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A NEAR-INTEGER WORKING POINT FOR POLARIZED PROTONS IN THE RELATIVISTIC HEAVY ION COLLIDER

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Abstract

To achieve the RHIC polarized proton enhanced luminosity goal of $150 \cdot 10^{30}\,\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ on average in stores at 250 GeV, the luminosity needs to be increased by a factor of 3 compared to what was achieved in 2006. Since the number of bunches is already at its maximum of 111, limited by the injection kickers and the experiments' time resolution, the luminosity can only be increased by either increasing the bunch intensity and/or reducing the beam emittance. This leads to a larger beam-beam tuneshift parameter. Operations during 2006 has shown that the beam-beam interaction is already dominating the luminosity lifetime. To overcome this limitation, a near-integer working point is under study. We will present recent results of these studies.

MOTIVATION

The current working point (Q_x, Q_y) for polarized proton beams in the Relativististic Heavy Ion Collider (RHIC) is constrained between 2/3 and 7/10. Additionally, the tunes in the two collider rings need to be different to avoid coherent beam-beam effects. This is usually accomplished by "mirroring" the tunes at the $Q_x = Q_y$ diagonal in the tune diagram.

During Run-6 it was observed that the beam lifetime in the ring with $Q_x < Q_y$ is significantly shorter than in the other ring, where $Q_y < Q_x$, due to the horizontal third-order betatron resonance, as illustrated in Figure 1. This effect currently limits the achievable luminosity in RHIC, because the increased beam-beam tune shift due to the required bunch intensity increase exceeds the available tune space.

To overcome this limitation, several schemes have been studied. First, the available tune space can be effectively increased by eliminating other sources of tune spread, such as nonlinear chromaticity [1]. The tune space thus available can subsequently be filled by beam-beam tune spread, allowing for a larger bunch intensity.

Secondly, attempts have been made to compensate the horizontal third-order resonance at $Q_x = 2/3$ [2].

Last, a totally different working point may be found which provides larger dynamic aperture than the current choice, thus allowing larger beam-beam tuneshift parameters and therefore providing enhanced luminosity. In this paper, we present the constraints that lead to the working point choice currently under considerations. We show results of dynamic aperture studies, and discuss possible implications of that new working point on machine operations.

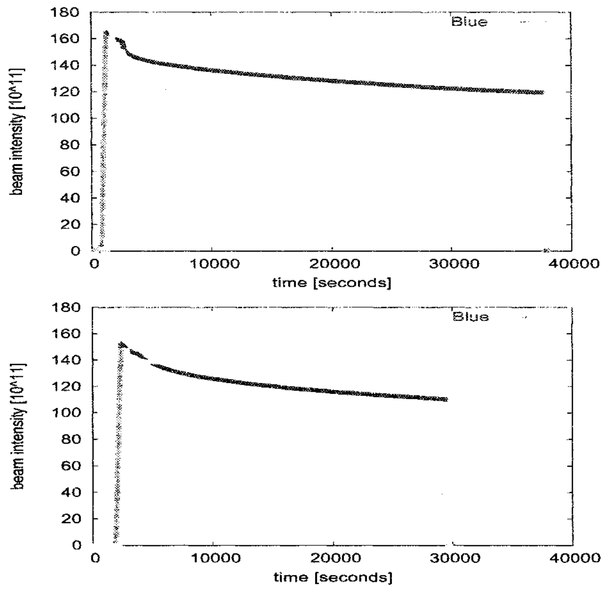

Figure 1: RHIC beam intensities during two stores in Run-6. In the top graph, tunes are set to (28.695, 29.685) in Blue and (28.685, 29.695) in Yellow. In the lower plot, tunes of the two rings are reversed.

WORKING POINT CHOICE

As a general rule, the dynamic aperture can be expected to increase if the order of betatron resonances crossed by the beam footprint is as high as possible. This is best achieved by selecting a working point close to an integer resonance. However, in the case of polarized proton beams in RHIC, spin dynamics aspects need to be considered as well.

In the presence of two Siberian Snakes, as is the case in RHIC, depolarizing resonances occur at

$$Q_y = \frac{k}{2 \cdot m}, \tag{1}$$

where k and m are integer numbers [3]. Furthermore, depolarization at even values of m occurs only in the presence of vertical closed-orbit distortions, and therefore require a sufficiently well-corrected vertical orbit. Figure 2 shows the stable polarization on resonance, as a function of the vertical tune, for a simplified accelerator model with two full Siberian Snakes [4]. The stable polarization is highest near the integer resonance, and near zero for a half-integer tune. Near-integer tunes are therefore preferred for spin dynamics reasons as well.

