SLAC-PUB-12581

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Contributed to European Particle Accelerator Conference (EPAC 06),
6/26/2006-6/30/2006, Edinburgh, Scotland

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Work supported in part by Department of Energy contract DE–AC02–76SF00515.

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OBSERVATION OF LONG-RANGE BEAM-BEAM EFFECT IN RHIC AND PLANS FOR COMPENSATION*

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Abstract

At large distances the electromagnetic field of a wire is the same as the field produced by a bunch. Such a long-range beam-beam wire compensator was proposed for the LHC, and single beam tests with wire compensators were successfully done in the SPS. RHIC offers the possibility to test the compensation scheme with colliding beams. We report on measurements of beam losses as a function of transverse separation in RHIC at 100GeV, and comparisons with simulations. We present a design for a long-range wire compensator in RHIC.

INTRODUCTION

To compensate the effects of long-range beam-beam interactions, electron lenses were tested in the Tevatron [1]; wires were proposed for the LHC [2], and tested with single beams in the SPS [3]. We report on possible long-range compensations with wires in RHIC.

Like in the LHC, long-range interactions in RHIC are localized in the interaction regions (Fig. 1). In the Tevatron, long-range interactions are distributed around the circumference, which makes compensation more complex [4]. In RHIC, with a bunch spacing of 108 ns (the current minimum) or more there are no parasitic beam-beam collisions in stores. For eRHIC [5] a bunch spacing of 36 ns is considered, which would lead to 4 long-range beam-beam interactions per IP.

To test a long-range beam-beam compensator in RHIC, there must be an observable effect from long-range interactions. We report on beam loss measurements at 100GeV, in which the vertical separation was varied. Simulations were carried out in an attempt to reproduce the observations. We present a design for a long-range compensator, to be installed in RHIC in 2006.

OBSERVATION OF LONG-RANGE BEAM-BEAM EFFECTS AT 100GEV

To test a long-range beam-beam compensator in RHIC, a single long-range interaction must produce a measurable effect (see below). As a first test, the beam loss rates of two colliding proton bunches was observed as a function of the vertical separation at the injection energy of 23 GeV [6] with a $\beta^* = 10$ m. This test was repeated at 100 GeV with $\beta^* = 1$ m. The main parameters of the 100 GeV test are shown in Tab. 1.

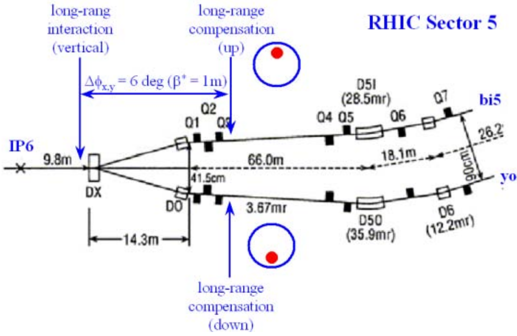

Figure 1: Location of the long-range beam-beam interaction and compensators for a beam test in RHIC.

Table 1: Main parameters for the RHIC test at 100GeV.

quantity	unit	value
proton energy	GeV	100.0
bunches per beam	...	12
bunch intensity	10^{11}	1.7
long-range location	m from IP	10.6
emittances $\epsilon_{x,y}$ (95%)	mm mrad	10-15
$\beta_{x,y}$, long-range location	m	105
tunes (Q_x, Q_y)	...	B(0.69,0.70) Y(0.71,0.69)
vertical separation	mm/σ	1–11/0.7–6.3

Since a single long-range interaction per turn has only a small effect, a tune was chosen where the beams are less stable than in normal operation. Arc octupoles were turned on in the Yellow beam to increase the tune spread. 132 magnets, all with the same strength of 4 m^{-2}, lead to a tune shift of about 0.0005 at one rms beam size on the nominal axis. No octupoles were used in Blue. The bunches interacted near the DX magnet, a location which can be compensated for (see below). The variation of the vertical separation creates a measurable effect in the beam loss rate when the beams are separated by less than 4 rms beam sizes (Fig. 2). This effect is still not very pronounced. To increase the signal-to-noise ratio further, 12 bunches were filled in both rings. The loss rate is averaged over these 12 bunches.

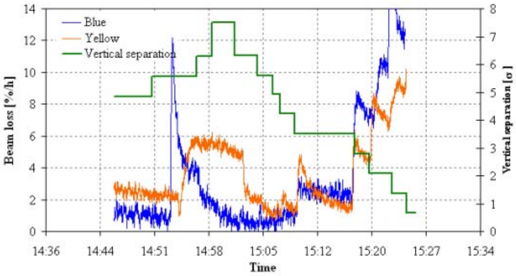

Figure 2: Beam loss and vertical separation at 100 GeV. Before 15:00h the Blue beam was moved to change the separation, after 15:00h the Yellow beam was moved.

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[*] Work performed under US DOE contract DE-AC02-98CH1-886, and with support from Renaissance Technology Corp. (USA).

