Observation of Mechanical Triplet Vibrations in RHIC*

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Abstract

Mechanical vibrations of the RHIC IR triplets has been identified as the dominant source of horizontal orbit jitter in the frequency domain below 20 Hz. Results of detailed measurements are be reported to characterize these effects.

1 INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) is designed and built to collide ions from protons to fully stripped gold at energies up to $250\,\mathrm{GeV}$ for protons and $100\,\mathrm{GeV/nucleon}$ for heavy ions. The two $3.8\,\mathrm{km}$ long superconducting storage rings (“Blue” and “Yellow”) of RHIC intersect at six equidistantly-distributed locations around the machine circumference, as shown in Figure 1. The nomenclature of these interaction regions (IRs) resembles a clock, with “12 o’clock” referring to the northernmost IR. Within each of these IRs, the superconducting low-β quadrupole triplet on the right – as seen from the center of the RHIC rings – bears the same number as the IR itself, while the left triplet is named after the arc to its left. For example, in the 6 o’clock interaction region, the right triplet is called the 6 o’clock triplet, while the left one is referred to as the 5 o’clock triplet. Four out of six IRs are equipped with detectors: BRAHMS (2 o’clock), PHENIX (6 o’clock), STAR (8 o’clock), and PHOBOS (10 o’clock). The 12 o’clock interaction region is occupied by polarimeters, while the RF cavities reside at 4 o’clock. However, all six IRs are equipped with identical magnets.

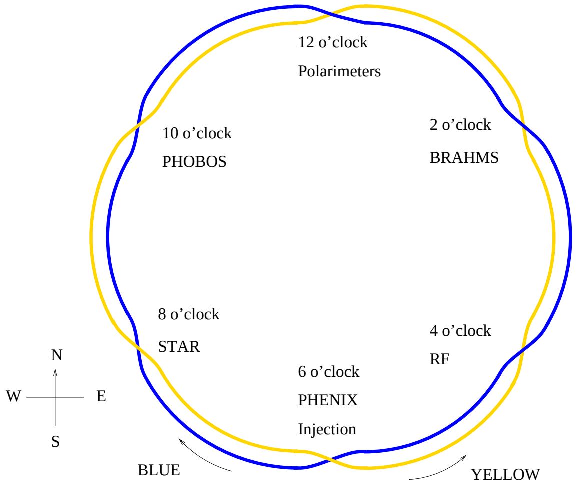

Figure 1: RHIC schematic overview

During the 2001 RHIC run, purely horizontal orbit jitter with frequencies around $10\,\mathrm{Hz}$ was detected in both rings [1]. This oscillation can be observed at all BPMs around the rings regardless of betatron phase, indicating distributed sources. At storage energy the amplitude of this vibration corresponds to $5\ldots10$ percent of the rms beam size at a nominal 6σ normalized emittance of $10\pi\,\mathrm{mm\,mrad}$. A spectral analysis of this orbit jitter revealed that spectra in both beams are almost identical, Figure 2. Therefore this effect was likely to be caused by single or multiple common vibration sources.

As already mentioned earlier, the two RHIC rings share only very few common magnetic elements in the IRs, while the D0 dipoles and the entire arcs are completely independent, Figure 3. The observed horizontal orbit oscillation could therefore be caused by power supply ripple on the DX dipoles, or by mechanical vibration of the triplet quadrupoles, which share a common cryostat for both rings though the actual magnets are mechanically independent. During a maintenance day in October 2001, vibration measurements were performed at all RHIC triplet cryostats to determine the sources of the orbit jitter.

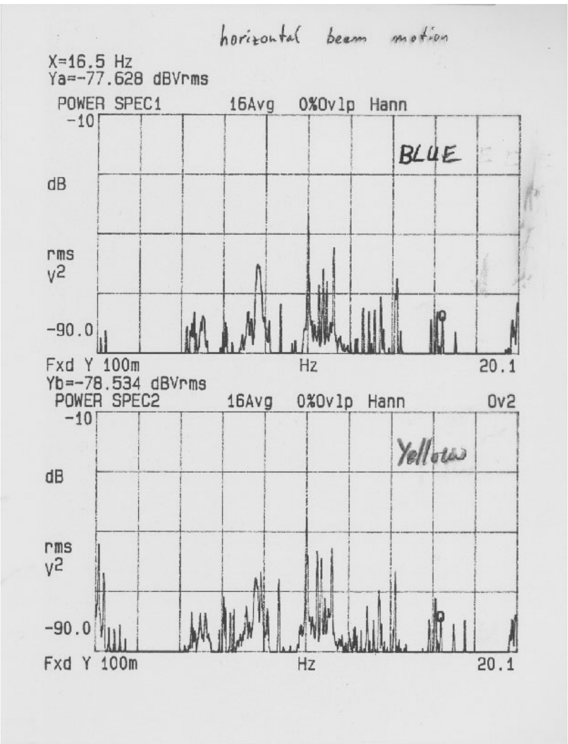

Figure 2: Simultaneously measured horizontal orbit vibration spectra in the BLUE (top) and YELLOW (bottom) RHIC rings.

