SIMULATIONS OF COHERENT BEAM-BEAM EFFECTS WITH HEAD-ON COMPENSATION *

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Abstract

Electron lenses are under construction for installation in RHIC in order to mitigate the head-on beam-beam effects. This would allow operation with higher bunch intensity and result in a significant increase in luminosity. We report on recent strong-strong simulations and experiments that were carried out using the RHIC upgrade parameters to assess the impact of coherent beam-beam effects in the presence of head-on compensation.

INTRODUCTION

The RHIC collider is currently operating between the 2/3 and 7/10 resonances with a beam-beam parameter of approximately 0.015 leaving little space for significant increase in luminosity. The RHIC luminosity upgrade program [1] aims at an increase of the luminosity by at least a factor of 2. In order to accommodate the significant increase in beam-beam tune spread it was decided to install electron lenses to compensate for the beam-beam nonlinearities and effectively reduce the tune spread at constant bunch intensity. This technology was first developed at the Tevatron where it was tested for head-on compensation [2] and then successfully used for abort gap cleaning [3] and collimation studies [4].

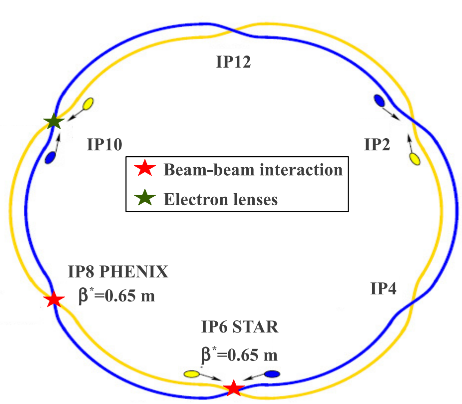

Figure 1: Layout of the RHIC collider. The colliding IPs are denoted by the red stars, the head-on compensation by the green star.

The RHIC collider consists of two rings where the beams are colliding in IP6 and IP8 as shown in Fig. 1. The two electron lenses, one for each ring, will be located close to IP10. Studies regarding dynamic aperture were performed and showed improvements for high beam-beam parameter [5] and the details on status and construction of the electron lens can be found in [6]. These simulations however did not cover the coherent beam-beam effects related to the electron lens which is a possible explanation of why the DCI experiment failed [7].

This paper reports on strong-strong beam-beam simulations performed using the RHIC lattice and upgrade parameters and related beam experiments to understand the impact of the coherent beam-beam effects in the presence of electron lenses.

HEAD-ON COMPENSATION

For round equal Gaussian beams, the particles of the two counter-rotating beams will experience at each IP radial angular kicks from the opposite beam of the form:

$$\Delta r' = -\frac{2Nr_0}{\gamma} \cdot \frac{1}{r^2} \cdot \left(1 - e^{\frac{-r^2}{2\sigma^2}}\right) \qquad (1)$$

where N is the number of particles per bunch, r_0 is particle classical radius, γ is the Lorentz factor, $r = \sqrt{x^2 + y^2}$ is the radial distance between a particle and the opposite beam and σ is the rms transverse beam size. This leads to an incoherent tune shift for the low amplitude particles:

$$\Delta Q_{p-p} = -\frac{Nr_0}{4\pi\epsilon_N} \qquad (2)$$

where ϵ_N is the normalized emittance. The minus sign comes from the interaction of particles with equal charges. When the protons interact with the low energy electron beam inside the electron lens they will experience an opposite sign tune shift of:

$$\Delta Q_{p-e^-} = \frac{r_0 IL(1+\beta_e)\beta^*}{4\pi\gamma ec\beta_e\sigma_e^2} \qquad (3)$$

where I is the electron current, L is the interaction length, $\beta_e c$ is the electron velocity, β^* is the β-function at the location of the interaction with the electron beam and σ_e is the electron beam size. If the interaction length and electron current, size and energy are properly set, it is therefore possible to fully compensate for the tune shift induced by the proton-proton interaction. In order to account for non-linear and amplitude dependent effects the electron beam profile has to match the proton one and the phase advance between the proton-proton interactions and the proton-electron interaction has to be a multiple of π.

In practice, it was shown that reducing the incoherent tune shift by too large amounts would degrade the lifetime

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and dynamic aperture and could also result in coherent instabilities [5]. The RHIC electron lenses are therefore intended at compensating for half the full beam-beam parameter, also allowing for a more flexible lattice design as the phase advance constraint has to be applied only between IP8 and IP10.

