STUDIES OF WIRE COMPENSATION AND BEAM-BEAM INTERACTION IN RHIC

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Abstract

The beam-beam interaction is one of the dominant sources of emittance growth and luminosity lifetime deterioration. A current carrying wire has been proposed to compensate long-range beam-beam effects in the LHC and the principle is now being experimentally investigated at RHIC. In this paper, we use simulations to study the effect of wire compensator on diffusive apertures, beam loss rates, and beam transfer function using a parallel weak-strong beam simulation code (BBSIM). In addition we extensively study diffusion of RHIC beams for different beam parameters. Emittance growth and lifetimes are investigated through the solution of the diffusion equation for the transverse action variables.

Table 1: RHIC parameters at deuteron-gold collision

quantity	unit	Blue	Yellow
energy, γ	Gev/n	107.396	107.396
bunch intensity	10^9	134	1
$\epsilon_{x,y}$(95%)	$mm\,mrad$	17	17
$(\beta_x, \beta_y)^\dagger$	m	$(1194, 393)$	$(411, 1180)$
$(\sigma_x, \sigma_y)^\dagger$	mm	$(5.6, 3.2)$	$(3.3, 5.5)$
(ν_x, ν_y)		$(.235, .225)$	$(.225, .235)$
$(IL)_{max}$	Am	125	125
L_w	m	2.5	2.5
r_w	mm	3.5	3.5
wire separation	mm	26-50	-

† beta function and rms transverse size at wire location.

INTRODUCTION

Long-range beam-beam interactions are known to cause beam loss in the Tevatron and are expected to deteriorate beam quality in the LHC. Compensation of their effects has been proposed for the LHC. The test of this principle is now underway at RHIC. Two current carrying wires, one for each beam, have been installed in the RHIC tunnel. Their impact on a beam was measured during the 2008 physics run with deuteron and gold beams. No attempt was made to compensate the beam-beam interactions since there were no parasitic interactions. In this report we discuss the results of numerical simulations of a wire acting on a deuteron beam in RHIC using a multi-particle tracking code BBSIM. The tracking code can estimate beam properties on a relatively short time scale. However simulations of a beam over the duration of a store are limited by the huge computation time. Instead we investigate the long-term behaviour of a beam using a diffusion equation approach [1] and apply it to RHIC deuteron-gold stores.

MODEL

A beam-beam simulation code BBSIM has been developed at FNAL over the past few years. BBSIM can track multi-particles and simulate nonlinear effects in a high energy circular accelerator. The effects of the long-range interactions in a collider may be alleviated by using an appropriately placed current carrying wire with a well defined value of the current. In BBSIM, the integrated magnetic fields from the wire are found from [2]. The integrated strength of the wire compensator should be commensurate with the integrated current of the beam bunch, i.e., $I_w L_w = ecN_b$, where N_b is the beam intensity. The parameters of deuteron-gold collision run and long-range beam-beam compensators for RHIC are listed in Table 1.

Growth of particle amplitudes may be described by diffusion coefficients in action-angle space. The diffusion coefficients contain the effects of nonlinearities present in the accelerators. The diffusion equation with diffusion coefficient tensor $\overleftrightarrow{D}$ is discretized in time using a θ scheme:

$$\frac{\rho^{n+1} - \rho^n}{\Delta t} = \frac{1}{2} \nabla_{\vec{J}} \cdot \left(\overleftrightarrow{D} \cdot \nabla_{\vec{J}} \right) \rho^{n+\theta}, \qquad (1)$$

where $\theta \in [1/2, 1]$ is a time decentering parameter chosen to adjust the numerical dispersion. The density at time level $n + \theta$ is given by a linear interpolation, $\rho^{n+\theta} = \theta \rho^{n+1} + (1 - \theta)\, \rho^n$. The formulation above is fully implicit. In a two-dimensional computational domain $[0, 1] \times [0, 1]$, the perfectly absorbing boundary condition is applied at along $J_x = 1$ and $J_y = 1$. However, the boundary conditions along $J_x = 0$ and $J_y = 0$ are not well-defined, except that the densities should be finite.

