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DESIGN OF AN RF-DIPOLE CRABBING CAVITY SYSTEM FOR THE ELECTRON-ION COLLIDER*

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Abstract

The Electron-Ion Collider requires several crabbing systems to facilitate head-on collisions between electron and proton beams in increasing the luminosity at the interaction point. One of the critical rf systems is the 197 MHz crabbing system that will be used in crabbing the proton beam. Many factors such as the low operating frequency, large transverse voltage requirement, tight longitudinal and transverse impedance thresholds, and limited beam line space makes the crabbing cavity design challenging. The rf-dipole cavity design is considered as one of the crabbing cavity options for the 197 MHz crabbing system. The cavity is designed including the HOM couplers, FPC and other ancillaries. This paper presents the detailed electromagnetic design, mechanical analysis, and conceptual cryomodule design of the crabbing system.

INTRODUCTION

The Electron-Ion Collider (EIC) is the next high energy collider that will be built at Brookhaven National Laboratory under the DOE Nuclear Physics program [1]. The EIC collides electrons with heavy ions at a range of center of mass energies from 20 to 140 GeV. The target high luminosities up to 10^{34} $cm^{-2}s^{-1}$ require head on collisions between bunches therefore, crabbing systems will be installed at the interaction region (IR) in each beam line.

EIC Crabbing Systems

EIC requires several crabbing rf systems on both Hadron Storage Ring (HSR) and Electron Storage Ring (ESR) [2]. Table 1 lists the transverse voltage (V_t) and no. of cavities per IR required by each system. The crabbing system for HSR is identified as one of the critical rf systems in EIC [2, 3].

Table 1: Crabbing Systems of EIC

	V_t [MV]		No. of cavities	
System	**HSR**	**ESR**	**HSR**	**ESR**
197 MHz	33.83	–	4	–
394 MHz	4.75	2.90	2	1

The nominal operating V_t for 197 MHz system in HSR is 8.5 MV with a maximum V_t of 11.5 MV per cavity. For the system in ESR, the maximum V_t is 3.5 MV per cavity. Two crabbing designs were considered for the EIC which are the Double Quarter Wave design (DQW) [4] and RF-Dipole design (RFD) [5, 6]. In this paper the RFD cavity design is presented which is designed for the HSR 197 MHz system.

197 MHz RFD CRABBING CAVITY

The HSR 197 MHz RFD crabbing cavity shown in Fig. 1 is designed to meet the following specifications [2].

- $E_p \leq 45$ MV/m and $B_p \leq 80$ mT
- Cavity length: Flange to flange cavity length < 150 cm
- Diameter with HOMs < 91 cm
- Bare cavity diameter without HOM < 70 cm

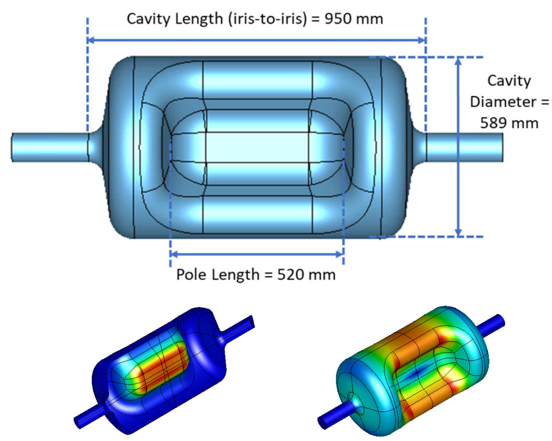

Figure 1: 197 MHz RFD cavity geometry (top), surface electric field (bottom-left) and surface magnetic field (bottom-right).

The rf-properties of the RFD cavity design are listed in Table 2.

