POWER REQUIREMENT AND PRELIMINARY COUPLER DESIGN FOR THE eRHIC CRAB CAVITY SYSTEM*

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Abstract

Crab cavities are deflecting cavities operated in such a way that the bunch center is in synchronism with the zero-crossing kick voltage. In that case, beam loading is zero for an on-axis beam. The crab cavity system of the electron-ion collider eRHIC will manipulate 275 GeV proton beams. At high energies, the beam offset can be as large as 2 mm (including mechanical and electrical offset tolerances). The beam loading resulting from such offset can greatly incur in large power requirements to the RF amplifier. The choice of external Q for the Fundamental Power Coupler (FPC) is critical to limit the power requirement to practical values. The loaded Q of the eRHIC crab cavities is mainly governed by the external Q of the FPC, so the external Q will also define the cavity bandwidth and thus the tuning requirements to counteract frequency transients from external perturbations. This paper discusses the choice of external Q for the FPC of the eRHIC crab cavities and introduces the design of a preliminary FPC antenna concept that would provide the appropriate external Q.

INTRODUCTION

Crab crossing is an essential mechanism in high-luminosity colliders. Crab cavities will be installed in the proton and electron rings of the electron-ion collider eRHIC. The collider will operate electron beams at energies ranging from 5 GeV up to 18 GeV and proton beams at energies between 41 GeV and 275 GeV. The maximum crabbing kick required to enable the full geometric overlap of the crossing bunches is 13.48 MV for the proton beam and 4.76 MV for the electron beam [1].

At high energies, the beam orbit may have an offset as large as 1 (realistic) to 2 (worst case) mm (including the mechanical/electrical offset tolerances) [2]. The proton beam current is expected to change from 0.442 A, for low energy operations, up to 0.691 A, for high energy operations. The electron beam current will vary from 1.280 A, for low energy operations, down to 0.260 A, for high energy operations. All the quoted values correspond to the ring-ring eRHIC design.

In this paper, we will analyze the impact of the foreseen operational scenarios on the eRHIC crab cavity system, and particularly, on the power required to operate this system. The choice of external Q for the FPC will be discussed and a preliminary design of FPC will be presented.

POWER REQUIRED BY A CRAB CAVITY

The RF power required to operate a crab cavity can be found from the expression derived for an accelerating cavity with the appropriate variable changes introduced in Ref. [3].

Assume an RF cavity operated at the deflecting mode intrinsic quality factor Q_0, external quality factor Q_e of the input coupler (FPC) and loaded quality factor Q_l. The coupling factor β is the ratio between Q_0 and Q_e ($\beta = Q_0/Q_e$). The RF power required to operate such cavity at a given accelerating voltage $V_\parallel$ is:

$$P_g = \frac{V_\parallel^2}{4(R/Q)_\parallel Q_e} \frac{(\beta+1)^2}{\beta^2} \times \left\{ \left[1 + \frac{I_b (R/Q)_\parallel Q_l}{V_\parallel} \cos\phi_0 \right]^2 + \left[\tan\psi' + \frac{I_b (R/Q)_\parallel Q_l}{V_\parallel} \sin\phi_0 \right]^2 \right\} \quad (1)$$

with

$$\tan\psi' = 2 Q_l \frac{\Delta\omega}{\omega} \quad (2)$$

being I_b the average beam current, ϕ_0 the synchronous phase and $\Delta\omega$ the frequency difference between the cavity without beam and the cavity with beam [4]. In the synchrotron convention here followed, the positive slope of the voltage finds is zero at $\phi_0 = 0$ [5]. Thus, $\phi_0 = \pi/2$ for maximum acceleration (synchronous particle “riding” on the crest of the voltage). The geometric shunt impedance $(R/Q)_\parallel$ (conventional figure or merit R/Q describing accelerating efficiency) is:

$$(R/Q)_\parallel = \frac{\left|V_\parallel(0)\right|^2}{\omega U} \quad (3)$$

according to linac convention. This is the same convention also followed by CST Microwave Studio, the high-frequency 3D electromagnetic field simulator used to design the eRHIC crab cavity [6].

For a deflecting cavity delivering a pure crabbing kick to a passing bunch, the bunch center must be synchronized for passage at zero-crossing voltage, i.e. $\phi_0 = 0$. As a result the amplifier sees no reactive component:

$$P_g = \frac{V_\parallel^2}{4(R/Q)_\parallel Q_e} \frac{(\beta+1)^2}{\beta^2} \left[1 + \frac{I_b (R/Q)_\parallel Q_l}{V_\parallel} \right]^2 \quad (4)$$

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* Work supported by Brookhaven Science Associates LLC under contract no. DE-SC0012704 with the U.S. Department of Energy.