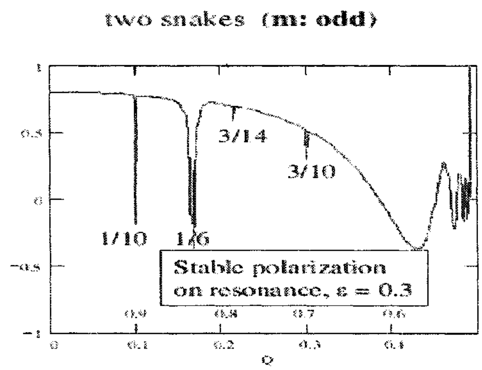

Figure 2: Snake resonances.

Now, one has to choose between tunes just above or just below the integer. Denoting the betatron phase advance between the two interaction points in RHIC as μ_1, and the phase advance for the whole ring as $\mu_0 = 2\pi Q_0$, the resulting phase advance in the presence of two collisions with beam-beam tuneshift parameter ξ is computed as

$$\begin{aligned}\cos\mu &= \cos\mu_0 - 4\pi\xi\sin\mu_0 \\ &\quad +8\pi^2\xi^2\sin\mu_1(\sin\mu_0\cos\mu_1 - \cos\mu_0\sin\mu_1).\end{aligned} \tag{2}$$

Similarly, the resulting β-function at the two interaction points can be expressed as

$$\begin{aligned}\beta^* &= \beta_0^* \cdot (\cos\mu_1\sin(\mu_0-\mu_1) \\ &\quad +\sin\mu_1\cdot(-4\pi\xi\sin(\mu_0-\mu_1)+\cos(\mu_0-\mu_1))) \\ &\quad /\sin\mu,\end{aligned} \tag{3}$$

where β_0^* denotes the lattice β-function at the IPs in the absence of beam-beam collisions.

If the phase advance μ_1 between the two IPs is an integer multiple of π, the resulting tune $Q = \mu/2\pi$ approaches the bare lattice tune $Q_0 = \mu_0/2\pi$ for tunes just below the integer. At the same time, β^* decreases below the β-function of the bare lattice, $\beta^* < \beta_0^*$. For tunes above the integer, this situation is reversed - the effective tune shift (and therefore beam-beam tune spread) becomes larger than the beam-beam tuneshift parameter ξ, and also the dynamic β-function increases, $\beta^* > \beta_0^*$.

However, unless the integer tune is changed, the phase advance between the two IPs in RHIC is close to $\mu_1 = \pi/2$. Therefore, the working point can be chosen either above or below the integer from this perspective.

DYNAMIC APERTURE

To determine the dynamic aperture at the proposed new working point, tracking studies have been performed, using both the UAL environment [5] and the Sixtrack code [6]. The results shown here were obtained using UAL, and they were found to be generally in good agreement with the Sixtrack results.

	28.675	28.68	28.685	28.69	28.695
29.695	< 4	5.7	6.8		
29.69	< 4	4.9			
29.685	< 4				7.1
29.68				7.5	7.7
29.675			7.1	6.5	6.6

Figure 3: Dynamic apertures in σ at the Run-6 working point.

	27.935	27.94	27.945	27.95	27.955	27.96	27.965
28.965	5.3	5.3	5.5	5.8	6.0		
28.96	5.6	5.8	6.1	6.3			
28.955	6.0	6.0	6.4				7.1
28.95	6.2	6.1				7.3	6.9
28.945	6.0				6.9	6.9	6.8
28.94				6.4	6.6	6.7	6.8
28.935			6.5	6.5	6.5	6.9	6.9

Figure 4: Dynamic apertures in σ for tunes below the integer.

The underlying nonlinear model was based on the latest interaction region magnet multipole error data [7]. Two interaction points were included to simulate the beam-beam effect, using a 95 percent normalized beam emittance of $\epsilon_n = 15\,\pi\mathrm{mm\,mrad}$ and a bunch intensity of $2\cdot 10^{11}$ protons. Tune modulation was included by modulating an additional thin-lens quadrupole at one interaction points; frequencies and modulation depths were based on beam measurements at RHIC.

To establish a baseline for comparisons, the dynamic aperture at the current RHIC polarized protons working point was determined by tracking. The dynamic aperture above the diagonal turned out to be smaller than below the diagonal, and drops rapidly if the horizontal tune is lowered towards $Q_x = 2/3$, as shown in Figure 3. This is consistent with observations in RHIC, where the beam with a tune above the diagonal has a significantly shorter lifetime than the opposing beam below the diagonal.

Below the integer, dynamic apertures are comparable to those below the diagonal at the current working point, as Figure 4 shows. The tune space of large dynamic aperture is rather large.

