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197 MHz WAVEGUIDE LOADED CRABBING CAVITY DESIGN FOR THE ELECTRON-ION COLLIDER*

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Abstract

The Electron-Ion Collider will require crabbing systems at both hadron and electron storage rings in order to reach the desired luminosity goal. The 197 MHz crab cavity system is one of the critical rf systems of the collider. The crab cavity, based on the rf-dipole design, explores the option of waveguide load damping to suppress the higher order modes and meet the tight impedance specifications. The cavity is designed with compact dogbone waveguides with transitions to rectangular waveguides and waveguide loads. This paper presents the compact 197 MHz crab cavity design with waveguide damping and other ancillaries.

INTRODUCTION

The Electron-Ion Collider (EIC) is designed to collide electron and protons with center of mass energies varying from 20 to 100 GeV with possible upgrade to 140 GeV [1]. The goal for electron-proton luminosity is ~10^{34} cm^{-2} s^{-1}. EIC will be operating with a primary interaction region (IR) at IR6 and a second interaction region at IR8 planned in the upgrade of the machine as shown in Fig. 1.

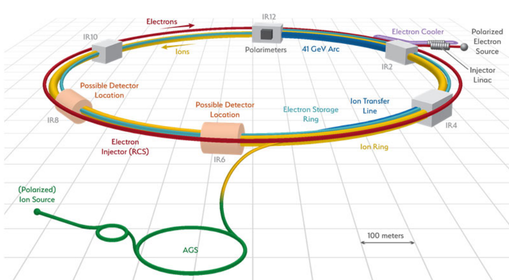

Figure 1: Layout of the Electron-Ion Collider.

Crabbing systems will be installed at both hadron storage ring (HSR) and electron storage ring (ESR) to achieve the required luminosity levelling.

- HSR → 197 MHz and 394 MHz cavity systems
- ESR → 394 MHz cavity system

The large crossing angle of 25 mrad requires higher transverse voltage in cancelling the effect due to Piwinski angle [2]. The transverse voltage requirements for the IR6 are listed in Table 1.

The 197 MHz crabbing cavity is one of the critical components identified among the EIC rf systems that will be prototyped first along with the 591 MHz single-cell cavity.

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Table 1: Total Transverse Voltage and Number of Cavities

System	HSR	ESR
197 MHz	33.83 MV	–
394 MHz	4.75 MV	2.90 MV
197 MHz	8	–
394 MHz	4	2

The system requirements for the 197 MHz crabbing cavity are listed below.

- Nominal transverse voltage per cavity = 8.5 MV
- Maximum transverse voltage per cavity = 11.5 MV
- Peak fields at 11.5 MV: E_p < 45 MV/m & B_p < 80 mT
- Impedance thresholds per cavity (considering simultaneous operation of both interaction regions):
  - Longitudinal < 10 kΩ
  - Transverse-H < 0.132 MΩ
  - Transverse-V < 0.66 MΩ
- Dimensional constraints:
  - Beam pipe aperture = 100 mm
  - Cavity length (flange-to-flange) < 1.5 m
  - Beam line space per side for HSR < 12.5 m

197 MHz CRABBING CAVITY DESIGN

Both 197 MHz and 394 MHz crabbing cavities are based on the rf-dipole design [3]. The 197 MHz crabbing cavity design includes two HOM dampers, the fundamental power coupler (FPC) and pick up as shown in Fig. 2. The length of the bare cavity is 1.5 m and 0.6 m in diameter. The poles in the cavity were optimized to achieve a balance peak field of 1.78 mT/(MV/m). The optimized pole length is 524 mm with a pole height of 240 mm. The rf-properties of the 197 MHz crabbing cavity are listed in Table 2.

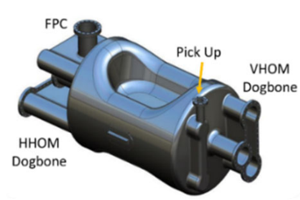

Figure 2: 197 MHz crabbing cavity.

The cavity is designed with four identical dogbone-shaped waveguides to maintain the field symmetry to a feasible extent. However, different dogbone waveguide lengths still contribute to the field asymmetry further enhanced by the FPC. The impact on the dynamic aperture

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due to the higher order multiple components are being analysed [4]. The dogbone waveguides in the horizontal orientation propagate the fundamental mode whereas the dogbone waveguides in the vertical orientation do not couple to the fundamental mode. Therefore, one of the horizontal waveguides is selected for the FPC and a vertical waveguide is used to place the pickup.