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SIMULATIONS

Beam-beam simulations have been carried out by several groups. Here we report on the work done at FNAL, LBNL and SLAC. Work at CERN is reported in [7]. The models used are similar in most respects but differ in some details. The basic model common to all the simulations includes the linear lattice, sextupoles to correct the chromaticity to 2 units in both planes and synchrotron oscillations. The nonlinearities of the IR quadrupoles which may be important have not been included in any of these models. Neither were octupoles included that were used in the experiment. One of the main simulation goals is to find changes in beam quality as the vertical separation between the beams is varied.

The model used in the FNAL code BBSIM is a weak-strong model and includes random dipole kicks to mimic gas scattering. Tune footprints, diffusion coefficients, emittance growth, and lifetimes are calculated by this code. Fig. 3 shows the tune footprints for the blue beam at the tunes (0.68, 0.69) for beam separations of 3 and 10 σ. At this working point the footprint is clear of the neighboring 3rd and 10th order resonances.

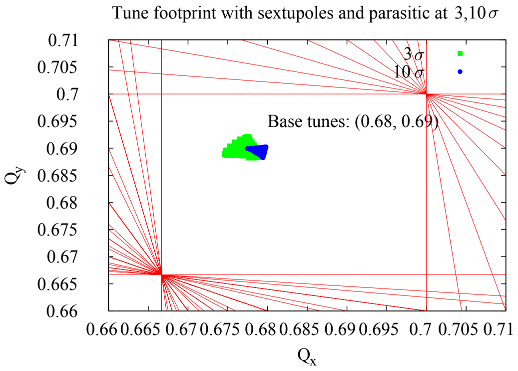

Figure 3: Tune footprints with beam separations at 3 (in green) and 10 σ (in blue). At 10σ, the beam-beam interaction has little impact on the tune spread, it is almost entirely due to the sextupoles.

Fig. 4 shows the diffusion coefficient in the vertical plane vs separation for the initial amplitudes 3 and 4 σ. At 3σ amplitude, the diffusion drops sharply as the separation increases from 5 to 6 σ while at 4σ amplitude the change with separation is more gradual.

The diffusion coefficients $D(J)$, with J as the initial action, have also been used to estimate the escape time τ_{esc} to an absorbing boundary at action J_A as $\tau_{esc} = \int_0^{J_A} J\ dJ/D(J)$. We interpret the escape time as a measure of the beam lifetime. Fig. 5 shows this lifetime as a function of the beam separation. The lifetime varies nearly linearly with separation over this range of separations.

The SLAC code PlibB was used in the weak-strong mode to track $\approx 1.3 \cdot 10^5$ Gaussian-weighted macroparticles for $\approx 10^5$ turns and calculate the loss rates of particles. Loss rates were determined by weighing the particles having crossed a given aperture at regular intervals during the tracking process. Fig. 6 shows the loss rate as a function of the beam separation. This calculation predicts a qualitative change in the losses at a separation of 5σ - losses are flat for smaller separations but fall steeply at larger separations.

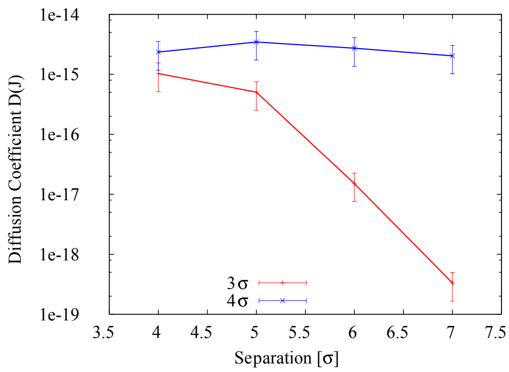

Figure 4: Diffusion coefficients (from BBSIM) vs beam separation at initial amplitudes of 3 and 4σ. Tunes at (0.68, 0.69).

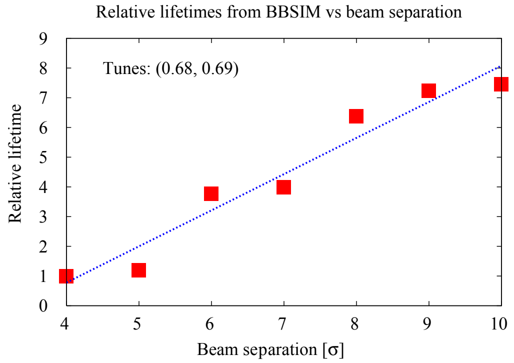

Figure 5: Relative lifetime vs separation with BBSIM.

The LBNL strong-strong code BeamBeam3D has been used to examine emittance growth of the two beams at different separations. These simulations show that there is significant emittance growth at separations below 4σ and there is little sensitivity of the emittance growth to tune values at separations above 6σ.

