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UNDERSTANDING THE RHIC TRIPLET MAGNET VIBRATIONS IN PREPARATION FOR EIC

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Abstract

Throughout its operation, the RHIC triplet magnets have been subject to a mechanical vibration around 10 Hz. These mechanical vibrations were found to produce a beam orbit jitter that was detrimental to the collider luminosity. During RHIC operation, this has been effectively mitigated by the implementation of a fast feedback orbit control system. For the Electron Ion Collider (EIC) Hadron Storage Ring (HSR), the RHIC triplet package will be modified, magnets will be removed, and the cryogenic lines will be rearranged inside the cryostat. A comprehensive analysis of the RHIC triplet vibration has been undertaken to ensure that the planned triplet piping modifications would not increase the current triplet magnet vibrations and overwhelm the existing fast feedback control system. This paper aims to describe the current understanding of the root cause and kinematic of the RHIC triplet vibrations and offer mitigation options for EIC.

INTRODUCTION

During commissioning and early operation, RHIC has been plagued by a horizontal beam orbit jitter leading to luminosity degradation. The beam jitter, and the luminosity loss had a frequency around 10 Hz [1] and they were found to come from the triplet quadrupole magnets roll vibrations. A fast orbit feedback system was implemented and used until the end of RHIC operation. For EIC, the RHIC triplet cryostat will be modified to rearrange the cryogenic distribution piping and remove the D0 superconducting dipoles. This study was undertaken to ensure the expected roll vibration would stay under control and to find ways to improve the triplet stability.

MOTIVATION

The so-called triplets are the string of final-focusing quadrupole magnets located on each side of the six interaction region (IR) of RHIC, which are long drift straight section (grey areas in Fig. 1).

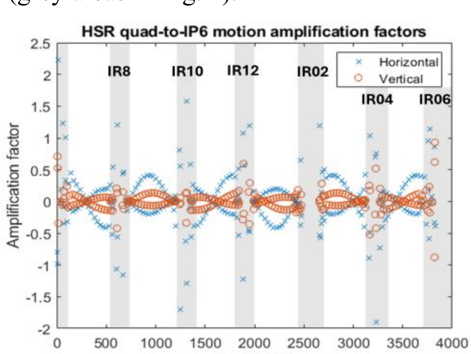

Figure 1: Transfer function from HSR quad motion to collision IP beam motion for a 275 GeV proton lattice [2].

While these triplet magnets have a moderate quadrupole field gradient compared to the arc quadrupole (48 T/m vs. 71 T/m), they are longer and their location at a much larger beam beta function makes them particularly susceptible to beam orbit alteration. Figure 1 depicts the transfer function between each quadrupole motion and the associated beam orbit motion at the collision IP for the EIC HSR. The triplet quadrupoles consistently have higher amplification factors compared to the arcs quadrupoles (Fig.1). And a stable beam orbit is particularly critical for EIC given its reduced IP beam size compared to RHIC [2] and high susceptibility to beam emittance blowup from beam-beam interaction.

PREVIOUS INVESTIGATIONS

From early on, the RHIC beam orbit jitter has been attributed to a triplet cold mass vibrations and linked to a helium pressure oscillation [3]. Direct investigations of the triplet vibrations with geophones and laser doppler have been made at the triplet sector 5 and 6 [4] and show that the beam orbit oscillation matches well with the Q2 sector 5 measured vibration (Ref. [4], Fig. 5). Pressure transducers were mounted on the cryogenic system at IR6 valve box and show a clear oscillation of the pressure in the magnet helium line at ~10.7 Hz with a peak-to-peak amplitude of 6.8 kPa [5]. Recent physics simulations show that the beam emittance growth from the beam-beam interaction at the IP explained the fast luminosity degradation seen before the implementation of the 10 Hz fast orbit feedback system [6].

VIBRATION MEASUREMENTS

Vibration measurements have been made in the RHIC tunnel during the maintenance days of RHIC run 2025 and were reported in [2]. The same setup has been used to measure the vertical vibration on the triplet magnet cryostat supports. The triplet vacuum vessel supports have an overhang which translates a magnet roll into a vertical distortion of the vacuum vessel supports that can be measured by a geophone (Fig. 2). Table 1 reports the vertical motion resonance as well as the integrated rms displacement measured on the vacuum vessel.

