STATUS OF HEAD-ON BEAM-BEAM COMPENSATION IN RHIC[*]

W. Fischer[†], Z. Altinbas, M. Anerella, M. Blaskiewicz, D. Bruno, M. Costanzo, W.C. Dawson,
D.M. Gassner, X. Gu, R.C. Gupta, K. Hamdi, J. Hock, L.T. Hoff, R. Hulsart, A.K. Jain,
R. Lambiase, Y. Luo, M. Mapes, A. Marone, R. Michnoff, T.A. Miller, M. Minty, C. Montag,
J. Muratore, S. Nemesure, D. Phillips, A.I. Pikin, S.R. Plate, P. Rosas, L. Snydstrup, Y. Tan,
C. Theisen, P. Thieberger, J. Tuozzolo, P. Wanderer, S.M. White, W. Zhang
Brookhaven National Laboratory, Upton, New York, USA

Abstract

In polarized proton operation the RHIC performance is limited by the head-on beam-beam effect. To overcome this limitation two electron lenses are under commissioning. We give an overview of head-on beam-beam compensation in general and the specific design for RHIC, which is based on electron lenses. The status of installation and commissioning are presented along with plans for the future.

INTRODUCTION

Head-on beam-beam compensation had been first proposed as a 4-beam $e^+e^-e^+e^-$ scheme for COPPELIA [1], and was implemented for DCI [2]. The DCI experience, however, fell short of expectations, with luminosities with 2, 3 or 4 beams about the same. The shortfall is generally attributed to coherent beam-beam instabilities [3–5], and head-on beam-beam compensation has not been tested again after DCI.

A number of proposals were made though, such as for the SSC [6, 7], Tevatron [8], LHC [6, 7, 9–11], and B-factories [12]. In hadron colliders the compensation can be done by colliding positively charged beams with a negatively charged low-energy electron beam, in a device usually referred to as an electron lens. This avoids the coherent instabilities seen in DCI since the electron beam will not couple back to the hadron beam, except for single pass effects. These can be significant [13, 14] and may require the addition of a transverse damper in RHIC. Two electron lenses were installed in the Tevatron [8, 13, 15–19], where they were routinely used as gap cleaner, but not for head-on beam-beam compensation. The Tevatron experience is valuable for a number of reasons: (i) the reliability of the technology was demonstrated as no store was ever lost due to the lenses [20]; (ii) the tune shift of selected bunches due to PACMAN effects was corrected leading to lifetime improvements [16]; (iii) the sensitivity to positioning errors, transverse profile shape, and electron beam current fluctuations was explored [21]; (iv) experiments with a Gaussian profile electron beam were done; and (v) a hollow electron beam was tested in a collimation scheme [19]. For the design of the RHIC electron lenses we have benefited greatly from the Tevatron experience. We have also drawn on the expertise gained in the construction and operation of an Electron Beam Ion Source (EBIS) at BNL [22, 23], a device similar to an electron lens but for a different purpose.

In RHIC there are 2 head-on beam-beam interactions at Interaction Points IP6 and IP8 (Fig. 1), and 4 long-range beam-beam interactions with large separation (about 10 mm) between the beams at the other IPs. The luminosity is limited by the head-on effect in polarized proton operation [24–30] as can be seen in Fig. 2. Bunches with two collisions experience a larger proton loss throughout the store than bunches with only one collision. The enhanced loss is particularly strong at the beginning of a store. Beam-beam effects in other hadron colliders are reported in Ref. [31–36].

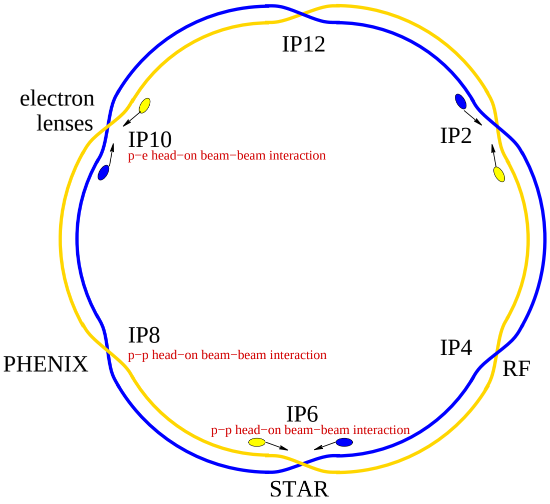

Figure 1: General layout of RHIC with locations of the head-on beam-beam interactions and electron lenses.

