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338 MHz CRAB CAVITY DESIGN FOR THE eRHIC HADRON BEAM*

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Abstract

Crab crossing is an essential mechanism to restore high luminosity in the electron-hadron collider eRHIC. The current ring-ring eRHIC design envisages a set of crab cavities operating at 338 MHz. This set of cavities will provide the crabbing kick to the hadron beam of eRHIC. Double-Quarter Wave (DQW) cavities are compact, superconducting RF deflecting cavities appropriate for crab crossing. This paper summarizes the main design requirements and presents an optimized RF design of a DQW cavity for the crabbing system of the ring-ring eRHIC hadron beam.

INTRODUCTION

Crab crossing is an essential mechanism to restore high luminosity in the electron-hadron collider eRHIC. The current eRHIC design envisages the collision of 7 cm-long proton bunches with 0.43 cm-long electron bunches. Both proton and electron bunches have a nominal transverse size of 0.123 mm at the Interaction Point (IP). With a full crossing angle of 22 mrad, the Piwinski angle is 6.26 rad for the proton beam and 0.38 rad for the electron beam. This translates into a significant luminosity reduction with respect to head-on collisions unless crab crossing is implemented.

The crabbing system of the ring-ring eRHIC shall provide a 13 MV kick to the 275 GeV proton beam. The main requirements for such crabbing system are listed in Table 1 [1]. The required kick will be delivered by 3 cavities operating at 338 MHz. This frequency is close to the crabbing system of HL-LHC [2]. The crabbing system for eRHIC will use DQW cavities, like the HL-LHC.

Table 1: Main Requirements for Crabbing System of Ring-ring eRHIC Proton Beam

Parameter	Magnitude	Unit
RF frequency	338	MHz
Full crossing angle	22	mrad
Beta function at cavity location	1200	m
Beta function at IP	0.94	m
Transverse beam size at IP	0.123	mm
Bunch length	7	cm
Piwinski angle	6.26	rad
Cavity aperture	100	mm
Beam energy	275	GeV
Total voltage per IP per side	13	MV
Number of cavities	3	

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THE DOUBLE QUARTER WAVE CAVITY

Quarter Wave Resonator (QWR) cavities are coaxial devices operating in the TEM mode and offering a compact solution for acceleration or deflection of particle beams. In a QWR, with length of $\lambda/4$, the inductance in the shorted end fully transforms into a capacitance in the opened end. A QWR is sketched in Fig. 1.

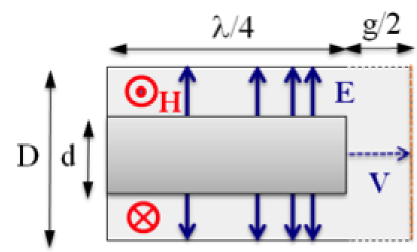

Figure 1: Quarter Wave Resonator (QWR).

The TEM mode operation of the coaxial line is characterized by a radial electric field and an azimuthal magnetic field which amplitude is inversely proportional to the radial coordinate. The peak surface magnetic field H_{peak} in a QWR is located in the inner conductor of the coaxial line, in the shorted end, taking the following value:

$$H_{peak} = \frac{V}{60\pi d \ln (D/d)}, \quad (1)$$

where V is the voltage in the opened end, d is the inner conductor diameter and D is the outer conductor diameter.

A QWR provides a deflecting voltage if the particle beam crosses the cavity in the transverse direction (that is, along the orange line indicated in Fig. 1), but also provides a residual accelerating voltage. The DQW – a symmetrized version of a QWR – does not provide an accelerating voltage to the beam. The deflecting voltage V_t in a DQW cavity is proportional to the voltage V and to the plate length (that is, d) as follows:

$$V_t \approx \frac{d}{g} V, \quad (2)$$

where g is the gap or distance between the two plates. Eq. (2) provides the maximum values that V_t can take, due to the curvature of the field along the beam path [3]. Combining Eq. (1) and Eq. (2), the peak surface magnetic field in a QWR can be written in terms of the required deflecting voltage as:

$$H_{peak} \approx \frac{g}{d^2 \ln (D/d)} V_t. \quad (3)$$

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DQW CRAB CAVITIES FOR eRHIC

Whereas the second beam pipe of LHC imposes tight constraints to the HL-LHC DQW cavity geometry, there is no tight space constraint in eRHIC. Thus, the proton eRHIC crab cavity has a cylindrical body with circular section, what simplifies manufacturing and trim tuning.

