6th North American Particle Accel. Conf. (NAPAC2025), Sacramento, CA, USA JACoW Publishing
ISBN: 978-3-95450-261-5 ISSN: 2673-7000 doi: 10.18429/JACoW-NAPAC2025-TUP051

IMPEDANCE AND WAKEFIELD STUDIES OF THE EIC RCS 591 MHz FIVE-CELL CAVITY

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Abstract

The Electron-Ion Collider (EIC) is a next-generation accelerator complex designed to enable high-luminosity collisions between highly polarized electrons and ions. A central component of its Electron Injection System (EIS) is the Rapid Cycling Synchrotron (RCS), which accelerates electron bunches from 750 MeV to 5, 10, or 18 GeV using a total of eight 591 MHz 5-cell superconducting RF cavities. To ensure stable acceleration of high-charge bunches, we conducted detailed impedance and wakefield studies of the cavity structure using both frequency- and time-domain methods. Wakefield solvers (ECHO3D, ECHOz1, ECHOz2, CST), eigenmode analysis, and multi-particle tracking with ELEGANT were employed to evaluate longitudinal and transverse impedance effects and to determine instability thresholds. These studies provide critical input for the cavity design and operating parameters required to preserve beam quality and stability in the RCS.

INTRODUCTION

As illustrated in Fig. 1, the Electron–Ion Collider's Electron Injection System (EIS) relies on a Rapid Cycling Synchrotron (RCS) (see Fig. 2) to accelerate a single 28 nC bunch from 750 MeV to 5, 10, and an 11 nC bunch to 18 GeV [1]. A central element of this lattice is the eight 591 MHz, 5-cell superconducting RF cavities. Ensuring beam stability against both impedance-driven and wakefield-induced effects is therefore critical. In this paper, we present a comprehensive suite of impedance studies—encompassing wakefield calculations, eigenmode analyses, and multi-particle beam-tracking simulations—to assess stability risks.

CAVITY GEOMETRY

The initial design derives from the BNL 650 MHz 5-cell cavity, scaled to 591 MHz [2], with the HOM coupler removed to simplify the model, as shown in Fig. 3(a). The modified configuration in Fig. 3(b) employs a standard beam-pipe diameter of 274 mm, extended to 800 mm in length to accommodate a future Beam Line Absorber (BLA). Because the BLA absorbs HOM power and consequently heats up, it must be positioned sufficiently far from the cryogenic cavity to avoid thermal loading. A 500 mm-long taper transitions the 274 mm section down to a 36.32 mm inner-diameter pipe. The iris diameter between cavity cells is 178.2 mm, while that between the cavity and the beam pipe is 182.6 mm.

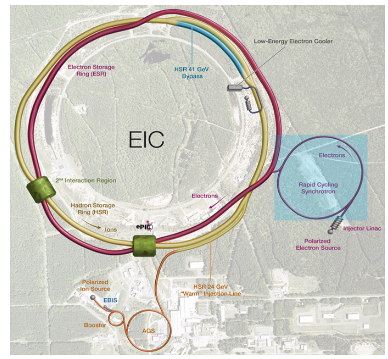


Figure 1: EIC top view with RCS highlighted in blue.

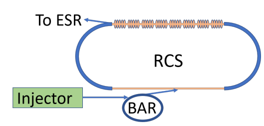
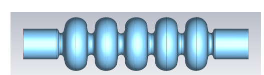
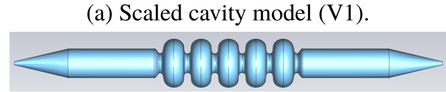


Figure 2: Schematic layout of the RCS, the Beam Accumulator Ring (BAR), and the Injector Linac.



(a) Scaled cavity model (V1).



(b) Scaled and modified cavity model (V3).

Figure 3: 5-cell 591 MHz cavity models.

Note: Neither the V1 nor V3 cavity and taper designs are final; they're intended solely for impedance-target studies.

WAKEFIELD SIMULATIONS

Benchmarking

Wakefield simulations were carried out using ECHO3D [3] for the scaled cavity model. The results were cross-checked and benchmarked against GdfidL [4] and CST [5] for short-range wakes with a 7 mm RMS bunch length. Loss factors are listed in Table 1, and wake potentials are plotted in Fig. 4.

Additionally, loss factors were computed from the eigenmode simulation data via Eq. (1) for monopole modes

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Table 1: Loss Factors for the V1 Cavity Model (σ_z = 7 mm)

Code	k_{loss} **(V/pC)**
ECHO3D	1.68
ECHO1z	1.67
GdfidL	1.66
CST Eigenmode	1.78
CST Wakefield	1.25

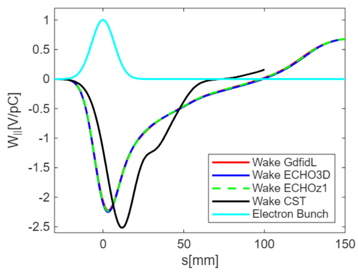

Figure 4: Wake potentials for the V1 cavity model with an RMS bunch length of σ_z = 7 mm.

$$k_{\text{loss, monopole}} = \frac{\omega_i}{4}\left(\frac{R}{Q}\right)_i \exp\left[-\left(\frac{\omega_i\,\sigma_z}{c}\right)^2\right], \tag{1}$$

with ω_i being the angular frequency of the i-th resonant mode, $(R/Q)_i$ being its shunt impedance divided by quality factor, σ_z being the RMS bunch length, and c being the speed of light in vacuum. The calculated results are presented in Fig. 5. All codes show excellent agreement, with the exception of the CST wakefield solver.