SIMULATION RESULTS

Fig. 1 (top left) presents tune footprints obtained by tracking single particles and applying the FFT with a Hanning filter to the particle coordinates. The red dots correspond to particles with no wire kicks. The different colors correspond to different beam-wire separations. As the separation decreases, the tune shifts increase and the spreads broaden. The separation distances were varied from 6σ to 15σ in the experiments. For example at the smallest separation of 6σ, the beam tune spread spans only higher 13^{th} and 17^{th} order resonances. The lower 5^{th} and 7^{th} order resonances are near the working point, but the beam does not span them.

The results of dynamic aperture calculation are shown in Fig. 1 (top right). Net chromaticities in both planes are

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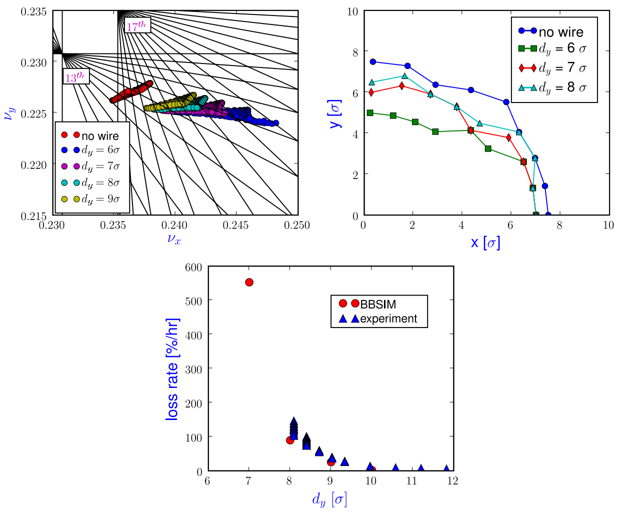

Figure 1: Plot of tune footprint (top left), dynamic aperture (top right), and beam loss rate (bottom) versus wire separation distance.

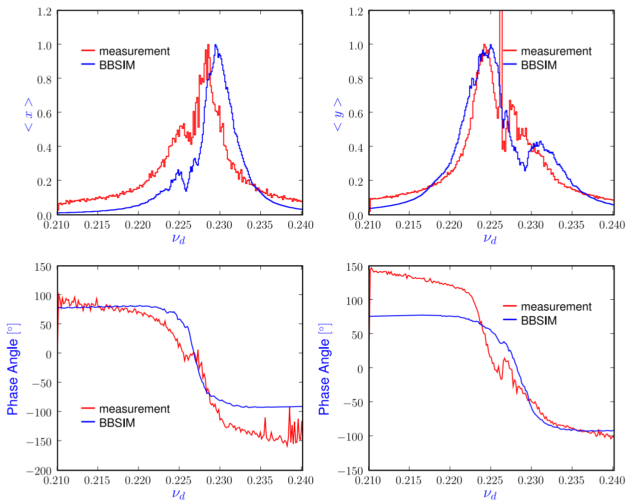

Figure 2: Horizontal (top left) and vertical (top right) beam transfer functions, and (bottom left) phase angle of horizontal BTF and (bottom right) phase angle of vertical BTF.

set to (+2,+2) using the chromaticity sextupoles. The tunes are set to (28.235,29.225). Tracking is carried out over 10^6 turns corresponding to 13 seconds storage time. When the wire is not present, the effects on the dynamic apertures from magnetic multipole field errors in the interaction regions and sexupole magnets are evaluated. The dynamic aperture is around 7.5σ in all directions. The effect of IR multipole field errors is dominant because of the large beam size in these magnets at collision energy. The dynamic aperture is not affected much by small changes in the chromaticity. In RHIC, the beam-wire separation is entirely in the vertical plane. The dynamic aperture is highly dependent on the angle of the wire position with the horizontal axis. The dynamic aperture in the vertical plane is found to decrease linearly as the vertical separation decreases.

