LHC BEAM-BEAM COMPENSATION STUDIES AT RHIC*

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Abstract

Long-range and head-on beam-beam effects are expected to limit the LHC performance with design parameters. To mitigate long-range effects current carrying wires parallel to the beam were proposed. Two such wires are installed in RHIC where they allow studies of strong long-range beam-beam effects, as well as compensation of a single long-range interaction. The tests provide benchmark data for simulations and analytical treatments. To reduce the head-on beam-beam effect electron lenses were proposed for both the LHC and RHIC. We present the experimental long-range beam-beam program and report on head-on compensations studies at RHIC, which are based on simulations.

INTRODUCTION

Beam-beam effects are expected to limit the performance of the LHC [1–4]. Incoherent, PACMAN, or coherent effects can be caused by both head-on and long-range interactions. Head-on effects are important in all colliders and total beam-beam tune shifts as large as 0.028 were achieved in the Sp$\bar{\text{p}}$S [5] and Tevatron [6]. Long-range effects, however, differ in previous and existing colliders.

Figure 1 shows the basic layout of the beam-beam interaction and compensation studies in RHIC. At store there are nominally 2 head-on interactions, in IP6 and IP8, and long-range interactions with at least 15 σ separation in the other IPs. 3 Yellow bunches couple to 3 Blue bunches. For studies a DC wire was installed in each ring in IR6. 2 electron lenses will be installed near IP10. Table 1 shows the main parameters for polarized protons.

In the LHC there are 30 long-range beam-beam interactions localized in each of 4 interaction regions [3]. Locations in warm sections of the interactions are reserved to accommodate long-range beam-beam wire compensators (Fig. 2), or electron lenses. These locations have about equal horizontal and vertical β-functions.

The two main LHC luminosity upgrade scenarios are an early separation (ES) and a large Piwinski angle (LPA) scheme [4]. In the ES scheme the number of long-range interactions is reduced to 4 per IP, at 4-5 σ. The LPA scheme maintains the small crossing angle, with long bunches with up to 4×10^{11} protons. The LPA scheme would benefit from both long-range and head-on compensation.

The performance limitation imposed by beam-beam effects may be ameliorated by compensation techniques.

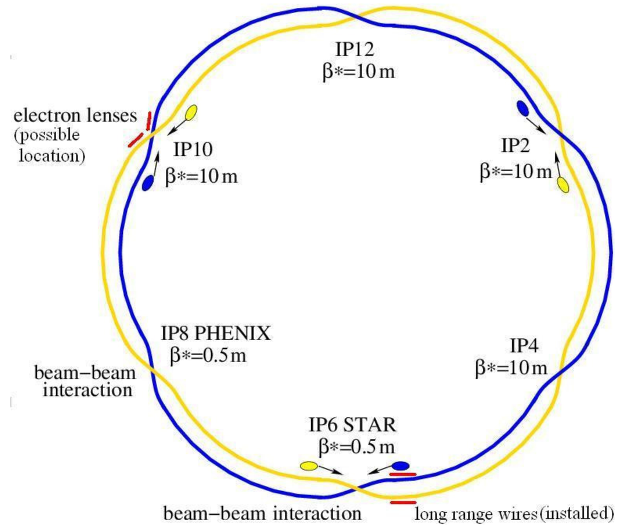

Figure 1: Beam-beam interactions in RHIC and locations of wires and electron lenses. The shown β^* values are for the polarized proton design configuration at 250 GeV, which has not been implemented yet.

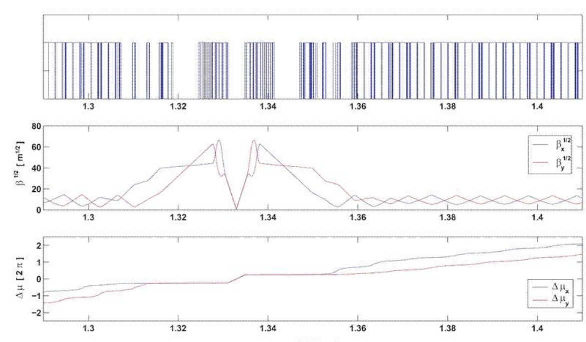

Figure 2: LHC IR lattice functions. At $s = 13.433$ km, with approximately equal transverse β-functions, a long-range wire compensator or electron lens could be placed.