Table 2: RF Properties of the 197 MHz RFD Cavity

Property	**V_t [MV]**		**Unit**
E_p/E_t^*	2.97		
B_p/E_t^*	5.27		[mT/(MV/m)]
G	99.8		[Ω]
R/Q	1106.0		[Ω]
R_tR_s	1.10×10^5		[$Ω^2$]
V_t per cavity	8.5	11.5	[MV]
E_p	33.2	44.9	[MV/m]
B_p	58.8	79.6	[mT]
Total V_t	34		[MV]
No. of cavities	4	3	

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HIGHER ORDER MODE DAMPERS

The impedance thresholds for the 197 MHz crabbing cavity system are longitudinal impedance of 3.75×10^3 Ω and transverse impedance of 1.35×10^6 Ω/m [2]. The RFD cavity is designed with two higher order mode (HOM) dampers as shown in Fig. 2, which are broadband waveguide type couplers. The waveguides on the end plates of the cavity in horizontal (HHOM) and vertical (VHOM) orientations to suppress the modes up to 2 GHz including the monopole modes and dipole modes in both transverse directions. The waveguide is attached to the cavity with a dogbone style waveguide stub that transitions into a rectangular waveguide [7]. The dogbone shape is a compact waveguide design that allows low cut off frequency. The 1st HOM of the RFD cavity is 350 MHz and the dogbone cut off frequency is 348 MHz. Figure 3 shows the impedances following the circuit definition calculated from the method described in Ref. [8]. All the modes up to 2 GHz are well damped below the thresholds. The impedances are calculated with ideal loads and will be reoptimized with real load parameters.

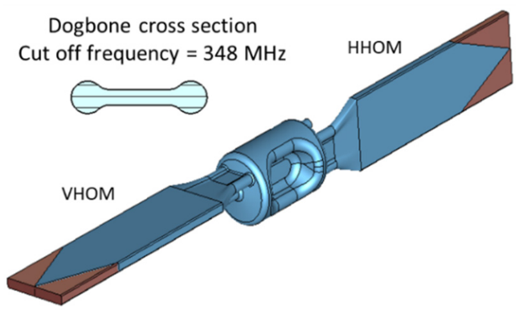

Figure 2: HOM dampers of the 197 MHz RFD cavity.

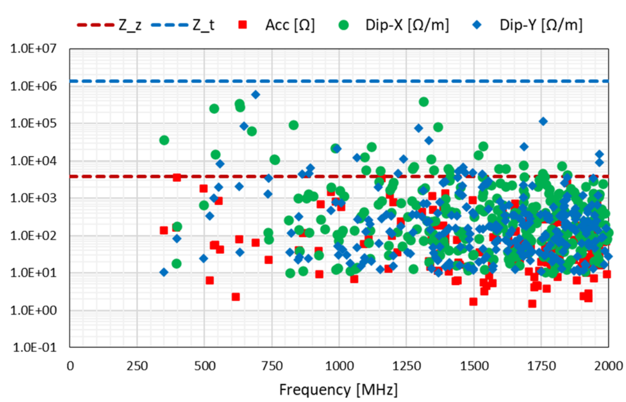

Figure 3: HOM impedances of the 197 MHz RFD cavity.

Beam Induced HOM Power

The EIC has several bunch filling schemes and the two important schemes used in estimating the beam power are listed below.

- 1160 buckets on with 100 buckets off at 98.52 MHz bunch repetition rate
- 290 buckets on with 25 buckets off at 24.63 MHz bunch repetition rate

The HOM power induced by the two beam patterns for a beam current of 1 A and a bunch length (σ_z) of 60 mm are shown in Fig. 4. The worst-case scenario that leads to higher induced beam power is from the bunch pattern with 290 buckets on with 25 buckets off.