Fig. 1 (bottom) shows the result of long-term particle tracking to calculate the beam loss rate when wire compensator is present. The tracking is done with hollow Gaussian beam distributions in transverse and longitudinal planes with 5×10^3 particles, and carried out over 10^7 turns over different wire separations for the wire current $I_w = 50A$. The loss rates are calculated by extrapolating the simulated loss rate from 10^7 turns to infinity. There are significant fluctuations in the measured loss rate at each separation, but simulated loss rates are reasonably close to the measured values. For example at 8σ separation, the difference between simulation and measurement is $\sim$30%. A sharp increase of loss rate is found in simulations at a 7σ wire separation in agreement with observations. Similar good agreement of the onset of losses between simulations and measurements during the RHIC 2007 run were reported earlier [3].

Fig. 2 shows the beam transfer functions for RHIC collision energy and working point $(28.234, 29.226)$. A sinusoidal driving force is introduced into a beam in both horizontal and vertical planes. Because the beam response remembers a driven nonlinear oscillator, it is expected that response curves are different according to the direction of the frequency sweep, i.e., downward or upward. In order to avoid the uncertainty, the relaxation time is applied just before starting BTF evaluation at each successive driving frequency. The response curve for deuteron-gold collision energy reveals two peaks. One peak is close to the horizontal tune, and the other is near the vertical one. In simulation, the sign change of phase angle is clearly seen near the nominal tune, and agrees reasonably with the measured beam response.

The diffusion coefficients can be calculated numerically from $D_{ij} = \langle (J_i(N) - J_i(0))\,(J_j(N) - J_j(0)) \rangle / N$, where $J_i\,(0)$ is initial action, $J_i\,(N)$ action after N turns, $\langle\rangle$ average over simulation particles, and (i, j) are x or y. They are calculated by loading 10^2 particles with the same action in horizontal and vertical planes but different angles, tracked over $N = 10^6$ turns and averaged over every 10^2 turns to suppress action fluctuations. BBSIM evaluates the diffusion coefficients in two-dimensional action space with the boundary determined by the dynamic aperture obtained above. Fig. 3 shows the simulated diffusion coefficients for three different RHIC runs: gold-gold, deuteron-gold, and proton-proton. They are averaged and plotted to compare with the measurement (in 2002) of coefficients obtained by fitting the time-dependent loss rate after moving the collimator [4]. The vertical axis is a logarithmic scale. It should be noted that dependence of diffusion coefficients on the initial action is exponential. However, since the measured coefficients are fitted by a power law, i.e. $D \sim J^n$, they agreed with simulations only at large actions. Due to measurement limitations, the diffusion coefficients were not measured at small actions. Conversely it is difficult to calculate the coefficients in simulations at large action because

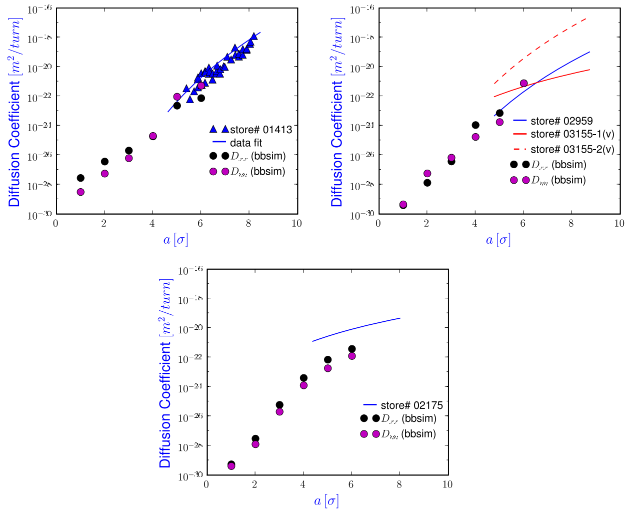

Figure 3: Diffusion coefficients of gold-gold (top left), deuteron-gold (top right), and proton-proton (bottom) stores of RHIC. The coefficients are calculated for the blue ring. The coefficients were measured and fitted by R. P. Fliller [4] in some early stores.

