

# GROUND VIBRATION STUDIES IN THE RHIC TUNNEL IN VIEW OF EIC

F. Micolon, B. Podobedov, Brookhaven National Laboratory, Upton, NY, USA

## Abstract

As beam sizes get smaller at the collision point, the ground vibrations and their amplification through the accelerators supporting structures need more careful considerations. These mechanical disturbances can produce a beam orbit jitter that is detrimental to a collider, through loss of luminosity, beam-emittance blowup or collimator loss. In preparation for the Electron-Ion Collider (EIC), measurements of the ground vibrations in the RHIC tunnel were carried out. This paper will summarize the measurement methodology and present its main results. The expected effect on the hadron and electron beam jitter will be briefly reviewed and we will discuss some design consideration on the new electron ring magnet supports to mitigate this effect.

## INTRODUCTION

Ground vibrations have long been a point of attention for collider design. And this has become increasingly important as new collider projects aim at smaller beam size at the interaction point (IP). Vibration of accelerator components lead to beam orbit jitter at the IP. This can affect luminosity but also lead to beam emittance blow-up from beam-beam interaction. Beam orbit jitter can also lead to unwanted beam losses at the collimators.

During its early operation, RHIC was subject to a large horizontal beam orbit jitter from the high-focussing quadrupole magnets motion which impacted its luminosity [1]. The HL-LHC project has also seen a renewed interest for the subject with a smaller collision beam size [2], Super KEK-B sees luminosity variations correlated with vibrations of the final focussing magnet [3] and requires a fast orbit feedback system. And similarly, the FCC-ee project is also planned to include a fast orbit feedback system [4].

## MOTIVATION AND BEAM EFFECTS

EIC will collide flat beams with reduced vertical rms IP beam size ( $\sigma_{IP}$ ) compared to RHIC in a  $\sim 1:10$  vertical/horizontal ratio (see Table 1 from Ref. [5, 6]).

Table 1: RHIC and EIC RMS Beam Sizes Compared

Beam size at IP	Vertical	Horizontal
RHIC [5]	77 $\mu\text{m}$	77 $\mu\text{m}$
EIC [6]	8.5 $\mu\text{m}$	95 $\mu\text{m}$

EIC will also operate at the limits of beam-beam tune-shift in both colliding rings (HSR and ESR), as well as with record-large crossing angle at the IP. It was shown in Ref. [7, 8] that to limit the hadron beam emittance growth to  $<10\%/hr$ , the beam jitter needs to be  $\leq 2.5\% \sigma_{IP}$ . For EIC,  $2.5\% \sigma_{IP}$  equates to 213 nm rms of tolerable vertical beam jitter and 2.4  $\mu\text{m}$  rms horizontal.

In previous studies, the RHIC tunnel was reported as having a poor vibration stability [9] compared to other accelerator sites, with up to 118 nm rms integrated displacement @1Hz. This study aims to improve our understanding of the RHIC vibration environment and inform the design of vibration-sensitive accelerator equipment for EIC.

## SETUP AND METHODOLOGY

Vibration data were collected in the RHIC tunnel during the run 25 maintenance days to be representative of a physics run conditions (pumps, fans, cryogenic plant). All measurements were done during daytime when human activities are generating the most cultural noise [9].

A SM-24 geophone was used to probe the vertical ground velocity. The signal acquisition was done through a ADS1256 24-bits ADC with a 32x PGA owing to the relatively low sensitivity of this geophone. The SM-24 geophone has its natural resonance frequency at 10 Hz, its sensitivity has been extrapolated from 10 Hz to 4 Hz. The results were processed to get the displacement PSD and the integrated displacements RMS from 100 Hz to 4 Hz following the methodology described in [10].

A data acquisition rate 500 Hz is found to be a good trade-off between frequency resolution and ADC noise. Blank acquisitions of the complete acquisition system (without geophone) give a voltage noise of  $\sigma \sim 0.5 \mu\text{V}$ . Using the SM-24 sensitivity, the corresponding integrated RMS displacement is always  $<0.2\text{nm}$  which shows that the signal-to-noise ratio is appropriate for this analysis.

Note: while the integrated RMS displacement is commonly given between 100-1 Hz, we will report values from 100-4 Hz for the tunnel due to the limitations of our setup. At selected locations, two L4-C geophones were used for coherence measurements down to 1 Hz.