On the other hand, the crab cavities in eRHIC must crab the beams in the horizontal plane. This is another difference with respect to HL-LHC, where the current plan is to use the DQW cavities for the vertical kick configuration in IR1. Figure 2 shows a DQW cavity oriented to provide a horizontal crabbing kick. The different kick configuration may require a different solution for the tuning system and the integration of the cavity into the cryomodule. Additional differences between the DQW cavities for HL-LHC and eRHIC are discussed in Ref. [4].

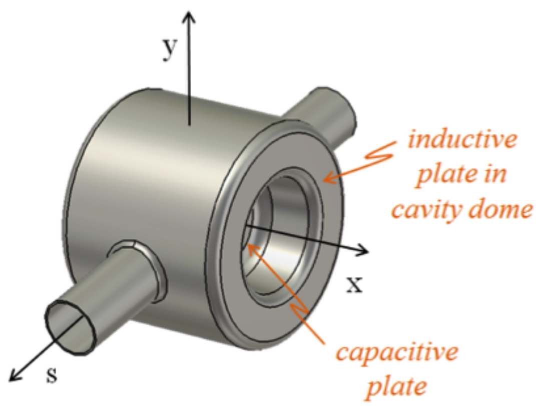

Figure 2: DQW cavity oriented to provide horizontal crabbing kick (x-direction) where s is the beam axis.

FIRST DESIGN OPTIMIZATION

The ultimate operational field of a niobium SRF cavity is limited to about 200 mT before magnetic quench. In addition, high peak surface electric fields may also limit the cavity performance due to field emission. Emitted electrons can impact on the cavity walls, heating the cavity surface and thus increasing the surface resistance, with the consequent increase in dissipated power. These electrons also consume power when accelerated by the electromagnetic field excited in the cavity. The first design optimization of the eRHIC DQW cavities focuses on maximizing the deflecting voltage while minimizing the magnetic and electric peak surface fields. Electric and magnetic field distributions for a typical DQW cavity are shown in Fig. 3. The geometric parameters that define a basic DQW cavity are illustrated in Fig. 4.

Field Optimization

The ratio V_t/H_{peak} in a DQW cavity, given by Eq. (3), finds a maximum for:

$$D/d = e^{1/2} \sim 1.65. \quad (4)$$

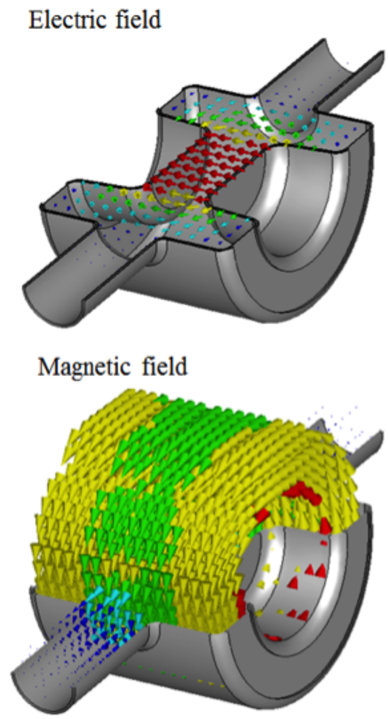

Figure 3: Field distribution in a DQW cavity.

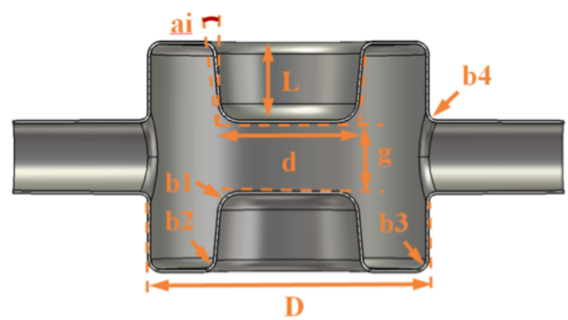

Figure 4: Geometry parameters of a basic DQW cavity.

Then, the ratios V_t/H_{peak} and V_t/E_{peak} were evaluated in CST [5] for DQW cavities with different values of D and d. Every cavity was tuned to 338 MHz by adjusting the inner conductor length L. The distance between capacitive plates g (also known as gap) and beam pipe diameter were 100 mm. Contrary to predicted in Eq. (4), the optimal D/d that maximizes V_t/B_{peak} depends on D, as seen in Fig. 5. However, the expression did not account for the length of the cavity, port opening or blending of the edges.