MODEL

The simulation code BeamBeam3D [8] was used for this study. BeamBeam3D is a fully parallelized 3-dimensional code allowing for self-consistent field calculation of arbitrary distribution and tracking of multiple bunches. The transport from one IP to the other is done through linear transfer maps. The beam fields are calculated by solving the Poisson equation using a shifted integrated Green function method which is efficiently computed with a FFT-based algorithm on a uniform grid.

In order to correctly model the RHIC lattice the Twiss parameters are extracted at each IP, including the one where the head-on compensation takes place, and used to compute the transfer maps. As shown in Fig. 1, the symmetry of the different colliding IPs allows to reduce the number of bunches to 3 per beam to simulate the full collision pattern.

The electron lens is modeled as a thin lens round Gaussian kick located exactly at IP10 for both beams. The size of the electron beam is determined by the lattice parameters. The phase advance between IP8 and IP10 is set exactly to π by artificially shifting the phase between these two IPs and evenly compensating the global tune change with the other arcs.

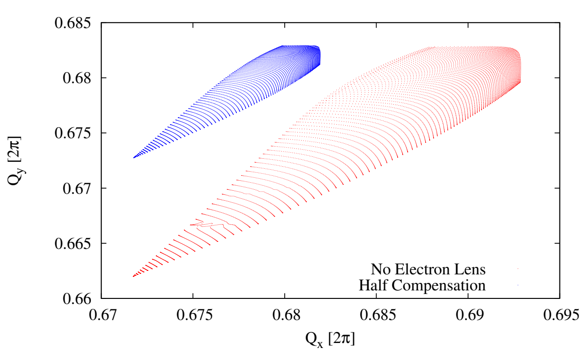

Figure 2: Tune footprint computed with BeamBeam3D for an intensity of $3.0 \cdot 10^{11}$ protons per bunch with and without compensation.

Figure 2 shows the footprints calculated with BeamBeam3D for an intensity of $3.0 \cdot 10^{11}$ protons per bunch without compensation and with half compensation. The footprint with compensation was artificially shifted for better visibility. As expected we observe a reduction of the tune spread by a factor of 2. One can also see that the footprint without compensation is crossing the $3Q_y$ resonance indicating that the machine can not be operated with such high beam-beam parameter.

COHERENT BEAM-BEAM SIMULATIONS

In addition to the single particle effects described in the previous sections, colliding beams will experience coherent dipole oscillation driven by the beam-beam force. In the simplest case of one interaction point (IP) two main modes arise corresponding to the two bunches oscillating in phase (σ-mode) or out of phase (π-mode). The σ-mode will oscillate at the betatron frequency and the π-mode will be shifted, negatively for equally charged beams, with respect to the σ-mode by an amount $Y \cdot \xi$ where Y is the Yokoya factor and ξ the beam-beam parameter [9]. Coherent beam-beam modes are routinely observed at the RHIC collider with BTF measurements [10].

The collision pattern at RHIC can be reduced to three colliding bunches theoretically giving rise to six coherent dipole modes. In reality, only two modes are observed as the other ones are located inside or very close to the incoherent tune spread and are Landau damped.

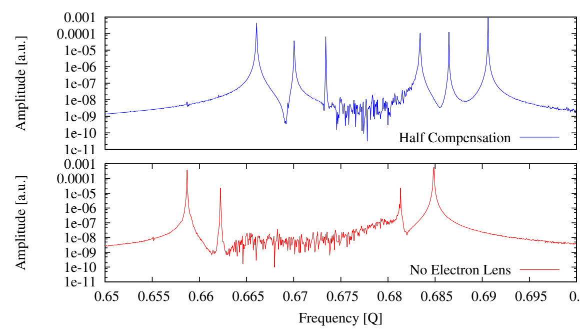

Figure 3: Simulated coherent modes with (top) and without (bottom) half compensation with a bare lattice tune of 0.685.

Figure 3 shows a strong-strong simulation of the RHIC lattice with and without compensation. The bare lattice tunes used for this simulation are (0.695,0.685) as defined in the design and the beam-beam parameter ξ per IP is approximately 0.011. Only the vertical plane is shown but a similar picture is observed in the horizontal plane. The coherent modes are excited with an initial kick of 0.1 σ.

As predicted by the weak-strong simulations in Fig. 2 the incoherent continuum is reduced by the head-on compensation. The lattice tunes, or σ-mode on this plot, are shifted by $\xi/2 \approx 0.005$ corresponding to the coherent beam-beam tune shift induced by the quadrupolar part of the beam-beam force. This effect can be easily predicted and corrected for. The phase advance between IPs is also modified leading to slightly different relative frequencies of the modes.