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ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEPMF012

The Panofsky-Wenzel theorem [7] establishes a relationship between transverse and longitudinal voltages:

$$V_\perp = -\frac{ic}{\omega}\frac{V_{||}(y)}{y} \tag{5}$$

where y is the deflection axis and $V_\perp$ is the transverse (crabbing) voltage. Now, by analogy to Eq. 3 we define:

$$(R/Q)_{||}(y) = \frac{|V_{||}(y)|^2}{\omega U} \tag{6}$$

$$(R/Q)_\perp = \frac{|V_\perp|^2}{\omega U} \tag{7}$$

Combining Eq. 5 and Eq. 7 together we express $(R/Q)_\perp$ in function of $V_{||}(y)$:

$$(R/Q)_\perp = \left(\frac{c}{\omega}\right)^2 \frac{|V_{||}(y)|^2}{\omega U y^2} \tag{8}$$

Returning back to Eq. 4, we proceed to replace $V_{||}$ by $V_{||}(y)$ and $(R/Q)_{||}$ by $(R/Q)_{||}(y)$. Then we substitute Eq. 5 and Eq. 8 to get:

$$P_g = \frac{V_\perp^2}{4(R/Q)_\perp Q_e}\frac{(\beta+1)^2}{\beta^2}\left[V_\perp + I_b\frac{\omega}{c}y(R/Q)_\perp Q_l\right]^2 \tag{9}$$

The eRHIC crab cavities will be based on superconducting technology. The external Q for the FPC (Q_e) will then be the main contributor to the loaded Q of the cavities ($Q_0 \gg Q_e$), so $\beta >> 1$ and $Q_l \sim Q_e$, leading to the simplified expression provided in Ref. [8]:

$$P_g = \frac{1}{4(R/Q)_\perp Q_l}\left[V_\perp + I_b\frac{\omega}{c}y(R/Q)_\perp Q_l\right]^2 \tag{10}$$

Note that the required power depends on beam parameters (I_b, y), cavity characteristics (ω, $(R/Q)_\perp$), and coupler design (Q_l). For a centered beam ($y = 0$) and/or zero beam current ($I_b = 0$), the expression is just:

$$P_g = \frac{V_\perp^2}{4(R/Q)_\perp Q_l} \tag{11}$$

CHOICE OF EXTERNAL Q FOR THE FPC

The choice of the loaded Q, and consequently the external Q for the FPC, must consider the power available in the scenario of maximal beam offset y or in case of fast frequency transitions due to external perturbations; provide a practical bandwidth Δf ($\Delta f = f/Q_l$) that relaxes the demand on tuning precision; and lead to reasonable dissipative losses in the coupler that do not compromise the reliable operation of the cavity.

The crabbing system of eRHIC uses the so-called Double-Quarter Wave (DQW) cavities [6]. The largest power demand in the eRHIC crab cavity system comes from the operation with the high-energy, high-current proton beam (E_0 = 275 GeV, I_b = 0.691 A). Four crab cavities will provide a total crabbing kick of 13.48 MV to the eRHIC proton bunches (3.37 MV per cavity). Each cavity will be fed by its own RF power amplifier. Here we limit the maximum output power provided by a tetrode or solid-state amplifier to 40 kW and assume that 20% of the forward power will be lost in the line connecting amplifier and coupler [9]. Effectively, only 32 kW will be available to feed the crab cavity. Figure 1 shows the power required by a single 338 MHz crab cavity ($(R/Q)_\perp = 364\ \Omega$ [6]) to deliver a 3.37 MV kick to the high-energy, high-current proton beam of eRHIC. For the worst beam offset (y = 2 mm), the required power stays below 32 kW for loaded Q values between 7×10^5 and 2×10^6.

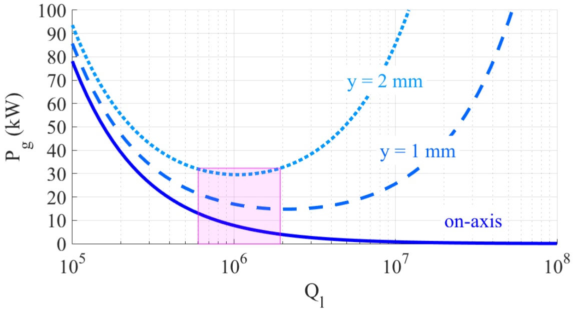

Figure 1: Power required by a 338 MHz DQW crab cavity in function of the selected loaded Q for different beam offsets. The red square frames the Q range for which the required power is, at most, 32 kW with a 2 mm offset.

Preliminary FPC Design

Each eRHIC crab cavity will be equipped with a single FPC. Enough coupling is achieved by introducing a coaxial loop in a port opened in one of the beam pipes (see Fig. 2). The coaxial loop provides high coupling to dissipative loss ratio and, in comparison with a hook, a loop brings the added advantage of allowing better cooling to the end tip exposed to the highest magnetic fields. The coaxial loop is made of copper due to the superior conductivity of this material over normal-conducting niobium (the end tip of the coupler is typically at temperatures well above the critical temperature of niobium). With an external Q of 1.17×10^6, the coaxial loop dissipates about 38 W when providing the necessary RF power to deliver a 3.37 MV deflecting kick. The coaxial loop is shielded from the helium bath by the external coaxial tube. The external Q leads to a sufficiently large bandwidth of almost 290 Hz.

