CONVERSION OF 28 MHZ CAVITIES TO 24.6 MHZ CAVITIES FOR THE EIC HADRON STORAGE RING

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Abstract

The Hadron Storage Ring of the Electron-Ion Collider (EIC) will require 600 kV of 24.6 MHz RF voltage for capture and acceleration. Four 28 MHz normal-conducting Quarter Wave Resonator (QWR) cavities from the Relativistic Heavy Ion Collider (RHIC) will be modified for this purpose. We present the main requirements for the EIC HSR 24.6 MHz cavities, along with the RF design and multiphysics validation. The design is mature and meets all the requirements.

INTRODUCTION

The EIC Project plans to start operation in 2034 [1][2]. The normal conducting RF (NCRF) systems for the EIC hadron storage ring (HSR) consist of 4 types of unique cavity resonators: a 24.6 MHz capture and acceleration, a combined 49.2 MHz and 98.4 MHz bunch splitting system [3], and a 197 MHz storage system. Four 28 MHz cavities, two installed in the yellow ring and two in the blue ring, have operated in Relativistic Hadron Ion Collider (RHIC) for more than twenty years [4]. The RHIC 28 MHz cavities are quarter-wave resonators made of ASTM A36 carbon steel with a copper-plated finish. To reduce cost, we will reuse their large outer conductor, vacuum pump, fundamental power coupler (FPC) for the EIC HSR 24.6 MHz system. We designed new long inner conductors, short inner conductor, short outer conductor, h-HOM dampers, e-HOM dampers, mechanical tuners and increased the number of ferrite fast tuners to four. Standard 25 Ohm HOM windows are used across the 98, 49, and 24.6 MHz cavity systems to minimize the design effort and cost.

DESIGN AND SIMULAITOINS

The 24.6 MHz cavities are designed to provide an accelerating voltage of 150 kV per cavity (Fig. 1). The system requires 60-kW input power from a tetrode power amplifier. The new EIC 24.6 MHz cavity parameters are summarized in Table 1 with a comparison with the RHIC 28 MHz cavity. The total RF longitudinal impedance (circuit definition) of the 24.6 MHz NCRF cavity system shall not exceed 90 kΩ·GHz. The total RF transverse impedance (horizontal and vertical, circuit definition) of the 24.6 MHz NCRF cavity system shall not exceed 2.5 MΩ/m. The cavity geometry and the HOM damper design are optimized via electromagnetic simulation in CST Studio to meet the beamline impedance thresholds [5].

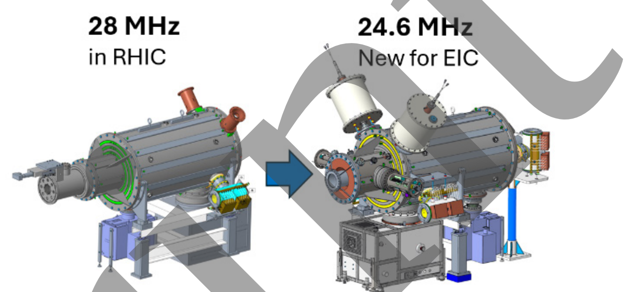

Figure 1: Conversion from RHIC 28 MHz cavity system to new EIC 24.6 MHz cavity system.

Table 1: Cavity Parameters Comparison

Cavity Parameters	28 MHz in RHIC	24.6 MHz for EIC
Frequency (MHz)	28.175	24.631
V_{acc} per cavity (kV)	300	150
E_{peak} (MV/m)	15	5.3
H_{peak} (A/m)	8e3	6e3
Q	15400	14000
R/Q cir. [Ω]	64.3	42

Tuning

The nominal frequency of 24.631 MHz corresponds to harmonic number 315 of the 78 kHz revolution frequency of the storage ring. The cavity shall provide a tuning range sufficient to cover at least one revolution frequency (−40 kHz to +40 kHz relative to 24.631 MHz). To accommodate different species energy ramping, an additional 120 kHz tuning margin shall be included, resulting in minimum required a total tuning range of 200 kHz (−160 kHz to +40 kHz relative to 24.631 MHz).

Two mechanical tuners are symmetrically mounted on the short outer conductor of the cavity, with their locations optimized to satisfy impedance requirements. The tuner mechanical design is shared with the 49 MHz and 98 MHz cavity systems [3]. The cavity has a nominal frequency of 24.631 MHz and provides a tuning range from −202 kHz to +58 kHz for the tuner insertion from 0 to −2 inches, as shown in Figure 2. A negative insertion value indicates that

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the tuner is retracted radially outward from the cavity beam axis, while a positive value indicates insertion into the cavity.

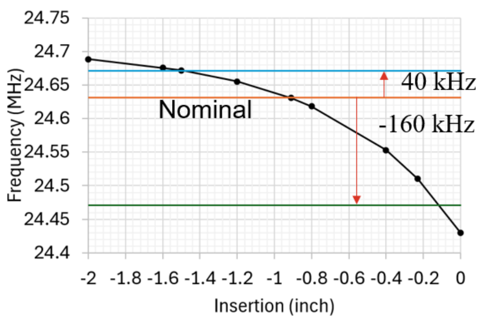

Figure 2: Tuning curve: frequency vs insertion length of the tuner.