From these measurements, it appears that the odd sectors are more affected than the even sectors. Helium flows counterclockwise in the ring, so the helium leaves the valve box at each IR (cryogenic valves, heat exchanger, current leads) before going to the odd sector triplets, it flows through the arc magnets before reaching the even sector triplet and is finally routed to the valve box of the next IR. This suggests that pressure oscillations are generated in the valve boxes and are damped through the next arc before they reach the even sector triplets. It is also clear all cold masses of a given triplet show the same peak frequency. This can be explained by the stiff torsional coupling of the interconnect bellows between cold masses.

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Table 1: Triplet Vacuum Vessel Vibration Measured

Triplet (magnet)	**Frequency (Hz)**	**Vacuum vessel rms motion (nm)**
1 (Q1)	13.4	8.8
	17.7	6.2
2 (Q1)	None	-
3 (Q1/Q2/Q3)	13.4	**36.6/44.5/77.3**
4 (Q1/Q2)	24.9	4.8/4.5
	29.5	2.2/6.7
5 (Q1/Q2/Q3)	10.3	**81.3/53/126**
6 (Q2)	17.6	3.6
7 (Q1)	None	-
8 (Q1)	None	-
9 (Q1/Q2)	10.2	**23.5/56.5**
	16.4	13.6/6.3
10 (Q1)	19.5	5.6
11(Q1/Q2/Q3)	10.2	**51.7/6.3/62.8**
12 (Q1)	20	16

TRIPLET HELIUM DISTRIBUTION

Unlike the arc cold-to-warm transitions which contain the cryogenic line jumpers [7], the RHIC triplet cryogenic distribution was not designed with a pressure-balancing feature due to lack of space. The distribution from the cryogenic transfer lines is done through flexible stainless steel braided hose welded directly to the magnet cold mass. The cold masses are supported by relatively flexible Ultem® supports for thermal-insulation and will move inside the cryostat under the pressure load.

The RHIC triplets have two interfaces with the cryogenic distribution lines: one at the Q1-D0 interconnect (Fig. 2) and the other at Q3 non-IP end (Fig. 3).

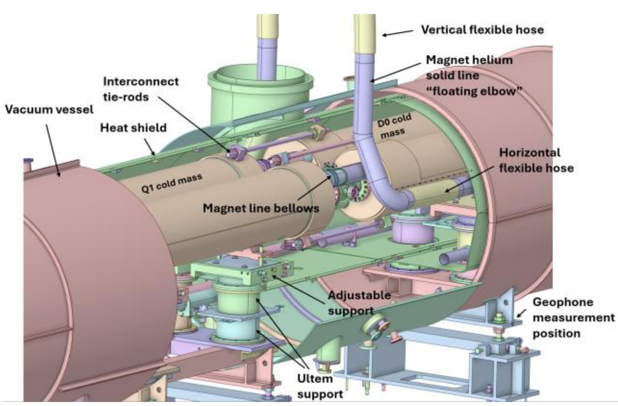

Figure 2: CAD cutaway of D0-Q1 interconnect.

In the D0-Q1 interconnect, the helium distribution utilizes a "floating" elbow design, with the elbow connected by both a vertical and horizontal flexible hose on either side. (Fig. 2). The flexible hoses have longitudinal and transverse flexibility, but once pressurized they stretch and the outer braid will sustain the longitudinal load. When under pressure the floating elbow will move freely until it finds an equilibrium position in which the flexible hose will be sustaining the pressure load through longitudinal reaction force. Assuming the axial stiffness is much greater than the transverse stiffness when pressurized, we will consider that this floating elbow arrangement does not produce significant pressure loads on the cryoassembly. While credible, this assumption would deserve further testing.

