STRONG-STRONG SIMULATION OF LONG-RANGE BEAM-BEAM EFFECTS AT RHIC*

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Abstract

Long-range beam-beam interactions can cause significant degradation of beam quality and lifetime in high energy ring colliders. In this paper, we report on numerical simulation of the long-range beam-beam interactions at RHIC using a parallel strong-strong particle-in-cell code, BeamBeam3D. The simulation includes nonlinearities from both the beam-beam interactions and the arc sextupoles. Scan studies in tune space show strong emittance growth islands around 7th and 11th order resonances. The large emittance growth inside the resonance island is driven by the dynamic tune modulation together with the nonlinear forces from beam-beam interactions and sextupole magnet. The emittance growth decreases quickly as the beam-beam separation increases from four to six sigmas.

INTRODUCTION

Long-range beam-beam interaction plays an important role in limiting the performance of LHC [1]. Conducting wires have been proposed to compensate the long-range beam-beam interactions at LHC [2]. In the US LARP project, RHIC is used as a test bed to study the long-range beam-beam interactions and the compensation through conducting wire. In this paper, we report on studies of the betatron tune dependence of emittance growth subject to the long-range beam-beam interactions, the nonlinear sextupole fields, and the machine chromaticity at RHIC. This study will help with the choice of working points to maximize the signal to noise ratio in future experiments.

COMPUTATIONAL MODEL

In this study, we have used a parallel strong-strong beam-beam simulation code, BeamBeam3D [3], to study the long-range beam-beam interactions at RHIC. In this model, the colliding beams are modeled by a number of macroparticles. Each macroparticle is characterized by its charge, mass, and phase space coordinates. These macroparticles are transported inside the collider subject to the external focusing and acceleration. At the interaction points, the charged particles in one beam receives the electromagnetic forces, i.e. beam-beam forces, from the other oppositely moving beam. In the model used in this study, the beam-beam forces are computed self-consistently by solving two Poissons equations during each collision. Here, we have used a shifted Green function method to efficiently solve the Poisson equation for two separated beams [4]. Between each long-range beam-beam interaction, the particles are transported through RHIC using a number of linear transfer matrices generated from the MAD-X program. Sextupole nonlinear effects are included as a thin lens kick for macroparticles between linear transfer maps. Using a linear transfer map, we neglect the chromatic effects. On the other hand, one major purpose of sextupole magnets is to correct the chromatic effects from quadrupole magnets. Without including the chromatic effects of quadrupole magnets, including sextupole nonlinearity together with a fully linear transfer map (including dispersion) in our computational model could significantly exaggerate the chromatic effects of the machine. A tracking test without beam-beam interaction shows the chromaticity from the simulation is about 70, which is much higher than the designed machine chromaticity 2. In order to avoid this problem, we used only 4x4 linear transfer matrix from the original 6x6 transfer matrix, which neglects the effects of dispersion. The chromatic effects are added in later on through a single tune modulation kick, with a linear transfer map to account for the synchrotron motion. Some physical parameters used in this study are given in Table 1:

Table 1: RHIC physical parameters in simulations

Parameter	Unit	Value
proton energy	GeV	100
protons per bunch, Nb	10^{11}	2
emittance eN x,y 95%	mmmrad	15
beta* (beam1, beam 2)	m	(0.9,1)
rms bunch length	m	0.7
rms momentum deviation		0.3e-3
synchrotron tune	10-3	3.7
chromaticity		(2,2)
beam-beam seapartion	sigma	4-6

SIMULATION RESULTS

To help the choice of machine working point, we have carried out a tune scan of the blue beam in RHIC for 4 sigma, 5 sigma, and 6 sigma beam-beam separations using above strong-strong model. The betatron tunes of the yellow beam are fixed as (0.72, 0.73). The averaged emittance growth as a function of betatron tunes of the blue beam

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is given in Fig. 1 for 4 and 6 sigma separations. Those simulations were done using 82,000 macroparticles of each beam for 50,000 turns. Three major islands in emittance growth are seen in Fig. 1 for 4 sigma separation. These islands are due to the 7th order and the 11th order sum resonances. As the separation increases from 4 to 6 sigmas, the emittance growth in those resonance islands has dropped more than one order of magnitude due to the weaker beam-beam interactions. The emittance island becomes smaller and tends to spread out. For 6 sigma separation, only one island structure is clearly visible. The other two islands are not especially clear except that larger emittance growth is observed in the regions of 7th and 11th order resonances.