Because of the amplitude dependence of the beam-beam forces a proper head-on compensation cannot be done with magnets but requires another particle beam. The compensation of head-on beam-beam effects was first tested in the 4-beam e^+e^- collider DCI. The DCI experience however fell short of expectation because of strong coherent effects [7]. Head-on beam-beam compensation was proposed for the SSC [8], Tevatron [9], and early on the LHC [10].

The compensation of long-range effects in the Tevatron was proposed with electron lenses [9], and in the LHC with wires [11]. A partial long-range beam-beam compensation was successfully implemented in the e^+e^- collider

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Table 1: Main RHIC parameters relevant for beam-beam effects, for polarized protons. Note that the polarized proton bunch intensity is also limited by intensity dependent depolarization effects in the AGS.

quantity	unit	achieved	goal
beam energy E	GeV	250	250
bunch intensity N_b	10^{11}	1.1	2.0
rms emittance ϵ	mm mrad	1.85	3.3
rms bunch length	m	0.7	0.30
beam-beam parameter ξ/IP	...	0.0078	0.0074
no of IPs	...	2	2
β^* at IP6, IP8	m	0.7	0.5
$(\Delta\psi_x, \Delta\psi_y)_{IP6-IP10}$	π	(19.1, 19.6)	
$(\Delta\psi_x, \Delta\psi_y)_{IP8-IP10}$	π	(8.4, 10.9)	

DAΦNE [12].

This article is an abridged and updated version of Ref. [13].

LONG-RANGE BEAM-BEAM COMPENSATION STUDIES

To investigate strong long-range interactions, test compensation schemes, and benchmark simulations, experimental data are needed. In the SPS wires were installed for this purpose [14–17]. The wire experiments in RHIC complement these studies. The beam lifetime in RHIC is typical for a collider and better than in the SPS wire experiments. In addition, head-on effects can be included, and with properly placed long-range interactions and wires, the compensation of a single long-range interaction is possible.

Wires in RHIC

The wire parameters are shown in Table 2 [18]

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 [19]. It is possible to place a wire after Q3 to compensate for a vertical long-range beam-beam interaction near the DX magnet (Fig. 3). In the Blue ring the wire is installed above the beam axis, in the Yellow ring below the beam axis (see Fig. 4).

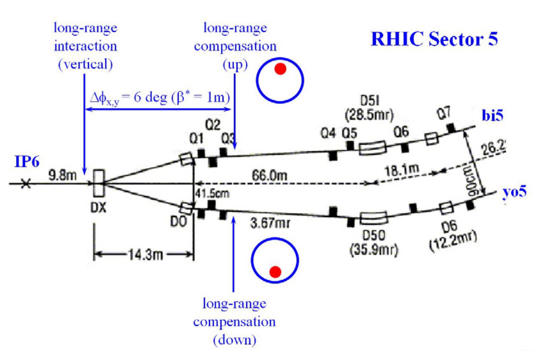

Figure 3: Location of wires in RHIC and location of long-range beam-beam interaction for compensation.

Integrated strength. To compensate a single long-range interaction, the compensator's integrated strength (IL) must be the same as the opposing 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 Table 2).

Table 2: Parameters for RHIC Wires. The wire material is Cu at 20°C. The nominal wire strength is for a single long-range interaction with a proton bunch intensity of 2×10^{11}.

quantity	unit	value
strength (IL), nominal	A m	9.6
max. strength $(IL)_{max}$	A m	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	Ω m	1.72×10^{-8}
heat conductivity λ	W m^{-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
current ripple $\Delta I/I$ (at 50 A)	10^{-4}	< 1.7
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

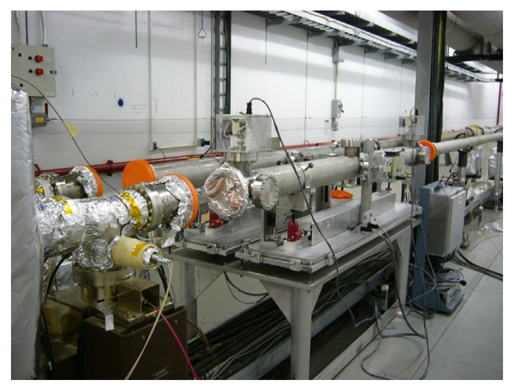

Figure 4: The two long-range beam-beam wires in the RHIC tunnel during installation.

