LONG-RANGE BEAM-BEAM COMPENSATION IN RHIC

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Abstract

In order to avoid the effects of long-range beam-beam interactions which produce beam blow-up and deteriorate beam life time, a compensation scheme with current carrying wires has been proposed. Two long-range beam-beam compensators were installed in RHIC rings in 2006. The effects of the compensators have been experimentally investigated. An indication was observed that the compensators are beneficial to beam life time in measurements performed in RHIC during 2009. In this paper, we report the effects of wire compensator on beam loss and emittance for proton-proton beams at collision energy.

INTRODUCTION

In high energy storage-ring collider such as the Tevatron, long-range beam-beam interactions are known to cause emittance growth or beam loss, and are expected to deteriorate beam quality in the LHC. Increasing the crossing angle to reduce their effects has several undesirable effects, the most important of which is a lower luminosity due to the smaller geometric overlap and the excitation of synchro-betatron resonances. For the LHC, a wire compensation scheme has been proposed to compensate the long-range interactions by applying external electromagnetic forces [1]. At large beam-beam separation the electromagnetic force which a beam exerts on individual particles of the other beam is proportional to $\frac{1}{r}$, which can be generated and canceled out by the magnetic field of a current-carrying wire. This principle has been tested at RHIC. Two current carrying wires, one for each beam, have been installed between the magnets $Q3$ and $Q4$ of IP6 in the RHIC tunnel. An attempt was made to compensate the beam-beam interactions during the 2009 physics run with two colliding proton beams. It was observed that the beam loss rates in the Yellow ring were reduced as the vertical wire separation was varied [2]. In addition, the beam loss was recovered when the wire compensator was moved back from the location where the loss rate was minimized. However, it is not fully understood why the improvement of beam life-time was not observed in the Blue ring. In this report we discuss the results of numerical simulations of a wire acting on proton-proton beams in RHIC using a multi-particle tracking code BBSIMC [3].

MODEL

For a finite length of a wire embedded in the middle of a drift length L and tilted in pitch and yaw angles, the transfer map of a wire can be written as

$$\mathcal{M}_w = S_{\Delta x,\Delta y} \odot T^{-1}_{\theta_x,\theta_y} \odot D_{L/2} \odot \mathcal{M}_k \odot D_{L/2} \odot T_{\theta_x,\theta_y},$$

where T_{θ_x,θ_y} represents the tilt of the coordinate system by horizontal and vertical angles θ_x, θ_y to orient the coordinate system parallel to the wire, $D_{L/2}$ is the drift map with a length $\frac{L}{2}$, $\mathcal{M}_k$ is the wire kick integrated over a drift length, and $S_{\Delta x,\Delta y}$ represents a shift of the coordinate axes to make the coordinate systems before and after the wire agree. While particles at small r undergo a linear tune shift, the particles with $r \gg \sigma$ experience a $\frac{1}{r}$ force. The long-range effect is nonlinear and may vary from bunch to bunch if the the bunch pattern is asymmetric. The wire current required to compensate a long-range interaction is $(I_w L_w) = n_* q_* c$, where I_w is the wire current, and L_w its length. In current operation of RHIC with 108

Table 1: RHIC parameters at Au injection stage.

quantity	unit	proton beam
energy, γ	GeV	100
bunch intensity	10^{11}	1.7
$\epsilon_{x,y}$(95%)	mm mrad	25
(β_x^*, β_y^*)	m	(0.7, 0.7)
(β_x, β_y) at lrbb	m	(172, 174)
(β_x, β_y) at wire	m	(506, 1515)
(ν_x, ν_y)		B (28.700, 29.681)
		Y (28.703, 29.679)
(ξ_x, ξ_y)		(1, 1)
$\sigma_{\Delta p/p}$		1.4×10^{-4}
σ_z	ns	1.5
$I_w L_w$	Am	12.5 - 125
L_w	m	2.5
r_w	mm	3.5
wire separation	mm	30 - 60

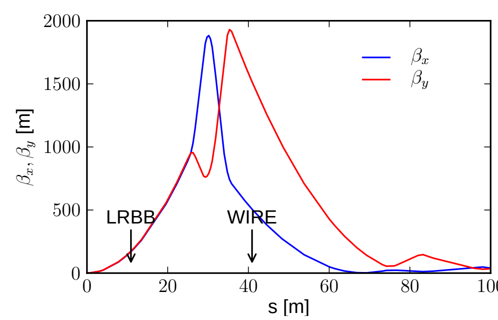

Figure 1: Beta function at long-range beam-beam (LRBB) interaction and wire compensator locations.