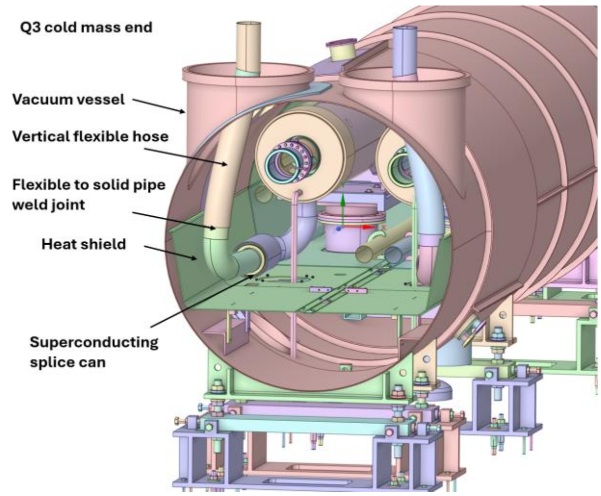

Figure 3: CAD cutaway of the Q3 end.

On the Q3 magnet end, the helium distribution only has a vertical flexible hose connect to an elbow. This elbow joint attaches to the cold mass off-axis from the magnet centerline. When the pressure in the helium line fluctuates, this lever arm will create a rolling torque on the magnet.

Note, on Fig. 2 and Fig. 3 the assemblies are simplified and do not give justice to the integration challenge (Fig. 4).

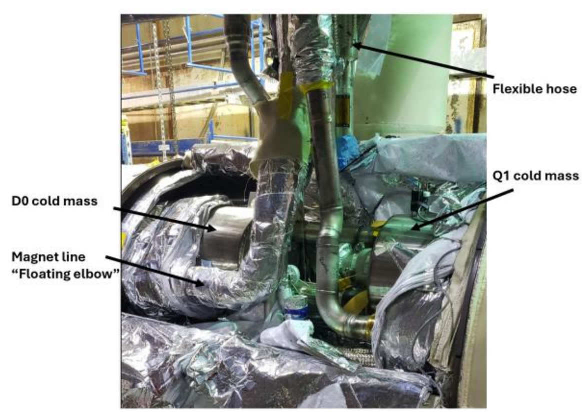

Figure 4: Triplet cryostat D0-Q1 interconnect opened during a repair in 2025.

HARMONIC ANALYSIS

To evaluate the credible motion of the quadrupole magnets inside the cryostat, a FE harmonic model has been used. We have assumed that the cold mass bellows (Fig.2) introduce a stiff coupling around their longitudinal axis, so all cold masses effectively roll as one unit. The transverse stiffness of the cold mass interconnect was calculated from the very short magnet line bellows Ø4"(101 mm) geometry with only 2 convolutions.

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The longitudinal translation is considered to be suppressed by the interconnect tie-rods (Fig. 2).

The magnet line flexible hose connecting to the Q3 solid pipe has a OD Ø4.42" (112 mm). A pressure oscillation of 6.8 kPa will then induce a variable axial load of +/- 67 N. With the solid pipe interface being offset from the magnet vertical center-plane, this lever arm will create a rolling torque on the Q3 cold mass.

Figure 5 represents the simulated displacement amplitude of the quadrupoles center from a +/- 67 N load as discussed. The Ultem support stiffness and structural damping at cryogenic temperature is obtained from [8]. The loading frequency is swept from 5 to 25 Hz and the resulting amplitude is plotted for each frequency.

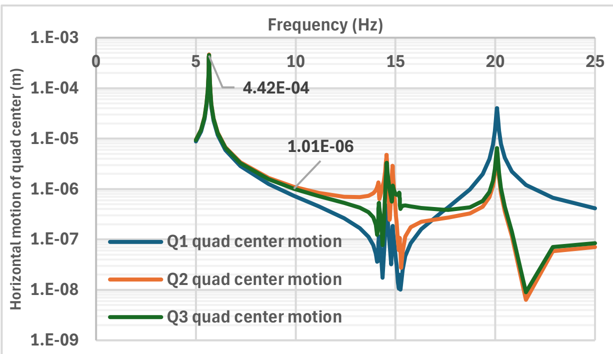

Figure 5: Harmonic analysis of the triplet quad motion wrt Q3 pressure load excitation frequency.