In the LHC, $(IL) = 80$ A m is required for the 16 long-range interactions on either side of an IR [11]. Such a strength is also expected to lead to enhanced diffusion at amplitudes larger than 6 σ [19]. To study the enhanced diffusion, the RHIC wire is designed for $(IL)_{max} = 125$ A m.

Wire temperature. The wire's temperature should not exceed 100°C. We use $n = 3$ heat sinks cooled with forced air, spaced apart by $L/(n-1)$. The maximum temperature increase in the center between 2 heat sinks is

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

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. We have $\Delta T_{max} \leq 15$ K.

Table 3: Au Beam Parameters for Long-Range Experiments

quantity	unit	Blue	Yellow
beam energy E	GeV/n	100	
rigidity $(B\rho)$	T m	831.8	
number of bunches	...	23	
distance IP6 to wire center	m	40.92	
β_x at wire location	m	1091	350
β_y at wire location	m	378	1067

Power supply requirements. To limit emittance growth, a current ripple of $\Delta I/I < 10^{-4}$ is required [19]. $\Delta I/I < 1.7 \times 10^{-4}$ was measured, where the upper limit is given by the noise floor of the measurement.

Experiments and Simulations

The main observable in the long-range experiments is the beam lifetime, which is observed as a function of the long-range strength (or wire current), the distance between beam and the wire (or other beam), tune and chromaticity.

Long-range experiments were done with 2 proton beams at injection, 2 proton beams at store, gold beams and wires at store, and deuteron beams and wires at store. No proton beams were available for store experiments with wires yet. Experiments including the head-on effect as well as the compensation of a single long-range interaction are best done with protons since the largest beam-beam parameters can be attained with protons. Observed orbit and tune changes agree with calculations under well controlled experimental circumstances [20, 21].

Most of the the wire experiments so far were done with gold beams (Table 3). Figure 5 shows a typical parameter scan, however with deuterons. First the wire current is set, then the distance to the beam is reduced. At close distance, the current is decreased, and again increased.

It was speculated that the beam lifetime τ can be expressed as $\tau = Ad^p$ where A is an amplitude, d the distance between wire and beam, and p an exponent. For the SPS p had been found to be about 5, and for the Tevatron to be about 3 [22]. The fitted exponents in all RHIC measurements range from 1.7 to 16, i.e. p is not constrained within a narrow range. 10 of the 13 obtained p values are between 4 and 10. Figure 6 shows the fitted exponents p as a function of the ion tunes in the upper part, and the proton tunes in the lower part. Ion tunes near the diagonal and away from either horizontal or vertical resonances show smaller exponents p. The experiments also showed that the beam lifetime is reduced with increased chromaticity [20].

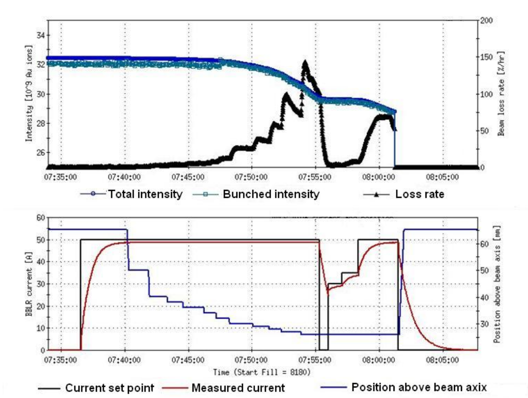

Figure 5: Long-range beam-beam experiment in RHIC with deuterons at store. The upper plot shows the total and bunched beam intensity (blue curves) and the calculated beam loss rate (black curve). The lower plot shows the set point for the wire current (black curve), the measured current (red curve), and the wire position above the beam pipe center (blue curve).

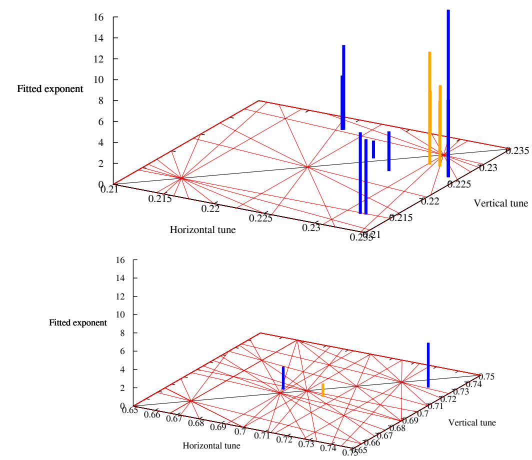

Figure 6: Fitted exponents p for long-range beam-beam experiments as a function of the ion tunes (top) and the proton tunes (bottom). The fitted exponents range from 1.7 to 16.

