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SIMULATION STUDY OF BEAM-BEAM EFFECTS IN ION BEAMS WITH LARGE SPACE CHARGE TUNESHIFT *

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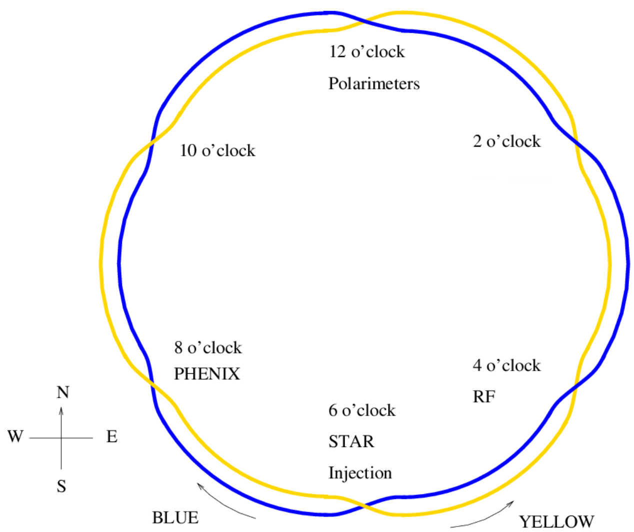

Figure 1: Schematic view of the Relativistic Heavy Ion Collider RHIC with its two interaction points STAR at the 6 o'clock position and PHENIX at 8 o'clock.

Abstract

During low-energy operations with gold-gold collisions at 3.85 GeV beam energy, significant beam lifetime reductions have been observed due to the beam-beam interaction in the presence of large space charge tuneshifts. These beam-beam tuneshift parameters were about an order of magnitude smaller than during regular high energy operations. To get a better understanding of this effect, simulations have been performed. Recent results are presented.

INTRODUCTION

In order to search for the critical point in the QCD phase diagram, the Relativistic Heavy Ion Collider RHIC (Figure 1) needs to provide Au-Au collisions at a range of center-of-mass energies, as low as 5 GeV. At these low energies, space charge effects become important, and the space charge tune shift parameter becomes much larger than the beam-beam parameter. When RHIC was operated at center-of-mass energies of 7.7 and 11.5 GeV, the beam-beam effect led to a significant reduction in beam lifetime [1, 2], in spite of the fact that the beam-beam parameter was about an order of magnitude smaller than the space charge tuneshift, as shown in Figure 2.

To gain a better understanding of this unexpected effect, a simulation code has been developed. The following sections present the simulation method and some results obtained from the simulation.

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beam energy [GeV]	2.5
95% normalized emittance [μm]	20
beam-beam parameter per IP	0.003
space charge tune shift	0.1
synchrotron tune	0.01
$\Delta Q_{\rm min}$	0.0025

Table 1: Parameter set used in the simulations.

THE SIMULATION MODEL

The basic idea of the simulation method is to assume that any modifications to the particle distribution in the beam occur very slowly compared to the total time simulated. We can therefore treat the space charge force in a similar fashion as the one used in weak-strong beam-beam simulations, where the distribution of particles in the strong beam is considered unaltered by the beam-beam interaction. For our space charge simulations, we therefore assume that the particle distribution remains Gaussian throughout the entire simulation time. The RMS width of this Gaussian distribution is then determined according to the β-functions at the locations where individual space charge kicks are applied. In addition, these individual space charge kicks are modulated due to the synchrotron oscillation of the individual particles. Each space charge kick is therefore scaled by

$$f(s) = \frac{1}{\sqrt{2\pi}\sigma_s} \cdot \exp\left(-\frac{s^2}{2\sigma_s^2}\right), \qquad (1)$$

with

$$s = s_0 \cdot \sin\psi_s, \qquad (2)$$

where σ_s is the RMS bunch length, s_0 the synchrotron oscillation amplitude of the individual particle, and ψ_s its synchrotron phase. Table 1 lists the machine and beam parameter set used in the simulation.

