eRHIC CRAB CAVITY CHOICE for RING-RING DESIGN

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Abstract

The future electron ion collider eRHIC adopts large crossing angle (22 mrad) to allow fast separation of two beams in the ring-ring scheme. Crab cavities are required to recover the luminosity from geometric losses. Initial calculation shows that the frequency of the cavities for the ion beam is no more than 338 MHz. In this paper, we discuss the crab cavity related lattice parameters for both ion and electron beams in ring-ring design, the frequency choice, and the cavity design considerations.

INTRODUCTION

The proposed electron-ion collider at Brookhaven National Laboratory (eRHIC), as shown in Figure 1, is designed for high luminosity in the range from 10^{32} to 10^{33} cm^{-2}s^{-1} over a center-of-mass energy range from 30 to 140GeV [1].

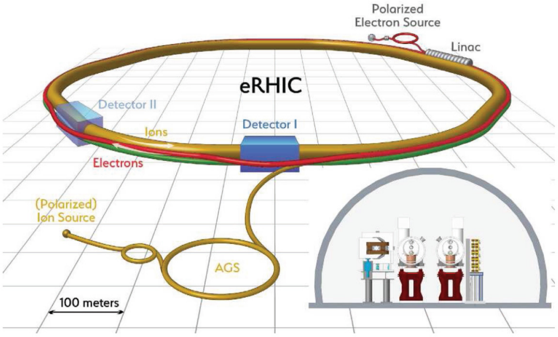

Figure 1: Schematic overview of the eRHIC facility.

To achieve such high luminosity, eRHIC adopted fast separation between the ion and electron beam lines after the interaction point. A careful study took into account the physics objectives of an EIC and constraints on the detector layout [2]. This included issues like separation of the forward hadron beam from neutral particles coming from the IP, synchrotron radiation issues and more. The study established that a separation dipole is incompatible with the physics and detector constraints. Therefore, a crossing angle is the only solution (as is present in all eRHIC designs) and thus, some form of crab cavities must be used to overcome the luminosity penalty introduced by the crossing angle.

Different types of crab cavities have been designed over the past 25 years [3]. In 2007, the High Energy Accelerator Research Organization in Japan for the electron-positron collider (KEKB) demonstrated the first operation of crab cavities in colliders, and a corresponding luminosity increase was observed. The squashed elliptical single cell crab cavity at 509 MHz for KEKB achieved a deflecting voltage of 2.8 MV at 2.8 K [4][5].

For the LHC HiLumi upgrade program, beam studies showed that applying local crabbing at interaction region would boost the luminosity by 70% [3]. The location for crab cavity installation was limited due to existing beamline layouts. In demand for a compact crab cavity, the Double Quarter Wave Crab Cavity (DQWCC) at 400 MHz was designed to provide 3.4 MV at 2 K for vertical crabbing. The proof-of-principle DQWCC successfully reached 4.6 MV at 1.9 K [6], with a dimension much more compact than the KEKB design as shown in Figure 2.

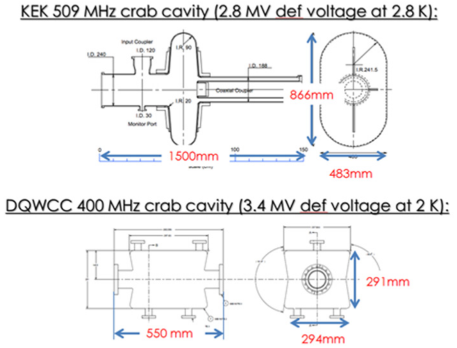

Figure 2: Dimension comparison of the DQWCC and the commissioned crab cavities at KEK.

Two DQWCCs were built at CERN to be tested in the Super Proton Synchrotron (SPS) in 2018. For fabrication and processing studies, two prototypes were built, cleaned, and tested in the US in advance. The bare cavity cryogenic tests of all four cavities reach > 4.5 MV, with field emission onset at 3.2 MV or beyond [7][8]. The current status of the crab cavity development for HiLumi LHC upgrade can be found in Ref. [9].