Another simple measure of assessing the long-range beam-beam effect in experiments is to measure the distance between the beam and wire (or other beam) at which the beam lifetime become smaller than a certain value, for example 20 h. An amplitude range between 3.5 and 17 σ is observed in RHIC with no clear correlation between this distance and the fitted coefficient p. In 2 cases the distance was found to be as large as or larger than 10 σ, and most cases fall between 4 and 10 σ. Operation with less than 5 σ separation appears to be difficult [23].

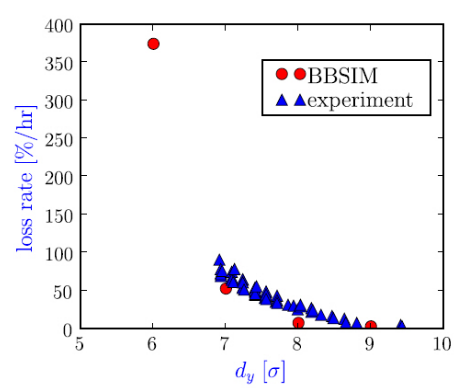

Figure 7: Comparison of measured and simulated beam loss rate as a function of distance between wire and and beam. Experiment with gold beam at store, wire strength of 125 A m [24].

One important goal of the experiments is to benchmark simulations. In several simulations the onset of large losses as a function of the distance between wire and beam was reproduced within about 1 σ [17, 21, 24, 25]. One such comparison is shown in Fig. 7.

HEAD-ON BEAM-BEAM COMPENSATION STUDIES

If a collision of a proton beam with another proton beam is followed by a collision with an electron beam, the head-on beam-beam effect can be canceled exactly if the following 3 conditions are met:

1. The proton and the electron beam produce the same amplitude dependent force.
2. The phase advance between the two beam-beam collisions is a multiple of π in both transverse planes.
3. There are no nonlinearities between the two collisions.

In practice this cannot be achieved, and the goal of the simulation studies is to find out how far one can deviate from these three condition. With tolerances established one can then assess if these can be achieved with the technology available.

Electron Lenses in RHIC

Two electron lenses are currently installed in the Tevatron [26] where they are reliably used as an operational gap cleaner [27]. They were also shown to improve the lifetime of antiproton bunches suffering from PACMAN effects [28]. The experience with the construction and operation of the Tevatron electron lenses provides invaluable input into an assessment of the practicability of head-on beam-beam compensation. In RHIC it is planned to install 2 electron lenses near IP10 with parameters close to those of the Tevatron. (Fig. 1, Table 4). A successful demonstration of head-on beam-beam compensation in RHIC would also allow to use this technique in the LHC.

Simulation Studies

A number of simplifications are used for the simulations so far. First, the electron lenses are exactly at IP10, while 2 lenses for both beams would need to be installed with a few meters offset from the IP. Second, the electron beam of the electron lens is infinitely stiff (see Refs. [30, 31] for a discussion). Third, a lattice for polarized proton operation at 250 GeV is used with $\beta^* = 0.5$ m in IP6 and IP8, and $\beta^* = 10$ m in all other IPs (see Fig. 1 and Table 1).

Table 4: Parameters for RHIC Electron Lenses [29], Adapted from the Tevatron Electron Lenses [26]

quantity	unit	value
electron kinetic energy K_e	keV	5.0
electron speed $\beta_e c$	...	$0.14c$
electron transverse rms size	mm	0.57
effective length L_{elens}	m	2.0
full head-on compensation		
no of electron in lens N_e	10^{11}	3.5
electron beam current I_e	A	1.2

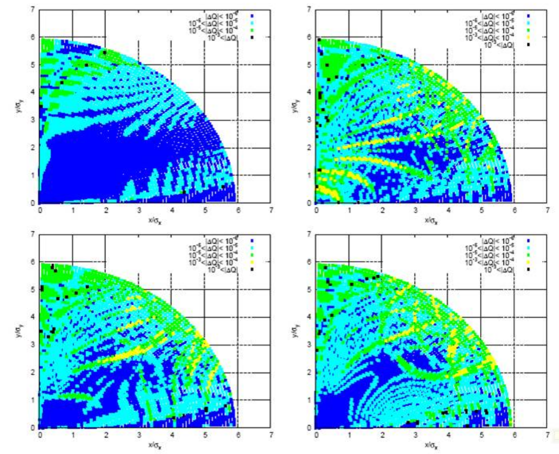

Figure 8: Tune diffusion without beam-beam interaction (top left), with beam-beam interaction (top right), with half (bottom left), and with full beam-beam compensation [32].