Fast tuning required during heavy-ion beam transition crossing, four ferrite tuners are installed, providing a tuning range of 20 kHz within 2 ms, as described in detail in [6]. No fundamental mode damper (FMD) is required for the 24.6 MHz system.

HOM impedance and power

Loop-coupled HOM (h-HOM) dampers with filters are installed separated by 82° in azimuth at the existing ports on the long outer conductor. The filters are optimized to minimize transmission of the fundamental-mode power within the cavity tuning bandwidth, limiting leakage to approximately 0.05 W per h-HOM damper at nominal frequency (Fig. 3). Rexolite material is used as the mechanical support for the filters and its dielectric constant at 24.6 MHz is ε = 2.53 + 0.00078i, where the imaginary part is interpolated from posted values 0.00030 at 1 MHz, 0.00063 at 10 MHz and 0.00167 at 10 GHz.

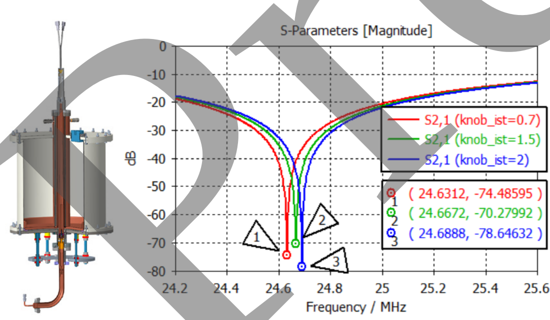

Figure 3: H-HOM damper with filter (left); S21 of h-HOM filter with the tuning knob insertion length 0.7, 1.5 and 2 inches (right).

The E-HOM dampers are spaced 90° apart in azimuth on the short outer conductor and each experience about 2.9 W of fundamental-mode power leakage.

For the 6-inch diameter beampipe, the cutoff frequencies are 1500 MHz for the TM_{01} (longitudinal) mode and 1150 MHz for the TE_{11} (transverse) mode. By optimizing the coupling of both h-HOM and e-HOM dampers to the cavity, all HOMs identified by the eigenmode solver below the cutoff frequencies are below the specified impedance thresholds both in longitudinal and transverse directions (Fig. 4).

The HOM power by the proton beam bunches has been calculated. As shown in Fig. 5, the beam current spectra for protons are presented for two high-current 275 GeV beam scenarios: 0.7 A with 290 bunches and 1.0 A with 1160 bunches.

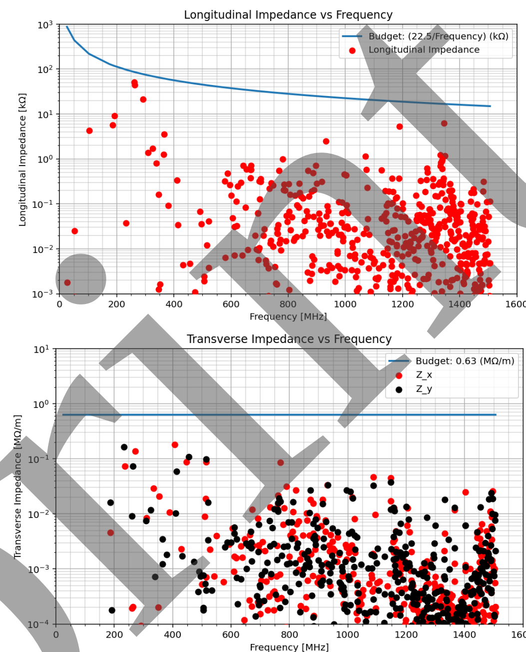

Figure 4: (1) longitudinal impedance of HOM (red points), impedance threshold for a single 24.6 MHz cavity (blue curve); (2) Transverse impedance of HOM (red is the horizontal and black is the vertical), impedance threshold for a single 24.6 MHz cavity (blue curve)

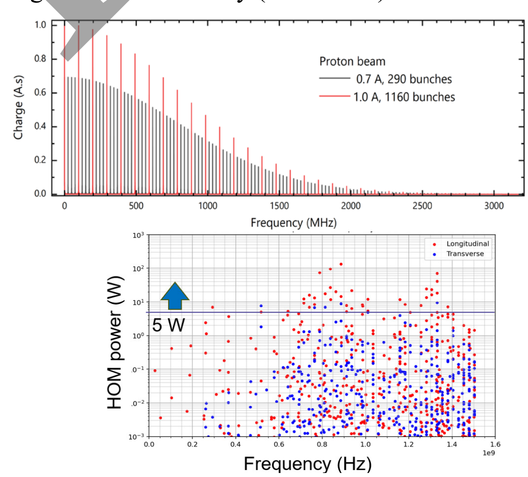

Figure 5: Beam current spectrum of proton in two bunch settings: 0.7 A 290 bunches and the 1.0 A 1160 bunches (up). b the HOM power induced by 0.7 A 290 proton bunches (down).