We consider the partial indirect compensation of the head-on beam-beam effect with one electron lens in each ring. Together with intensity and emittance upgrades [37] our goal is to approximately double the luminosity over what can be achieved without these upgrades.

This article is a summary of previous studies and progress reports on the RHIC head-on beam-beam compensation with electron lenses [38–74], updated with the latest available information.

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[†] Wolfram.Fischer@bnl.gov

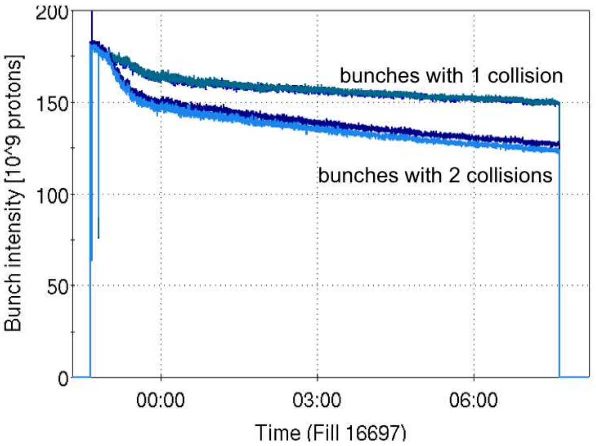

Figure 2: Time-dependent intensity of polarized proton bunches with 1 and 2 head-on collisions during the 2012 Run.

HEAD-ON BEAM-BEAM COMPENSATION

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 kick can in principle be reversed. For simplicity we only consider the horizontal plane and beams with a Gaussian transverse distribution. Figure 3 shows the beam line layout for head-on compensation, and Fig. 4 the normalized phase space view.

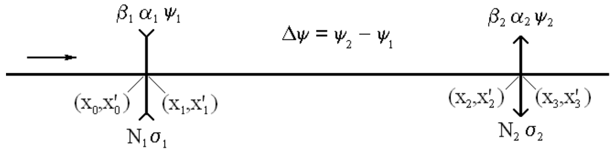

Figure 3: Schematic of head-on beam-beam compensation in a beam line view. At the first location, with lattice parameters $(\beta_1, \alpha_1, \psi_1)$, a proton experiences a beam-beam kick from another proton bunch with intensity N_1 and rms beam size σ_1. At the second location, with lattice parameters $(\beta_2, \alpha_2, \psi_2)$, another beam-beam kick is generated by the electron beam with effective bunch intensity N_2 and rms beam size σ_2.

Before experiencing a beam-beam kick from another proton beam at location 1, a proton has the transverse phase space coordinates (x_0, x'_0). Then the proton receives a kick from the other proton beam [75]

$$\Delta x'_0 = \frac{2N_1 r_0}{\gamma x_0}\left[1 - \exp\left(-\frac{x_0^2}{2\sigma_1^2}\right)\right] \tag{1}$$

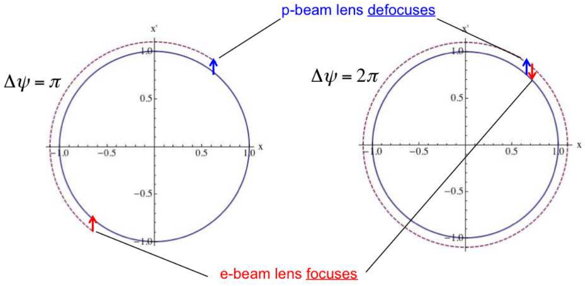

Figure 4: Schematic of head-on beam-beam compensation in a normalized phase space view.

where N_1 is the bunch intensity of the other proton beam, γ the relativistic factor of the proton receiving the kick, r_0 the classical proton radius, and σ_1 the rms beam size of the other proton beam. The new coordinates are then

$$\begin{aligned} x_1 &= x_0 \qquad (2)\\ x'_1 &= x'_0 + \Delta x'_0. \qquad (3)\end{aligned}$$

