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591 MHz SRF CAVITY DESIGN FOR THE EIC ESR

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591 MHz SRF CAVITY DESIGN FOR THE EIC ESR*

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Abstract

The Electron-Ion Collider (EIC) is a next generation particle accelerator to be built at Brookhaven National Laboratory, in partnership with Thomas Jefferson National Accelerator Facility. The Electron Storage Ring (ESR) of RIC requires a 10 MW RF storage system to restore beam power lost by a 2.5 A electron beam. The RF system will use 18 single-cell 591 MHz Superconducting RF (SRF) cavities. Effective damping of higher-order-modes (HOMs) is critical to ensure beam stability. This paper presents the design of the single-cell 591 MHz cavity, including cavity geometry optimization, multipacting evaluation, and HOM damping analysis.

INTRODUCTION

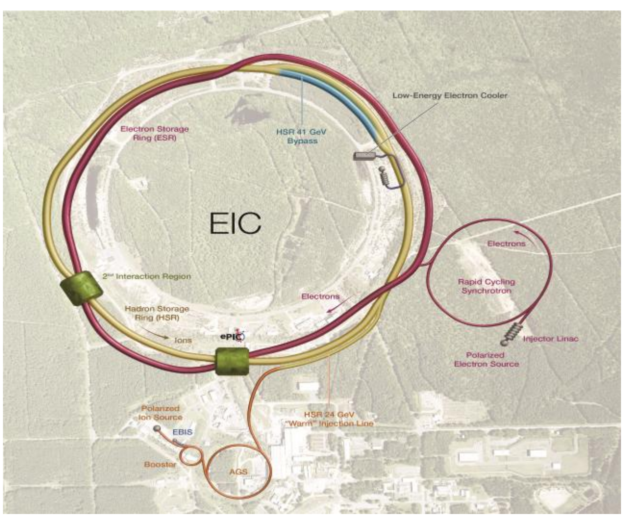

Figure 1: Schematic layout of the EIC.

The EIC [1] to be built at BNL will be a discovery machine, providing answers to long-elusive mysteries of matter related to our understanding of the origin of mass and the spin of the proton, and probing the structure of dense gluon systems in nuclei that make up the entire visible universe. The EIC includes a hadron accelerator that provides hadron beams and an electron accelerator that provide electron beams. The hadron accelerator will use upgraded components and infrastructure of the Relativistic Heavy Ion Collider (RHIC) accelerator system. The electron accelerator chain is new, which includes electron injector, Rapid Cycling Synchrotron (RCS) and Electron Storage Ring (ESR). Figure 1 shows the schematic layout of EIC.

The maximum synchrotron radiation in ESR is up to 10 MW. To compensate such large energy loss, 18x591 MHz single-cell SRF cavities are needed. Since 2021, the cavity design has been evolving, reaching maturity [2]. The first cavity design was presented in [3]. This paper presents the second iteration of the cavity design.

CAVITY DESIGN

Design requirement

The EIC ESR SRF cavity has a tight impedance requirement for beam stability and acceptable transient beam loading. The detail requirements are shown in Table 1.

Table 1: ESR SRF cavity design requirement

Parameters	Requirement
Frequency [GHz]	0.591
R/Q [Ω]	< 80
Max. Voltage [MV]	4
B [mT] @4 MV	< 80
E[MV/m] @4MV	<40
Longitudinal HOM impedance [Ω-Hz]	< 2.9E12
Transversal HOM impedance [Ω/m]	< 1.3E6
Max. power (2 FPCs) [kW]	800

All the impedance values mentioned in this paper are based on the accelerator definition. The higher-order-mode (HOM) impedance requirements listed above are likely more conservative because it is assumed that all the 18 cavities have the same HOMs.