## GROUND VIBRATION RESULTS

### EIC Machine Detector Interface – Sector 5

In sector 5, vibration data were collected with the L4-C geophone setup down to 1 Hz at I-05Q10 ( $\sim 154\text{ m}$  from the IP) and at I-05Q2 ( $\sim 28\text{ m}$  from the IP) (see Figs. 1 and 2).

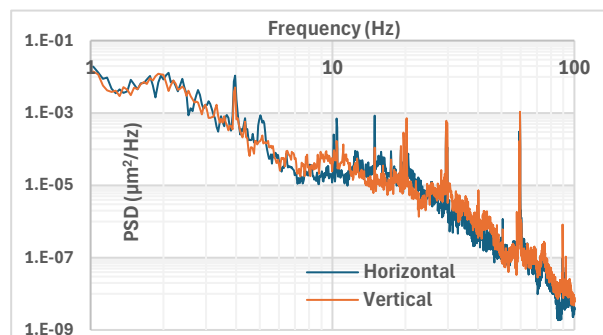


Figure 1: Displacement PSD for I-05Q2.

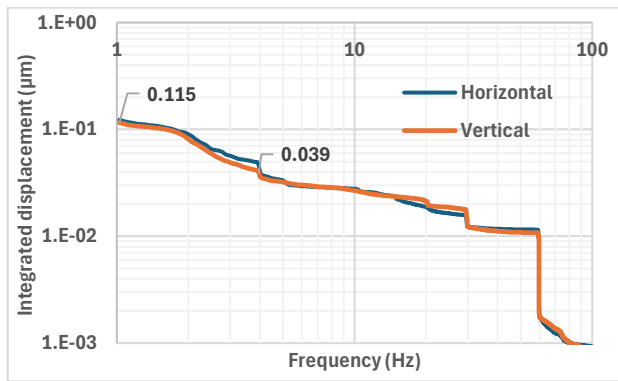


Figure 2: Integrated ground motion RMS for I-05Q2.

The total vertical rms displacement is 115 nm @1 Hz which is close to prior predictions [9] and 39 nm @4 Hz. Notable excitation of the ground can be seen at 60 Hz, 30 Hz and 20 Hz (Figs. 1 and 2). RHIC sector 05 is near the cryogenic plant and the STAR detector service buildings, so technical noise is particularly acute there.

### Ground Vibration Through the RHIC Ring

Two main sources of external vibrations have been identified, the cryoplant located above ground is producing noticeable resonances at [60,30,20] Hz in sextant 4-5 (Figs. 3 and 4). This is unfortunately the location of the new final focusing quadrupole close to the EIC detector at IR6.

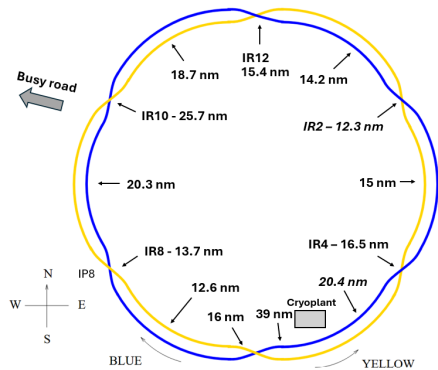


Figure 3: Vertical integrated RMS ground motion @4 Hz.

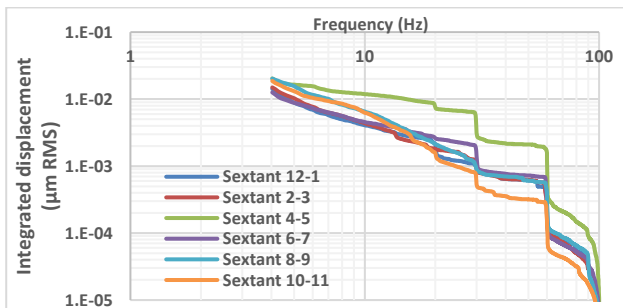


Figure 4: Vertical RMS integrated motion averaged for each RHIC sextant.

A busy public road is running along the northwest side of RHIC (Fig. 3) and is producing a higher background in sector 8-9 and 10-11 between 30-4 Hz (Fig. 4). For almost all sectors, ground resonances are seen at [60,30,20] Hz. These are typical of electrical equipment operated at 60 Hz AC (vacuum pumps, fans). The isolation of all rotating

electrical equipment in the tunnel would help reduce this background significantly.

All vibration data are stored and available [11].

### Ground Coherence Measurements

Coherence is representative of the ground motion wavelength for a given frequency. When a ground motion affects a portion of the collider simultaneously, it is not as detrimental to the beam as an uncoherent motion of each quadrupole. Coherence measurements have been made in the RHIC arc for distances of 0, 8 and 16 m (Fig. 5).