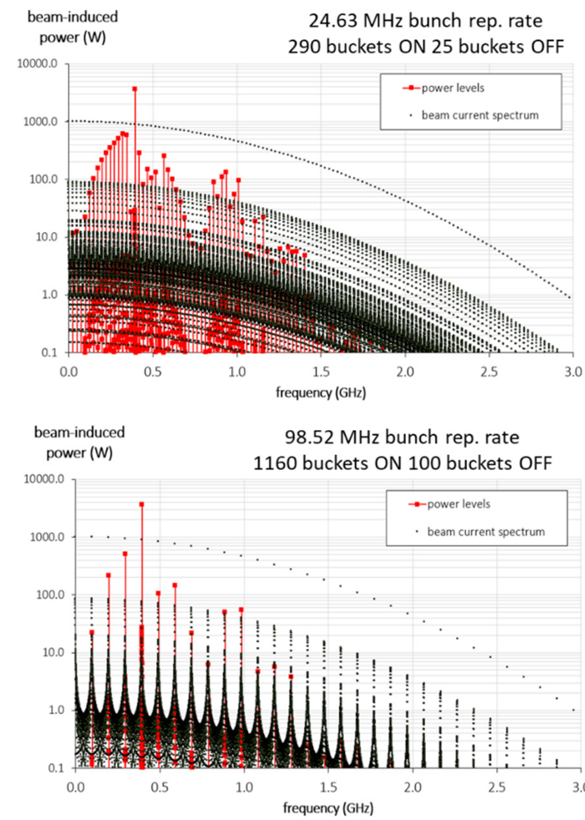

Figure 4: Induced HOM beam power of the 197 MHz RFD cavity for the two bunch filling schemes.

The accumulated beam power is shown in Fig. 5 for all the EIC bunch filling schemes and the beam power estimates are listed in Table 3. The beam power induced by the transverse modes are estimated at a beam offset of 1 cm and the contribution is less than 150 W. Figure 5 clearly shows that the mode at 394 MHz dominates the accumulated HOM power. The estimated maximum HOM power is about 10 kW.

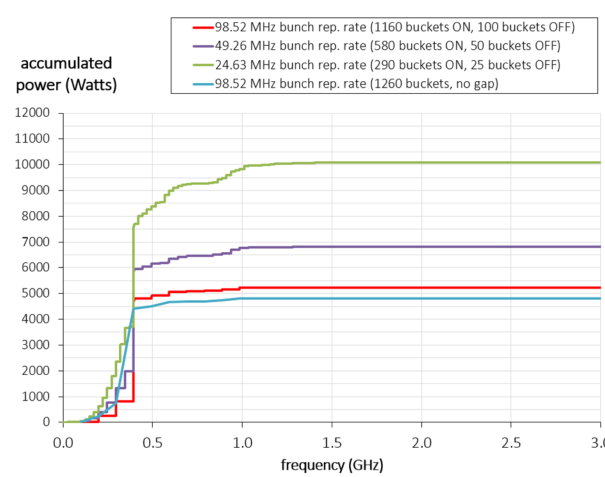

Figure 5: Accumulated HOM beam power of the 197 MHz RFD cavity.

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Table 3: Accumulated HOM Beam Power

Bunch Filling Scheme	Accumulated Beam Power [kW]
1160 buckets ON 100 buckets OFF	5.5
290 buckets ON 25 buckets OFF	10
1260 buckets ON No gaps	4.8

FUNDAMENTAL POWER COUPLER

The fundamental power coupler (FPC) for the EIC crabbing system requires a Q_{ext} of 3×10^6 at a beam off set of 0.5 mm as shown in Fig. 6.

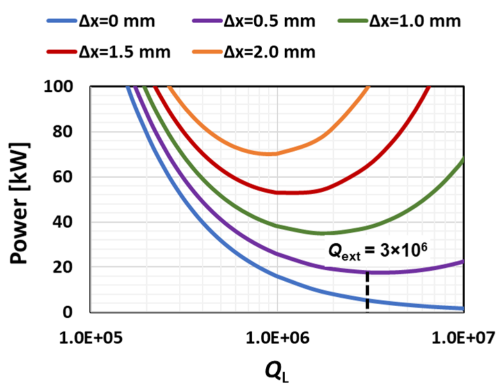

Figure 6: Input power as a function of beam off set for the EIC 197 MHz crabbing system.