Cavity geometry

The SRF cavity geometry optimization follows typical elliptical cavity design recipes, starting from fundamental mode optimization, and then HOM damper optimization. Figure 2 shows the Superfish model of ESR SRF cavity

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geometry. The radius of the small beampipe is 90 mm, which is 15 mm larger than the first cavity design to reduce impedance and ease the cold-to-warm bellow design. The radius of the larger beampipe stays the same as for the first cavity, i.e., 137 mm, which is enlarged from the cavity's iris to maintain the fundamental mode's R/Q while propagating the HOMs.

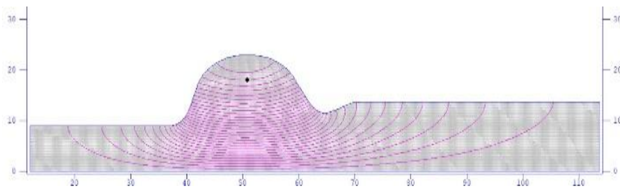

Figure 2: EIC ESR cavity.

Table 2 listed the fundamental mode electromagnetic properties for the previous and new cavity design. Most parameter values are the same, except for a maximum electric surface field reduction of about 12 % with respect to the previous cavity. The ESR SRF cavities will operate in continuous-wave (CW) mode with an electron beam current up to 2.5 A, thus it is imperative to have small peak surface electric field at the operation gradient to save cavity conditioning time during operation.

Table 2: ESR SRF cavity

Parameters	New cavity	Previous cavity
Frequency [GHz]	0.591	0.591
R/Q [Ω]	76.7	77.4
B [mT] @4 MV	76.9	76.5
E[MV/m] @4MV	28.5	32.3

Short-range wakefield

The SRF cavities are one of largest contributors to the short-range wakefield in ESR. With a larger small beampipe aperture and an updated cavity's geometry, the new cavity design features reduced longitudinal and transversal short-range wakefields by about 40%, as seen in Figure 3.

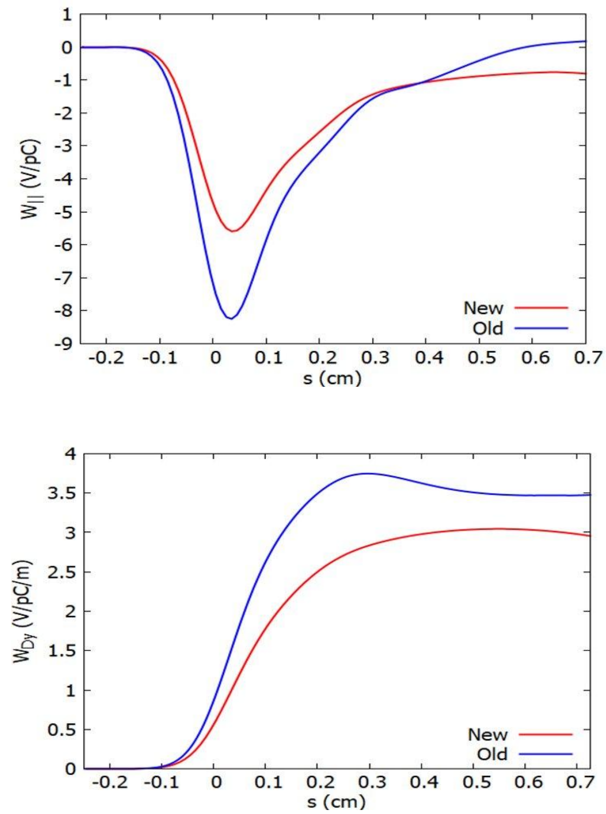

Figure 3: Top: longitudinal short-range wakefield; Bottom: transversal short-range wakefield.

HOM damping

HOM damping is a critical challenge for the EIC ESR SRF cavity. The HOM damping scheme follows the previous design, i.e., using SiC beam line absorbers (14 mm thickness, 240 mm length), as shown in Figure 4. Figure 5 and Figure 6 show the longitudinal and transversal HOM damping results up to cutoff frequency of the beampipe. These results demonstrate that the cavity and HOM damping scheme designs satisfy the design requirement.