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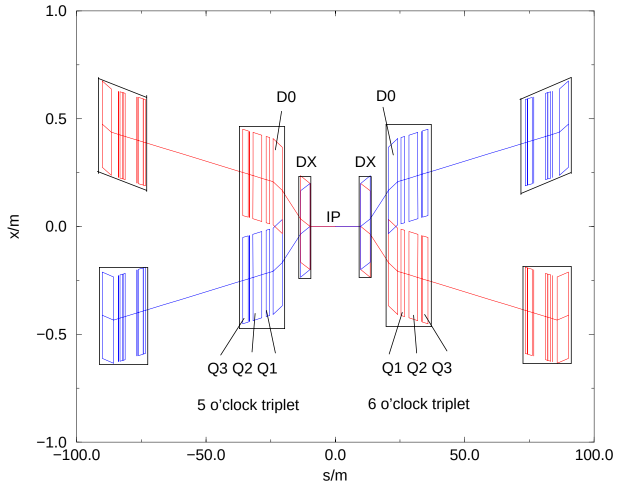

Figure 3: Schematic view of a RHIC interaction region lattice. Both beams collide head-on at the interaction point (IP) and are separated by the DX dipoles. Both orbits are bent back to an almost parallel direction by the D0 dipoles. Strong focusing is provided by superconducting triplets consisting of the quadrupoles Q1, Q2, and Q3.

2 VIBRATION MEASUREMENTS

Vibration measurements were performed on the outside of all RHIC cryostats, usaing a 3-axis accelerometer. This sensor was connected to a spectrum analyzer to study vibration characteristics in all three directions. Each triplet showed one or two dominant lines around $10\,\mathrm{Hz}$ in the horizontal direction, while few exhibited significant lines in the vertical plane. The dominant frequency lines detected in the horizontal plane clearly explain almost all dominant lines present in the horizontal beam jitter spectrum. As an example, Figure 4 shows the acceleration spectrum of horizontal motion of the 4 o'clock triplet, together with the spectrum of horizontal beam orbit vibration. The two peaks at $10.14\,\mathrm{Hz}$ and $16.50\,\mathrm{Hz}$ can be clearly identified in the beam jitter spectrum. Table 1 summarizes all major peaks within the beam jitter spectrum (Figure 2), together with the triplet at which these lines could be identified in the vibration spectrum of the cryostat, and the amplitude of the cryostat vibration. As this table shows, 13 out of 14 dominating frequencies in the horizontal beam jitter spectrum can be explained by mechanical motion of specific triplets.

3 MECHANICAL CONSIDERATIONS

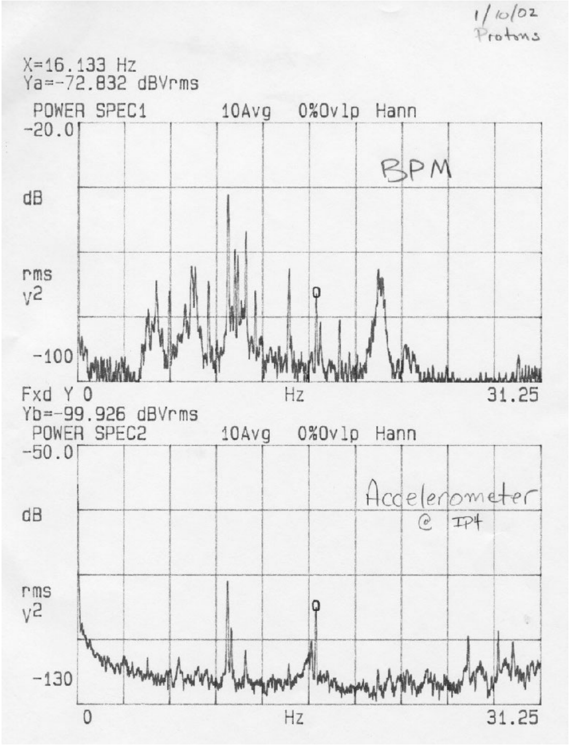

Figure 4: Simultaneously measured beam orbit vibration spectra in the YELLOW RHIC ring (top) and the 4 o'clock triplet acceleration (bottom).