We benchmarked ECHO3D against the TESLA cavity [6] by comparing the loss factors for a Gaussian bunch with an RMS length of σ_z = 0.7 mm. As shown in Table 2, the results roughly agree, exhibiting no significant deviations.

Short-Range Wakefield Simulations

The most reliable approach to determine the microwave instability (MWI) threshold is multi-particle tracking with pseudo-Green functions derived from wakefields computed for a Gaussian bunch of σ_z = 0.5 mm, since analytical models frequently misestimate the threshold. For a rough Transverse Mode Coupling Instability (TMCI) estimate at zero chromaticity, one can combine the transverse kick factor

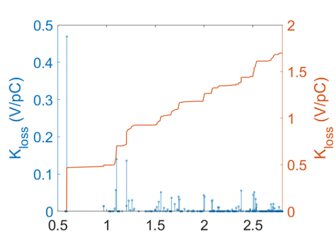

Figure 5: Loss factors from eigenmode analysis of the V1 cavity model: individual mode contributions (blue) and cumulative loss factor (orange).

Table 2: Loss Factor Comparison for the TESLA Cavity (σ_z = 0.7 mm)

	k_{loss} **(V/pC)**
Ref. [6] reported	10.2
ECHO3D	11.68

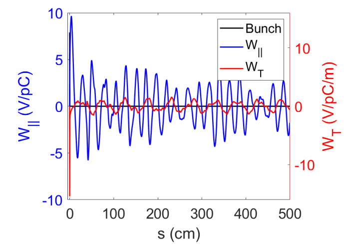

Figure 6: Wakefield of a 0.5 mm RMS bunch length.

with the local beta functions; however, we obtain a more accurate TMCI threshold by including vertical dipole wakefields in full particle-tracking simulations throughout the energy ramp.

Wakefields were computed using ECHOz1 ($W_{\parallel}$) and ECHOz2 ($W_{\perp}$) for σ_z = 0.5 mm. The resulting longitudinal loss factor is $k_{\parallel}$ = 11.448 V/pC and the transverse kick factor is $k_{\perp}$ = 1.324 V/pC/m. These values, along with the wake potentials shown in Fig. 6, feed into the impedance budget to evaluate beam stability and RF heating for a single 28 nC bunch circulating in the RCS. The associated heating contribution is moderate. The loss factor is also used to benchmark the results for the specific geometry.

Long-Range Wakefield Simulations

Long-range wakefield simulations using ECHO failed to resolve the high-frequency spectrum because of time-bin and memory limits. In a cylindrical beam pipe, the cutoff frequencies for the monopole (TM_{01}) and dipole (TE_{11}) modes are given by

$$\begin{aligned} f_{\text{cutoff, monopole}} &= \frac{\chi_{01}\,c}{2\pi\,r_{\text{pipe}}} = 6.36\ \text{GHz} \\ f_{\text{cutoff, dipole}} &= \frac{\chi_{11}\,c}{2\pi\,r_{\text{pipe}}} = 4.88\ \text{GHz}\ , \end{aligned} \tag{2}$$

where c is the speed of light, χ_{01} = 2.405 is the first zero of $J_0(x) = 0$ and χ_{11} = 1.8412 is the first zero of $J_1'(x) = 0$. To excite components above these cutoff frequencies, one needs a shorter bunch and finer mesh, but ECHO limits each run to 100,000 time bins. We therefore used a 15 mm RMS bunch, a 3 mm mesh spacing, and a 300 m wake length. The finite wake length sets the minimum frequency bin to

$$\Delta f = \frac{1}{L_{\text{wake}}/c} \approx 1\ \text{MHz}\ , \tag{3}$$

so the spectral resolution is only 1 MHz—insufficient to resolve peak bandwidths and accurately extract Q-values or R/Q from the wakefield spectrum.

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Table 3: The Most Dominant Modes

F (MHz)	R/Q	Mode	Trapped In
1105.02	63.5 Ω	TM01	Pipes
1094.07	43.2 Ω	TM01	Pipes
1083.17	21.1 Ω	TM01	Pipes
1735.21	20.8 Ω	TM03	Cavity
1103.82	13.9 Ω	TM01	Pipes
768.77	811.5 Ω/m	TE11	Pipes
1136.56	651.8 Ω/m	TE11	Cavity
749.52	575.6 Ω/m	TM11	Pipes
832.74	268.5 Ω/m	TE11	Cavity
779.72	249.7 Ω/m	TM11	Pipes

EIGENMODE SIMULATIONS

We employed CST eigenmode solver to determine the longitudinal and transverse modes of cavity model V3 under two boundary-condition (BC) schemes:

1. "Open" in the beam-axis direction and "perfect-electric" ($E_t = 0$) on all other faces, using the lossy solver;
2. "Perfect-electric" ($E_t = 0$) on all faces, using the lossless solver.