After transport through the linear beam line the coordinates are

$$\begin{aligned} x_2 &= M_{11}x_1 + M_{12}x'_1 \qquad (4)\\ x'_2 &= M_{21}x_1 + M_{22}x'_1 \qquad (5)\end{aligned}$$

with [76, 77]

$$\begin{aligned} M_{11} &= \sqrt{\frac{\beta_2}{\beta_1}}\,(\cos\Delta\psi + \alpha_1 \sin\Delta\psi) \qquad (6)\\ M_{12} &= \sqrt{\beta_1\beta_2}\,\sin\Delta\psi \qquad (7)\\ M_{21} &= -\frac{1+\alpha_1\alpha_2}{\sqrt{\beta_1\beta_2}}\sin\Delta\psi + \frac{\alpha_1-\alpha_2}{\sqrt{\beta_1\beta_2}}\cos\Delta\psi \qquad (8)\\ M_{22} &= \sqrt{\frac{\beta_1}{\beta_2}}\,(\cos\Delta\psi - \alpha_2 \sin\Delta\psi) \qquad (9)\end{aligned}$$

and $\Delta\psi = \psi_2 - \psi_1$. In the electron lens the proton receives the kick

$$\Delta x'_2 = -\frac{2N_2 r_0}{\gamma x_2}\left[1 - \exp\left(-\frac{x_2^2}{2\sigma_2^2}\right)\right] \tag{10}$$

where N_2 is the effective bunch intensity of the electron lens beam (i.e. the number of electrons the proton passes in the lens), and σ_2 the rms beam size of the electron lens beam. The coordinates after passing the electron lens are then

$$\begin{aligned} x_3 &= x_2 \qquad (11)\\ x'_3 &= x'_2 + \Delta x'_2. \qquad (12)\end{aligned}$$

One can now express the final coordinates (x_3, x'_3) as a function of the intensities (N_1, N_2) and require for exact compensation that

$$\begin{aligned} x_3(N_1,N_2) &= x_3(0,0) \quad \text{and} \qquad (13)\\ x'_3(N_1,N_2) &= x'_3(0,0), \qquad (14)\end{aligned}$$

i.e. the final coordinates are the same with and without beam-beam interaction and compensation. From the condition (13) it follows that $M_{12} = 0$ and therefore $\Delta\psi = k\cdot\pi$, with k being an integer. From the condition (14) it follows that $N_1 = N_2$ and $\sigma_1^2/\sigma_2^2 = \beta_1/\beta_2$.

Therefore, if the following three conditions are met the beam-beam kicks are canceled exactly:

1. The ion and the electron beam produce the same amplitude dependent force by having the same effective charge and profile.
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 can be achieved only approximately. Deviations from condition 1 include

- an electron current that does not match the proton bunch intensity,
- an non-Gaussian electron beam profile (assuming that the proton beam transverse profile is Gaussian),
- an electron beam size different from the proton beam size,
- time-dependence of the electron and proton beam parameters;

deviations from condition 2 include

- a phase advance $\Delta\psi \neq k\pi$ between the head-on collision and electron lens,
- long bunches, i.e. $\sigma_s \gtrapprox \beta^*$;

and deviations from condition 3 include

- lattice sextupoles and octupoles as well as multipole error between the head-on collision and the electrons lens.

Tolerances were studied extensively in simulations and reported in Ref. [70], bunch length effects are investigated in Refs. [47, 48]. The Tevatron experience also provides tolerances for positioning errors, transverse shape and size mismatches, and electron current variations. We give the tolerances for all devices below.

We plan to compensate for only one of the two head-on collisions in RHIC since a full compensation would lead to a small tune spread and could possibly lead to instabilities.

RHIC ELECTRON LENS DESIGN

In designing the electron lens we were aiming for a technically feasible implementation that comes as close a possible to the ideal compensation scheme outlined above. In addition, a major design consideration is the ease of commissioning and operation. Our goal is a commissioning largely parasitic to the RHIC operation for physics. The main design process can be summarized as follows:

Condition 1 (same amplitude-dependent forces from proton beam and electron lens) has a number of implications. Since both proton beams are round in the beam-beam interactions ($\beta_x^* = \beta_y^*$ and $\epsilon_x = \epsilon_y = \epsilon_n$), we also require $\beta_x = \beta_y$ at the electron lens location, and matched transverse proton and electron beam profiles, i.e. the electron beam profile is also Gaussian with $\sigma_{p,x} = \sigma_{e,x} = \sigma$ and $\sigma_{p,y} = \sigma_{e,y} = \sigma$. $\beta_x = \beta_y$ limits the electron lens locations to the space between the DX magnets. In these locations the RHIC lattice also has a small dispersion.