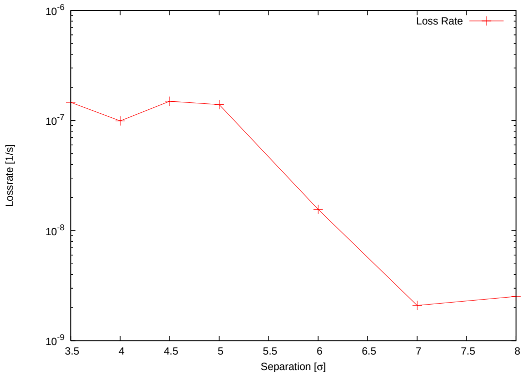

Figure 6: Loss rates vs beam separation with PLIBB.

COMPENSATOR DESIGN

The compensator design is based on experience gained with the SPS units. Design considerations are: the location in ring, the integrated strength (IL), the wire temperature T in operation, the positioning range and accuracy, power supply requirements, controls, and diagnostics [6]. The design parameters are shown in Tab. 2.

Location in the ring. For a successful compensation the phase advance between the long-range interaction and the compensator should be no larger than about 10 degrees [8]. Lattices with $\beta^* \leq 1.0$ m have such small phase advances between the entrance to the DX and the exit of Q3. Thus it is possible to place a wire in the warm region after Q3 to compensate for a long-range beam-beam interaction near the DX magnet (Fig. 1). One compensator can be installed in each ring (see Fig. 7), one above and one below the beam axis, to compensate for a vertical long-range interaction.

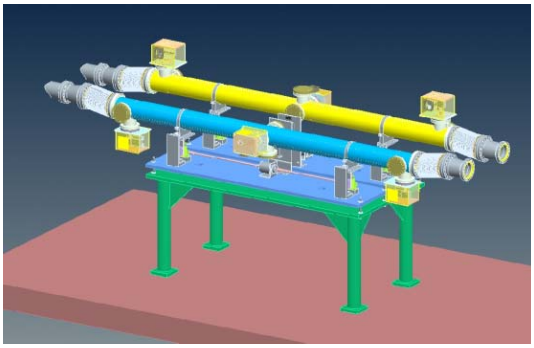

Figure 7: View of two long-range beam-beam compensators in the RHIC ring, mounted on a vertically movable stand.

Integrated strength. To compensate a single long-range interaction, the compensator's integrated strength (IL) must be the same as a bunch's current integrated over its length $(IL) = N_b ec$, where I is the current in the wire, L its length, N_b the bunch intensity, e the elementary charge, and c the speed of light (see Tab. 2).

In the LHC, an integrated strength of 80 Am is required to correct for the 16 long-range interactions on either side of an IR [2]. Such a strength is also expected to lead to enhanced diffusion at amplitudes larger than 6 rms transverse beam sizes [8]. To study the enhanced diffusion in RHIC, the compensator is designed for $(IL)_{max} = 125$ Am.

Wire temperature. The wire's temperature should not exceed 100°C to avoid increased outgassing of the vacuum components. We will use n heat sinks cooled with forced air, spaced apart by $L/(n-1)$. The maximum temperature increase in the center between 2 heat sinks is [9]

$$\Delta T_{max} = \frac{1}{8\pi^2}\frac{\rho_e}{\lambda}\frac{(IL)^2}{(n-1)^2 r^4}, \tag{1}$$

where ρ_e is the electrical resistivity, λ the heat conductivity, and r the wire radius. To move the wire compensator close to the beam, its radius should not be much larger than an rms transverse beam size. The calculated temperature change with 3 heat sinks is shown in Tab. 2.

Table 2: Parameters for RHIC compensators. The wire material is Cu at 20°C. The nominal strength is for a single long-range interaction.

quantity	unit	value
strength (IL), nominal	Am	9.6
max. strength $(IL)_{max}$	Am	125
length of wire L	m	2.5
radius of wire r	mm	3.5
number of heat sinks n	...	3
electrical resistivity ρ_e	Ωm	1.72×10^{-8}
heat conductivity λ	Wm^{-1}K^{-1}	384
thermal expansion coeff.	K^{-1}	1.68×10^{-5}
radius of existing pipe r_p	mm	60
current I, nominal	A	3.8
max. current in wire I_{max}	A	50
electric resistance R	mΩ	1.12
max. voltage U_{max}	mV	55.9
max. power P_{max}	W	2.8
max. temp. change ΔT_{max}	K	15
max. length change ΔL_{max}	mm	0.4
vertical position range	mm/σ_y	65/10.6

Power supply requirements. To avoid emittance growth, a current ripple of $\Delta I/I < 10^{-4}$ is required [8]. In a second stage a pulsed or modulated power supply can be tested, which is of interest for the LHC. With 100% modulation depth, such a power supply is very challenging.

SUMMARY

A long-range beam-beam effect is observable in RHIC at 100 GeV, with a single interaction per turn. The beam loss rate is weakly sensitive to the transverse separation at well selected tunes. Simulation results so far seem to be consistent with this observation. Two compensators are being constructed, and it is planned to install them in 2006.

ACKNOWLEDGMENTS

The authors are thankful for comments to A. Drees, H.C. Hseuh, V. Ptitsyn, T. Roser, T. Russo, and S. Tepikian.

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