EFFECT OF TRIPLET MAGNET VIBRATIONS ON RHIC PERFORMANCE WITH HIGH ENERGY PROTONS

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Abstract

In this report we present recent experimental data from the Relativistic Heavy Ion Collider (RHIC) illustrating effects resulting from ~10 Hz vibrations of the triplet quadrupole magnets in the interactions regions and evaluate the impact of these vibrations on RHIC collider performance. Measurements revealed modulation of the betatron tunes of appreciable magnitude relative to the total beam-beam parameter. Comparison of the discrete frequencies in the spectra of the measured beam positions and betatron tunes confirmed a common source. The tune modulations were shown to result from feed-down in the sextupole magnets in the interaction regions. In addition we show that the distortions to the closed orbit of the two counter-rotating beams produced a modulated crossing angle at the interaction point(s).

INTRODUCTION

RHIC consists of two counter-rotating superconducting accelerators with six symmetrically located interaction regions [1]. On either side of each interaction region are installed three super-conducting quadrupole magnets (triplets) which are used to transversely focus the beams at the interaction points (IPs). Mechanical vibrations of the triplets were diagnosed as the dominant source of horizontal orbit "jitter" [2] during early commissioning of RHIC. Measurements with accelerometers located both external [2] and internal [3] to the cryostats revealed a strong correlation in the detected mechanical motion and the frequency spectrum of the beam position. Later tests identified liquid helium flow as the cause of the mechanical vibrations [4]. Fortunately, with the exception of one unsuccessful attempt to operate with vertical betatron tunes close to integer in run-8, the effects of continuous orbit distortions driven by the vibrating triplets were relatively benign.

During run-9 polarized protons were accelerated up to 250 GeV [5] and later to 100 GeV [6] per beam and collided at two locations. The beta-function at the IPs were reduced from 1.0 m to 0.7 m and the transverse beam emittances were ~25% smaller than in past runs [7] resulting in correspondingly larger beam-beam parameters. In run-9 measurements of various beam parameters were found to be dominated by the driven beam oscillations. Improved measurement resolution also allowed new dynamics to be revealed. In this report we present the experimental observations and discuss the possible impact of the triplet vibrations on the performance of RHIC in run-9 with high energy protons now colliding in the strong-strong limit of the beam-beam interaction.

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BETATRON TUNE MODULATIONS

Shown in Fig. 1 are measurements of the betatron tunes made during run-9 following numerous improvements [8] to the measurement hardware and data processing. The data evidence strong peak-to-peak tune modulations of $\sim 10^{-3}$ in both transverse planes. From the expanded view, the modulations are seen to be out of phase which suggests that the modulations were not instrumental. The integrity of these data was independently confirmed using a fast (~ 50 Hz modulation frequency) quadrupole.

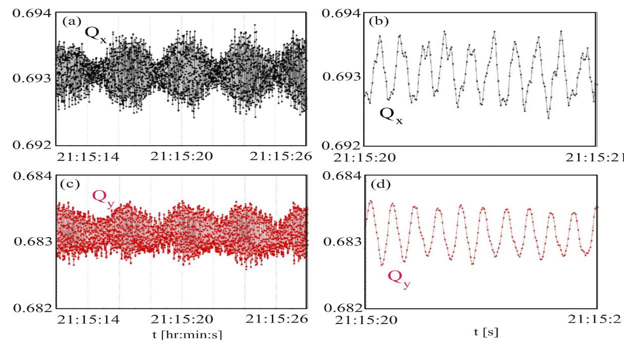

Figure 1: Measured tunes at 250 GeV evidencing modulations. Plotted are the horizontal (Q_x:a,b) and vertical (Q_y:c,d) tunes with expanded time scale on the right.

The peak-to-peak amplitudes of these tune modulations were not insignificant compared to the estimated peak beam-beam parameter of ~0.008/IP and the rather narrow tune window for run-9 bounded by the orbital resonance at Q_y=2/3 and spin resonance at Q_y=7/10. These observations, together with the run-8 experience at near-integer tune, have renewed interest in efforts to reduce the effects of the 10 Hz orbit distortions [9-10].