RESULTS

Instead of a simplified model ring consisting of a number of FODO cells, the actual RHIC lattice is used in the simulations. While this approach may at first glance seem overly complicated, it avoids artificial effects when the beam-beam interaction is introduced. Consider a model ring consisting of N identical FODO cells, with a betatron phase advance of ψ_x, ψ_y per cell. Though the intended tune of this model ring is $N \cdot \psi_x/(2\pi)$, $N \cdot \psi_y/(2\pi)$, the strict

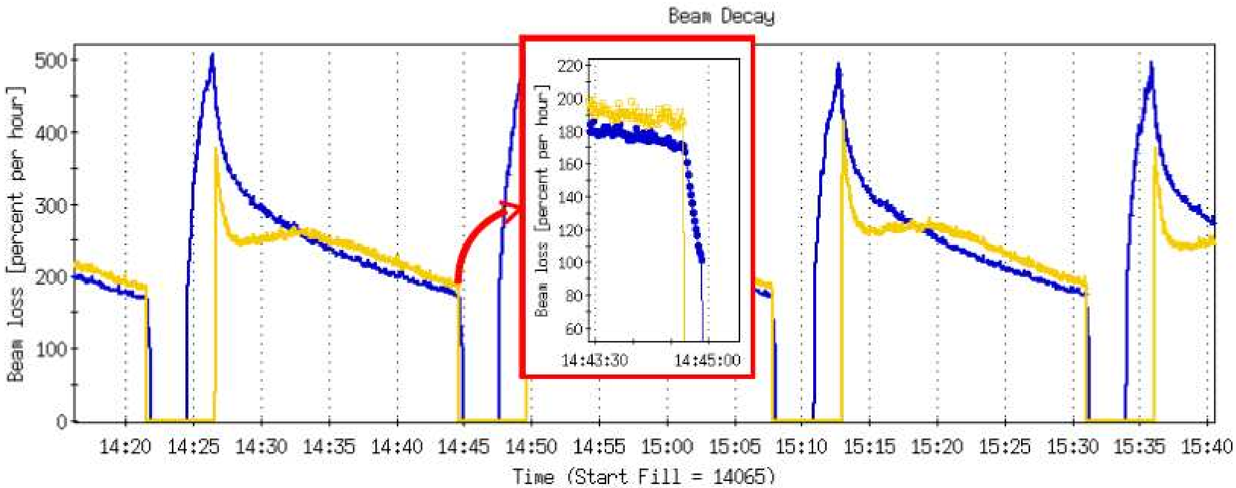

Figure 2: Beam decay rates during several $\sqrt{s_{\mathrm{NN}}} = 11.5\,\mathrm{GeV}$ stores. At the end of each store, the Blue beam decay dramatically improves as soon as the Yellow beam is dumped (see insert). Note that the algorithm to calculate the beam decay has a time constant of 20 seconds. Hence, the actual drop in instantaneous beam decay is even more dramatic than suggested by this picture.

periodicity of the lattice results in an effective tune that equals the tune of a single FODO cell, $\psi_x/(2\pi)$, $\psi_y/(2\pi)$. If we now introduce a single beam-beam interaction after N FODO cells, this periodcity is broken and the lattice tune becomes $N \cdot \psi_x/(2\pi)$, $N \cdot \psi_y/(2\pi)$. Since this tune in general does not equal the tune of a single FODO cell, comparing results with and without beam-beam interaction becomes impossible.

Space charge kicks are applied at each element of non-zero length in the RHIC lattice description, at 4135 lattice locations around the circumference of RHIC. With 1000 particles being tracked, this large number of space charge kicks takes about 24 hours for 20000 turns. With this relatively small number of turns, no significant effect of the beam-beam interaction on the transverse emittances was found at either 7.7 GeV or 11.5 GeV center-of-mass energy. When the space charge force was increased to reflect the conditions at a lower center-of-mass energy of only 5 GeV, tracking over 20000 turns became sufficient to reveal the effect of the beam-beam force, as shown for a single working point of $(Q_x, Q_y) = (28.18, 29.19)$ in Figure 3. In these simulations, the sum of the space charge tune shift and the beam-beam tune shift are constant - without beam-beam interaction, the space charge tune shift is set to $\zeta = 0.106$, while with beam-beam the space charge tune shift is set to $\zeta = 0.1$ and the beam-beam parameter at each of the two IPs is chosen as $\xi = 0.003$. This choice of parameters ensures that any observed effect of the beam-beam interaction in the presence of space charge cannot simply be attributed to a larger total tune spread.