Above the integer, the dynamic aperture is smaller than below, though there is no sudden drop as observed at the current working point above the diagonal.

DEPOLARIZING RESONANCES

The proposed near-integer working point is in close vicinity of the 7th order ($Q_y = \pm 1/(2\cdot 7)$, see Equation 1) depolarizing snake resonance, which imposes a possible limitation. To determine the strength of this resonance, tracking studies were performed using a simplifed accelerator model. Since it is difficult to determine polarization

	28.055	28.06	28.065	28.07	28.075	28.08	28.085
29.085	5.5	6.3	6.2	5.6	5.8		
29.08	5.0	5.1	5.3	5.3			
29.075	5.8	5.8	5.5				5.2
29.07	5.9	5.8				5.5	5.3
29.065	6.2				5.8	5.5	5.6
29.06				5.9	6.0	5.7	5.5
29.055			6.2	6.1	6.2	5.6	5.5

Figure 5: Dynamic apertures in σ for tunes above the integer.

lifetimes in the order of several hours from tracking studies, the resonance strength was artificially increased until significant depolarization occured. The same model was then run at the $Q_y = 10/14$ depolarizing resonance, where depolarization measurements were performed in RHIC that resulted in a polarization lifetime of several hours. Tracking showed that the polarization lifetime at $Q_y = \pm 1/14$ can be expected to be at least an order of magnitude longer than at the $Q_y = 10/14$ resonance, which would be fully sufficient.

RESISTIVE WALL INSTABILITY

A possible constraint on the working point choice may arise due to the resistive wall instability. With tunes close to the integer, a working point above the integer is generally preferred, since the growth rate of the resistive wall instability is smaller there than below the integer. However, based on the RHIC impedance model, chromaticities in the order of 2 to 4 should be sufficient to counteract the instability on either side of the integer resonance.

BEAM EXPERIMENTS

During Au operations in Run-7, beam experiments were performed in RHIC to experimentally study the feasibility of near-integer tunes. Since both closed orbit distortions and β-beat are expected to increase close to the integer, these experiments were aimed at measuring the β-beat, which is a possible limitation in the available tune space due to its $1/\sin(2\pi Q)$ dependence. During the experiment, tunes were set to $(28.08, 29.05)$ in the Blue ring and to $(27.93, 28.94)$ in the Yellow ring. Vertical β-functions at all BPMs around the two rings were measured using the AC dipole [8]; the results are shown in Figure 6.

The β-beat in the Blue ring turned out to be remarkably small, while the Yellow ring showed about 20 percent β-beat. This is consistent with observations at other working points in the past, which have shown the β-beat to be significantly larger in the Yellow than in the Blue RHIC ring. The cause of this difference remains under investigation.

A harmonic β-beat correction algorithm is currently being developed to correct optics distortions at near-integer tunes, which are expected to be dominated by the $2 \cdot Q$ harmonic. This algorithm will be tested in futture beam

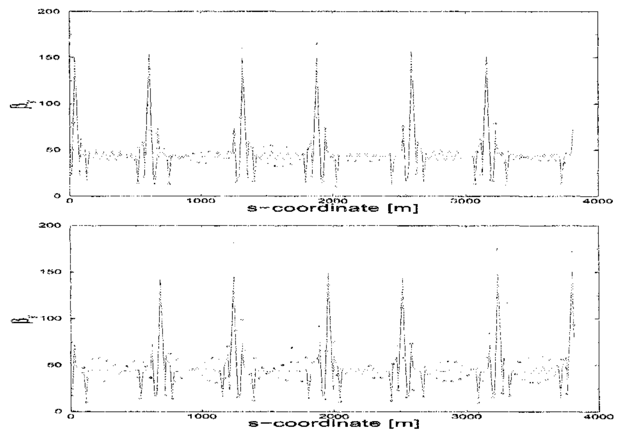

Figure 6: Measured RHIC injection optics with the new working points in Blue (top) and Yellow (bottom).

experiments prior to the polarized proton run.

Additionally, these experiments showed that the resistive wall instability is weaker than expected, since near-zero chromaticities – as are required for AC dipole measurements – did not result in an instability.

CONCLUSION

Based on tracking studies and beam experiments presented in this paper, it is planned to operate the two RHIC rings at different working points during the upcoming polarized proton run in FY2008. One ring will remain at the current working point around $(28.695, 29.685)$, while the other ring will be operated near the integer resonance, around $(27.96, 28.95)$. Both working points were found to provide dynamic apertures greater than 7σ in tracking studies. Operating the two rings a two totally different tunes also has the additional advantage that this avoids coherent beam-beam effects altogether.

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