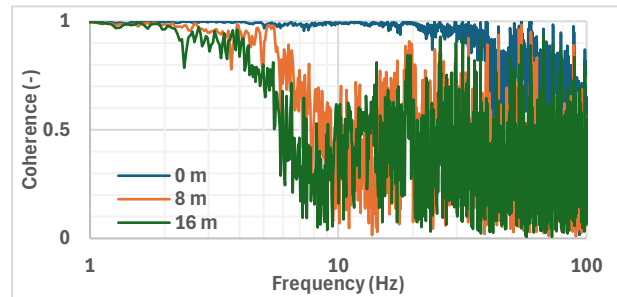


Figure 5: Vertical coherence measurements at I-05Q10.

These results are consistent with previously published coherence measurements of other collider sites [12, 13]. The distance between two consecutive quadrupoles for RHIC (and EIC HSR) is 15 m, and 9 m for the EIC ESR. From Fig. 5, at 16 m the ground motion waves are still coherent up to 4 Hz and sharply lose coherence thereafter. Although some contribution of lower frequency may be missed, we will use the values measured at 4 Hz as a first approach of the uncorrelated quadrupole motion effect on the beam jitter at the interaction point.

### EFFECTS ON THE HSR BEAM

The HSR is leveraging the existing RHIC magnets and supports [14], we will try to estimate the beam orbit jitter from the ground motion alone, without the contribution of the new MDI magnets. With their high beta-function they will have a greater effect on the beam so careful engineering of their dynamic behaviour is a must.

### Measurement and Simulation of Amplifications

RHIC superconducting (SC) magnets are supported inside their vacuum vessels on Ultem® supports for thermal insulation, so they behave as inverted pendulums. Vertical amplification measurements were performed on one of the spare RHIC CQS magnets and used to validate a finite element (FE) model (Fig 6). Vertical and transverse displacement are extracted from this FE model. Measurements were made at room temperature. At cryogenic temperature, the Ultem supports stiffness is expected to increase and their structural damping to drop sharply [15].

Similar measurements on a spare RHIC dipole did not show any obvious roll resonance, probably thanks to the horizontal bend of the cold mass along its length. Note, this analysis is based on measurement of stand-alone magnets. Possible crosstalk between interconnected magnets was not evaluated and would need to be measured in the tunnel.

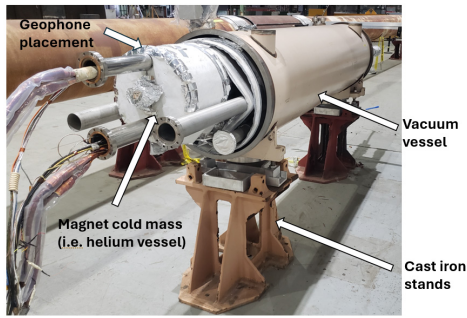


Figure 6: HSR CQS used for amplification measurements.

### Estimation of the HSR Beam Stability

Figure 7 reports the transfer function between any HSR quadrupole motion and the beam displacement at the IP. Quadrupoles with higher contribution are the final focusing magnet at each IRs. Assuming a random uncorrelated motion of each quadrupole, the amplification between all quadrupole uncorrelated motion and beam displacement at the IP is estimated around 2.6x vertical and 7.3x horizontal.

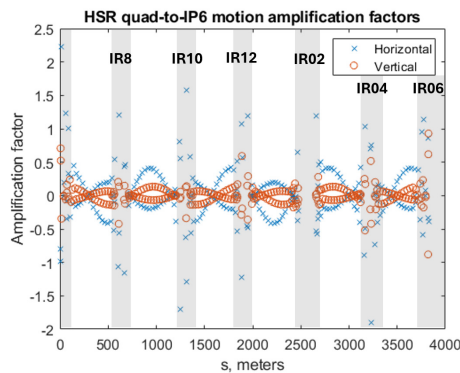


Figure 7: Transfer function for HSR quadrupole motion to collision IP beam motion for a 275 GeV proton lattice.

We will optimistically assume the RHIC triplet roll vibration from the helium distribution is suppressed [16] and the new IR and warm magnets do not introduce additional amplifications. By compounding the magnet amplification spectrum with the ground motion spectrum from sector 4-5 (Fig. 4), the HSR beam jitter would be 179 nm vertical ( $2\% \sigma_{IP}$ ) and 1437 nm horizontal ( $1.5\% \sigma_{IP}$ ) in otherwise ideal conditions (Fig. 8). The roll angle was measured around 110 nrad rms on a standalone CQS (Fig. 6).

