80 mT, what determines a minimum of 4 cavities for full crabbing (about 5.5 MV per cavity). The number of cavities has to be doubled to implement the local crossing scheme. No additional cavities are required for the ion beams. The ratio between the proton beam energy (275 GeV) and the fully-stripped gold ($_{79}Au^{197}$) beam energy (110 GeV/u) was chosen to be equal to the A/Z ratio.

Table 1: Comparison between circular-cylinder and elliptical-profile DQW cavities for eRHIC. Electromagnetic quantities calculated with CST Microwave Studio [14]

Parameter	Circular	Elliptical	Unit
$(R/Q)_\perp$	514	610	Ω
G	57	61	Ω
$B_p^{max}/V_\perp$	16.4	14.6	mT/MV
$E_p^{max}/V_\perp$	9.6	6.4	1/m
Length (along s-axis)	400	480	m
Width (along x-axis)	700	572	m
Height (along y-axis)	400	400	m

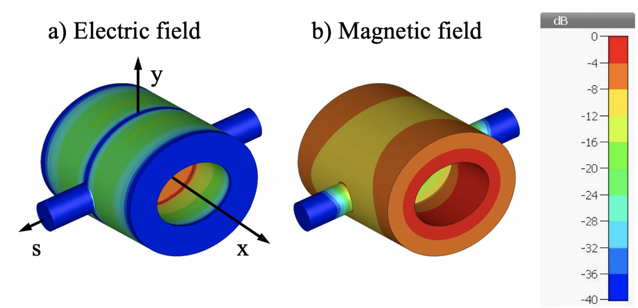

Figure 2: Electromagnetic field distribution for fundamental (crabbing) mode of the 200 MHz elliptical-section DQW cavity generated with CST Microwave Studio [14].

CRAB CAVITY OPERATION

Power Requirement

The generator power (P_g) necessary to operate a crab cavity is given by [3]:

$$P_g = \frac{1}{4(R/Q)_\perp Q_l}\left[V_\perp + I_b\frac{\omega}{c}y(R/Q)_\perp Q_l\right]^2 \qquad (2)$$

where Q_l is the loaded quality factor, I_b is the average beam current, and y is the beam offset. For on-axis operation ($y = 0$), the expression to calculate the generator power is reduced to:

$$P_g = \frac{V_\perp^2}{4(R/Q)_\perp Q_l} \qquad (3)$$

and is independent of the beam current and the cavity frequency. Considering a reasonable power of 5 kW for on-axis operation at the maximum operating voltage of 5.5 MV

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per cavity, the power coupler of the 200 MHz eRHIC crab cavity should establish a coupling of around 2×10^6, which provides a sufficiently broad bandwidth of 400 Hz. The power requirement in the case of off-axis operation (Eq. 2) is displayed in Fig. 3 considering different beam offsets. For a maximum beam offset of 2 mm [15], the generator power is below 50 kW (framed area in pink) if the loaded quality factor is between 0.6 and 2×10^6.

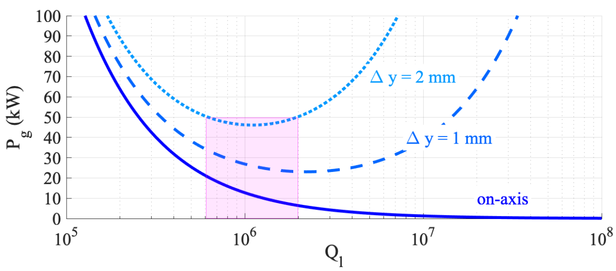

Figure 3: Generator power required by a 200 MHz crab cavity with $(R/Q)_\perp = 610\ \Omega$ and $Q_l = 2 \times 10^6$ for delivery of 5.5 MV deflecting voltage to 1 A average current beam. Power requirement below 50 kW in framed region.

Tuning Requirement

The power required to operate the crab cavity at a given voltage will vary if the cavity is detuned with respect to the generator. The power variation is given by [3]:

$$\Delta P_g = \frac{V_\perp^2}{(R/Q)_\perp} Q_l \left(\frac{\Delta\omega}{\omega}\right)^2 \qquad (4)$$

where $\Delta\omega$ is the detuning or difference between the generator and cavity frequencies. Additional power overhead is thus needed to compensate the power demand increase due to fast frequency fluctuations from microphonics. A 30 kW overhead will suffice to compensate shifts as large as 100 Hz.

In eRHIC, the hadron path length will be corrected to compensate the velocity change at the different energies, from the lowest energy proton beam (41 GeV) to the highest energy proton beam (275 GeV), and the frequency of the cavities stays fixed, matching the electron storage ring frequency. If the hadron path length was not corrected, the frequency of the crab cavities in the hadron ring should be shifted by 48 kHz between operation to avoid unreasonable power consumption.

SUMMARY AND OVERVIEW

A first design of the crab cavity geometry for the eRHIC crabbing system was presented. The cavity operates at 200 MHz and has an elliptical section that increases the kick efficiency and allows operation at lower peak fields than the circular-cylinder DQW cavity.

We intend to investigate geometric modifications that help reducing further the magnetic peak field in the cavity with the scope of operating the cavity at higher deflecting voltages. The work will continue with the evaluation of alternative cavity geometries aiming at further reducing the cavity dimensions, and the development of a Fundamental Power Coupler and HOM dampers adequate for the application. The idea is follow similar approach as for the 338 MHz crab cavity design discussed in Ref. [3].

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