CORRELATION WITH BEAM POSITION

Beam position monitor (BPM) data were taken concurrently with those shown in Fig. 1 and Fourier analyzed as shown in Fig. 2. The same set of discrete frequencies were detected in the position and tune spectra indicating that the tune modulations resulted directly from feeddown in higher order multipole fields sampled by off-axis beam trajectories driven by the triplet vibrations. As shown in Fig. 3, measurements taken before and after multipole corrections in the IR sextupoles [11] showed a clear reduction of tune variations from $1.2 \times 10^{-3}/1.6 \times 10^{-3}$ in the horizontal (Q_x) and vertical (Q_y) tunes to $< 0.5 \times 10^{-4}$.

EFFECT ON BACKGROUNDS

On many occasions during run-9, the detector backgrounds and/or beam decay signals were observed to oscillate with a period of τ~20 seconds. An example is given in Fig. 4. From the corresponding Fourier spectra of the beam positions, this structure (as well as that shown in Fig. 1) is now understood as a modulation ("beating") of two dominant nearby (Δf=1/τ=0.05 Hz) excitations.

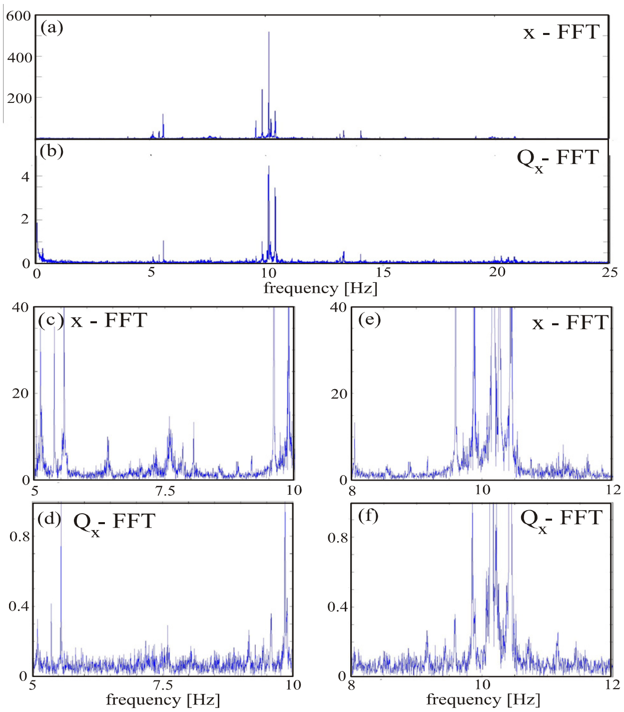

Figure 2: Fourier transforms of the horizontal beam positions (a,c,e) and horizontal betatron tunes (b,d,f) with full scale of 0-25 Hz (top), an expanded view about 5-10 Hz (bottom left) encompassing known mechanical resonant frequencies [9], and about 8-12 Hz comprising the dominant observed frequencies (bottom, right).

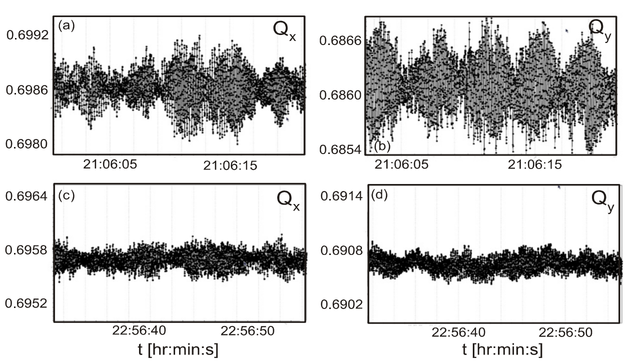

Figure 3: Measured betatron tunes before (a,b) and after (c,d) IP multipole corrections which reduced modulations.

