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DESIGN OF A PROOF-OF-PRINCIPLE CRABBING CAVITY FOR THE JEFFERSON LAB ELECTRON-ION COLLIDER*

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Abstract

The Jefferson Lab design for an electron-ion collider (JLEIC) requires crabbing of the electron and ion beams in order to achieve the design luminosity. The Center for Accelerator Science at Old Dominion University has designed, fabricated and successfully tested a crab cavity in 2012 under very early machine design [1-3]. The JLEIC machine design and parameters have matured over a couple of years. The crab cavity design has also evolved to provide the best crabbing option. A number of options for the crabbing cavities have been explored [4, 5], and the one which has been selected for the proof-of-principle is a 952.6 MHz, two-cell rf-dipole (RFD) cavity. This paper summarizes the electromagnetic design of the cavity and its HOM characteristics.

JLEIC LAYOUT AND PARAMETERS

Jefferson Lab proposes to build an electron-ion collider (EIC) facility called Jefferson Lab Electron-Ion Collider (JLEIC), having a peak luminosity over 10^{34} cm^{-2} s^{-1}, and a collider center of mass energy range ~20 to ~100 GeV upgradeable to ~140 GeV. The JLEIC ion ring is based on an innovative figure-8 synchrotron design as shown in Fig. 1. JLEIC maximally leverages the existing CEBAF capability for production of polarized electron beams. Figure 1 also shows a local crabbing scheme which is a crucial part of JLEIC design to achieve the high luminosity [6].

Required crabbing transverse voltage is determined by the following equation [7].

$$V_t = \frac{cE_b \tan\left(\frac{\varphi_{crab}}{2}\right)}{2\pi f_{rf}\sqrt{\beta_x^* \beta_x^c}} \tag{1}$$

The beam parameters of highest energy case are listed in Table 1.

CRAB CAVITY DESIGN

Design Optimization

Several rf geometries of crabbing cavities with different shapes and operating frequencies have been evaluated as shown in Fig. 2 [5]. Dimensional constraints and design requirements related to peak surface fields, impedance threshold, higher multipole components, higher order mode management, and an aspect of fabrication were taken into consideration in designing the crabbing cavity geometry. After comparison, a 952.6 MHz two-cell RFD crabbing cavity was chosen with anticipation of upgrade.

Figure 3 shows the geometry of the final cavity design and Table 2 summarizes its rf properties at its highest energy of each beam.

Table 1: Beam Parameters [6]

Parameter	Unit	Electron	Proton
Frequency, f_{rf}	MHz	952.6	
Crossing angle, φ_{crab}	mrad	50	
Beam energy, E_b	GeV	12	200
Beam current	A	0.39	0.75
Betatron function at IP, β_x^*	cm	6.6	2.1
Betatron function at crab cavity, β_x^c	m	200	650
Total crabbing voltage per side per beam	MV	4.2	21.5

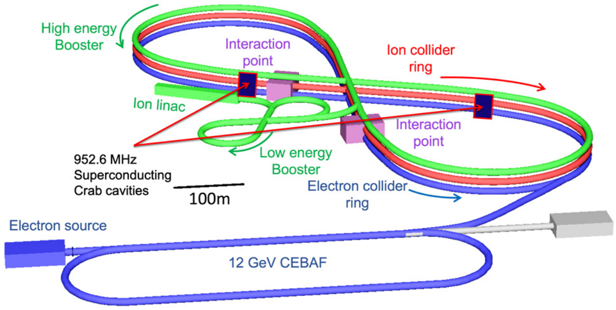

Figure 1: JLEIC machine layout.

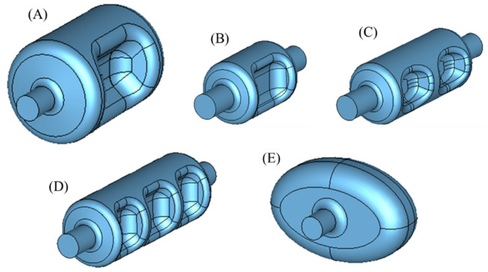

Figure 2: Crabbing cavity geometries considered for JLEIC. (A) 476.3 MHz Single Cell RFD Cavity, (B) 952.6 MHz Single Cell RFD Cavity, (C) 952.6 MHz 2-Cell RFD Cavity, (D) 952.6 MHz 3-Cell RFD Cavity, and (E) 952.6 MHz Squashed Elliptical Cavity.