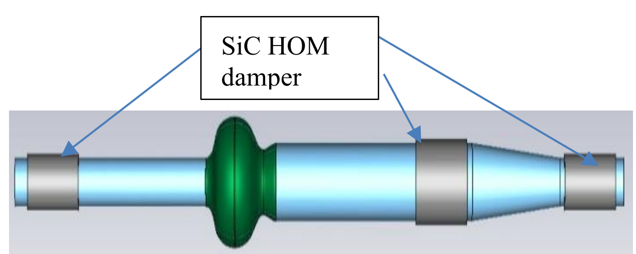

Figure 4: HOM damping scheme for the ESR SRF cavity.

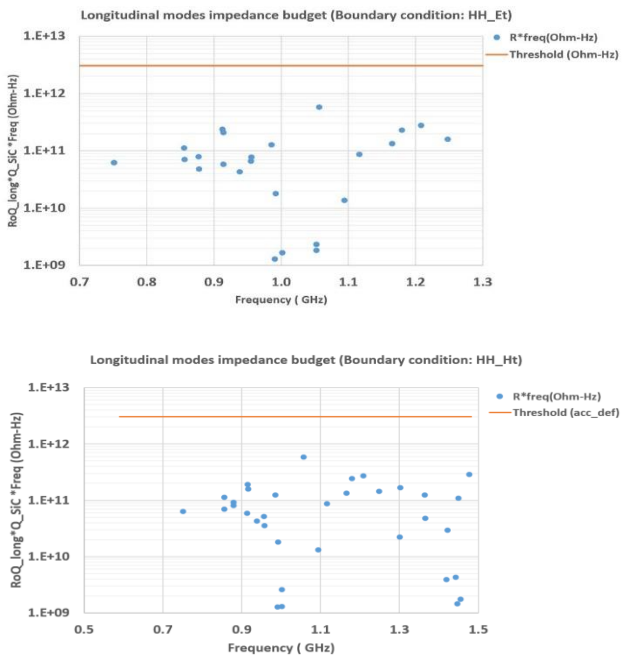

Figure 5: Longitudinal impedance.

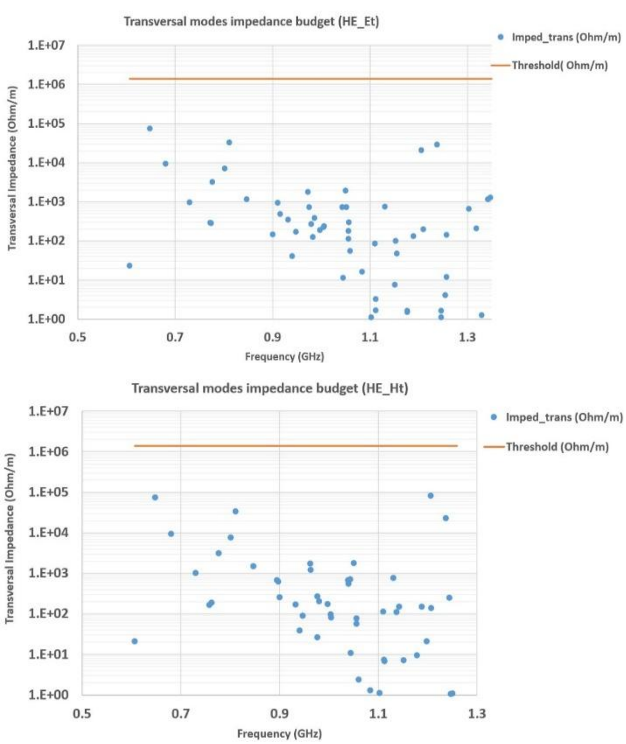

Figure 6: Transversal impedance.

Multipacting

Multipacting simulations on the cavity were carried out in Fishpact [4] and ACE3P [5]. The cavity is expected to undergo 120° C bake for the last cavity surface processing step, so it is reasonable to believe that the niobium surface will present SEY below 1 for an electron impact energy below 40 +/- 2 eV. Figure 6 shows the multipacting simulation results, which show good agreement between Fishpact and ACE3P.