Table 1: Reference cases for RHIC beam-beam and beam-lens interactions. Bunch intensities without electron lenses are expected to saturate at about 2×10^{11} due to head-on beam-beam effects [30, 70].

quantity	unit	value		
proton beam parameters				
total energy E_p	GeV	100	255	255
bunch intensity N_p	10^{11}	2.5	2.5	3.0
$\beta_{x,y}^*$ at IP6, IP8 (p-p)	m	0.85	0.5	0.5
$\beta_{x,y}^*$ at IP10 (p-e)	m	10.0	10.0	10.0
lattice tunes (Q_x, Q_y)	...	— (.695,.685) —		
rms emittance ϵ_n, initial	mm mrad	— 2.5 —		
rms beam size at IP6, IP8 σ_p^*	μm	140	70	70
rms beam size at IP10 σ_p^*	μm	485	310	310
rms bunch length σ_s	m	0.50	0.40	0.20
hourglass factor F, initial	...	0.88	0.85	0.93
beam-beam parameter ξ/IP	...	0.012	0.012	0.015
number of beam-beam IPs	...	— 2+1* —		
electron lens parameters				
distance of center from IP	m	— 2.0 —		
effective length L_e	m	— 2.1 —		
kinetic energy E_e	keV	7.8	7.8	9.3
relativistic factor β_e	...	0.18	0.18	0.19
electron line density n_e	$10^{11}\mathrm{m}^{-1}$	1.0	1.0	1.2
electrons in lens N_{e1}	10^{11}	2.1	2.1	2.5
electrons encountered N_{e2}	10^{11}	2.5	2.5	3.0
current I_e	A	0.85	0.85	1.10

*One head-on collision in IP6 and IP8 each, and a compensating head-on collision in IP10.

The tolerances for the main solenoid field straightness and for the relative beam alignment are easier to meet with a larger proton beam. A larger beam is also less susceptible to coherent instabilities [13, 71]. The β-function at IP10 cannot be larger than 10 m at 250 GeV proton energy without modifications to the IR10 superconducting magnets buses and feedthroughs. Such modifications are currently not considered because of costs, but could be implemented if coherent instabilities occur and cannot be mitigated by other means.

With a fully magnetized electron beam the beam size in the main solenoid σ_e is given by its size at the cathode σ_{ec}, and the solenoid fields at the cathode B_{sc} and in the main solenoid B_s as $\sigma_e = \sigma_{ec}\sqrt{B_{sc}/B_s}$. For technological and cost reasons the field B_s cannot be much larger than 6 T, and a strong field makes a correction of the field straightness more difficult. The field B_{sc} has to be large enough to suppress space charge effects. With the limits in the B_{sc} and B_s fields, and a given beam size σ_e the electron beam size and current density at the cathode follow, and must be technically feasible. Unlike the Tevatron electron lenses we use a DC electron beam to avoid the noise possibly introduced through the high voltage switches. A DC beam requires the removal of ions created in the electron lens through residual gas ionization.

Condition 2 (phase advance of multiples of π between p-p and p-e interaction) can be realized through lattice modifications. We have installed four phase shifter power supplies for both transverse planes of both rings so that the betatron phase between IP8 and the electron lenses in IR10 can be adjusted. To have $\Delta\psi = k\pi$ in both planes of both rings also required that the integer tunes be changed from $(28, 29)$ to $(27, 29)$ in the Blue ring, and from $(28, 29)$ to $(29, 30)$ in the Yellow ring in order to find a solution. With the new lattices higher luminosities were reached in 2013 than in the previous years, but the polarization was lower. The lower polarization is still under study and may not have been the result of the new lattices. Other lattice options are also under study: (i) A solution was found for the Yellow ring that maintains the integer tunes of $(28, 29)$ and has the correct phase advances; (ii) The phase advance of a multiple of π may also be realized between IP6 and the electron lenses.