EFFECT ON LUMINOSITY

An outstanding puzzle concerned the effectiveness of orbit feedback [12] designed to suppress the relative offset between beams at the IPs as this was shown in simulation to cause emittance growth [13]. Unfortunately no discernible improvement was observed with this feedback.

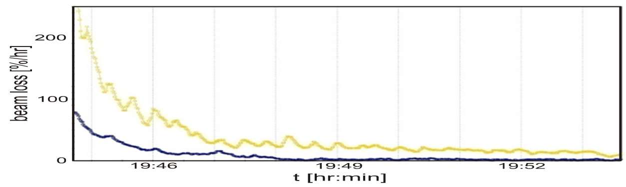

Figure 4: Beam loss rates in each accelerator, inferred from a wall current monitor, versus time evidencing the beating of two nearby excitation frequencies.

MODULATED CROSSING ANGLE AT THE INTERACTION POINT

This apparent discrepancy can be explained if the closed orbit distortions were predominantly manifest as modulated crossing angles rather than transverse offsets at the IPs. Shown in Fig. 5 are beam positions measured on either side (+/-8.33 m) of the IP in each accelerator with color coding for the BPMs the same in both plots. At a fixed time, the data show that a bunch accelerated in one direction has an inward pointing trajectory as it approaches the IP while the opposing bunch has a trajectory pointing outwards as it approaches the IP; that is, the colliding bunches experienced a crossing angle which was modulated by the 10 Hz closed orbit distortion driven by the vibration of the triplet quadrupoles.

The amplitude of the crossing angle produced significant long-range beam-beam interactions between the head of one bunch and the tail of the opposing bunch: with design (95%, normalized) emittances of ε=10π mm-mrad, the run-9 beta-function at the IP of β*=0.7m and beam energy E=250 GeV, the rms beam size and rms angular diver-gence at the IP were 65 μm and 100 μrad, respectively. With BPMs located ~10 m from the IP and ±500 μm peak amplitude of the 10 Hz oscillations, the deviation from a straight trajectory through the IP corresponds to a maximum tilt angle of 50 μrad or 100 μrad between the head of one bunch and the tail of the other bunch. With a FWHM bunch length of σ_z=5 ns, at a displacement of σ_z the relative displacement between the colliding particles was 60 μm which was about equal to the transverse beam size.

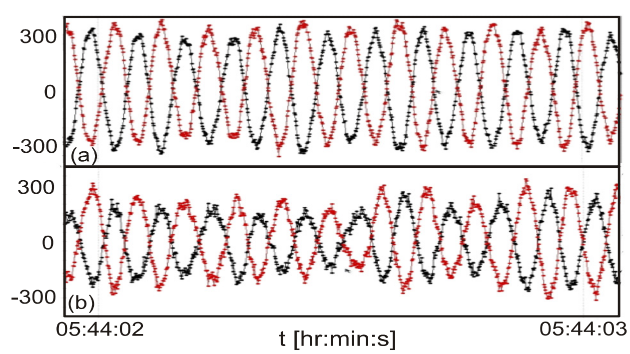

Figure 5: Beam positions (μm) as measured on either side of an IP for one beam (a) and the counter-rotating beam (b) demonstrating a modulated crossing angle at the IP.

EFFECT ON LUMINOSITY, REVISITED

For the past few years the luminosity lifetime of high intensity protons has evidenced an increasingly large initial rapid decay followed by the majority of the store characterized by longer lifetimes. As shown in Fig. 6 for a few stores from the end of run-9, the beam loss at the onset of collisions was typically 10 to 20 %. The driving mechanism(s) for these losses has (have) not yet been conclusively determined.

