

RF DESIGN OF THE 49 AND 98 MHZ NORMAL-CONDUCTING CAVITIES FOR BUNCH SPLITTING IN THE EIC HSR*

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Abstract

Two normal-conducting RF cavities at 49 MHz and 98 MHz have been developed for the bunch-splitting system in the Hadron Storage Ring of the Electron-Ion Collider. Both cavities use compact quarter-wave-resonator structures to satisfy RF, mechanical, and tunnel-integration constraints. Key components, including the fundamental power coupler (FPC), fundamental mode damper (FMD), higher-order-mode (HOM) dampers, mechanical tuners, and pickup couplers, were optimized to meet all design performance requirements. HOM impedances and powers satisfy their limits across the full tuning range. Frequency shifts due to mechanical tolerances can be compensated by trim tuning to adjust the cavity gap. Multipacting studies were carried out using SPARK3D. The designs of both cavities fulfill the performance and interface requirements and are ready to proceed to the procurement phase.

INTRODUCTION

The Electron-Ion Collider (EIC) [1, 2] is being constructed on the existing Relativistic Heavy Ion Collider (RHIC) complex to provide high-luminosity collisions between polarized electron and hadron beams. The Hadron Storage Ring (HSR) will reuse the upgraded RHIC Yellow ring, and requires substantially higher beam current, shorter bunch length, and a much larger number of bunches than RHIC operation.

The HSR RF system [2, 3] combines refurbished RHIC cavities with newly developed RF systems for beam capture, acceleration, bunch splitting, and bunch compression. The bunch-splitting process is performed in two stages: three 49 MHz normal-conducting RF (NCRF) cavities provide 500 kV total voltage to split 290 bunches into 580, followed by four 98 MHz NCRF cavities providing 600 kV total voltage to further split the beam into 1160 bunches.

The 49 MHz and 98 MHz cavities are designed as quarter-wave resonators (QWR), following the general concept of the existing RHIC 28 MHz cavities [4]. To reduce technical risk and simplify fabrication, installation, and operation, common or similar solutions are adopted for key RF components wherever practical. Compared with RHIC operation, the EIC HSR beam conditions impose more stringent higher-order-mode (HOM) damping requirements [3]. This paper summarizes the cavity design requirements, cavity and key component RF designs, HOM impedance results, fabrication-error compensation, and multipacting studies for

Table 1: RF design requirements for the 49 and 98 MHz cavity systems. E-HOM/H-HOM denote electrical/magnetical coupled HOM dampers.

Parameter	49 MHz	98 MHz
Number of cavities	3	4
Nominal frequency (MHz)	49.263	98.525
Total RF voltage (kV)	500	600
Voltage per cavity (kV)	167	150
Manufactured Q_0	≥ 10000	≥ 7650
FPC Q_{ext}	$(4.6 \pm 0.2)e3$	$(3.9 \pm 0.2)e3$
FPC window rating (kW)	120	120
Pickup Q_{ext}	$(5.3 \pm 1.0)e7$	$(5.4 \pm 1.0)e7$
Tuner range (kHz)	-280 → +40	-120 → +120
FMD Q_{ext} fully inserted	≤ 250	≤ 150
Min FMD power handling (kW)	5	5
H-HOM damper power (kW)		≤ 5 each
E-HOM damper power (kW)		≤ 0.5 each
Fund. leakage from damper (kW)		≤ 0.2 each
Longitudinal impedance		$\leq 90 \text{ k}\Omega \cdot \text{GHz}$
Transverse impedance		$\leq 2.5 \text{ M}\Omega/\text{m}$

the two cavities. The main RF design requirements for the cavity systems are summarized in Table 1. All impedance values and R/Q in this paper are given in the circuit definition.