Each triplet cryostat contains eight cold masses: two cold masses for the two D0 dipoles, and two for each pair of quadrupoles Q1, Q2, and Q3. Each of these cold masses is suspended on two posts, which for mechanical considerations can be regarded as springs, as schematically shown in Figure 5. The connection between the cold masses is stiff only in the longitudinal direction, while it is designed to allow independent transverse motion [2]. Therefore, coupled motion of the cold masses is neglected.

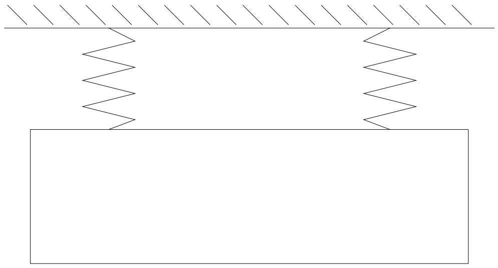

Figure 5: Mechanical model of a quadrupole cold mass suspended on two posts, indicated as springs here.

The configuration with two posts allows for two oscillation modes for each cold mass, a dipole mode with resonance frequency $f_d = \sqrt{2D/m}$, and a quadrupole mode with resonance frequency $f_q = \sqrt{2Ds^2/\Theta}$. Here, D denotes the spring constant of the posts, m the mass of the cold mass, s the distance from the center of the cold mass to the location of the post, and Θ the moment of inertia of the cold mass. Approximating the cold mass as a solid cylinder with length L and radius R, its moment of inertia can be calculated as

$$\Theta = \frac{mR^2}{4} + \frac{mL^2}{12}. \tag{1}$$

Frequency/Hz	Triplet	Amplitude/nm
7.75	12	42
8.825	8, 9	33, 83
10.14	4, 5, 11, 12	211, 24, 90, 16
10.625	9	57
10.825	1, 2	33, 141
11.00	11	33
11.325	5	250
12.700	(10)	(23)
13.000	1	15
13.275	unknown	
13.55	9, (2)	6, (63)
14.325	1, 2, 3	30, 18, 39
15.950	2	18
16.133	3	13
16.500	8	2

Table 1: Dominant frequency lines of beam orbit vibration as shown in Figure 2, and triplets where these frequencies have been detected in the horizontal vibration spectrum. The third column contains the corresponding triplet vibration amplitues. Numbers in brackets indicate locations where the corresponding frequency is present in the vertical triplet vibration spectrum only.

	Q1	Q2	Q3
m/kg	1130	2580	2260
R/m	0.35	0.35	0.35
L/m	2.24	4.90	4.37
l/m	1.44	3.39	2.10
k/m^{-2}	$-5.76 \cdot 10^{-2}$	$5.61 \cdot 10^{-2}$	$-5.57 \cdot 10^{-2}$
s/m	0.49	1.44	1.19
Θ/kgm^2	481	5182	3614
β/m	404	551	248
f_d/Hz	21.2	14.0	15.0
f_q/Hz	15.8	14.3	14.1

Table 2: Mechanical parameters of the quadrupole cold masses in the triplet, together with the corresponding β-functions, magnetic lengths l, and magnet strengths for $\beta^* = 2\,\mathrm{m}$ at the IP.

In the transverse horizontal direction, the spring constant of these posts is $D = 6.0 \cdot 10^4\,\mathrm{lbs/in} \approx 1.0 \cdot 10^7\,\mathrm{N/m}$. The resulting resonance frequencies f_d and f_q for the quadrupole cold masses are listed in Table 2. Most of the resonance frequencies calculated for this simple mechanical model are well within the region detected on the beam, though they do not explain observed frequencies as low as $8 \cdot 11\,\mathrm{Hz}$.

4 BEAM DYNAMICS EFFECTS

The magnet vibration amplitude σ_q can be inferred from the measured beam orbit jitter, using the expression for a closed-orbit distortion caused by N quadrupoles having an uncorrelated misalignment of σ_q [3],

$$\sigma_{\mathrm{co}}(s) = \frac{\sqrt{\beta(s)}\sqrt{\langle\beta\rangle}}{2\sin\pi\nu}\frac{\sigma_q}{|f|}\sqrt{N}, \qquad (2)$$

where $\sigma_{\mathrm{co}}(s)$ and $\beta(s)$ are the rms orbit jitter amplitude and the β-function at the observation point s, ν is the betatron tune, and $f = kl$ is the focal length of the quadrupole with length L and strength k. Since orbit jitter can be observed at all locations around the machine, with an rms amplitude of about 5 percent of the nominal beam size, the left side of this equation can be replaced by

$$\sigma_{\mathrm{co}}(s) = 0.05 \cdot \sqrt{\epsilon \cdot \beta(s)}. \qquad (3)$$

