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Niobium-coated copper cavities for the eRHIC crabbing system

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Crabbing of hadron bunches in particle colliders requires high kick voltages in the order of MV. The crabbing system of the High Luminosity Large Hadron Collider (HL-LHC) will be using Double-Quarter Wave (DQW) and Radio-Frequency Dipole (RFD) cavities, both compact deflecting cavity designs fabricated from bulk Nb sheets. In the same fashion, the baseline crabbing system for the electron Relativistic Heavy Ion Collider (eRHIC) will consist of a series of DQW cavities. Encouraging cryogenic RF performances of a Nb/Cu Quarter-Wave Resonator (QWR) and the proposal of a niobium-coated copper (Nb/Cu) Wide-Opened Waveguide (WOW) cavity for deflecting purposes stimulated the necessity to review the possibilities of Nb/Cu cavities for the future crabbing system of eRHIC. This note will study the feasibility of using WOW cavities for the eRHIC crabbing system and will compare the expected performances of DQW and WOW cavities based on the latest cryogenic RF results.

I. INTRODUCTION

Bunch crabbing is an essential mechanism to increase luminosity in future particle colliders. The Large Hadron Collider (LHC) will be equipped with crab cavities as a part of its luminosity upgrade (HiLumi LHC project). Two different designs of cavities will be employed. Double-Quarter Wave (DQW) cavities will be used for the crabbing system of the Interaction Point 1 (IP1) and Radio-Frequency Dipole (RFD) cavities for IP5. The cavities operate at 400 MHz in Continuous-Wave (CW) mode [1]. The dissipated power per cavity should be at most 10 W at 4.1 MV deflecting voltage (20% margin above the nominal 3.4 MV) [2]. As result of this low heat load and high field demands, all the cavities are made from bulk Nb sheets. The cavities are immersed in a superfluid helium bath at 2 K for lower BCS resistance and pressure fluctuations. In a similar way, the crabbing system for the electron Relativistic Heavy Ion Collider (eRHIC) will also use DQW cavities made from Nb sheets. In the hadron ring, there will be four cavities per IP per side. Each DQW cryomodule will host two DQW cavities. In the most demanding scenario (275 GeV proton beam with cooling) each cavity is required to deliver a maximum deflecting voltage of 3 MV (11.9 MV out of 4 cavities). The cavities will operate at 338 MHz at 2 K in CW mode [3].

The choice of bulk Nb over niobium-coated copper (Nb/Cu) is mainly driven by the significant quality factor deterioration of the latter with the RF field. Yet, the Nb/Cu cavities present promising features. First, the high thermal conductivity of the Cu substrate ensures a good cooling of the Nb thin film. Such property is important to prevent the thermal runaway in case of large power dissipated by a local surface defect [4]. It also allows thicker substrates that, despite making the cavity more difficult to handle due to its increased weight, will lead to more structurally-stable cavities less sensitive to perturbations during transportation, installation and operation (helium pressure, Lorentz force, microphonics) [5]. Second, given the increased thermal stability provided by the copper substrate, the purity of niobium (RRR) does not need to be maximized to provide good thermal conductivity so its value can be chosen to minimize the BCS resistance [6, 7]. Third, Nb/Cu cavities are less sensitive to magnetic flux, allowing the cavity operation with no magnetic shields [4, 8]. Fourth, high precision machining of bulk copper meets tighter tolerances than forming of niobium sheets, with advantages in terms of tuning and . And last but not least, opting for Nb/Cu cavities reduces raw material costs [9].

Taking on the potential benefits of Nb/Cu cavities, an alternative deflecting cavity is under development at CERN. The so-called Wide-Opened Waveguide (WOW) resonator is a Nb/Cu cavity with reduced trasnverse dimensions and natural damping of Higher-Order Modes (HOM) [10]. In the meantime, a seamless Quarter-Wave Resonator (QWR) for the HIE-ISOLDE (High Intensity and Energy Isotope mass Separator On-Line) facility reached more than 126 mT with a quality factor (Q_0) of 9×10^8 during a cryogenic RF test conducted at 2.3 K in the SRF facility of CERN [11].

In the following we will analyze the feasibility of using WOW cavities for the eRHIC crabbing system and compare the expected performances of DQW and WOW cavities according to the latest cryogenic RF results of the HIE-ISOLDE seamless cavity.

II. DQW CAVITIES FOR THE eRHIC CRABBING SYSTEM

The DQW cavity is a deflecting cavity compact in transverse and longitudinal dimensions. The cavity design was developed to meet the compactness requirements for the HL-LHC crabbing system imposed by the second beam pipe. The DQW cavity also presents the added advantage of procuring the deflecting kick with its fundamental mode [12]. The design is complemented with the development of HOM filters [13].