The second scheme introduced extra (nonphysical) eigenmodes and systematically under-predicted several R/Q values. Since the cavity is physically connected to beam pipes, an open BC at the two beam ports—allowing fields to propagate into the pipes—is more realistic. We therefore adopted BC scheme 1 for all subsequent eigenmode calculations.

Longitudinal eigenmodes were ranked by their R/Q, and the top 100 modes were selected for ELEGANT [7] tracking simulations. These 100 modes also includes the 50 modes with the highest intrinsic quality factors (Q_0). For the dipole modes, we extracted the 50 modes with the largest R/Q . Some of the most dominant modes are given in Table 3. The similar mode types appear twice in the table at different frequencies: the lower-frequency instance is trapped in the beam pipe, while the higher-frequency one resides in the cavity. In the last column, we indicated where these modes are trapped.

ELEGANT TRACKING

ELEGANT long-range wakefield tracking was carried out assuming constant R/Q while scanning the loaded quality factor Q_L. We modeled eight identical cavities, each HOM frequency varied by a relative RMS spread $\sigma_f/f = 0.001$. Monopole modes primarily perturb beam energy, with only secondary effects on the transverse phase space; dipole modes deflect the beam transversely. These are implemented via the RFMODE and TRFMODE elements, which require as input each mode's shunt impedance, frequency, and Q_L.

For efficient multi-turn tracking, we represented a single turn of the 1421.25725 m RCS ring with the ILMATRIX element (including chromatic optics) and lumped synchrotron-radiation damping and quantum excitation into the SREFFECTS element. A single 28 nC bunch was tracked through 10 k passes as its energy ramped from 0.75 to 5 GeV. This

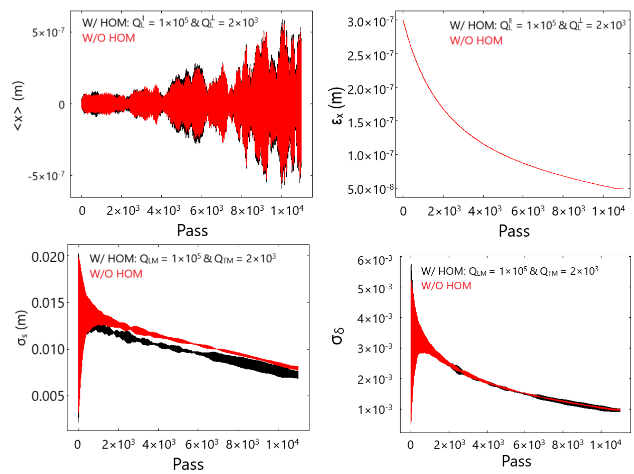

Figure 7: ELEGANT tracking results.

framework—ILMATRIX plus SREFFECTS—is sufficient to assess HOM- and wakefield-driven current limits; future work will replace it with full element-by-element tracking.

Initial Q_L scans were performed separately for monopole and dipole modes. With the optimal values identified ($Q_L^{\parallel} = 1\times10^5$, $Q_L^{\perp} = 2\times10^3$), final multi-pass simulations including both mode types were executed. Fig. 7 compares these (black curves) to a no-HOM baseline (red). The transverse centroid $\langle x\rangle$, horizontal emittance ε_x, RMS bunch length σ_s, and RMS energy spread σ_δ all remain stable over the full ramp.

CONCLUSION

A comprehensive impedance and wakefield characterization of the 591 MHz five-cell SRF cavity for the EIC RCS has been carried out using frequency- and time-domain solvers (ECHO3D, ECHO1D, CST), eigenmode analysis, and multi-particle tracking in ELEGANT. Short-range simulations yielded loss factors in excellent agreement across codes, while eigenmode studies—under realistic ("open") boundary conditions—identified the dominant monopole and dipole HOMs. Long-range wakefield tracking, assuming invariant R/Q with a relative frequency spread $\sigma_f/f = 0.001$, demonstrated stable beam dynamics for a single 28 nC bunch accelerated to 5 GeV, provided the loaded quality factors satisfy $Q_L^{\parallel} = 1\times10^5$ and $Q_L^{\perp} = 2\times10^3$. These findings establish clear HOM-damping targets and guide cavity and coupler design to preserve beam quality.

ACKNOWLEDGEMENTS

Notice: This work was produced in part by Jefferson Science Associates, LLC under Contract No. AC05-06OR23177 and Brookhaven Science Associates, LLC, Contract DE-SC0012704 with the U.S. Department of Energy. The publisher acknowledges the U.S. Government license and provides public access under the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

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