Assuming that the three quadrupole cold masses in each of the twelve triplets vibrate independently, the rms quadrupole vibration amplitude σ_q can be estimated using the mean focal length ($\langle|f|\rangle^{-1} = \sum|kl|/3 = 0.13\,\mathrm{m}^{-1}$ and $N = 3 \cdot 12 = 36$) as $\sigma_q \approx 0.5\,\mu\mathrm{m}$, which is a factor of $2 \ldots 10$ times larger than what is observed on the triplet cryostat.

Calculating the corresponding value for the case that all cold masses within one triplet oscillate synchronously, the required oscillation amplitude σ_q can be estimated at $\sigma_q = 10.0\,\mu\mathrm{m}$, using $\langle|f|\rangle^{-1} = |\sum kl/3| = 0.011\,\mathrm{m}^{-1}$ and $N = 12$. This value is a factor $40 \ldots 200$ larger than the measured cryostat vibration amplitudes. It is therefore likely that the orbit jitter is caused by independent vibration of individual cold masses.

Since the optics in the IRs is asymmetric in Blue and Yellow (Figure 6), vibration of the common cold masses results in relative orbit offset at the IP – and since the phase advance in inner and outer arcs is different, there is also an orbit offset at all the other IPs. This modulated beam-beam offset may cause transverse emittance growth, which in turn might explain the fast luminosity degradation during the first minutes of each fill, Figure 7. This effect is currently being studied by simulations.

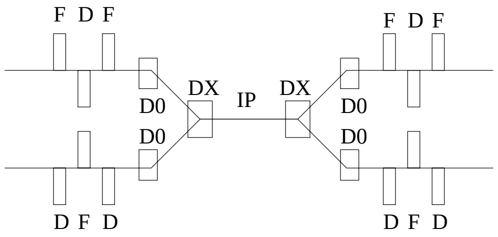

Figure 6: Schematic drawing of the IR optics.

5 CONCLUSION

It has been confirmed that horizontal orbit jitter around $10\,\mathrm{Hz}$ is indeed caused by mechanical vibrations of the

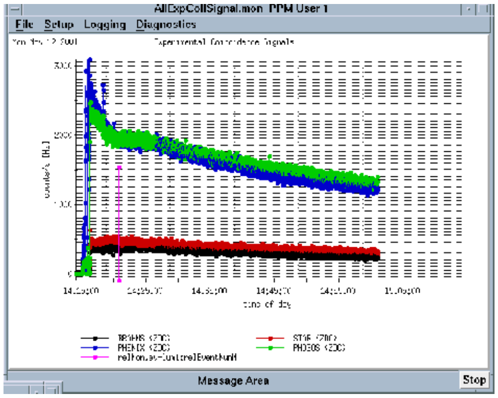

Figure 7: Luminosity during the first 45 minutes into a store.

IR triplet quadrupoles. A possible explanation of these vibrations is an oscillating helium pressure wave in the downward-angled leads of the triplets [4]. When liquid helium reaches the warm end of the lead, it quickly warms up and changes into its gaseous phase, leading to a greatly increased volume. This helium gas pushes the liquid helium back until an equilibrium is reached. The helium gas is subsequently pumped away, leaving room for liquid helium, which flows back to the warm end of the lead, where the whole process repeats. The resulting pressure wave oscillation could introduce sufficient force to the cold mass to cause the observed vibration. The mechanical resonance frequency of the cold mass on its two posts is also near 10 Hz, snf this could further enhance the effect.

This scenario is consistent with the observation that the mechanical triplet vibration could no longer be detected during the shutdown after the machine had been warmed up. A more direct test of this hypothesis could be performed by increasing the helium flow in the leads such that the entire lead is eventually cooled to liquid helium temperature, avoiding the reflection of liquid helium. However, this test cannot be performed easily, because the helium flow is determined by fixed orifices.

If this model explains the observed triplet vibrations, an increased helium flow in the leads will eliminate it entirely. Other possible remedies include installation of an active feedback system to stabilize orbit jitter at the IPs. However, such a system would have to rely on the common beam position monitors near the IPs, which are currently not reliable enough for this purpose [5].

Simulation studies are being performed to investigate possible emittance growth caused by beam centroid motion at the interaction points during beam collisions, and associated beam-beam driven tune modulation. This work is still in progress, as well as vibration measurements on the cold masses of one sample triplet.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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