Table 2: RF Properties

Property	Value	Unit
Nearest HOM	336.0	MHz
E_p^* (at E_t^* = 1.0 MV/m)	2.94	MV/m
B_p^* (at E_t^* = 1.0 MV/m)	5.24	mT
$[R/Q]_t$	1137.8	Ω
G	379.2	Ω
R_tR_s	4.3×10^5	Ω^2
E_p (at V_t = 11.5 MV)	44.43	MV/m
B_p (at V_t = 11.5 MV)	79.25	mT

The current FPC is a coaxial antenna through electric field as shown in Fig. 3. The FPC port is placed closer to the cavity to get adequate coupling as electric field drops to zero at the shorted dogbone end. The FPC is designed to a coupling of 1.75×10^6 assuming a beam off-set of 0.6 mm with a frequency shift of 50 Hz due to microphonics. The resultant rf heating at the tip of the antenna is 270 W. The FPC is expected to deliver about 60 kW in operation. The pickup coupler is designed to extract about 1 W of the fundamental operating mode.

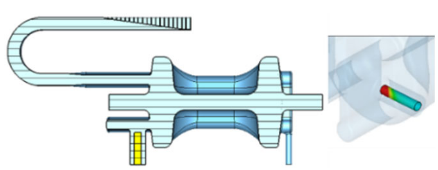

Figure 3: FPC coaxial antenna and the rf heating of the 197 MHz crabbing cavity.

WAVEGUIDE LOADED HOM DAMERS

The 197 MHz crabbing cavity is designed with two HOM couplers: Horizontal-HOM (HHOM) and Vertical-HOM (VHOM) dampers to suppress HOMs up to 2.0 GHz as shown in Fig. 4 (left).

Two damping schemes are currently being studied for the 197 MHz crabbing cavity: waveguide-loaded dampers [5], which is the baseline design, and the design with coaxial couplers [6]. Both schemes attach the HOM dampers to the cavity through dogbone-shaped waveguides. The crabbing cavity with coaxial couplers transitions to three identical coaxial couplers placed on the dogbone waveguides as shown in Fig. 4 (right). Both schemes meet the impedance requirements for the HOMs up to 2.0 GHz. Further analysis will be carried out including mechanical analysis and the final scheme will be selected following a fabrication and a cost evaluation.

The 197 MHz crabbing cavity uses compact dogbone-shaped waveguides to allow effective HOM propagation [7]. The dogbone-shaped waveguide allows fitting waveguides on the end caps of the cavity where a standard rectangular waveguide would not fit. The dogbone waveguide is designed with a cut off frequency as low as 347 MHz to allow propagation of all the HOMs.

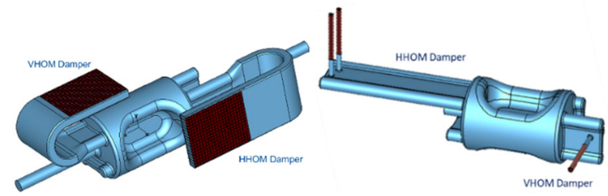

Figure 4: 197 MHz crabbing cavity with waveguide loaded HOM dampers (left) and crabbing cavity with coaxial couplers (right).

The dogbone waveguides are transitioned to rectangular waveguides following a tapered section as shown in Fig. 4. The bare cavity design is identical for both damping schemes. The dogbone flanges of the cavity will be fabricated out of Nb and sealed with indium, and the circular flanges will be SS 316LN conflat flanges sealed with Cu gaskets. The lengths of the dogbone waveguides in the bare cavity are chosen to maintain an rf field at the flange interface below 2.5 mT at 11.5 MV. Since the HHOM waveguide propagates the fundamental mode further, the HHOM dogbone length is longer than the VHOM dogbone. The overall length of the HHOM waveguide is adjusted to minimize the fundamental power seen by the load and the current design value is 100 W.

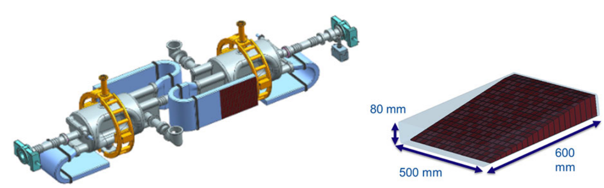

Figure 5: Layout of two 197 MHz crabbing cavities in cryomodule (left) and HOM waveguide load (right).

The waveguides are bent and folded around the cavity allowing space for the tuner. Figure 5 shows the compact layout of two 197 MHz crabbing cavities in a cryomodule placed in 180 rotations to minimize the beam line space.

HOM Load Design

The waveguide loaded cavity is designed with real HOM loads as shown in Fig. 5. The HOM load is a rectangular waveguide design with ramped tiles consisting of 17×20 rows. The tiles are 1” sized separated with a 0.1” gap. The tiles are designed of *AlN-SiC* composite material (STL-100) from Sienna Technologies Inc. [8]. The tiles will be water cooled and the loads are placed on the cavity allowing easy anchoring and cooling by placing the mounting board facing the vacuum vessel in the cryomodule. The S_{11} at the load start face are shown in Fig. 6 and has good absorption for all the HOMs.