Condition 3 (no nonlinearities between the p-p and p-e interactions) is best realized when the p-e interaction is as close as possible to the p-p interaction. With the location in IR10 (Fig. 1) there is only one arc between the p-p interaction at IP8 and the p-e interaction in IR10. In this configuration, a proton, after receiving a beam-beam kick in IP8, passes a triplet with nonlinear magnetic fields from field errors, an arc with chromaticity sextupoles and dodecapoles in the quadrupoles as dominating nonlinear field errors, and another triplet in IR10. β^* cannot be too small to avoid bunch length effects [47, 48]. In simulations a value as low as $\beta^* = 0.5$ m was found as acceptable [70].

The location of both the Blue and Yellow electron lens in IR10, in a section common to both beams (Fig. 5), allows the local compensation of the main solenoid effect on both linear coupling and spin orientation by having the two main solenoids with opposing field orientations. At 255 GeV proton energy, one superconducting solenoid with 6 T field introduces coupling leading to $\Delta Q_{min} = 0.0023$ [51], and increases all spin resonance strengths by 0.003 [78]. In this configuration it is also possible to ramp the magnets together during RHIC stores without affecting the beam lifetime or spin orientation.

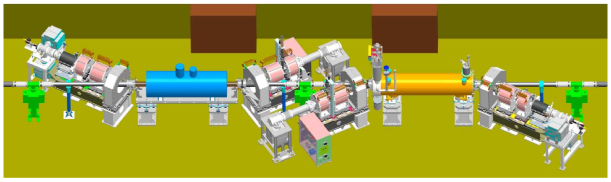

Figure 5: Layout of the two electron lenses in IR10. In 2013 the Blue lens (left) has the EBIS spare solenoid installed instead of the superconducting solenoid designed for the electron lens. In each lens three beams are present, the two proton beams and the electron beam acting on one of the proton beams. The proton beams are vertically separated.

The instrumentation must allow for monitoring of the electron beam current and shape as well as the relative position and angle of the electron and proton beam in the electron lens. Two modes are foreseen: a setup mode in which the electron beam current is modulated and affects only a single bunch in RHIC, and a compensation mode with a DC electron beam. The main parameters of the electron beams are presented in Tab. 1.

A RHIC electron lens consists of (Fig. 6): an electron gun, an electron beam transport to the main solenoid, the superconducting main solenoid in which the interaction with the hadron beam occurs, an electron beam transport to the collector, an electron collector, and instrumentation.

Electron gun

The electron gun (Fig. 7, Tab. 2) [59] has to provide a beam with a transverse profile that is close to Gaussian. Considering the magnetic compression of the electron beam into the main solenoid center with maximum magnetic field of 6.0 T, a cathode radius of 4.1 mm gives a Gaussian profile with 2.8 rms beam sizes. The perveance of the gun is $P_{gun} = 1.0 \times 10^{-6}$ AV$^{-1.5}$. The current density of the electron beam on its radial periphery can be changed with the control electrode voltage (Fig. 7, top) while the general shape of the beam profile remains Gaussian. The cathodes (LB_6 and IrCe) were produced at BINP in Novosibirsk [79]. With a nominal current density of 12 A/cm^2 IrCe was chosen as cathode material for a long lifetime (>10,000 h).

An assembled gun is shown in Fig. 7. The gun has 3 operating modes: (i) DC for continuous compensation; (ii) 100 Hz for electron beam positioning with BPMs – the electron current rises between the last 2 RHIC bunches and falls in the abort gap; (iii) 78 kHz for single-bunch compensation – rise and fall time as in the 100 Hz mode.

The gun and collector vacuum is UHV compatible, with a design pressure of 10^{-10} Torr, and interface to the RHIC warm bore with a nominal pressure of 10^{-11} Torr. For this reason all of the components are bakeable to 250°C. The gun and collector chambers will have a confined gas load by using a conductance limiting aperture, and enough installed pumping speed. All vacuum chambers interfacing with the RHIC warm bore will be made from stainless steel.

