BEAM-BEAM INTERACTION IN THE ASYMMETRIC ENERGY GOLD-GOLD COLLISION IN RHIC*

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Abstract

In this article, we study the beam-beam interaction in a possible future gold-gold collision with different particle energies in the Relativistic Heavy Ion Collider (RHIC). Since RF harmonic numbers are different for the two rings, bunches collide in 110 or 111 turn followed by 10 turns without collision. We will carry out 6-D numeric simulations to study the stability of bunch centers and the transverse emittance growth. The nonlinear beam-beam interaction force, chromaticities, and synchrotron motion are included. Both weak-strong and strong-strong simulation models are used.

INTRODUCTION

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is a double-ring superconducting collider. Since its first operation in 2000, we had collided gold-gold, deuteron-gold, copper-copper, uranium-uranium, copper-gold, and polarized protons. Physics experiments show interests in colliding gold-gold with asymmetric energies, one beam with the particle energy at 10 GeV and the other at 100 GeV. The center-of-mass of two bunched is moving longitudinally during the collision.

To maintain collisions at the experiment detectors, it is crucial to have the same bunch spacings for both rings. To collide the Au ions around 10 and 100 GeV, we could have the relativistic energy factors for particles in the high and low energy rings as 107.4 and 7.79. With current 28 MHz RF system, the harmonic numbers for the high and low energy rings are 360 and 363. If we inject bunches every 3 buckets and leave 10 bunch gap for the abort gap, there are 111 and 110 bunches in the high and low energy rings. To match the beam sizes at the interaction point, the β^*s at IPs are 10.7 m and 0.8 m for the high and low energy rings. Table 1 lists the machine and beam parameters from our preliminary design.

There are a few challenges in colliding Au ions with energies 10 and 100 GeV. First, to assure head-on beam-beam collision, if we only adjust the first two dipoles to IPs, there is not enough physical apertures in the these magnets. Secondly, with current RHIC magnet power supplies, if we only use quadrupoles in the same interaction regions (IRs), it is difficult to achieve $\beta^* = 10.7$ m for the high energy ring and $\beta^* = 0.8$ m for the low energy ring. The first challenge may be solved by generating orbit offsets in the whole IR so that the common angle of orbits between the first dipoles will be reduced. By launching appropriate β-waves from adjacent IRs, it is possible to achieve the required β^*s for both rings.

Table 1: Beam and Optics Parameters (as used in this study)

Parameter	High Energy Ring (Yellow)	Low Energy Ring (Blue)
Energy γ	107.4	7.79
Harmonic Number	360	363
Bunch Number	110	111
RMS emittance	15 μm	15 μm
$(dp/p_0)_{rms}$	2.3×10^{-4}	5.0×10^{-4}
RMS bunch length	0.75 m	1.25 m
β^*	10.7 m	0.8 m
σ^*	0.5 mm	0.5 mm
Beam-beam Parameter	0.0015	0.0015

The third challenge is the asymmetric beam-beam interactions. If we align the first bunches from both rings at IP, bunches in the high energy ring will have collisions in 111 turns, followed by 10 turns without collision. While for bunches in the low energy ring, they will have collisions in 110 bunches, followed by 10 turns without collision. Since the RF harmonic number of the low energy ring is 363, we only can have collisions at one of two RHIC detectors, either at IP6 or at IP8.

Asymmetric beam-beam interaction had been studied based on linear map analysis and simplified 2-D or 4-D multi-particle tracking [1–3]. In this article, with the machine and beam parameters listed in Table 1, we will carry out 6-D numeric simulations to study the stability of bunch centers and the transverse emittance growth. The nonlinear beam-beam interaction force, chromaticities, and synchrotron motion are included. Both weak-strong and strong-strong simulation models are used.

LINEAR MAP TREATMENT

First we determine the stability of linear motion of Au ion with missing beam-beam interaction. We assume that there are beam-beam interaction in the first m turns, followed by n turns without beam-beam interaction. The 4-D linear map of $m+n$ turns is given by

$$T_{m+n} = \prod^{n} M_{arc} \prod^{m} M_{arc} N_{bb}, \tag{1}$$

where M_{arc} is the one-turn map without beam-beam interaction, N_{bb} is the linear beam-beam kick map. If the absolute value of the trace of T_{m+n} is bigger than 1, then the linear motion is unstable.

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* This work was supported by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy.

ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-TUPRO034

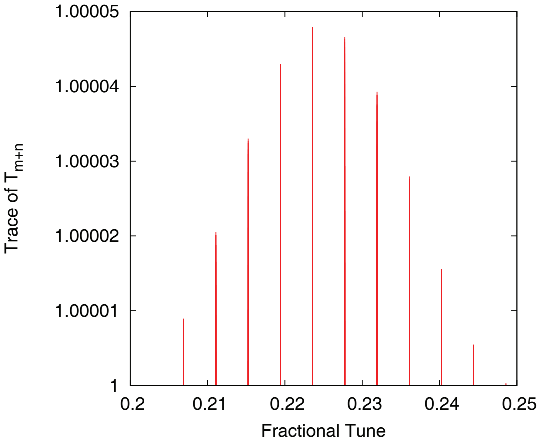

Figure 1: Trace of 120 turn map T_{m+n} for the high energy ring. Trace larger than 1 means unstable linear motion.

As an example, Figure 1 shows the trace of T_{m+n} for the high energy ring with fractional tunes between 0.2 and 0.25, which is the working tune space for the RHIC ion runs. The step size of tune scan is 5×10^{-5}. From Fig. 1, there are several isolated unstable tunes in the shown tune range. The distance between adjacent unstable tunes are about 0.004, which is approximately $0.5/(m+n)$. Missing beam-beam interaction in some turns excites half-integer resonances and there are totally $(m+n)$ unstable tunes for each integer tune.

WEAK-STRONG SIMULATION

In the following sections we will carry out multi-particle simulation to study the stability of the bunch centers and to calculate the transverse emittance growth with missing beam-beam interaction. First, we use the weak-strong beam-beam interaction model. The particle coordinates are $(x, p_x, y, p_y, z = -c\Delta t, \delta = dp/p_0)$. The strong beam is assumed rigid and its position and beam sizes are not changed during the particle tracking. The weak beam are represented by 10,000 macro-particles. 4-D beam-beam kick of a round Gaussian distribution is used to calculate the kicks from the strong beam to the macro-particles in the weak beam.

Since we do not have complete lattices for both rings, in the simulation the ring is simply represented by an uncoupled linear 6×6 one-turn map. The tunes change from turn-by-turn through the first order chromaticities,

$$Q_{x,y} = Q_{x,y,0} + \xi_{x,y}\delta. \tag{2}$$

A RF cavity is added to simulate the synchrotron motion,

$$\Delta\delta = \frac{eV}{E_0}\sin(2\pi f_{rf}\Delta t + \phi_0), \tag{3}$$

$$-c\Delta t = -(\frac{1}{\gamma_t^2} - \frac{1}{\gamma^2})\delta L. \tag{4}$$

Figure 2 shows the calculated rms transverse beam sizes for a Au ion bunch in the high energy ring up to 120,000 turns. The set tunes without beam-beam interaction are (28.2300, 29.2257), the first order chromaticities are (2,2). From above linear map treatment, these tunes are unstable. However, through the weak-strong simulation, we do not observe unstable motion of the bunch center or transverse emittance growth. This can be explained by the transverse tune changes from turn to turn and the tune spreads in the transverse and longitudinal motions.

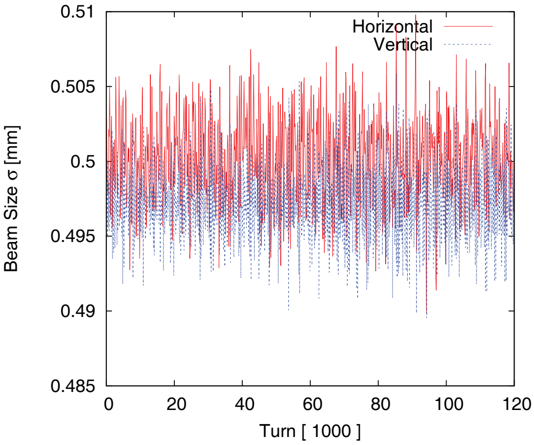

Figure 2: Calculated rms transverse beam sizes up to 120,000 turns for a Au ion bunch in the high energy ring. Weak-strong beam-beam interaction model is used.

STRONG-STRONG SIMULATION

Next we carry out strong-strong simulation with missing beam-beam interactions. In the simulation, there are 110 bunches in the high energy ring and 111 bunches in the low energy ring. Each bunch is represented by 10,000 macro-particles. We update the positions of bunch centers and beam sizes each turn. Again the 4-D beam-beam kick of a round Gaussian distribution is used to calculate the kicks to the particles in one ring from the opposite bunches in the other ring. Message Passing Interface (MPI) is used to speed up the calculation.

Figure 3 shows the rms beam sizes up to 120,000 turns for No. 61 bunches in the high and low energy rings. The bunch intensity is 1.0×10^9. The tunes are: (28.2299, 29.2261) for the high energy ring, (28.2286, 29.2265) for the low energy rings. These tunes are taken from the 2014 Au-Au run. The first order chromaticities are (2,2). From Fig. 3, fast beam size growth happens in the horizontal plane in both rings. This instability is caused by coherent beam-beam interaction between all bunches in both rings with missing interaction in some turns.