Tuning Requirement

The delivered power must be increased by ΔP_g if the cavity is detuned by a small amount $\Delta\omega$:

$$\Delta P_g = \frac{V_\perp^2}{(R/Q)_\perp}Q_l\left(\frac{\Delta\omega}{\omega}\right)^2 \tag{12}$$

Assuming a centered beam ($y = 0$), the power overhead is about 25 kW during nominal operation ($V_\perp$ = 3.37 MV)

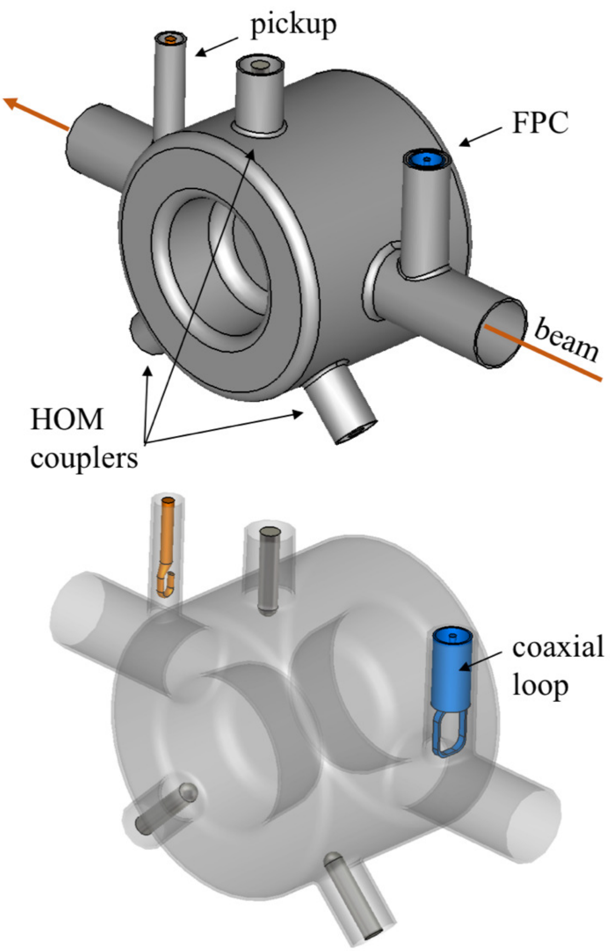

Figure 2: eRHIC crab cavity with FPC.

of an eRHIC crab cavity. Such overhead is sufficient to compensate the power demand increase resulting from fast frequency shifts as large as 272 Hz. Fast frequency transitions are mainly expected from microphonics. The eRHIC crab cavities will operate in Continuous-Wave (CW) mode and the active tuning system should be capable of correcting the cavity frequency due to Lorentz force detuning.

The operational frequency of the eRHIC crab cavities is equal to the harmonic number h times the revolution frequency f_r ($h = 4320$) [10]. 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 nominal eRHIC circumference $\mathscr{C}$ is 3833.845 m [1].

The electron beam of eRHIC has a large Lorentz factor γ ($\gamma = 1/\sqrt{1-\beta_r^2}$) over all the energy range (from 5 to 18 GeV). Consequently, the frequency of the electron crab cavities does not need to be changed. On the other hand, the cavity frequency will have to shift by 83 kHz between operation with the lowest energy proton beam (41 GeV) and the highest energy proton beam (275 GeV). This frequency shift would lead to a large power demand (several hundreds of kW) if no action is taken. The eRHIC crab cavities will be equipped with a dynamic tuning system with sufficient tuning range to correct frequency shifts resulting from operation with different energy beams, Lorentz force detuning and microphonics. The tuning concept is similar to the one implemented and successfully tested for the LHC DQW cavities [11]. The mechanism will act on the cavity central plates, a region of high frequency sensitivity (0.4 MHz/mm) as it concentrates the largest electric stored energy. Constraining the dynamic tuning to the elastic regime and fixing the maximum allowable stress given by niobium at room temperature (σ = 48 MPa), the maximum displacement of one plate will be limited to 0.18 mm. This small displacement provides a broad frequency range (± 0.14 MHz) for operation.

CONCLUSIONS

Each eRHIC crab cavity will be powered by its own 40 kW amplifier. The power will be fed by a single FPC opened in one of the beam pipes. The coupler consists on a coaxial loop which provides adequate coupling while dissipating reasonable amount of power. The loaded Q leads to a large bandwidth that guarantees stable operation of the cavities. In the presence of reasonable beam offsets, the installed power should suffice to provide the nominal crabbing voltage. The installed power should be enough to compensate for fast frequency transients of few hundreds of Hz; larger frequency shifts will be corrected by the active tuning system.

A dedicated LLRF system will be developed for successful control of the different systems involved in the cavity operation. Multipacting studies for an eRHIC crab cavity with FPC will follow. The RF design of the FPC will be complemented with the development of an adequate cooling system.

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