The FPC for the 197 MHz RFD crabbing cavity is designed as a horizontal coupler with a coaxial antenna as shown in Fig. 7. The coaxial antenna has rf losses of 56 W at nominal operating voltage of 8.5 MV. The field antenna is designed horizontally with a coupling of $\sim10^{11}$.

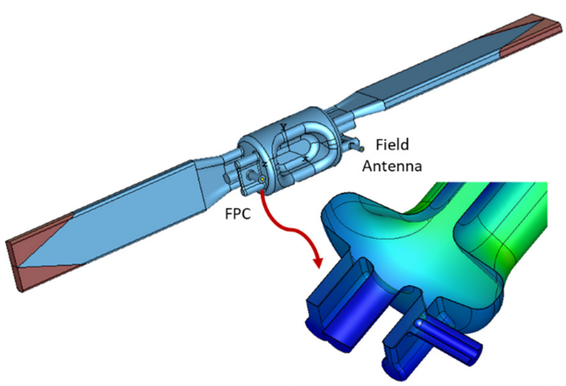

Figure 7: FPC and field antenna designs of the 197 MHz crabbing system.

MECHANICAL ANALYSIS

Preliminary mechanical analysis carried out on the 197 MHz RFD cavity (Fig. 8) shows that cavity center body requires a thickness of 4 mm with end plates with a thickness of 5 mm to maintain the stress limits within 50 MPa.

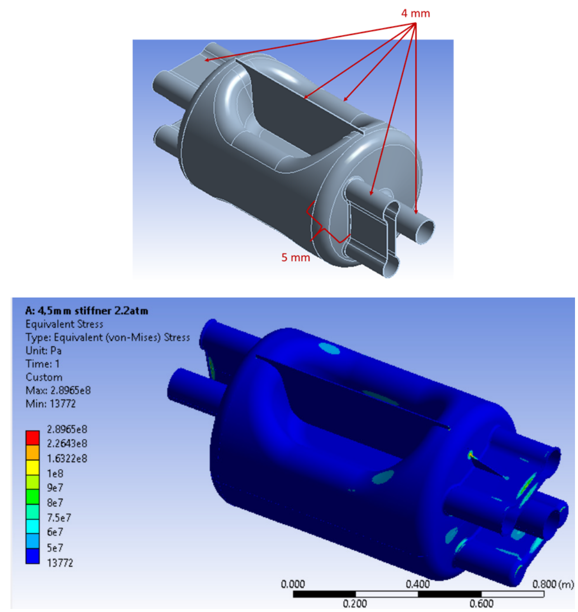

Figure 8: Cavity thickness (top) and equivalent stress (bottom) of the 197 MHz RFD cavity.

Conceptual Cryomodule Design

The conceptual cryomodule scheme (Fig. 9) shows the two 197 MHz crabbing cavities per cryomodule with curved waveguides leading to a compact cryomodule. Two 197 MHz cryomodules with a single 2-cavity 394 MHz cryomodule fit in the beam line space allocated for the crabbing system in the HSR. Detailed cryomodule design including the tuner concept is on-going.

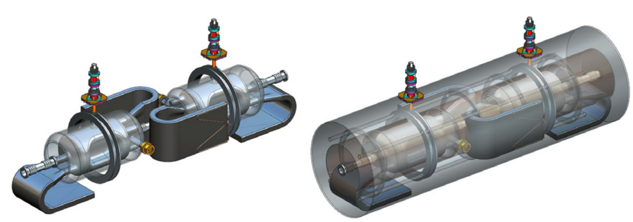

Figure 9: Conceptual cryomodule design of the 197 MHz RFD crabbing system.

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CONCLUSION

The crabbing system is one of the critical components of the EIC. The low frequency, low impedance thresholds and limited available space make the design of the 197 MHz for the HSR particularly challenging. We have presented here a preliminary design that meets all the rf and mechanical requirements. Following the down-selection of the RFD as the cavity design for the 197 MHz system and as the primary option for the 394 MHz system, further optimization and finalization of the design is undertaken as a close collaboration between ODU, JLab, BNL, and SLAC.

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