Several DQW cavities have been designed and tested for the HL-LHC. All of them are bulk Nb cavities. One of the DQW prototypes fabricated by the United States LHC Accelerator Research Program (US LARP) reached a 5.9 MV deflecting voltage before quench. The corresponding mag-

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netic field at that voltage level is about 125 mT [14]. That value is comparable to the field reached by other best performing bulk Nb cavities also following a standard surface treatment based on Buffered Chemical Polishing (BCP) [15–18]. Recent cryogenic RF tests of a DQW prototype with one of its HOM filters demonstrated successful operation beyond 4.1 MV, reaching a maximum deflecting voltage of 4.7 MV limited by quench.

With more relaxed space constraints, the eRHIC DQW cavity geometry takes a much simpler cylindrical shape with circular section and lower peak fields. The latest DQW cavity design for the eRHIC crabbing system (version with no ports other than for the beam) is presented in Ref. [19]. The cavity is depicted in Fig. 1. Geometric and electromagnetic properties of the DQW cavity are listed in Tables I and II, respectively.

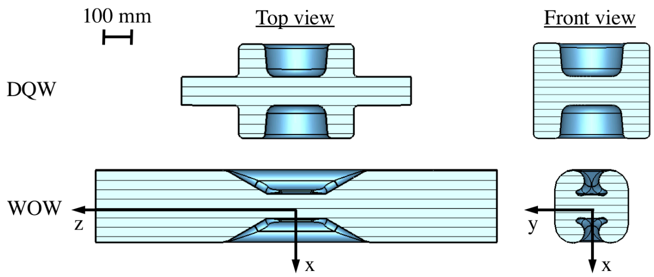

FIG. 1. Views of DQW and WOW cavities operating at 338 MHz with 100 mm-diameter aperture. (Only vacuum volumes displayed.)

TABLE I. General geometry dimensions (wall thickness not considered) of the eRHIC DQW [19] and WOW cavities operating at 338 MHz with 100 mm-diameter aperture in horizontal kick configuration.

	DQW	*WOW*	
Cavity length (along beam axis)	400	1670	mm
Cavity height (vertical)	400	298	mm
Cavity width (horizontal)	328	298	mm
Beam pipe inner diameter	100	100	mm

TABLE II. Electromagnetic properties of the eRHIC DQW [19] and WOW cavities operating at 338 MHz with 100 mm-diameter aperture.

		DQW	*WOW*	
Fundamental frequency	f_0	338	338	MHz
Transverse R/Q (linac definition)	R_t/Q	364	344	Ohm
Geometry factor	G	104	111	Ohm
Max. peak surface magnetic field[a]	B_p	52	84	mT
Max. peak surface electric field[a]	E_p	32	50	MV/m

[a] For nominal deflecting voltage of 3 MV.

III. THE WOW CAVITY

The WOW cavity is a Nb/Cu ridged-waveguide resonator. The cavity has wide-open sides for natural damping of the HOMs and a shape adapted to facilitate the insertion of multiple cathodes for a satisfactory niobium coating of the whole cavity inner surface. The WOW cavity design is discussed in Ref. [5]. The cavity is notably compact in the transverse plane and satisfies the clearance requirements imposed by the second beam pipe of the LHC [20]. A first prototype of this cavity is now being fabricated. The coating system is under development. First cold tests are expected by the end of 2019 [21].

For this study, the cavity presented in Ref. [5] has been scaled to satisfy the requirements of the eRHIC crabbing system: deflecting mode at 338 MHz; 100 mm-diameter aperture. The applied scaling factor is just the ratio between the HL-LHC and eRHIC crab cavity frequencies (400 MHz / 338 MHz ≈ 1.2). Cavity dimensions scale linearly with this scaling factor. The geometric shunt impedance (R/Q) and the geometry factor (G) are independent of the frequency (f). Geometric and electromagnetic properties of this scaled WOW cavity are found in Tables I and II, respectively. The 338 MHz WOW cavity is displayed in Fig. 1 next to the 338 MHz DQW cavity for dimensional comparison.

IV. DISCUSSION

A. Heat load

As a rule of thumb, each watt dissipated into the 2 K bath requires about a kilowatt of cryogenic plant power. Heat loads should be kept under budget for reasonable cryogenic plant capacity and operation cost.

Each eRHIC crab cavity needs to deliver large crabbing kicks of up to 3 MV to the passing bunches, which translates into large surface currents. The high bunch repetition rate (few tens of ns) and the large filling rise time of the cavities (about a ms) requires the cavities to be operated in CW mode. The fast quality factor deterioration with RF field of the Nb/Cu cavities has a severe impact on the heat load, which becomes aggravated by operation in CW mode. Latest test results of a seamless QWR for the HIE-ISOLDE facility show, however, remarkable operation of a Nb/Cu cavity at 2.3 K with low-field Q_0 of about 2×10^9 reaching a maximum field of 126 mT with Q_0 of 9×10^8 [11]. The HIE-ISOLDE QWR parameters can be found in Ref. [22]. Table III summarizes the seamless QWR parameters relevant to this study.