Figure 4 show the rms beam sizes for No. 61 bunch in the low energy ring with reducd bunch intensities 0.5×10^9 and 0.2×10^9 in both rings. With a lower bunch intensity, the growth time of instability is reduced. With bunch intensity 0.2×10^9, there is no obvious beam size growth up to 120,000 turns. There is no octupoles in the optics model. We tried doubling the chromaticity sets from 2 to 4. Simu-

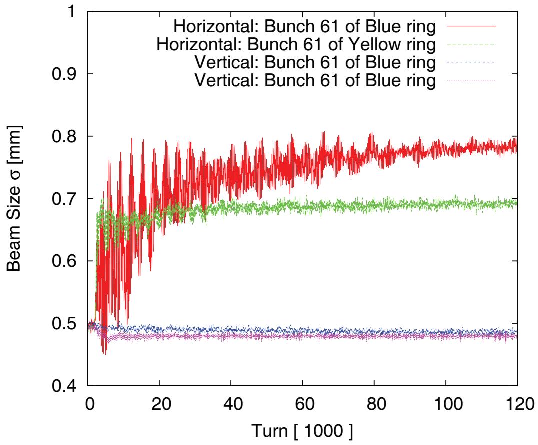

Figure 3: Calculated rms beam sizes of No. 61 bunches in the both rings from strong-strong simulation.

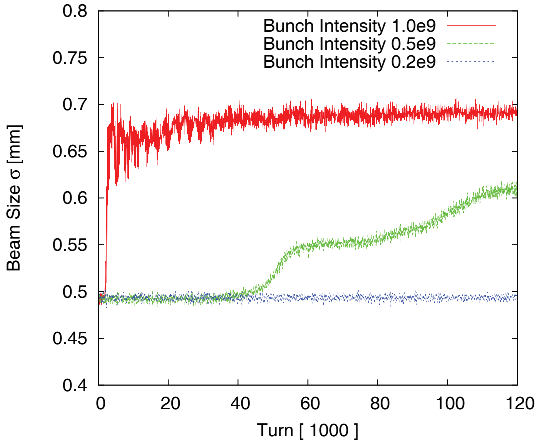

Figure 4: Calculated rms beam size of No. 61 bunch in the high energy ring with reduced bunch intensities.

lation shows that the beam size growth is slowed down but is not cured with bunch intensity 1.0×10^9.

Bunch-by-bunch transverse damper is being built to counter act the possible TMCI in the coming RHIC polarized proton operation with electron lenses [4]. We include dampers in the code simply through

$$\Delta x' = -2g < x' > \tag{5}$$

each turn at IP. $< x' >$ is averaged x' for each bunch, g is the gain of damper. Figure 5 show the bunch center motion of No. 61 bunch in the high energy ring with $g = 0.005$, which corresponds a damping time about 500 turns. There is no emittance growth in both rings. Fast transverse dampers cure the coherent beam-beam instability in our case. More sophisticated simulation with dampers is needed to guide the system design.

BEAM EXPERIMENT

Besides the simulation studies, beam experiment is being carried out in RHIC to study the stability of bunch center

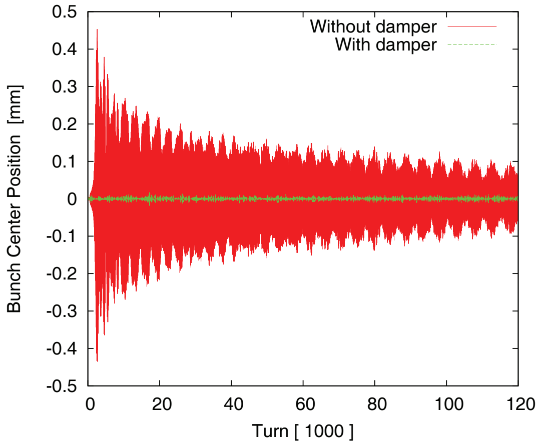

Figure 5: Bunch center motion of No. 61 bunch in the high energy ring without and with dampers.

and emittance blow-up with missing beam-beam interaction in some turns. In the experiment, we use the electron lenses to generate a missing beam-beam interaction pattern same as the ones used above. The difference is that the beam-beam force here is focusing between the Au ion bunches and the electron beam. During the experiment, we record the beam lifetime and emittance growth. Preliminary results are obtained, data analysis is on-going.

SUMMARY

In this article we study the asymmetric beam-beam interaction in the possible future RHIC Au-Au collision with asymmetric particle energies at 10 and 100 GeV. There are 111 and 110 bunches in the low and high energy rings. Linear analysis shows that there are isolated unstable tunes separated by about 0.004. Multi-particle weak-strong simulation does not show instability even with the unstable tunes. Multi-particle strong-strong simulation shows emittance growth due to coherent beam-beam interaction between all bunches in both rings. Preliminary simulation shows that this instability can be suppressed by fast bunch-by-bunch dampers.

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