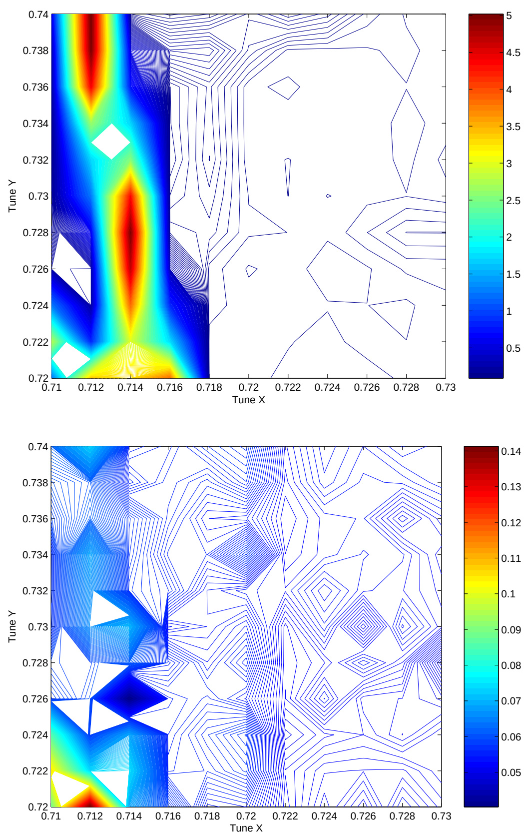

Figure 1: Averaged emittance growth as a function of betatron tunes for 4 sigma and 6 sigma separation including tune modulation.

Dynamic tune modulation plays an important role in causing emittance growth and limiting the beam lifetime [5, 6, 7]. It provides synchrotron sidebands and an extra dimension for chaotic particles to move across the resonance structures in phase space. This provides a dynamic process for a particle to move to large amplitudes. To see more clearly the effects of tune modulation, we look into a working point (0.714, 0.726) in the emittance island of the 7th order resonance. Fig. 2 shows the horizontal and vertical emittance growth evolution of the blue beam with and without dynamic tune modulation. It is seen that the tune modulation generates much stronger emittance growth than the case without tune modulation.

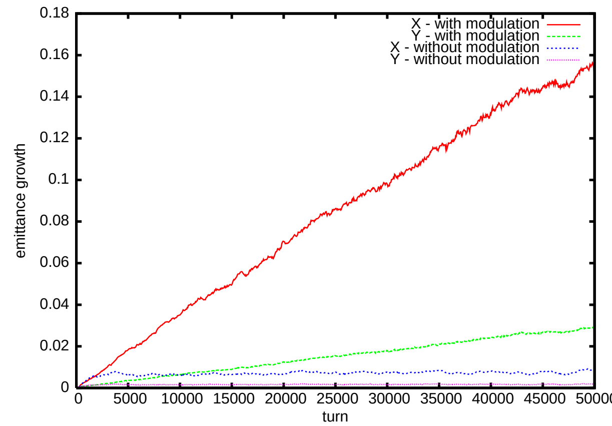

Figure 2: Horizontal and vertical emittance growth evolution of the blue beam with and without tune modulation at working point (0.714, 0.726) for 4 sigma separation.

Using the same tune working point but no dynamic tune modulation, we also compared the emittance growth with and without given machine chromaticity at RHIC. These results are shown in Fig. 3. It is seen that without and with a 2.0 static machine chromaticity does not significantly increases the emittance growth. This suggests that increasing the initial tune footprint might not lead to significant emittance growth. Fig. 4 shows the emittance growth evolution at the same working point with and without nonlinear sextupole magnets. In both cases, the tune modulation due to machine chromaticity and synchrotron motion was included. The absence of sextupole nonlinearity helps to lower the emittance growth by about 50%. However, even without the sextupole nonlinearity, the emittance growth due to the time dependent tune modulation together with long-range beam-beam interactions is still much larger than the case without tune modulation as shown in Fig. 3.