In the frequency range of interest (frequencies lower than 400 MHz) and temperatures of 2.3 K, the BCS resistance is around or below 1 nΩ and the RF surface resistance is typically dominated by the residual surface resistance. For example, the BCS surface resistance (R_{BCS}) is only 0.74 nΩ at 338 MHz and 2 K, in contrast to the typical surface resistances – never smaller than 9 nΩ – found for several RF tests of similar cavity geometries treated following a standard surface treatment [14]. In our following discussion we will:

1) assume that the residual surface resistance is independent on the cavity frequency; 2) disregard the frequency-dependency of the BCS resistance as it is negligible. Under these terms, we can directly extrapolate the results from the seamless QWR to the eRHIC WOW cavity.

Thus, to estimate the power dissipated in the walls of the eRHIC WOW cavity at nominal deflecting voltage of 3 MV, we obtain the expected Q_0 by multiplying the Q_0 of the QWR at 84 mT – the maximum peak surface magnetic field found in the eRHIC WOW cavity at nominal deflecting voltage – ($Q_0 \sim 1.2 \times 10^9$) by the ratio between the eRHIC WOW cavity and the HIE-ISOLDE seamless QWR geometry factors (111 Ω / 30 Ω = 3.7). The dissipated power P_0 is given by:

$$P_0 = \frac{V_t^2}{Q_0 \cdot R_t/Q} \quad (1)$$

where V_t is the deflecting voltage and R_t/Q is the geometric shunt impedance for the deflecting mode. At the nominal deflecting voltage of 3 MV, the eRHIC WOW cavity would dissipate about 7 W, in the same order of magnitude as the heat load of a bulk Nb DQW cavity.

TABLE III. Electromagnetic properties of the seamless QWR for HIE-ISOLDE [22].

Fundamental frequency	f_0	101.28	MHz
Transverse R/Q	R_t/Q	500	Ohm
Geometry factor	G	30	Ohm
Magnetic field over acc. gradient	B_p/E_a	9.3	mT / MV/m
Electric field over acc. gradient	E_p/E_a	5.3	1

B. RF power demand

The loaded Q of the crab cavities (and in turn, the power demand) is mainly driven by the choice of the external Q of the FPC (in the order of 10^6 for both HL-LHC and eRHIC versions [14, 23]). Even if the intrinsic Q (Q_0) decreases to 10^8 levels, still the external Q will define the required power.

C. Integration

The large apertures in the WOW cavity ends need to be terminated with a taper to meet the beam pipe dimensions and reduce the field of the fundamental mode in the pipe. In addition, the WOW cavity requires beam pipe HOM absorbers. The already long WOW cavity plus taper and beam pipe HOM absorbers becomes impractical for the current space reserved for the eRHIC crabbing system. Fig. 2 shows the location of the DQW cryomodules in eRHIC. Out of the four locations of the crab cavity in eRHIC, the shortest site only has 6.9 m in longitudinal direction. A full eRHIC DQW cryomodule equipped with two DQW cavities is shown in Fig. 3. The available space in the hadron ring is tight but sufficient to fit two cryomodules with two DQW cavities each. However, this space would not be enough to host the four WOW cavities required to provide the necessary crabbing kick. One could consider the option of operating the WOW cavities at higher deflecting voltage than nominal, to reduce the number of cavities from 4 to 3. The maximum deflecting voltage could be increased up to 4.5 MV (50% increase), limited by the maximum peak surface magnetic field of 125 mT. Nominal operation at such high voltage would lead to higher head loads as Q_0 degrades with the RF field, critically rely on paramount surface quality and leave no margin for unexpected field degradation. And still, the space would not be enough. Using only 2 WOW cavities to provide the required deflecting voltage would solve this integration issues, but would imply the operation of Nb/Cu cavities at extremely high peak surface fields (190 mT) never demonstrated before.

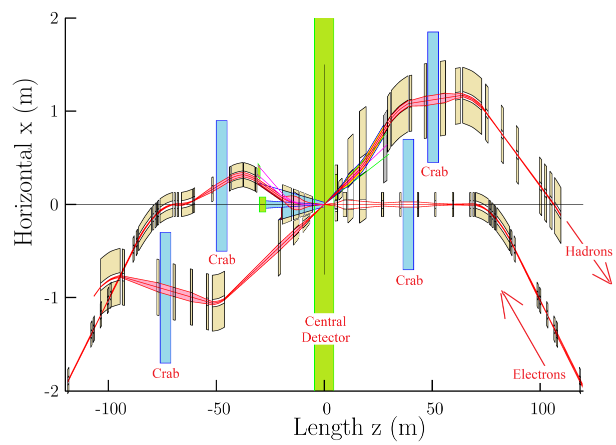

FIG. 2. DQW cryomodule integration in the eRHIC lattice. The cyan rectangles represent the total space occupied by the DQW cryomodules [3].