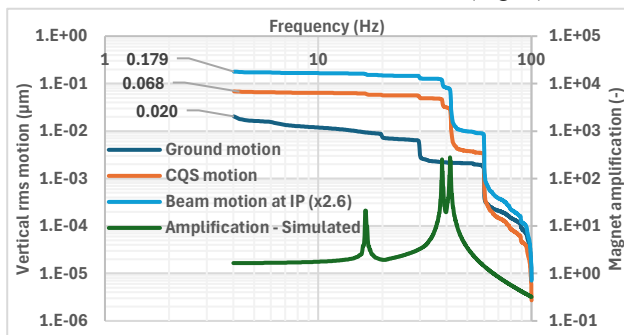


Figure 8: Ground-to-beam transfer function for a CQS.

For perspective, for RHIC the horizontal uncorrected beam jitter was 17  $\mu\text{m}$  initially, largely driven by the triplet

vibrations induced by helium pressure fluctuations. It was reduced to 1.4  $\mu\text{m}$  with a fast orbit feedback system [5].

### SOME CONSIDERATIONS FOR THE ESR

The ESR magnets will be positioned on girders currently being designed. The lattice of the ESR makes it more sensitive to the amplification of ground vibration with an expected transfer function between uncorrelated quadrupole motion and IP beam motion of 4.1x vertically and 14.8x horizontally (Fig. 9) [17].

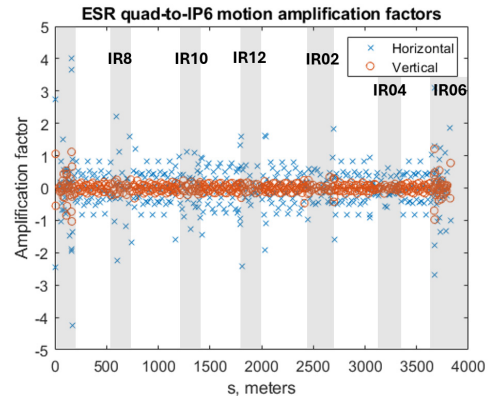


Figure 9: Transfer function for ESR quadrupole motion to collision IP beam motion for a 10 GeV electron lattice.

In an optimistic case where the girder ground vibrations amplification is x1.5 only, the vertical electron beam jitter would then be 126 nm vertical and 453 nm horizontal.

To avoid amplifying the tunnel ground vibration we should aim for girders to avoid resonances in the vicinity of the [20,30,60] Hz frequencies and obviously the low frequencies. Having the first resonances around 45 Hz (similar to Fig. 7) seems to offer a reasonable compromise.

Alternatively, a design with visco-elastic damping pads has previously been implemented on girders at ESRF with a good outcome [18]. Due to the large synchrotron radiation in the ESR, high water flow will be required in the vacuum chamber and magnets, the distribution of this water must be engineered not to increase the girders vibrations too significantly as was seen at SLAC SLC [19]. Large variations of tunnel and hardware temperature are also foreseeable, although they will happen over longer timescale.

For perspective, HERA was reported as having a vertical electron orbit motion  $\sim 2 \mu\text{m}$  at  $\beta^*=1 \text{ m}$  which was suspected to “injure the proton beam lifetime severely” [20].

### CONCLUSIONS AND OUTLOOK

The EIC design is sensitive to beam emittance blowup from beam-beam interaction if the beam jitter is too high. A systematic study of the tunnel ground motion has been conducted as well as measurements on spare RHIC magnets. Considering the effect of ground motion alone, and with optimistic assumptions, the cumulated beam jitter will be  $>2.6\% \sigma_{IP}$  (219 nm) vertical and  $>1.6\% \sigma_{IP}$  (1507 nm) horizontal from ground vibration alone. This is above the requirement to maintain a beam stability  $\leq 2.5\% \sigma_{IP}$ . A fast orbit feedback system will be required to ensure the orbit stability requirement is met.

