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 bunches 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 β∗ = 10.7 m for the high energy ring and β∗ = 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.

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

\[ T_{m+n} = \prod_{i=0}^{n} M_{arc} \prod_{i=0}^{m} M_{arc} N_{bb}, \]

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.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Energy Ring (Yellow)</th>
<th>Low Energy Ring (Blue)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy γ</td>
<td>107.4</td>
<td>7.79</td>
</tr>
<tr>
<td>Harmonic Number</td>
<td>360</td>
<td>363</td>
</tr>
<tr>
<td>Bunch Number</td>
<td>110</td>
<td>111</td>
</tr>
<tr>
<td>RMS emittance</td>
<td>15 μm</td>
<td>15 μm</td>
</tr>
<tr>
<td>((dp/p_0)_{rms})</td>
<td>(2.3 \times 10^{-4})</td>
<td>(5.0 \times 10^{-4})</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>0.75 m</td>
<td>1.25 m</td>
</tr>
<tr>
<td>(β^∗)</td>
<td>10.7 m</td>
<td>0.8 m</td>
</tr>
<tr>
<td>(σ^∗)</td>
<td>0.5 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Beam-beam Parameter</td>
<td>0.0015</td>
<td>0.0015</td>
</tr>
</tbody>
</table>
As an example, Figure 1 shows the trace of \( T_{m+n} \) for the high energy ring. Trace larger than 1 means unstable linear motion.

\[
T_{m+n} = \left( \frac{E - E_t}{E_t} \right) + \delta m + \phi_n.
\]

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 \((x_p, y_p, z_p) = \frac{-c\Delta t}{\beta} = \frac{dp}{\gamma}\).

A RF cavity is added to simulate the synchrotron motion,

\[
\frac{eV}{E_0} \sin(2\pi f \Delta t + \phi_0),
\]

where \(eV\) is the RF voltage, \(E_0\) is the particle energy, \(f\) is the frequency, \(\Delta t\) is the time step, \(\phi_0\) is the initial phase, \(\beta = \frac{1}{\gamma^2}\), and \(\gamma = \frac{E_0}{m_0 c^2}\) is the Lorentz factor.

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 2 shows the 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.

\[
\sigma_x = \sigma_y = \sigma_{x0} + \xi_{x0} \delta.
\]

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 \(5 \times 10^{-5}\). 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**

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

**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**

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.

\[
\Delta \delta = \frac{eV}{E_0} \sin(2\pi f \Delta t + \phi_0),
\]

\[
-c\Delta t = -\frac{1}{\gamma^2} \delta L.
\]
Bunch-by-bunch transverse damper is being built to counteract the possible TMCI in the coming RHIC polarized proton operation with electron lenses [4]. We include dampers in the code simply through
\[ \Delta x' = -2g < x' > \]
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.

**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.

**REFERENCES**