Table 2: Main parameters of the thermionic electron gun.

quantity	unit	value
perveance	μAV$^{-3/2}$	1.0
voltage	kV	10
current	A	1.0
profile	...	Gaussian
cathode radius	mm / σ	4.1 / 2.8
max B-field	T	0.8
modes	...	DC, 100 Hz, 78 kHz

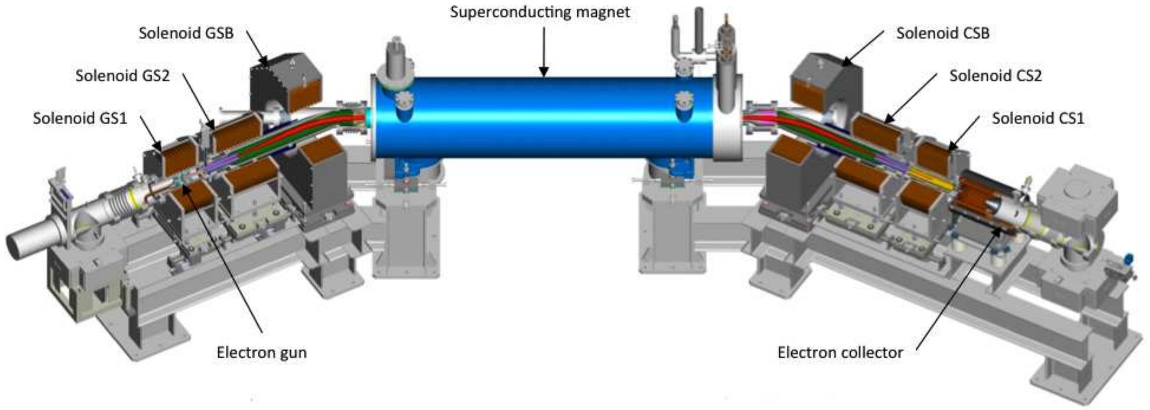

Figure 6: RHIC electron lens. The electrons in the DC beam move from left to right and interact with the protons, moving in the opposite direction, inside the superconducting solenoid.

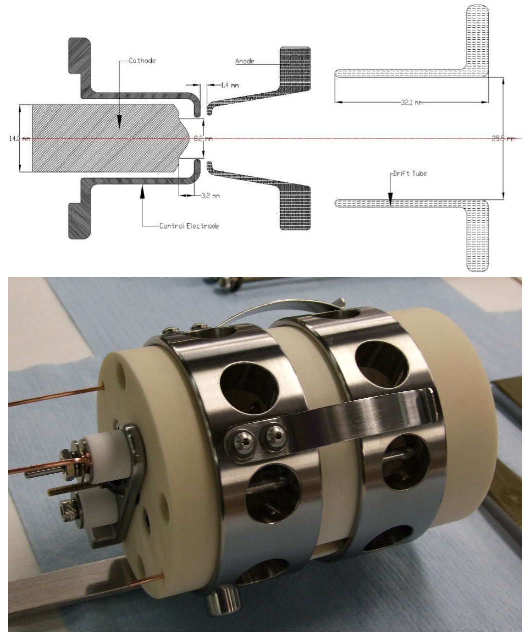

Figure 7: Gun schematic (top), and manufactured gun (bottom).

Electron collector

The collector spreads the electrons on the inside of a cylindrical surface that is water-cooled on the outside (Fig. 8). Simulations give a power density of 10 W/cm^2 for a 10 A electron beam, decelerated to 4 keV. The collector can absorb up to 4 times this power density [59]. The design is dictated primarily by the UHV requirements of RHIC. It separates the heavily bombarded area from the rest of the electron lens by using a small diaphragm. A magnetic shield leads to fast diverting electrons inside the collector. The reflector has a potential lower than the cathode and pushes electrons outwards to the water-cooled cylindrical surface. Under a load twice as high as expected from a 2 A electron beam the maximum temperature on inner surface of the shell is 102°C. This temperature is acceptable for the material (copper) and for UHV conditions in RHIC. 20 tubes with an ID = 8.0 mm are brazed to the outside of the cylindrical shell and are connected in parallel for water flow (Fig. 8).

The collector design also limits the flow of secondary and backscattered electrons from the collector towards the interaction region because the volume is magnetically shielded.

The gun and collector power supplies are referenced to the cathode. The gun supplies include the cathode bias supply, the cathode heater, the beam forming supply, and two anode supplies (DC and pulsed). The collector power supply is rated with 10 kV at 2 A, and will limit the energy deposited in the device should an arc occur. An ion reflector is powered with respect to the cathode potential. A suppressor element is powered with respect to the collector.