Cavities with smaller D showed a larger V_t/B_{peak} for the optimal D/d, as seen in Fig. 5. The larger L needed to tune the cavity (to balance the change in inductance) gets closer to $\lambda/4$ (for 338 MHz, $\lambda/4$ is about 0.2 meters). Consequently, the current in the inductive plates of the cavity (related to H_{peak}) is more efficiently transformed in the deflecting voltage V_t between the capacitive plates.

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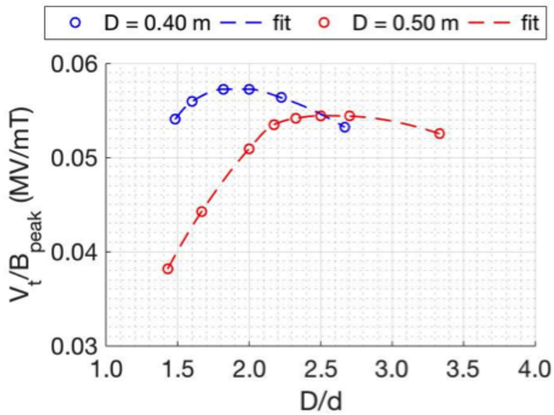

Figure 5: Ratio V_t/B_{peak} for DQW cavities with different values of D and d.

Preliminary Cavity Design

Table 2 summarizes the main characteristics of the preliminary DQW crab cavity design chosen for the eRHIC proton beam. It corresponds to a cavity with D of 400 mm, d of 200 mm and L of 114 mm. A small angle a_i of 5 degrees in the inner conductor wall allowed minimizing H_{peak} further. A sufficiently large radius $b1$ of 30 mm to blend the capacitive plate edges helped reaching larger V_t/E_{peak}.

The cavity design discussed here shows a slightly larger geometry factor than the HL-LHC DQW cavity (104 Ω instead of 87 Ω) and lower peak fields (10.5 m^{-1} and 17.2 mT/MV instead of 11.06 m^{-1} and 21.40 mT/MV). Taking 200 mT as the ultimate magnetic field before quench, the cavity performance would be limited to 11.6 MV.

Table 2: Main Characteristics of the DQW Crab Cavity for the Ring-ring eRHIC Proton Beam

Parameter	**Magnitude**	**Unit**
Crabbing mode frequency	338	MHz
First HOM frequency	520	MHz
Cavity width (horizontal)	328	mm
Cavity height (vertical)	400	mm
Cavity length (along beamaxis)	400	mm
Total volume	0.04	m^3
R_t/Q	364	Ω
Geometry factor	104	Ω
E_{peak}/V_t	10.5	1/m
B_{peak}/V_t	17.2	mT/MV

Choice of Cavity Parameters

The choice of D and d shall consider additional aspects besides the reduction of magnetic and electric peak fields. Firstly, D shall be limited for a reasonable size cavity. The cavity ports (for FPC and HOM dampers) will be opened in the inductive region to facilitate the cavity cleaning. Then, the 'plateau' in the cavity dome, defined by $(D-d)/2$, shall be larger than 75 mm to accommodate wide ports for sufficient HOM extraction.

The cavity frequency can be adjusted by varying the distance between the capacitive plates. Hence d must be large to allow sufficient tuning range but small enough to limit the tuning sensitivity. The frequency decreases approximately 1 MHz when displacing one of the capacitive plates by 1 mm.

In addition, the frequency of the first Higher Order Mode (HOM) shall be as far as possible from the fundamental (operating) mode. In this regard, cavities with larger D will be preferred. Cavities with larger D require shorter L to get in tune, thus leading to a first HOM with higher frequency.

SUMMARY AND OUTLOOK

The main requirements for the cavity were summarized and a first optimization of the design was presented.

The next steps of the cavity design will concentrate in determining the location and design of the cavity ports, followed by the design of input coupler, pickup coupler and HOM filters. Possible multipacting sites will be simulated to identify field regions leading to potentially harmful growth rates. The multipolar components of the cavity will be evaluated and the contribution of the cavities to the impedance budget of eRHIC will be estimated.

Appropriate stiffening must be designed for the cavity as well as the tuning system.

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