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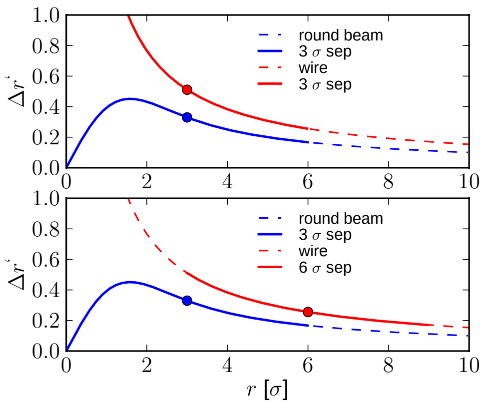

Figure 2: Kicks from Gaussian beam and current carrying wire as a function of distance. Maker circle represents the center of weak beam.

ns bunch spacing, there are no parasitic beam-beam collisions in the interaction region. In order to study the wire compensation, the interaction point is moved 10.95 m from the head-on location toward DX magnet as shown in Figure 1. The vertical separation between two beams is kept at 8 mm. At the new parasitic location, the vertical rms beam size is $\sigma_y = 2.7$ mm. The phase advance between the location of the wire to the location of the long-range interaction point is about 3° while the phase advance of the wire and the head-on is 89°. The integrated current for optimal tune compression is 8.16 Am when the beam-wire separation is equal to the beam-beam separation.

RESULTS

Figure 2 shows the kicks from Gaussian beam and current carrying wire. The wire strength and separation distance from the test beam are major parameters, as they determine the efficiency of wire compensating. The wire kicks in Fig. 2 are calculated using the minimum integrated strength of RHIC wire which is 12.5 Am, but not the optimum strength 8.16 Am. In principle the wire should cancel the long-range force which acts on the test beam. For the present experiment conditions, however, the wire kicks are at least 55 % larger than that of the other beam even at distances larger than 3 σ. In addition, the beam-beam separation is about 3.1 σ at the parasitic collision location. Since the amplitude of the test beam particles extends to larger than 3 σ amplitude, the beam-beam kicks experienced by the test beam cover the linear, transition, and $\frac{1}{r}$ regions, as shown in blue solid line of Fig. 2. A single wire is not practical for compensating the beam-beam forces with small separation distance, and makes a portion of large amplitude particles unstable due to its $\frac{1}{r}$ force. In order to avoid the unwanted beam blow-up, the separation distance may need to increase. It is, however, expected that a simple increase of the distance between the wire and the center of the test beam is not helpful to alleviating the beam-beam effects

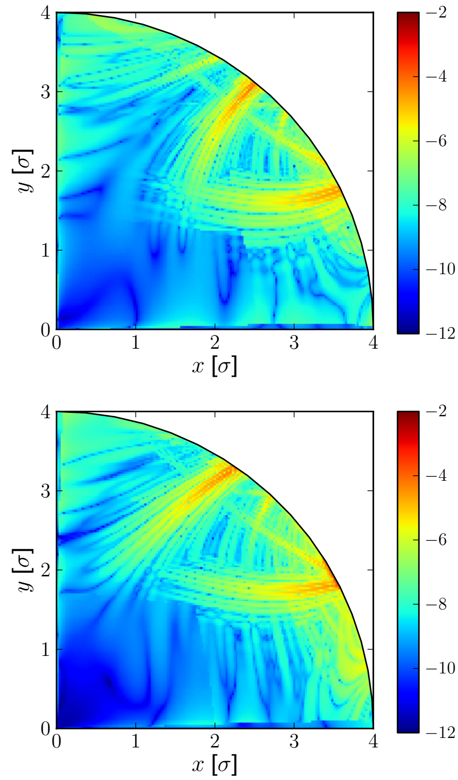

Figure 3: Frequency diffusion map: (top) long-range beam-beam integration only and (bottom) wire strength 12.5 Am and wire separation 50 mm.

because of the difference of the kicks exerted on the test beam, as shown in Fig. 2 (bottom). So, exact compensation requires that (i) the distance between the wire and any particle inside the beam be larger than 3 σ, (ii) the distance between the wire and the center of test beam be the same as the beam-beam separation, and (iii) the wire current be equivalent to beam intensity.

Figure 3 compares the frequency diffusion caused by the long-range beam-beam interaction with that by the parasitic collision and the wire of 12.5 Am and 50 mm separation. A large tune variation is generally an indicator of reduced stability. The wire increases the detuning of the betatron tune slightly for large amplitude particles. As the beam-wire separation decreases, the detuning becomes worse. The dynamic aperture calculated at different phase angles is the largest radial amplitude of particles that survive up to a certain time interval; in this simulation, 10^6 turns. The dynamic aperture is about 4.5 σ when the wire is turned off. In this case, a long-range interaction is present, but not head-on collision. At small wire separation, the dynamic aperture drops significantly, as shown in Fig. 4. As the separation increases, the dynamic aperture approaches that of the case without the wire. Figure 5 shows the beam loss as the wire-beam separation distance is varied. Initially we performed a tracking without wire compensator to see the beam loss caused by machine nonlinearities and a parasitic collision. By including a wire in the simulations, it is