The electron beam from the lens does not couple back to the proton beam. In the presence of head-on compensation, the distance in tune space covered by the coherent modes therefore remains approximately constant while the incoherent tune spread is significantly reduced. All six coherent modes are now observed as they are moved out of the continuum and not Landau damped anymore. Head-on compensation with electron lenses reduces the intrinsic stabilizing properties of the beam-beam interaction. This could give rise to coherent dipole instabilities driven by external sources of excitation such as impedance.

EFFECT OF THE 2/3 RESONANCE ON COHERENT MODES IN EXPERIMENTS

As seen in Fig. 3 even if the incoherent tune spread is reduced the tune space covered by the coherent modes remains constant and will overlap the 2/3 resonance in the case of the RHIC working point. While it is difficult to experimentally reproduce the reduction of the tune spread induced by the electron lenses we verified experimentally that driving the π-mode onto this resonance would not excite coherent dipole motion or degrade the beam lifetime.

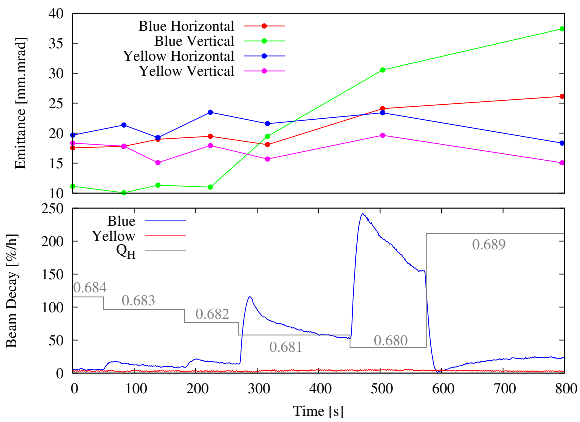

Figure 4: Tune scan towards the 2/3 resonance with colliding beams.

For this experiment we moved only the two tunes of the Blue beam toward the 2/3 resonance keeping the difference $Q_x - Q_y = 0.004$, see Fig. 4. This was done with a beam-beam parameter estimated to be 0.011. The onset of losses is observed at (0.687,0.683), at these tunes the location of the π-mode is 0.669 and the zero amplitude particles are at 0.672, no emittance blow-up is observed at that point. Losses are observed only in the blue beam, indicating that the π-mode, which has the same frequency for both beams, is insensitive to the 2/3 resonance. The stop-band of the 2/3 resonance with non-colliding beams was estimated to be around 0.005 which is consistent with losses of low amplitude particle in our case. As we moved the beam closer to the resonance strong losses associated with emittance blow-up were observed only in the blue beam. In addition, no unusual activity was observed on the BBQ spectrum during the whole experiment, pointing towards a reduction of the dynamic aperture rather than the excitation of coherent modes.

DISCUSSION

Self consistent strong-strong beam-beam simulations showed that while the head-on compensation with electron lenses would effectively reduced the incoherent tune spread, the coherent dipole motion arising from the coupling of two beams through the beam-beam force would not be affected. Consequently, the distance between the coherent modes and the continuum is increased which could lead to loss of Landau damping and coherent instabilities driven by external excitations. Due to the increased bunch intensity these modes would also overlap low order resonances such as the 2/3 resonance in the case of the RHIC working point.

It was demonstrated experimentally that when particles are moved inside the stop-band of this resonance, a significant reduction of the dynamic aperture was induced as expected, but no coherent instability were observed.

The coherent modes at RHIC are observed only when excited by the BTF measurements, and therefore naturally damped in normal running conditions. In addition to the experiment presented in this paper, we conducted additional checks to assess the stability of the modes:

- Vertical orbit modulation at 10 Hz frequency corresponding to the triplet vibrations
- White noise excitation
- Sinusoidal excitation of the π-mode

None of these excitations could drive any coherent instabilities. Another mechanism that could drive the beam unstable is impedance. A model is under construction to understand the interplay of beam-beam and impedance which could become relevant at the high bunch intensities foreseen for the RHIC luminosity upgrade program.

While it is difficult to draw any firm conclusions based on these observations, the fact that the beam-beam coherent modes are not self-excited and could not be driven unstable under strong excitations is rather encouraging. In the event that coherent dipole instabilities become a problem for the operation of the electron lenses they could eventually be cured by a fast bunch-by-bunch transverse damper.

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