With these space charge and beam-beam parameters, a tune scan is performed along a parallel to the coupling resonance in the range from $(Q_x, Q_y) = (28.13, 29.14)$ to $(28.23, 29.24)$, with $Q_y = Q_x + 1.01$. A straight line is fit-

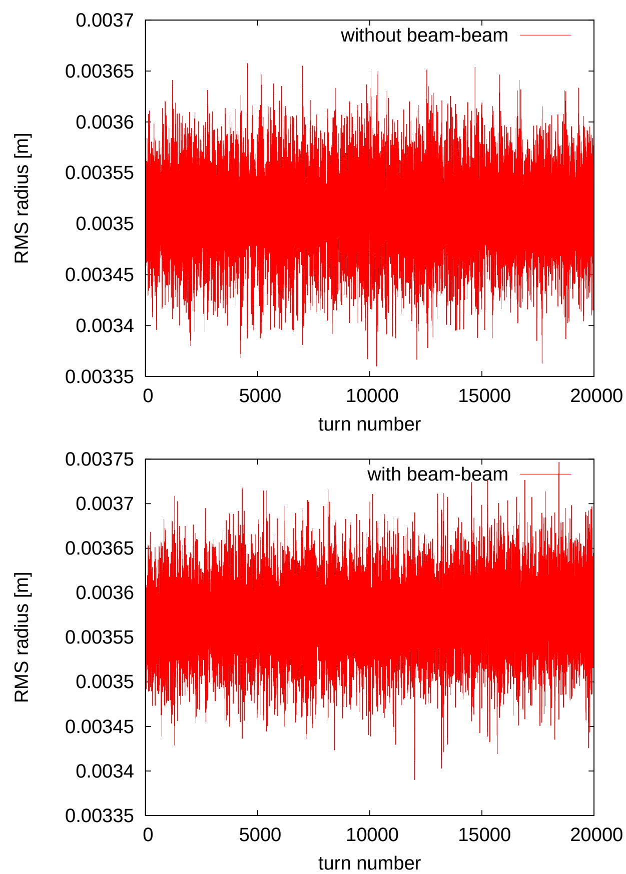

Figure 3: Turn-by-turn RMS beam radii as a function of turn number, without (top) and with (bottom) beam-beam interactions at the two RHIC IPs. The transverse tunes are set to $(Q_x, Q_y) = (28.18, 29.19)$.

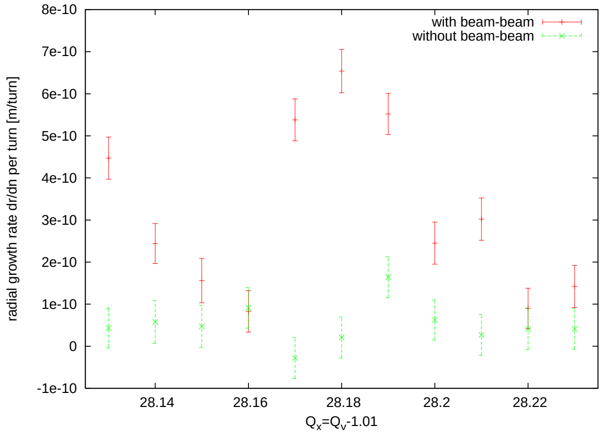

Figure 4: RMS radial growth rate $\mathrm{d}r/\mathrm{d}n$ as a function of tune, with (Q_x, Q_y) chosen such that $Q_y = Q_x + 1.01$.

ted to the turn-by-turn RMS radii, and the resulting slopes of the fit are plotted as radial growth rates $\mathrm{d}r/\mathrm{d}n$ in Figure 4.

As Figure 4 shows, adding beam-beam kicks at the two interaction points results in significant radial growth over essentially the entire tune range under study, in spite of the fact that the total tune spread from space charge and beam-beam is no larger than the tune spread from space charge only.

SUMMARY

In the presence of a large space charge tune shift, the beam-beam interaction resulted in a dramatic lifetime reduction during low-energy beam operations in RHIC. The simple space charge and beam-beam simulation model presented in this paper shows a similarly strong effect on emittance growth. Efforts are currently underway to directly simulate the observed effect on beam lifetime, which requires a much larger number of particle-turns than the emittance growth simulations presented, making these studies extremely CPU-time consuming.

ACKNOWLEDGMENT

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