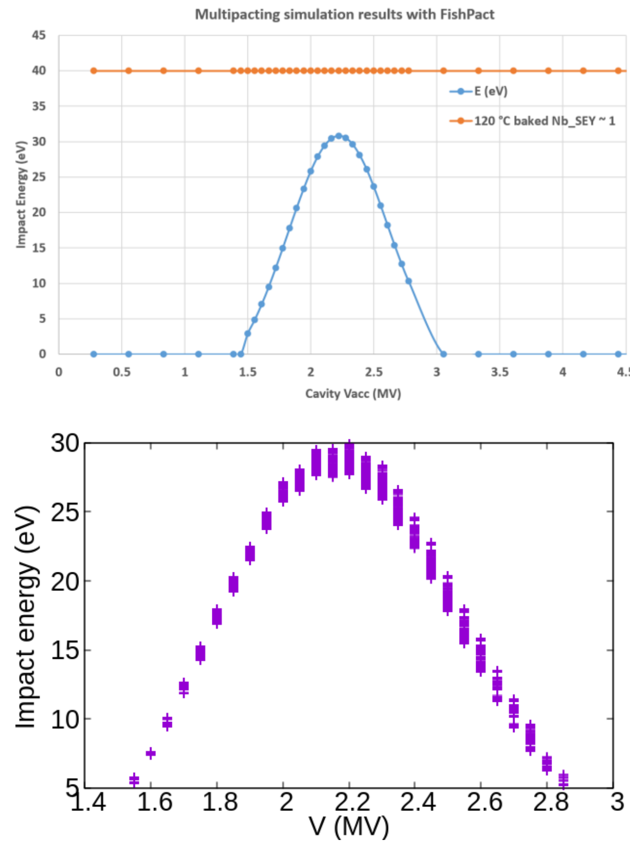

Figure 6: Top: Multipacting simulation done by Fishpact; Bottom: Multipacting simulation done by ACE3P.

EIC ESR CAVITY STRING

Cavity vacuum string layout

To further reduce beam impedance and SRF footprint in the ESR tunnel, a two single-cell cavities cryomodule was proposed and studied. The ESR cryomodule and cavity vacuum string is shown in Figure 7. The two cavities are connected by thelarge beam pipe, where a common SiC HOM damper is installed in the middle. There are two FPCs in each cavity, and the Qext for the cavity is 3E5. There are large cold-to-warm bellows around the SiC HOM damper and small cold-to-warm bellows at the small beampipes. At each end of the cryomodule, there is a gate valve on the small beam pipe for vacuum isolation.

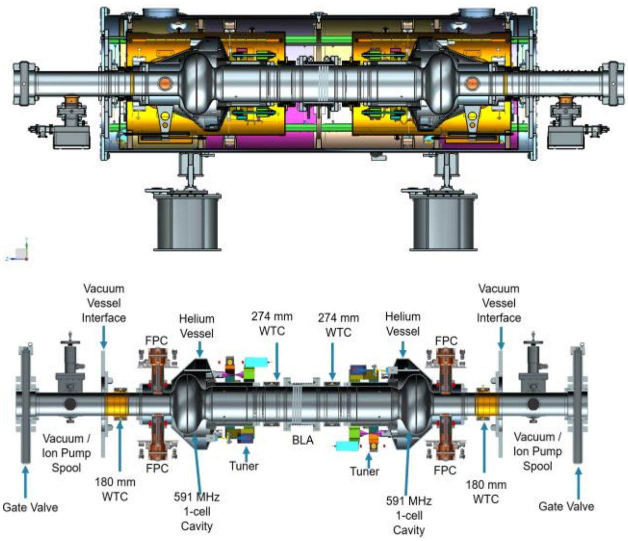

Figure 7: ESR SRF cavity string.