For eRHIC, lower frequency is required due to more than 30 times larger crossing angle compared to HiLumi LHC. Therefore, the compact size of DQWCC would benefit all aspects, including cost, fabrication, post-processing, installation, and beam dynamics.

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FREQUENCY DETERMINATION

In eRHIC, the bunch length for protons is one order of magnitude longer than that of the electron beam. Therefore, we only need to consider the frequency choice of the crab cavities for ion beam, which can be safely used for electron beam to reduce the number of cavity designs.

The parameters of the ring-ring scheme for eRHIC are listed in Table 1. Any mismatch at the IP between ion and electron bunches will lead to luminosity loss and potential beam dynamics problems due to synchro-betatron resonances. Simulations show that with low crab cavity frequencies, the crab kick fully compensate the geometric loss due to the crossing angle and the transverse deviation caused by crab cavity beam dynamics [10]. The ion bunches are distorted at higher frequencies as shown in Figure 3, and would cause mismatch with the electron bunches.

Table 1: Crab Cavity Related Parameters for Ring-Ring Scheme

	ion	electron
Crossing angle (mrad)	22	
Crab cavity frequency (MHz)	$4n \times 28.15$	
Horizontal beam size at IP (mm)	0.123	0.123
Horizontal transverse tune	0.31	0.08
β_x^* (m)	0.94	0.62
Longitudinal bunch length (cm)	7	0.43
Synchrotron tune	0.01	0.069
Piwinsky angle (rad)	6.3	0.4
Total voltage per side of IP (MV)	13	≤4
Cavity aperture (m)	0.1	≤0.1

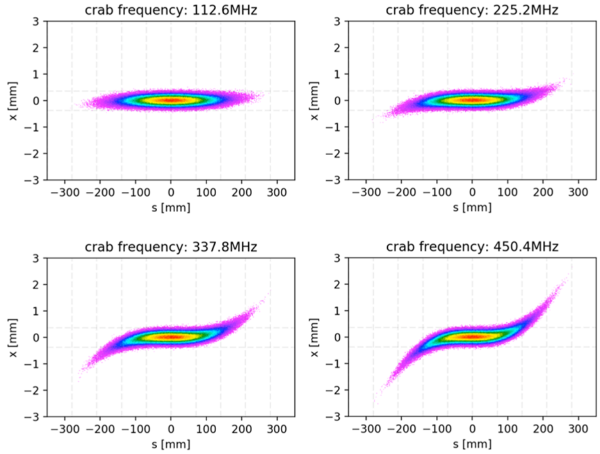

Figure 3: The ion beam tilting effect at IP for various crab cavity frequencies. The interval vertical grid lines correspond to the rms bunch length of the ion beam, and the horizontal grid lines marks the horizontal rms bunch size.

The luminosity calculation and simulation shows the degradation trend with the increase of the cavity frequency as shown in Figure 4. With the criteria of luminosity degrade to be above 90% of the ideal head-on case, the frequency of the crab cavity is set as 337.8 MHz, which corresponds to $n = 3$.

A weak strong simulation with the code Simtrack [11] shows that the luminosity and the rms beamsize of the ion beam do not degrade within 10^6 turns, which confirms we only need to consider the initial frequency choice [10].

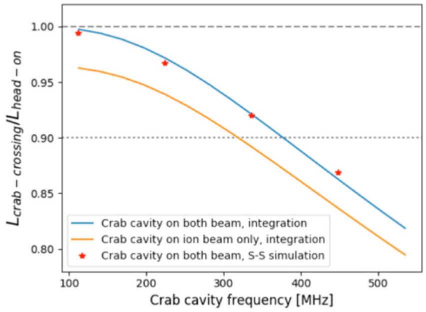

Figure 4: Luminosity degradation as function of crab cavity frequency.