At an excitation frequency of 10.2 Hz, the quad center lateral displacement is simulated to be 0.7/1.1/1.0 µm for Q1/Q2/Q3 quadrupole center respectively. It is noteworthy that a lower frequency would bring even higher magnetic center amplitudes (up to 442 µm at 6 Hz !).

POSSIBLE FIXES FOR EIC

Obviously, the best way to solve this problem would be to suppress or at least dampen the helium pressure oscillations. It seems probable that a thermoacoustic oscillation is being produced in a helium-filled vertical tube penetrating the valvebox. The pressure wave seems to propagate preferentially downstream of the valvebox, in the odd sectors (Table 1) which points at the valves or the superconducting current leads in the leadpot. However, finding the source of this oscillation and fixing it may not be straightforward.

Alternatively, a pressure-balancing device would help greatly alleviate or suppress the effect of pressure on the connected components. An elegant design is the “in-line pressure-balanced expansion joint” adopted for the RHIC arc cryogenic jumpers and is described in Ref [7]. It consists of three nested bellows and tie-rods that preserve the longitudinal and transverse bellow flexibility while suppressing the pressure loads on the connected components. The integration of this design may prove challenging.

Another way to mitigate the problem is to move the tie-in point between the flexible hose and the Q3 solid pipe in-plane with the magnet centerline. This would suppress the Q3 magnet roll excitation, due to the lateral lever arm of the flexible hose joint. This would however not help with the vertical excitation which currently has an amplitude of ~64 nm at 10.2 Hz and a resonance around 15 Hz (+/-1 µm).

Figure 6 shows a harmonic analysis result with the downward pressure force brought to the magnet center plane. It is found that the reduction in quad center horizontal motion will be reduced by a factor 10x.

In the current plan, all EIC triplet cryostat will be fully rebuilt to contain only one cold mass string except for triplet 7-8 and 11-12 [9]. The new cryostat design has shorter cold mass supports which will be inherently stiffer. Care must be taken to avoid bringing the coherent roll resonance closer to 10 Hz. Doing so would dramatically increase the effect of the pressure excitation on the horizontal quad motion (Fig. 5 and 6 peak at ~6 Hz).

And regardless of helium pressure excitation, the low frequency roll resonance brings a significant lateral motion from the ground excitation as visible on Fig.4 of Ref. [4]. This will contribute to degrade the beam stability, and the triplet magnets are critical to this stability (see Fig. 1). A way to suppress the low frequency roll should be investigated. A possible route is the implementation of horizontal G10 blades/spokes joining the top of the cold mass supports to the vacuum vessel, acting as horizontal stiffeners while preserving the cold mass alignment and enough flexibility for the contraction of the Ultem supports.

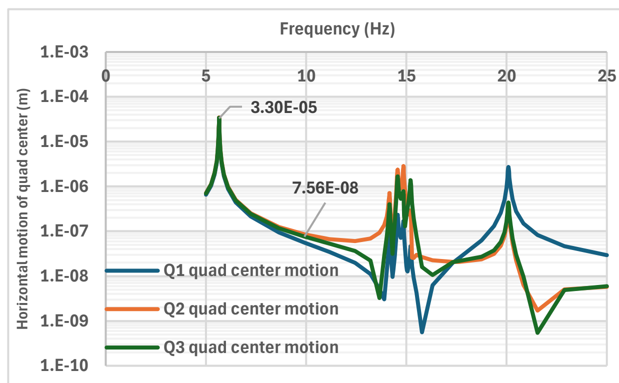

Figure 6: Harmonic analysis of the triplet quad motion - pressure force applied along the magnet centerline.

CONCLUSION

A lateral excitation of the triplet magnets, induced by helium pressure oscillations, has been problematic to the early operation of RHIC. In view of EIC, and the modifications to the triplet cryostat, a study of the root cause has been undertaken. It was found that the helium distribution piping improperly transfers the helium pressure load to the magnet supports. Ways to orient the redesign of the cryogenic distribution lines have been proposed and will help improve the overall hadron beam stability in the EIC HSR.

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