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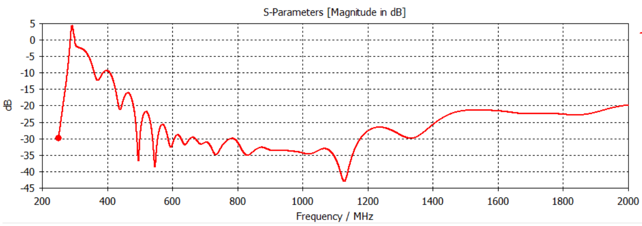

Figure 6: S_{11} at the entrance of the waveguide load.

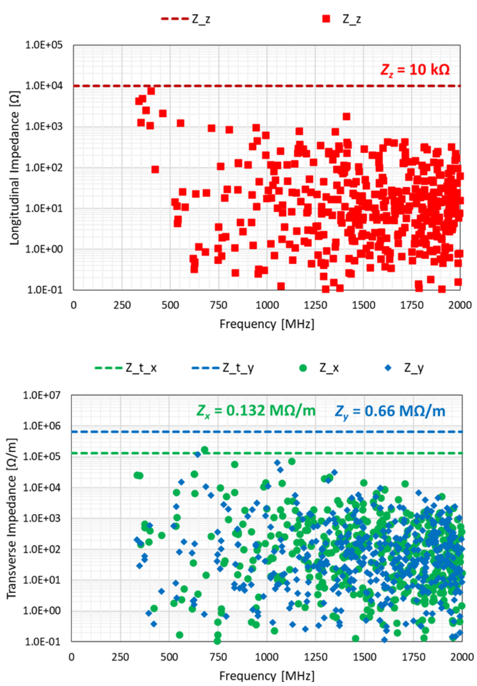

Figure 7: Longitudinal (top) and transverse (bottom) impedances up to 2.0 GHz.

HOM Impedances

The corresponding longitudinal and transverse impedances are shown in Fig. 7. The impedances are in circuit definition and includes the 0.5 factor. The HOM impedances meet the impedance thresholds except in a single mode. The maximum longitudinal impedance is 7.6 kΩ at 398.9 MHz. The 679 MHz mode has an impedance of 0.176 MΩ with a Q_{ext} of 821 and slightly exceeds the horizontal impedance threshold of 0.132 MΩ. Further optimization will be done to damp this mode below threshold.

HOM Power

Two beam filling schemes reaching a bunch length of $\sigma_z = 6$ mm were evaluated in determining the HOM power.

- 1160 bunches at 1.0 A
- 290 bunches at 0.74 A

The HOM power is estimated for both longitudinal (P_z) and transverse (P_t) modes assuming a frequency variation of ±0.2% as shown in Fig. 8. The total HOM powers are listed in Table 3. The HOM power for the transverse modes is estimated at a beam off set of 1 mm.

Table 3: HOM Power

Filling Scheme	P_z	P_t	Total P
1160 bunches	2.91 kW	156 W	3.07 kW
290 bunches	3.00 kW	258 W	3.26 kW

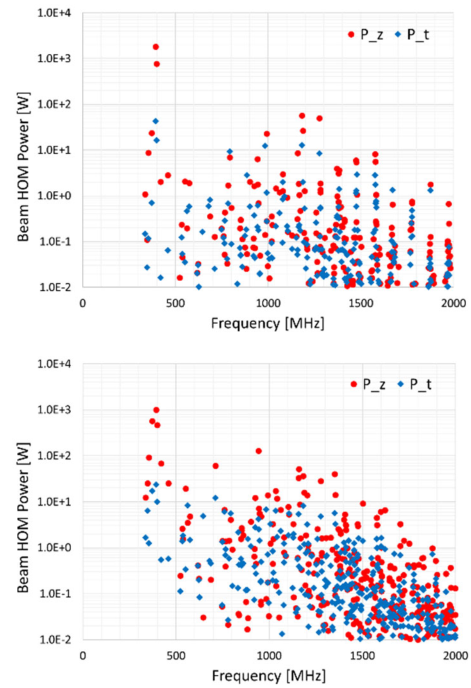

Figure 8: HOM power for filling schemes with 1160 bunches (top) and 290 bunches (bottom).

The total HOM power for both filling schemes are comparable. The worst-case scenario is from the filling scheme of 290 bunches at 0.74 A where the total HOM power is 3.26 kW. The largest HOM power is due to longitudinal modes at 372.8 MHz, 393.7 MHz, and 398.8 MHz. In the 1160 bunches filling scheme the largest HOM power is contributed by two longitudinal modes at 393.7 MHz and 398.8 MHz with an accumulated HOM power of 2.58 kW.

CONCLUSION

The 197 MHz crabbing system is one of the critical rf systems in the EIC. Currently two HOM damping schemes of waveguide loaded dampers and coaxial couplers have been analysed. The scheme with waveguide loaded dampers effectively suppress the HOMs up to 2.0 GHz. Further optimization will be done to minimize the impedance of the mode at 679 MHz. The total HOM power for both bunch filling schemes are comparable and can be easily handled by the HOM loads. HOM load designs with reduced number of tiles and low-cost load materials will be assessed. Currently detailed mechanical analysis is ongoing along with determining the fabrication sequence to fabricate a prototype cavity.

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