## REFERENCES

- [1] C. Montag *et al.*, “Observation of mechanical triplet vibrations in RHIC”, in *Proc. Nanobeam’02*, CERN-Proceedings-2003-001, p. 93, 2003.
- [2] M. Schaumann *et al.*, “The effect of ground motion on the LHC and HL-LHC beam orbit”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 1055, p. 168495, Oct. 2023. doi:10.1016/j.nima.2023.168495
- [3] M. Serluca *et al.*, “Vibration and luminosity frequency analysis of the SuperKEKB collider”, *Nucl. Instrum. Methods Phys. Res. A*, vol. 1025, p. 166123, Feb. 2022. doi:10.1016/j.nima.2021.166123
- [4] J. Salvesen, F. Zimmermann, and P. Burrows, “First studies on error mitigation by interaction point fast feedback systems for FCC-ee”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 3322-3325. doi:10.18429/JACoW-IPAC2024-THPG31
- [5] Y. Luo *et al.*, “Revisit the effects of 10 Hz orbit oscillation in the relativistic heavy ion collider”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 124-127. doi:10.18429/JACoW-IPAC2023-MOPA046
- [6] F. Willeke and J. Beebe-Wang, “Electron Ion Collider Conceptual Design Report 2021”, Brookhaven National Laboratory, Upton, NY, USA, Rep. BNL-221006-2021-FOR, Feb. 2021. doi:10.2172/1765663
- [7] B. Podobedov *et al.*, “Physics-driven specifications for the EIC ESR magnet power supply ripple”, in *Proc. IPAC’25*, Taipei, Taiwan, Jun. 2025, paper MOPS065, to be published.
- [8] D. Xu, M. Blaskiewicz, Y. Luo, D. Marx, C. Montag, and B. Podobedov, “Effect of electron orbit ripple on proton emittance growth in EIC”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 108-111. doi:10.18429/JACoW-IPAC2023-MOPA039
- [9] W. Bialowons, R. Amirikas, A. Bertolini, and D. Kruecker, “Measurement of ground motion in various sites”, in *Proc. EPAC’06*, Edinburgh, UK, Jun. 2006, paper MOPLS064, pp. 691-693.
- [10] DESY, [https://vibration.desy.de/data\\_analysis/fouriertransform](https://vibration.desy.de/data_analysis/fouriertransform)
- [11] BNL, <https://brookhavenlab.sharepoint.com/:f:/r/sites/erhic/tsd/Group%20Documents/Mechanical%20Engineering/RHIC%20tunnel%20vibration%20Run25?csf=1&web=1&e=wDF55k>
- [12] V. Shiltsev, B. Baklakov, P. Lebedev, C. Montag, and J. Rossbach, “Ground motion measurements in HERA”, in *Proc. PAC’95*, Dallas, TX, USA, May 1995, paper TAA01, pp. 2078-2080.
- [13] K. Artoos *et al.*, “Ground vibration and coherence length measurements for the CLIC nano-stabilization studies”, in *Proc. PAC’09*, Vancouver, Canada, May 2009, paper TH5RFP081, pp. 3636-3638.
- [14] F. Micolon *et al.*, “From RHIC to EIC hadron storage ring - overview of the engineering challenges”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 951-954. doi:10.18429/JACoW-IPAC2024-TUBD1
- [15] L. J. Wolf, J. H. Sondericker, and W. A. DeVito, “Elastic Moduli of Ultem and Noryl at Cryogenic temperatures using vibrating beam specimens”, Brookhaven National Laboratory, Upton, NY, USA, Rep. AD/RHIC/RD-21, Jun. 1990. doi:10.2172/1119145
- [16] F. Micolon and J. Greene, “Understanding the RHIC triplet magnet vibrations in preparation for EIC”, presented at NAPAC’25, Sacramento, CA, USA, Aug. 2025, paper WEP095, this conference
- [17] B. Podobedov and D. Marx, “ESR magnet vibrational specifications for dynamic orbit stability at the IP”, Brookhaven National Laboratory, Upton, NY, USA, Rep. BNL-222179-2021-TECH/EIC-ADD-TN-022, Sep. 2021. doi:10.2172/1823635
- [18] L. Zhang, M. Lesourd, and T. Lewis, “Vibration damping systems for magnet girder assembly at the ESRF”, in *Proc. PAC’01*, Chicago, IL, USA, Jun. 2001, paper TPAH109, pp. 1465-1467.
- [19] J. L. Turner *et al.*, “Vibration studies of the Stanford Linear Accelerator”, in *Proc. PAC’95*, Dallas, TX, USA, May 1995, paper RPB04, pp. 665-667.
- [20] W. Decking, K. Floettmann, and J. Rossbach, “Measurement of slow closed-orbit motion in the HERA electron ring in correlation with ground motion”, in *Proc. EPAC’90*, Nice, France, Jun. 1990, pp. 1449-1452.