CAVITY DESIGN

Based on the frequency studies above, the DQW type of crab cavity has been optimized for 337.8 MHz. The optimization considered the surface field, deflecting efficiency, latest SRF cavity fabrication capability, post-processing and higher order mode couplings.

The optimized cavity is shown in Figure 5, with the electric and magnetic field illustrated for the fundamental mode. Compared to the LHC, eRHIC does not have strict spacial limit between the beam pipes at the crab cavity location, thus we eliminated the narrow waist in the former cavity design which will lead to even further compactness.

The cavity is designed for horizontal deflection at 337.8 MHz. The cavity radius is 0.16m in the deflecting direction 0.20m in the other transverse direction. The total length of the cavity along beam pipe is 0.40m.

The first higher order mode (HOM) is 200 MHz above the fundamental mode, which facilitate the design of the HOM couplers. More detailed optimization of the cavity can be found in [12].

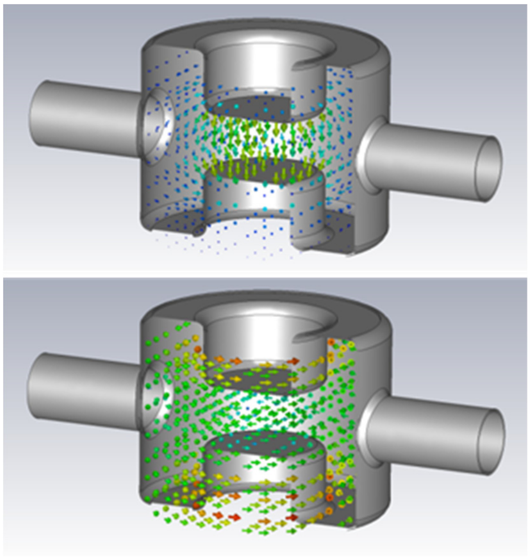

Figure 5: 337.8 MHz DQW crab cavity. Electric field (top) and magnetic field (bottom) of the fundamental mode.

IMPEDANCE STUDIES

The CST Particle Studio [13] calculates the wake field of a cavity with the impedance cut off frequency set to -20dB of the beam spectrum frequency. To evaluate the impedance of the 337.8 MHz crab cavity for eRHIC, a proton bunch of rms 7 cm with 17.76nC was used to excite the wake field.

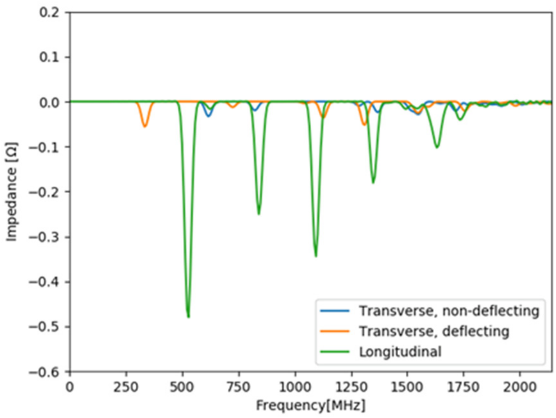

Figure 6: Wake impedance of the crab cavity in all three directions. The transverse impedance is evaluated with the heading beam having an offset of 1cm in the evaluated direction.

The impedances of all three directions are shown in Figure 6. The wake impedance Ω_k is defined as:

$$\Omega_k = W_k/I_k$$

where W_k is the wake field excited by the heading bunch, and I_k is the current. The negative sign indicating that the beam loses energy in all excited cavity modes due to wake impedance.

The loss factors of the cavity are shown in Fig. 7. For single bunch results, the loss factors, all above 0.01 V/pC, are not negligible with the cumulative longitudinal loss factor even close to 0.1 V/pC. This may lead to high HOM power excited in the cavity during operation. Further studies with beam spectrum are necessary to avoid beam instability from HOMs or high power extraction from HOM couplers.