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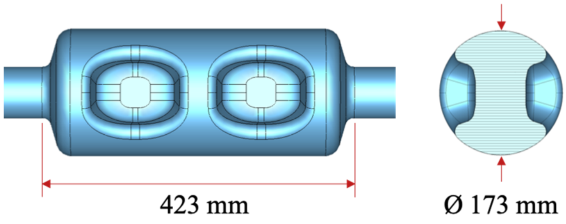

Figure 3: Final design of JLEIC crab cavity.

Table 2: 952.6 MHz Two-Cell RFD Properties

Property	**Unit**	**Electron**	**Proton**
Beam energy	GeV	12	200
Total crabbing voltage per side per beam	MV	4.2	21.5
No. of cavities	-	3	12
Voltage per cavity	MV	1.4	1.9
Peak electric field	MV/m	26	35
Peak magnetic field	mT	53	71
Surface resistance	nΩ	95	95
Shunt impedance	TΩ	0.27	0.27
Dissipated power	W	7.3	13.4

Multipacting Analysis

Multipacting analysis was done using Track3P package in SLAC ACE3P code suite [8]. Resonant particles are traced for 50 rf cycles with impact energies of 50-2000 eV. Most of the resonant particles have low impact energies and resonance occurs at much lower transverse voltage than the operating voltage. Past experience with other RFD cavities has shown multipacting levels can be processed easily and completely. Figure 4 shows the analysis results.

HOM Damping

Each HOM's R/Q was calculated to identify its impact to the beam. Figure 5 is showing categorized HOMs and their R/Q values. The same order mode turned out to be easy to manage thanks to its small R/Q.

After grouping the field shapes of the modes, conceptual HOM couplers (see Fig. 6) were added with the consideration of keeping the cavity as symmetric as possible.

To see the effectiveness of the HOM couplers, wakefields were simulated for different energy and current cases. Figure 7 is the longitudinal wakefields with thresholds. A couple of modes of high R/Q modes need improvement for high current beams.

Vertically polarized fields are well damped (see Fig. 8) but horizontally polarized fields need further investigation due to insufficient decay of wake potential (see Fig. 9).

Optimization of HOM couplers will be needed to damp all HOMs below thresholds.

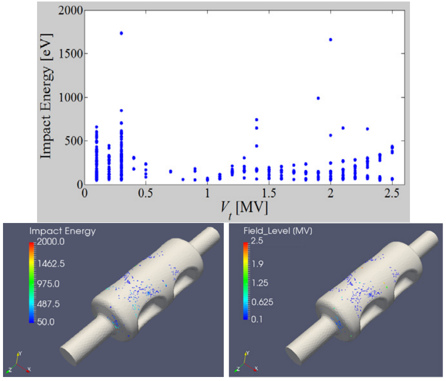

Figure 4: Impact energy vs. voltage and resonant particle locations.

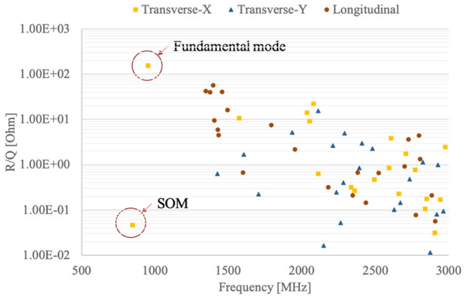

Figure 5: R/Q of HOMs.

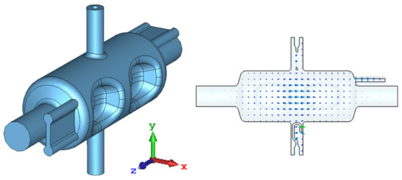

Figure 6: HOM couplers

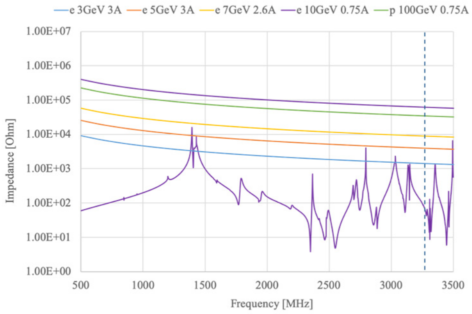

Figure 7: Longitudinal wakefields.