Superconducting main solenoid

A superconducting solenoid guides and stabilizes the low energy electron beam during the interaction with the proton beam, and allows for magnetic compression of the electron beam size to the proton beam size. The superconducting main solenoid is a warm bore magnet with an operating field of 1-6 T (Fig. 9). The cryostat includes a number of additional magnets for a total of 17 [62]. The main parameters are given in Tab. 3.

Fringe field (FF) solenoid coils at both ends are included to allow for a guiding and focusing solenoid field for the electrons of no less than 0.3 T between the superconducting magnet and the warm transport solenoids GSB and CSB (Fig. 6). To achieve the desired field uniformity over a range of field strengths B_s, anti-fringe field (AFF) coils are placed next to the FF coils. Both the FF and AFF coils on both ends can be powered independently to avoid forming a magnetic bottle with a low main field B_s, which traps backscattered electrons. Extraction of scattered electrons is also possible with a split electrode [69].

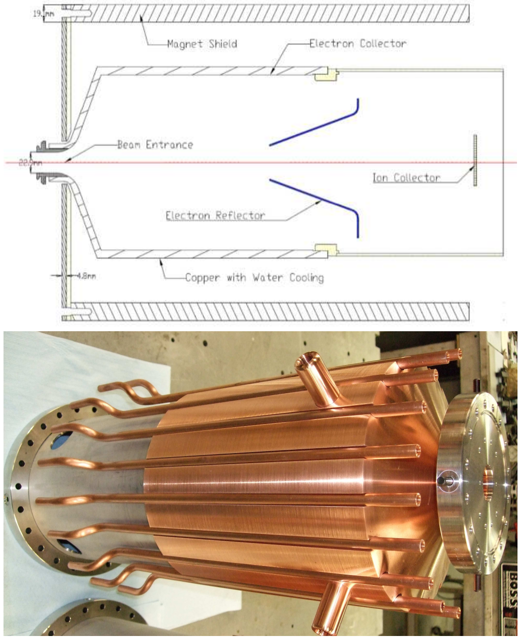

Figure 8: Collector schematic (top), and collector during manufacturing (bottom).

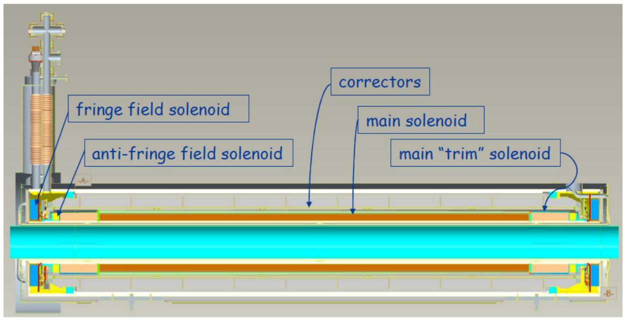

Figure 9: Superconducting main solenoid with fringe and anti-fringe solenoids, straightness and angle correctors.

Included in the cryostat are 5 short (0.5 m) dipole correctors in both the horizontal and vertical plane, to correct the solenoid field straightness to ± 50 μm. A long (2.5 m) dipole corrector in each transverse plane allows changing the angle of the electron beam inside the main magnet by ± 1 mrad (at 6 T) to align the electron and proton beams.

To reduce the number of layers in the main, FF, and AFF coils, and thereby the manufacturing time, a relatively large conductor was chosen, and the current in these coils is 430, 470, and 330 A respectively [62]. A total of 17 individual coils (main, 2 FF, 2 AFF, 10 straightness dipole correctors, 2 angle dipole correctors) can be powered.

The magnet is bath cooled at a temperature just above 4.5K, dictated by RHIC cryogenic system's main warm return header operating pressure. The current leads are all conventional vapor cooled leads with individual flow controllers. The magnet's thermal shield and supports intercepts are cooled by the balance of the boil-off vapor not used by the current leads, and also returns to the main warm return header. Total flow rate draw from RHIC cryogenic system is 1.6 g/s for each solenoid. Liquid helium can be supplied from a local Dewar when the RHIC refrigerator is not running.