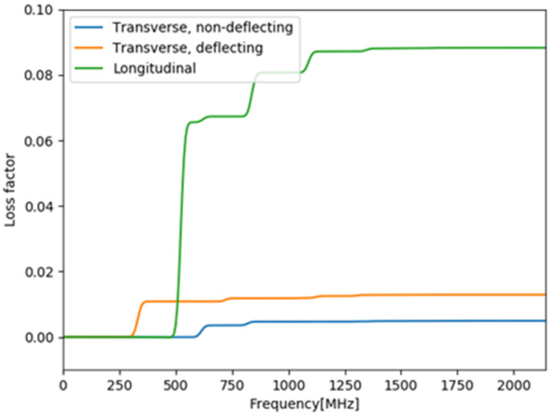

Figure 7: Cavity impedance and the loss factor of single ion bunch of 7 cm and electron bunch of 0.43cm.

CONCLUSION

The DQWCC cavity has been designed for the LHC HiLumi upgrade. Four cavities have been fabricated from the design for the SPS beam test, and all have reached high above the required deflecting voltage. The same type of cavity design is adopted for the eRHIC ring-ring scheme at 337.8 MHz. The cavity has been optimized based on the surface field and fabrication technique to fulfil the goal of delivering a high deflecting voltage above 4 MV per cavity with large safety margin. Wake field has been calculated for the cavity for impedance analysis. The higher order mode damping would be the next step in the design.

REFERENCES

[1] C. Montag *et al.*, “Overview of the eRHIC ring-ring design”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May 2017, paper WEPIK049, pp. 3035-3037.

[2] E. C. Aschenauer, A. Kiselev, B. Parker, and R. Petti, “Issues of Incompatibility of Dipole Beam Separation Schemes with EIC Physics”, in *eRHIC Note 49*, November 17, 2015, http://public.bnl.gov/docs/cad/Pages/Home.aspx/.

[3] Q. Wu, “Crab cavities: Past, present, and future of a challenging device”, invited talk Presented at *the 6th International Particle Accelerator Conference (IPAC’15)*, Richmond, VA, USA May 3 – 8, 2015.

[4] T. Abe *et al.*, “Beam Operation with Crab Cavities at KEKB”, Proceedings of PAC07, paper MOZAKI01, Albuquerque, NM, USA, 2007, pp. 27-31.

[5] K. Akai *et al.*, “Commissioning and Beam Operation of KEKB Crab-RF System”, 13th Workshop on RF Superconductivity, Beijing, China, Oct. 2007, pp. 632-636.

[6] B. P. Xiao *et al.*, “Design, Prototyping and Testing of a Compact Superconducting Double Quarter Wave Crab Cavity”, Phys. Rev. ST Accel. Beams **18**, 041004 (2015).

[7] Q. Wu, "Result Analysis and Next Steps for US-DQW Cavities", *Joint LARP CM28/HiLumi Meeting*, Napa Valley, CA, USA, 2017.

[8] A. Castilla, "CERN Cavity Results", *Joint LARP CM28/HiLumi Meeting*, Napa Valley, CA, USA, 2017.

[9] R. Calaga *et al.*, Crab Cavity for the HiLumi LHC, presented at SRF2017, Lanzhou, China, paper THXA03, this conference.

[10] Y. Hao *et al.*, "Frequency Choice Studies of eRHIC Crab Cavity", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, paper WEPIK049, pp. 3028-3030.

[11] Y. Luo, "SimTrack: A compact C++ code for particle orbit and spin tracking in accelerators", *Nucl. Instr. Meth. in Phys. Res. A, vol. 801*, pp. 95–103, 2015.

[12] S. Verdu-Andres, I. Ben-Zvi, Q, Wu， and B. P. Xiao, "eRHIC MHZ crab cavity design for the eRHIC hadron beam", presented at SRF2017, Lanzhou, China, paper TUPB001, this conference.

[13] CST Particle Studio 2015.