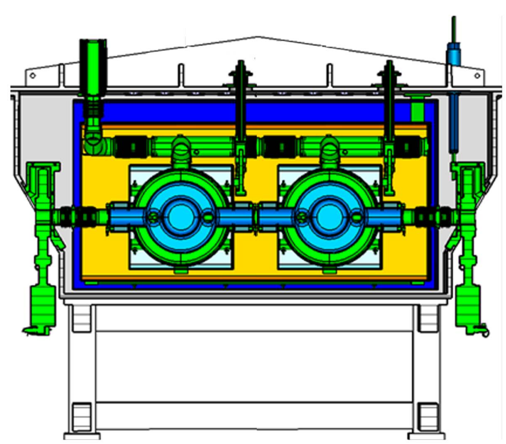

FIG. 3. An eRHIC DQW cryomodule equipped with two DQW cavities (courtesy of D. Holmes; modified accordingly to serve its purpose in this note).

D. Other observations

Despite the large beam pipe aperture in the WOW cavity, the geometric shunt impedance of the deflecting mode (R_t/Q) is very similar for both WOW and DQW cavities. The geometric shunt impedance R_t/Q is given by:

$$\frac{R_t}{Q} = \frac{\omega U}{V_t^2} \tag{2}$$

The deflecting voltage (V_t) is the result of electric and magnetic field contributions:

$$V_t = \int_{-\infty}^{+\infty} \left[E_x(z) \cos\left(\frac{\omega z}{c}\right) - c B_y(z) \sin\left(\frac{\omega z}{c}\right) \right] dz \tag{3}$$

where $E_x(z)$ is the x-component of the electric field along z, $B_y(z)$ is the y-component of the magnetic field along z and ω is the angular frequency. of the operational mode. Fig. 4 shows the electric and magnetic field components along the beam axis (z) that contribute to the deflecting kick in the x direction. The fields are scaled such that the stored energy in the cavities is 1 J. We observe that the field profiles are pretty similar, with the electric field profile peaking at the cavity center and the magnetic field peaking at the start and end of the cavity poles. Due to its large aperture, the width of the magnetic field profile peaks is larger for the WOW cavity. The width of the electric field profile peak is also larger for the WOW cavity as result of the longer, tapered poles [5]. However, the compactness of the DQW compensates this effect because it leads to higher field peaks. In the end, the deflecting voltage provided by both cavities, and in turn, the geometric shunt impedance, are close.

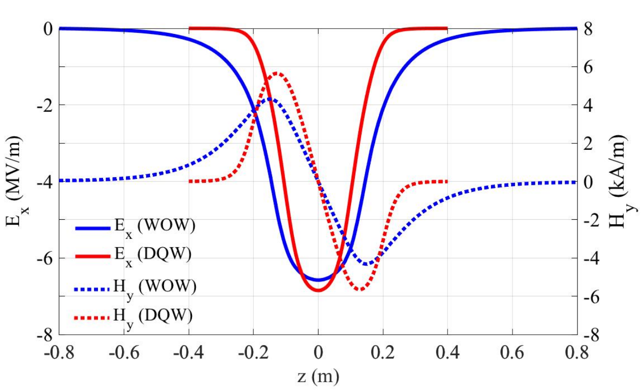

FIG. 4. Electric (E) and magnetic (H) field components along the beam axis ($x = 0, y = 0, z$-direction) contributing to the deflecting kick of DQW (solid) and WOW (dashed) cavities in the x-direction. Fields scaled such that stored energy in the cavities is 1 J.

V. CONCLUSIONS

The advantages of using WOW cavities for the eRHIC crabbing system (better thermal stability, less sensitive to perturbations, simple HOM damping method, etc.) find two main showstoppers related to integration and fabrication.

The main difficulty to adopt this cavity type for the eRHIC crabbing system is related to the amount of space required in the longitudinal dimension. Currently the space available for the eRHIC crabbing system is not sufficient to fit WOW-type cavities. The adoption of the WOW cavities for the eRHIC crabbing system baseline may require revisiting the space allocation in the accelerator lattice.

Another aspect to consider is the required surface quality of the eRHIC WOW cavities, based on state-of-the-art coating and surface treatment techniques which performance has not been proven yet in a cavity of similar geometry. The first WOW prototype will be tested by the end of 2019; the construction phase for eRHIC should commence in 2023 [3].

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