CAVITY AND COMPONENT RF DESIGN

Figure 1 (a) and (b) show the two cavities and their ancillaries, including the fundamental power coupler (FPC), quarter-wave stub (QWS) necessary to enable FPC water cooling and DC biasing, fundamental mode damper (FMD), two H-HOM dampers, two E-HOM dampers, two pickup couplers, two mechanical tuners, and a vacuum port for each cavity. The components use the same design concepts with dimensions adjusted for the different cavity frequencies and geometries. Port orientations accommodate the tunnel layout and maintain sufficient clearance for installation and maintenance.

CST Studio Suite was used for the electromagnetic simulations. The main simulated RF parameters are summarized in Table 2. The higher operating frequency of the 98 MHz cavity leads to a more compact geometry and a reduced beam-pipe diameter, half of the other NCRF cavities in HSR. The long inner conductor of the 98 MHz cavity is flared in the high magnetic field region to reduce the local RF power density, unlike the straight conductor in the 49 MHz design, as shown in Fig. 1 (c). Port blending radii were optimized to reduce peak fields, with the resulting maxima located on the nose of the long inner conductor for the electric field and on the H-HOM damper loop for the magnetic field.

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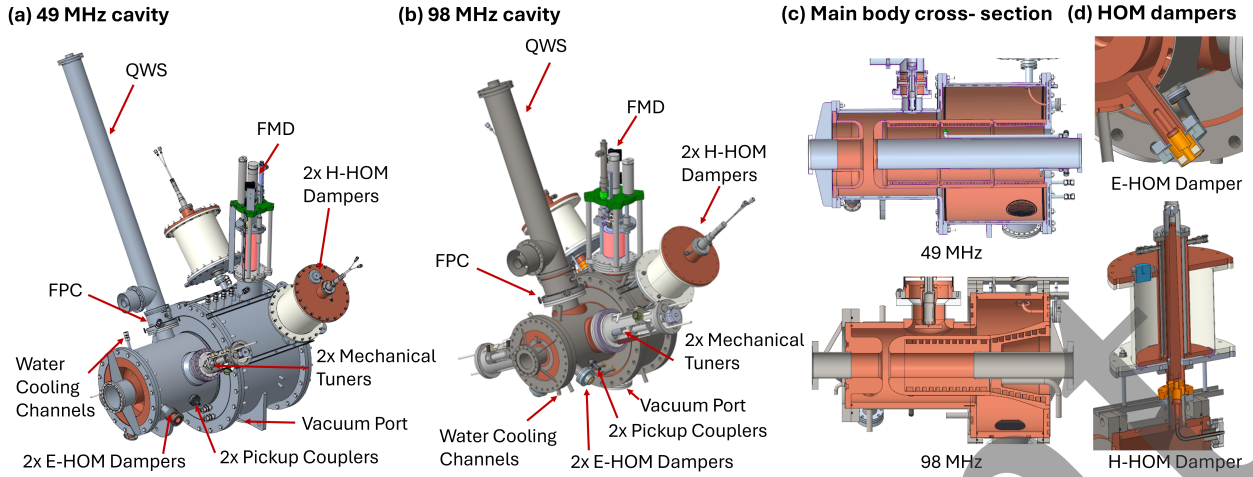


Figure 1: Designs of the (a) 49 MHz and (b) 98 MHz cavity, (c) cross-section of both cavities, and (d) HOM dampers using the 98 MHz cavity as an example.

Table 2: Simulated RF Parameters of the 49 and 98 MHz Cavities at the Design Voltage

Parameter	49 MHz	98 MHz
Frequency (MHz)	49.263	98.525
V_{acc} (kV)	167	150
R/Q (Ω)	26.1	23.3
Q_0	11643	8187
Peak E field (MV/m)	5.63	7.78
Peak H field (A/m)	1.23e4	2.37e4
Wall loss (kW)	45.1	59.4
Stored energy (J)	1.73	0.78

The FPC design differs from the loop-coupler configuration of the existing RHIC 28 and 197 MHz cavities. A broadband FPC window design based on the EIC ESR 591 MHz SRF cavity FPC [5, 6] supports 400 kW CW forward power, with 300 W allowable dissipation on the inner conductor. The antenna length was adjusted to meet the required Q_{ext} values, and calculated inner-conductor dissipations of 70 W and 136 W for the 49 and 98 MHz cavities, respectively. The power source of both cavity systems is a 120 kW solid state amplifier, sufficient to cover cavity wall loss, beam-loading compensation, and coaxial-line loss from the amplifier to the tunnel.