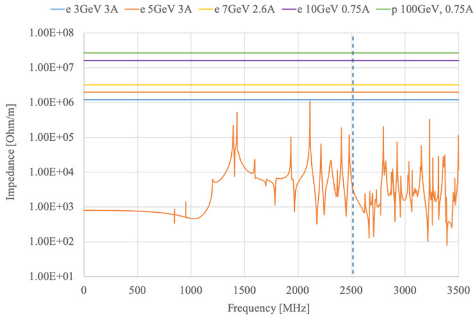

Figure 8: Transverse vertical wakefields.

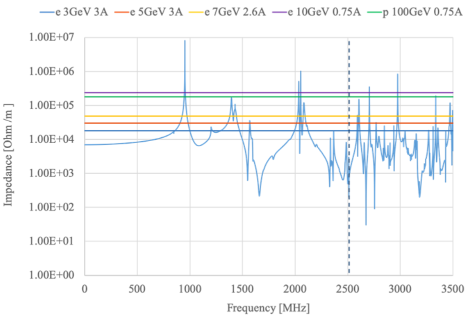

Figure 9: Transverse horizontal wakefields.

RF Power Coupling

In crabbing cavity, if the beam is exactly on the electric center of the cavity there is no longitudinal field which takes energy off from the beam. However, when the beam is off this axis, additional rf power has to be sup-plied as expressed by the equation below [9].

$$P_g = \frac{(1+\beta)^2}{4\beta R_t} \times \left\{\frac{1}{\cos\alpha_L}\left(|V_t| + \frac{I_b R_t}{1+\beta} k\Delta x \sin\phi_c\right)\right\}^2 \quad (2)$$

Where, I_b is the beam current, V_t is the transverse voltage per cavity, R_t is the transverse shunt impedance of the cavity, k is the wave number, Δx is the beam offset, β is the coupling coefficient. The cavity will be at a phase offset (ϕ_c) of 90° with the beam and will be in phase with the generator (α_L). Q_L is the loaded quality factor.

The maximum power is required at 5 GeV and 3.5 A electron beam case. The power requirement by loaded Q (Q_L) is plotted in Fig. 10.

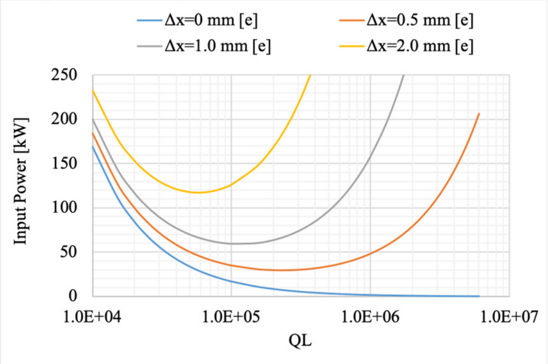

Figure 10: Input power requirement for electron beam of 5 GeV energy and 3.5 A current.

Lessons Learned from SPS Crab Cavity Test

The Center for Accelerator Science at Old Dominion University and SLAC collaboration designed the RFD crab cavity for LHC high luminosity upgrade [10]. The prototype with a full set of HOM dampers was successfully tested at JLab. Two prototypes of the other design for the LHC high luminosity upgrade (DQW cavity) was tested at SPS with the proton beam. The experience of fabrication, cavity treatment, and beam test for SPS tests has been incorporated in JLEIC crab cavity design. JLEIC will benefit even more from future SPS test of RFD cavity.

To cover all range of energy and current, the power coupler should have loaded Q between 6×10^4 – 2×10^5 for electron ring and 4×10^5 – 2×10^6 for proton ring. The cavity design allows the coupler location on the beam pipe with the adequate coupling strength (see Fig. 11).

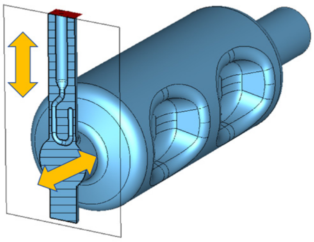

Figure 11: Input coupler, this particular coupler has loaded Q of 8.25×10^4.

CONCLUSION AND PLAN

The Center for Accelerator Science at Old Dominion University designed 952.6 MHz two cell RFD cavity for JLEIC after extensive design survey. The final design provides required crabbing transverse voltage while it satisfies other requirements such as multipoles, dynamic aperture, and multipacting behaviour [11]. The cavity's HOM spectrum has been characterized and the damper design has begun. The bare cavity design is complete and the fabrication has started.

Continuous effort is being made to improve HOM damping along with further wakefield analysis. Bench tests with the bare cavity will be performed, which will give confidence in simulations.

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