HOM damping in cavity string

Figure 8 shows the simulation model for HOM damping for the cavity string. The limited bandwidth in the FPC doorknobs results in trapped resonating modes between two FPCs. FPC length as adjusted to locate the FPC modes' frequencies away from the beam harmonic frequencies. In this study, conservative boundary conditions were used by considering SiC as the only HOM absorber, i.e., ignoring the RF surface loss in cavity and beampipe.

The whole spectrum, including FPC modes and HOMs, were calculated with this model. The results are shown in Figure 9. Although the impedance of three FPC modes are higher than the limit. The frequencies of these modes are further away from the beam harmonic frequencies and the impedance will reduce by orders of magnitude when RF surface loss is considered. Additional simulations with copper surface on the FPCs demonstrated that these two modes' Q reduced by a factor of 1000 and 100, respectively.

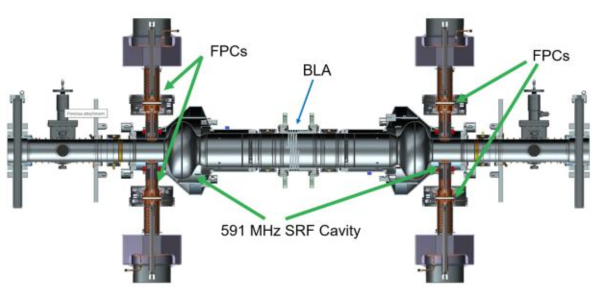

Figure 8. HOM damping simulation model for cavity string

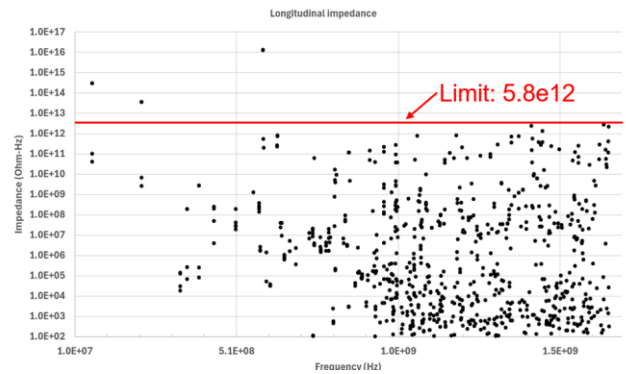

Figure 9. HOM damping results with conservative boundary condition.

In EIC ESR, a beam damper with damping rate of 1E-3 per second is planned to fight beam instability. Using the modes shown in Figure 9, coupled-bunch-instability simulations demonstrate that a damper as slow as 2E-4 per second is sufficient for the ESR. The result is shown in Figure 10.

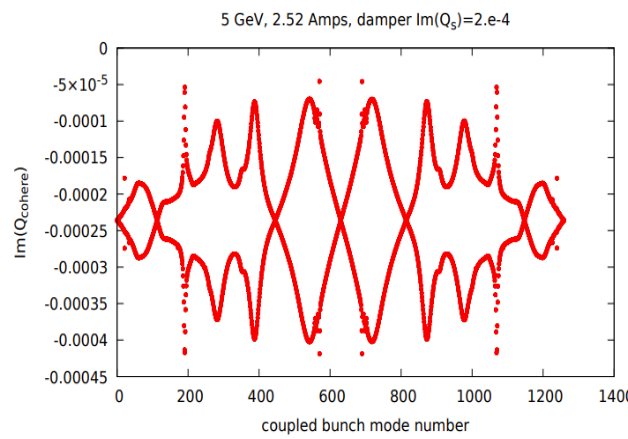

Figure 10. Coupled-bunch-instability simulation results with damper.

CONCLUSION

A single-cell SRF cavity was optimized for the EIC ESR. The cavity design fundamental mode fields meet the traditional SRF cavity requirements as well as the unique low R/Q requirement of the EIC ESR. Multipacting simulations finds no showstoppers. The HOM damping scheme adopted for this cavity string also meets the requirements. FPC modes were studied as well and they should not cause any trouble.

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