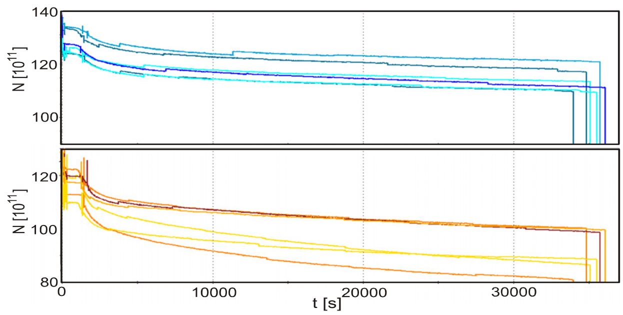

Figure 6: Total number protons, N, in each accelerator versus time from start of acceleration ramp during run-9.

Dynamic aperture limits probed by the modulated betatron tunes with beams out of collision are excluded based on the long lifetimes observed (t<1000 s in Fig. 6) before collisions. With collisions, this effect was also not observed based on evaluation of luminosity operations after the reduction of tune modulations shown in Fig. 4.

Alternatively the particle loss may be due to bringing the beams into collision (by removal of transverse relative offsets) or to the nonlinear beam-beam forces (both of which are present with and without orbit and tune modulations). Concerning the latter, at RHIC a relatively large portion of the tune diagram was sampled as the beam currents decayed since the betatron tunes with beams in collision were not regulated. To date there has not been any evidence of strong localized beam-beam resonances (although beam loss driven by multiple weak beam-beam resonances is not excluded).

Another possibility is that the modulated crossing angle caused particles towards the tail/head to experiencing closed orbit distortions due to long-range intrabunch beam-beam interactions. Figure 4 for example showed, somewhat inexplicably, that at the end of a store when the loss rates were typically smallest with well-collimated beams, particles existed that had been driven to large amplitudes. That the initial rapid decay of luminosity may be attributable to the modulated crossing angle is also shown in Fig. 7 where is plotted the luminosity (top) as measured by a zero degree luminosity detector (ZDC) and beam positions with monitors located at $\pm$8.33 m from the IP. While the luminosity measure at the onset of collisions may have a contribution from backgrounds, both the ZDC and BPMs evidenced similar time structure. Another observation of interest is the absence of documented evidence of the now characteristic 10 Hz beat frequencies in the measured decay rates with beams at full energy but without collisions.

SUMMARY

In this report we demonstrated that measurement precision in run-9 was often dominated by the presence of 10 Hz modulations of the closed orbit and betatron tunes. Tune modulations were resolved and the source identified as feed-down due to off-axis beam in the IP sextupoles.

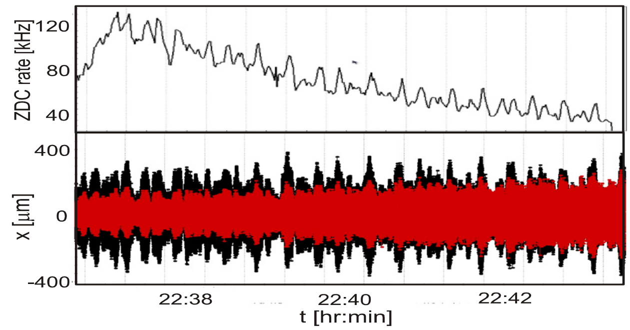

Figure 7: ZDC rate (a) and beam positions at the interaction point (b) evidencing similar time structure attributable to 10 Hz beat frequencies.

Experimental data were presented which demonstrated that the dominant effect of the triplet vibrations on the beam orbits at the IPs was a modulated crossing angle between the counter-rotating, colliding bunches.

Explanations for a few long-term puzzles were suggested by these studies. The structure in the beam decay was identified to be due to the beating of nearby excitations. The ineffectiveness of relative-displacement orbit feedback at the IPs was attributed to the dynamics being dominated by modulated crossing angles rather than relative transverse displacements.

The observed beam-beam performance at RHIC was postulated to be affected by the triplet vibrations which in run-9 were accompanied by significant tune modulation and modulation of the crossing angles at the IPs. The consequences of numerous other effects have yet to be considered including excitation of odd-order beam-beam, head-tail, or synchro-betatron resonances.

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