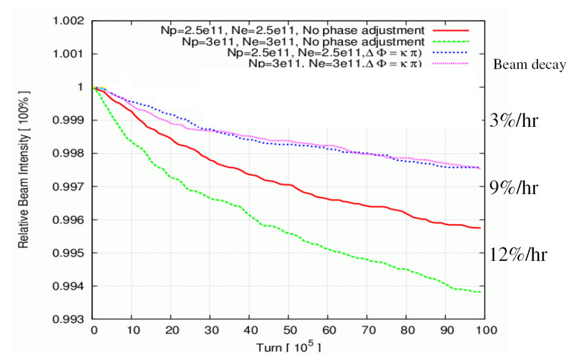

Figure 9: Beam lifetime simulations for increased bunch intensity and different phase advances between the IP and e-lens. Note that without compensation the beam-beam tune generated tune spread could not be accommodated for these bunch intensities.

The phase advance in the horizontal plane between IP6 and IP10 is close to a multiple of π, as well as in the vertical plane between IP8 and IP10. No optimization of the phase advance was done in this lattice.

Tune footprints can be compressed with electron lenses but this is not sufficient to improve the beam lifetime. At large compensation strength the tune footprints are folded over which leads to reduced stability. The folding can be avoided with a partial compensation.

It was found that almost all particles are chaotic with and without compensation [34], and that therefore chaotic borders cannot be used to evaluate head-on problems. Dynamic aperture calculations proved insensitive since they evaluate the stability of motion at large betatron amplitudes, where the beam-beam forces are small.

Other short-term measures calculated were tune diffusion (Fig. 8) and Lyapunov exponent maps [32], and diffusion coefficients sampled at a number of locations in phase space and fitted with an analytic function [34]. In all cases we find that the stability of motion is increased at amplitudes below 3 σ and decreased at amplitudes above 4 σ.

In many-particle simulations over a large number of turns with SixTrack the emittance growth was too noisy to distinguish cases. To distinguish cases with beam lifetime simulations more than a million turns are necessary. Figure 9 shows a parameter scan with and increased bunch intensity that could otherwise not be accommodated.

SUMMARY

Long-range beam-beam experiments were carried out in RHIC with 2 DC wires parallel to the beam. These experiments complement experiments in the SPS. The RHIC wires can create strong localized long-range beam-beam effects, comparable in strength expected in the LHC, with a beam that has a lifetime typical of hadron colliders and possibly including head-on beam-beam collisions.

The RHIC experiments confirmed that a visible effect of long-range beam-beam interactions should be expected, although their effect sensitively depends on a number of beam parameters such as the tune and chromaticity. Fitting the beam lifetime τ to an exponential function $\tau \propto d^p$ as a function of the distance d between the beam and the wire, exponents p in the range between 1.7 and 16 were found. The experimentally observed distance from the wire to the beam at which large beam losses set in could be reproduced in simulations within 1 σ. Distances smaller than 5 σ appear to be problematic to maintain good beam lifetime.

Long-range wire experiments with protons, and including the head-on effect, are still outstanding.

In simulations for head-on beam-beam compensation in RHIC, short-term measures such as diffusion maps, Lyapunov exponent maps and action diffusion coefficients all show an increase of the stability for betatron amplitudes below 3 σ, and a reduction of stability for amplitudes larger than 4 σ. This is particularly pronounced for full head-on compensation and suggests to use partial compensation only. For full compensation the tune footprints are already folded over at small amplitudes.

In operation there are only few particles beyond 4 σ, and whether the decreased stability at these amplitudes can be tolerated can be estimated in beam lifetime and emittance growth simulations over up to 10^7 turns with 10^4 macro-particles.

Long-term beam lifetime simulations confirm that the head-on effect should be compensated only partially, enough to obtain a small enough tune footprint with an increased beam-beam parameter, but not more.

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