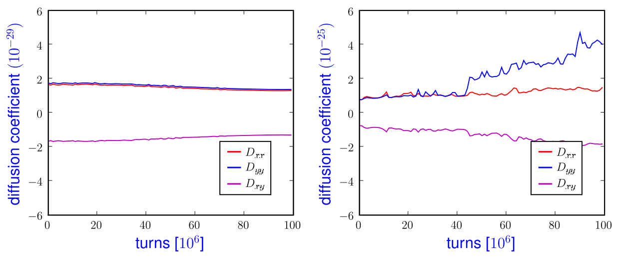

Figure 4: Diffusion coefficients history at actions $(J_x, J_y) = (1, 1)$ (left) and $(J_x, J_y) = (3, 3)$ (right). 10^8 turns corresponds to 21 minutes.

some of the particles are lost quickly.

Fig. 4 shows the time dependence of diffusion coefficients at different initial actions. At small action, the variation of coefficient is relatively small. However at large actions, one of the coefficients increases after about 4×10^7 turns. This suggests that the time scale for calculating these coefficients should not exceed $\sim 10^7$ turns.

Fig. 5 shows the horizontal and vertical emittance growth and beam intensity evolution for deuteron-gold store. Initial beam distribution is assumed to be Gaussian in phase space. The intensity is estimated by the zeroth moment of the density, i.e., $\langle\rho\,(t)\rangle = \int \rho d\vec{J}$, and the emittance by the first moment of density, i.e., $\epsilon_x \equiv \langle\rho\,(t)\,J_x\rangle = \int \rho J_x d\vec{J}$. In this calculation, only a single processor is used, and it takes 1 hour to simulate 10-hour store. This enables us to follow the beam over the duration of the store, something that is not yet feasible with direct tracking. The simulated emittances increase monotonically because the diffusion coefficients used are independent of time in this calculation. The diffusion coefficients underestimate the horizontal emittance growth but the agreement with the vertical emittance growth is quite good. The calculated intensity loss does not include the loss due to luminosity, which may explain the difference of beam intensities, shown in Fig. 5 (bottom). For example, the average luminosities are 10.4 and 12.9 in units of $10^{28} cm^{-1} s^{-1}$ at STAR and PHENIX respectively. Initial intensity is 91.6×10^9. The relative intensity loss due only to luminosity explains the observed intensity loss for most of the duration of the store

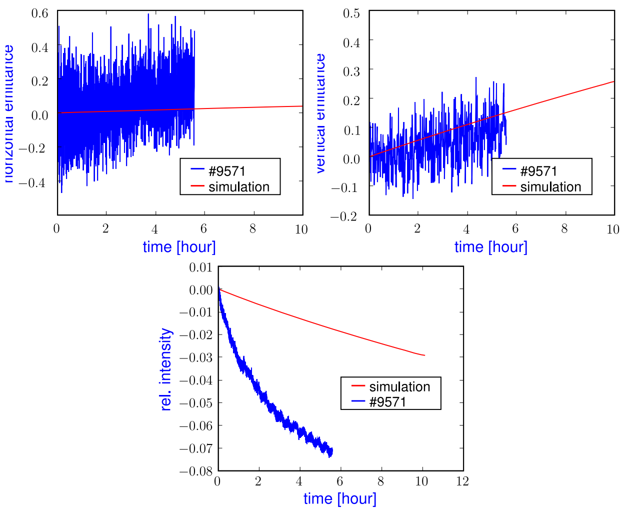

Figure 5: Time evolution of horizontal (top left) and vertical (top right) emittances, and (bottom) beam intensity for deuteron-gold store.

SUMMARY

In this paper, we investigated the effect of a wire compensator on deuterons at collision energy in RHIC using weak-strong simulations. The results show that the dynamic aperture is highly dependent upon the angle between the wire and beam particles and mostly linearly dependent upon the separation. The simulated loss rate differ from measured values by about 30%. The sharp onset of losses rate with decreasing wire separation are predicted to within 1σ of measured values. Diffusion coefficient tensors are evaluated for three different RHIC stores: p-p, d-Au, and Au-Au. They are compared with measured values, and used in a two-dimensional diffusion equation to investigate the emittance growth and lifetime of the deuteron beam over the length of a store.

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