Table 2: Power of HOM by Proton Beams (*Worst Case Scenario with 0.6 mm Transverse Offset and HOMs Aligning with the Highest Point in Beam Spectrum within ± 0.2% Frequency Shift.)

Proton beam (275 GeV)	**Case 1 (worst case)**	**Case 2**
Bunch number	290	1160
Harmonic buckets	315	1260
Average current (A)	0.7	1
RMS bunch length (m)	0.06	0.06
Longitudinal power (W)	962	723
Transverse power * (W)	102	53
Total HOM power (W)	1064	776

Table 2 summarizes the HOM power results. For the worst case, the total HOM power reaches 1064 W, where 36 modes with power above 5 W are found to contribute 875 W (82.2%) of the total. Of this, 77.4% are absorbed by the HOM dampers. The absorbed power per load is 170.5 W for each e-HOM damper and 167.9 W for each h-HOM damper, indicating that water cooling is not required.

Multiphysics validation

Frequency shifts arising from fabrication tolerances were estimated; accordingly, a 0.3-inch trimming allowance is reserved on the short inner conductor to enable final frequency tuning. Multiphysics simulations were performed in ANSYS Workbench to analyze RF-induced thermal distributions, the water-cooling system and thermal induced deformation [7].

The heat load, calculated in ANSYS HFSS at a cavity voltage of 165 kV (110% of the nominal operating voltage of 150 kV), was used as input for the thermal and fluid analyses. Fluid simulations indicate that a flow rate of 100 GPM is required for the entire cavity system (Table 3), with a maximum pressure drop of 19.89 psi.

Thermal simulations, accounting for both RF-induced heating and water cooling, show that the cavity operates within a temperature range of 30°C to 61.5°C (Fig. 6). This meets the requirement that the NCRF cavity must operate below a maximum steady-state temperature of 70 °C.

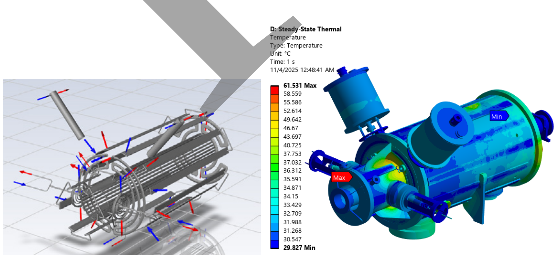

Figure 6: Water flow simulation (left); thermal simulation (right).

Table 3: Flow Rate of Water Cooling in 24.6 MHz System

Components	**Flow rate (GPM)**
Cavity main body	44
Ferrite tuners	44
Tetrode power amplifier	12
Total	100

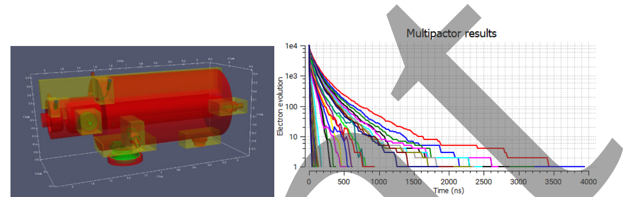

Figure 7: Highlighted 9 regions are performed multipacting analysis (left); electron evolution vs time (ns) (right).

Nine regions of the cavity were selected for multipacting analysis using Spark3D in CST Studio (Fig. 7) [5]. Simulations were conducted using secondary electron yield (SEY) curves for baked copper and TiN-coated alumina, considering three mechanical tuner positions: fully inserted, nominal, and fully extracted. The cavity voltage was scanned over a wide range: 0.1–1 kV in 0.1 kV steps, 1–10 kV in 1 kV steps, and 10–200 kV in 10 kV steps. No multipacting was observed in any of the analysed cases.

High power test after RHIC shutdown

Since the 28 MHz cavity FPC windows will be reused in the 24.6 MHz EIC cavities, they must withstand up to 60 kW of input power. New RTD (Resistance Temperature Detector) sensors were installed around the FPC window for monitoring. The cavity was operated at 60 kW input power (300 kV via detuning) for seven days, during which the FPC temperature remained stable at 54 ± 2°C and the vacuum pressure at 1×10^{-8} Torr. To account for transient beam loading during abort gap, the cavity was further tested at 78 kW (30% above nominal) with additional detuning and operated continuously for two days, maintaining an FPC temperature of 57 ± 2°C. These results confirm that the FPC windows meet the performance requirements for reuse in the EIC 24.6 MHz system.

CONCLUSION

The conversion of the existing RHIC 28 MHz cavities to 24.6 MHz cavities for the EIC HSR has been successfully designed and validated. The updated cavity system meets all key RF tuning requirements, while effectively reusing major components to reduce cost. HOM damping strategies ensure meeting the longitudinal and transverse impedance thresholds. Multiphysics simulations confirm adequate cooling capacity, structural stability and no multipacting under operating conditions. High-power testing of critical components further supports the feasibility of the design.

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