The RHIC 197 MHz FMD is frequency-specific and cannot be directly scaled to the 49 and 98 MHz cavities or meet the 5 kW power handling requirement. A RF window originally designed for the RHIC 56 MHz SRF cavity system [7, 8] is used instead, with an added motion system for variable insertion. The fully inserted FMD gives $Q_{ext} = 228$ with 2.3 kW worst-case power for the 49 MHz cavity, and $Q_{ext} = 116$ with 3.6 kW worst-case power for the 98 MHz cavity.

New mechanical tuners were developed since the RHIC 28 MHz beam-pipe bellows tuner could present large beam impedance and require significant longitudinal space, particularly for the smaller beam pipe of the 98 MHz cavity. Two tuners are symmetrically located on the small cylinder of

each cavity. The simulated tuning ranges are -403 to +208 kHz for the 49 MHz cavity and -483 to +500 kHz for the 98 MHz cavity, exceeding the required ranges.

Two electric-field pickup couplers are mounted on the small outer conductor. The port locations are adjusted to avoid a direct line of sight between the beam and the ceramic windows, while the coupler geometries are designed to provide the required Q_{ext} .

HOM DAMPER DESIGN

The HOM damper design is shown in Fig. 1 (d). Each cavity includes two E-HOM dampers on the small outer cylinder and two H-HOM dampers on the large outer cylinder, with each pair separated by 90 degrees to couple to different mode polarizations. The fundamental-mode leakage through the E-HOM dampers is limited to 0.1 W.

The H-HOM dampers are loop-coupled and connected to HOM filters similar to those used in the RHIC 28 MHz cavity to suppress fundamental-mode leakage. The filters were optimized to provide high reflection at the fundamental frequency while preserving HOM transmission. Since the filter response is sensitive to the capacitance gap size, Rexolite® supports were added in the gap to maintain the required mechanical tolerance. The low loss tangent of Rexolite® [9] minimizes dielectric power dissipation in the supports. Over the full mechanical tuning range, the maximum fundamental mode power leakage through the H-HOM dampers is 145 W for the 49 MHz cavity and 61 W for the 98 MHz cavity, both below the 200 W requirement.

The HOM damper windows adopt the same 25 Ω coaxial window design as the EIC 197 MHz crab-cavity HOM dampers [10]. This common window design originates from the CERN/HL-LHC crab-cavity HOM feedthrough concept. The 25 Ω geometry increases the inner-conductor diameter for improved mechanical robustness [11]. A 25-to-50 Ω taper transition connects each damper to a water-cooled dummy load rated for 5 kW up to 2 GHz.

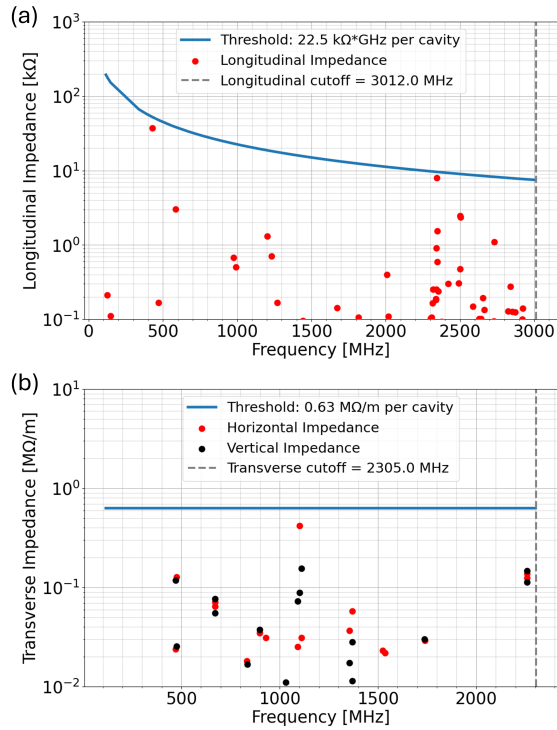


Figure 2: The (a) longitudinal and (b) transverse impedance results of the 98 MHz cavity