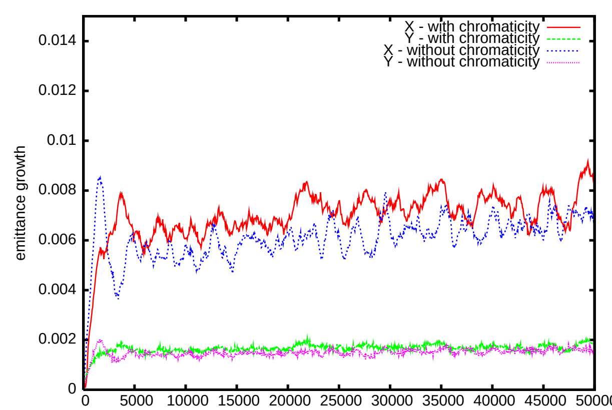

Figure 3: Horizontal and vertical emittance growth evolution of the blue beam with and without machine chromaticity at working point (0.714, 0.726) for 4 sigma separation.

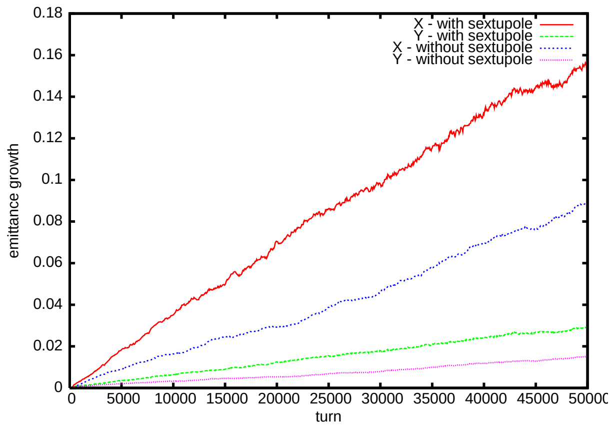

Figure 4: Horizontal and vertical emittance growth evolution of the blue beam with and without sextupole magnets at working point (0.714, 0.726) for 4 sigma separation.

To further explore the working point in the betatron tune space, we have carried out another tune scan for a reference point (0.71,0.69). Both the horizontal and the vertical tunes are varied from 0.68 to 0.72. Fig. 7 shows the averaged emittance growth as function of betatron tunes of the blue beam. One major emittance growth island can be seen around (0.716,0.715) due to the 7th order sum resonance. Another emittance growth island is around (0.68,0.716) due to a combination of the 7th order sum and difference resonance, the 10th order sum resonance, and the 12th order difference resonance.

SUMMARY

In this paper, we studied the emittance growth as a function of betatron tunes of the blue beam for long-range beam-beam interactions at RHIC. A number of emittance growth islands are observed in the betatron tune plane due to the 7th and the 11th order resonances. For 4 sigma beam-beam separation, the averaged emittance growth can be as high as 16% after 50,000 turns in a major 7th resonance. The large emittance growth is due to the interactions between the nonlinear beam-beam forces, the nonlinear sextupole forces, and the dynamic tune modulation from the machine chromaticity. As the beam-beam separation increases from four to six sigmas, the emittance growth drops by an order of magnitude.

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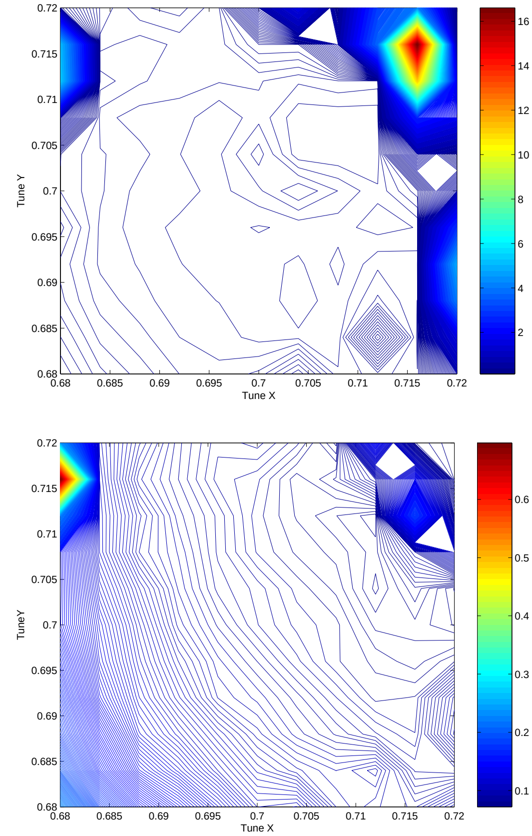

Figure 5: Averaged emittance growth as a function of betatron tunes for 4 sigma and 6 sigma separation including tune modulation.

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