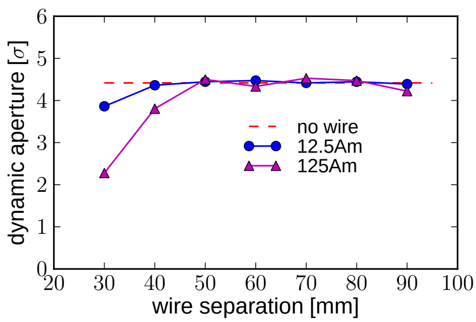

Figure 4: Angle-averaged dynamic apertures according to wire separation distance with wire strength 12.5 Am and 125 Am. Long-range interactions are present, but not head-on collisions.

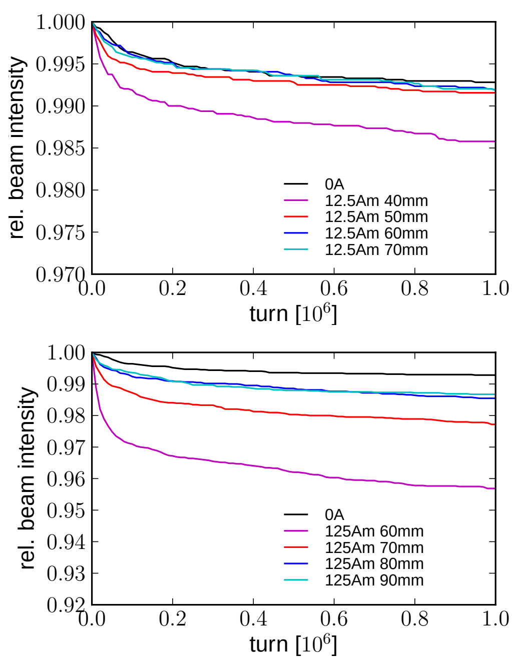

Figure 5: Beam intensity according to wire-beam separation distance with wire strength 12.5 Am and 125 Am. Long-range interactions are present, but not head-on collisions.

seen that the effects of the wire seems not beneficial to the beam life time because small beam-beam separation makes it difficult to cancel out the complex beam-beam force by a single wire. For high wire strength 125 Am, an emittance blow-up is observed at less than 40 mm separation. Even at large separation, the beam loss is about two times bigger with respect to the case without the wire.

Instead of including the long-range collision, we applied the normal operation condition of RHIC. Head-on collisions are included in the simulation together with the machine nonlinearities. Figure 6 shows the angle-averaged dynamic aperture for different beam-wire separation distance when the wire strength is 12.5 Am. Similarly to parasitic collision case, the dynamic aperture decreases at small

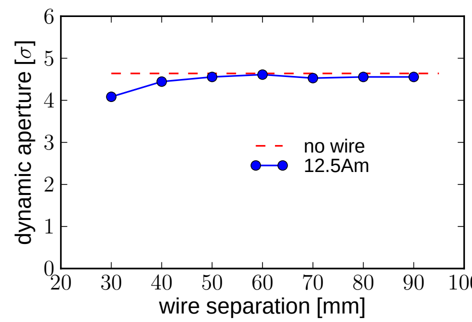

Figure 6: Angle-averaged dynamic apertures according to wire separation distance with wire currnet 5 A. Head-on collisions are present, but not long-range interactions.

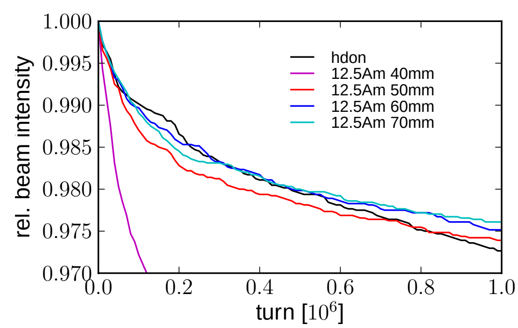

Figure 7: Beam intensity according to wire-beam separation distance with wire strength 12.5 Am. Head-on collisions are present, but not long-range interactions.

separation, and approaches to that without a wire. However, at a certain wire separation, the beam life time starts to increase compared to not having the wire, as shown in Fig. 7.

SUMMARY

Beam-beam compensation is studied under RHIC run-09 experimental conditions with a single wire in the Yellow ring. The results show that the parasitic collision with small separation is not compensated effectively using a single wire. However, the wire helps to increase the beam life time when the head-on collision is present. The effect of wire on head-on collision should be investigated further.

ACKNOWLEDGMENTS

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