Extensive parametric optimization of the damper coupler dimensions was performed to reduce the HOM impedances while satisfying the fundamental mode power leakage and HOM power limits. Figure 2 shows the longitudinal and transverse HOM impedance results for the 98 MHz cavity as an example, where all impedance values are below the specified thresholds. HOM powers were evaluated over the full mechanical tuning range for different beam operation modes, including a conservative worst case with a 0.6 mm transverse beam offset and HOM frequencies aligned with the beam spectrum peaks within a $\pm 0.2\%$ frequency shift. Total worst-case HOM powers, including cavity loss and damper loss, are 887 W for the 49 MHz cavity and 620 W for the 98 MHz cavity. Maximum powers are 236 W for each H-HOM damper and 53 W for each E-HOM damper in the 49 MHz cavity, and 46 W for H-HOM and 289 W for E-HOM in the 98 MHz cavity, leaving sufficient margin for the damper load ratings.

FABRICATION ERROR ANALYSIS AND TUNING

Fabrication-error studies were performed to evaluate the expected frequency shifts of the cavity bodies. The considered errors include length, diameter, centerline offset, and centerline tilt errors of the large outer conductor, small outer conductor, long inner conductor, and short inner conductor. Relative offsets between the individual parts of the long inner conductor were also included. A conservative worst-case estimate was obtained by summing the frequency shifts from all considered error cases.

Table 3: Fabrication-error Frequency Shifts and Tuning Margins

Parameter	49 MHz	98 MHz
Predicted frequency shift (kHz)	± 114	± 386
End-tip sensitivity (MHz/inch)	-0.723	-2.95
Reserved oversize (inch)	0.2	0.2
Frequency margin (kHz)	± 145	± 590

The predicted worst-case frequency shifts and the available correction margins are summarized in Table 3. Frequency correction is provided by machining the end tip of the short inner conductor. For both cavities, a 0.2 inches end-tip oversize is reserved, giving sufficient tuning margin to compensate the predicted fabrication-induced frequency shifts. Frequency recipes are being developed with the worst-case fabrication conditions included.

MULTIPACTING SIMULATION

Multipacting simulations were performed in SPARK3D for the final 49 and 98 MHz cavity models. The cavity volumes were divided into localized analysis regions, and the mechanical tuner positions were scanned at the fully inserted, nominal, and fully extracted positions. SEY curves for baked copper and TiN-coated alumina were used.

For the 49 MHz cavity, a three-point multipacting was found near the FPC window above 150 kV. The simulated order is 0.3–0.4 and the trajectory is unstable. For the 98 MHz cavity, a two-point multipacting was found between the FPC conductors around 50–80 kV. These barriers are expected to be processed by RF conditioning. If needed, they can be further suppressed by applying a 1 kV DC bias to the FPC inner conductor through the quarter-wave stub.

SUMMARY

RF designs of the 49 and 98 MHz normal-conducting quarter-wave cavities for the EIC HSR bunch-splitting system have been completed. Cavity geometries and key RF components were optimized to satisfy the fundamental mode, coupling, tuning, HOM damping, and interface requirements. HOM impedance and power evaluations show that the final damper configurations meet the specified limits with sufficient power-handling margin. Fabrication-error studies indicate that the predicted frequency shifts can be compensated by the reserved end-tip tuning margins. Multipacting simulations show that the identified barriers can be processed by conditioning or further suppressed by DC bias. These results establish the RF design basis for detailed engineering design, integration, and subsequent fabrication.

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