Table 3: Main parameters of the superconducting solenoids and corrector magnets in the same cryostat.

quantity	unit	value
cryostat length	mm	2838
coil length	mm	2360
warm bore inner diameter	mm	154
uniform field region	mm	± 1050
main coil layers	...	22 (11 double)
additional trim layers in ends	...	4 (2 double)
wire I_c specification (4.2 K, 7 T)	A	> 700
operating main field B_s	T	1-6
field uniformity $\Delta B_s/B_s$	...	± 0.006 (1-6 T)
field straightness, after correction	μm	± 50 (1-6 T)
straightness correctors (5H+5V)	Tm	± 0.010
angle correctors (1H+1V)	Tm	± 0.015
inductance	H	14
stored energy (6 T)	MJ	1.4
current (6 T)	A	430 (473*)

* First double layer disabled.

Both magnets were tested vertically and reached 6.6 T, 10% above the maximum operating field, after a few training quenches. The magnets are now fully cryostated. During the vertical test of the first magnet a short in the first layer was detected, and the first double layer was grounded permanently. This required raising the operating current from 440 A to 473 A.

The field measurement system is under development. With proton rms beam sizes as small as 310 μm in the electron lenses, a deviation of the solenoid field lines from straight lines of no more than 50 μm is targeted. A needle-and-mirror system has been constructed that can be used in the RHIC tunnel to both measure the straightness of the field lines, and verify the correction with the integrated short dipole correctors. The needle-and-mirror measurement system is being cross-checked with a vibrating wire system [80] using the 2nd superconducting solenoid.

Warm magnets

The electron beam is transported from the gun to the main solenoid, and from the main solenoid to the collector through three warm solenoids each (Fig. 6) [54, 59]. These provide focusing with a solenoid field of at least 0.3 T along the whole transport channel. Within the GS2 and CS2 solenoids are also horizontal and vertical steering magnets that can move the beam by ± 5 mm in the main solenoid in either plane.

The solenoids are made of pancake coils whose field errors were optimized [56]. The power consumption of both electron lenses with nominal parameters is limited to a total of 500 kW in order to avoid upgrades to the electrical and cooling water infrastructure in IR10. The main parameters are given in Tab. 4. All warm magnets and associated power supplies are installed (Fig. 10).

Table 4: Main parameters of the warm magnets.

quantity	unit	GS1 CS1	GS2 CS2	GSB CSB	GSX CSX	GSY CSY
ID	mm	174	234	480	194	210
OD	mm	553	526	860	208	224
length	mm	262	379	262	500	500
No layers	...	13	10	13	12	12
No pancakes	...	9	13	9		
inductance	mH	20	20	40	0.2	0.2
resistance	mΩ	40	50	80	20	20
current	A	1188	731	769	258	271
power	kW	58	26	45	1.4	1.7
ΔT	K	13.4	3.6	14.2	5.9	6.9
Δp	bar	1.5	1.5	1.5	1.5	1.5
solenoid field B_s	T	0.8	0.45	0.32		

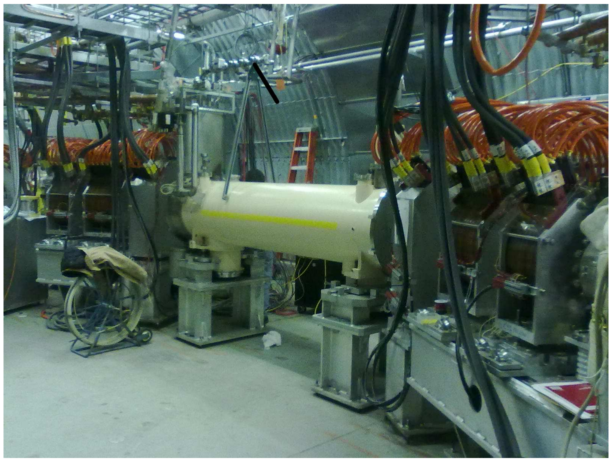

Figure 10: Yellow electron lens as installed in 2013. Visible are the gun side (left), the superconducting main solenoid (center), and the collector side (right).

Instruments and vacuum system

The instrumentation monitors the current and shape of the electron beam, electron beam losses, and the overlap of the electron with the proton beam. The following items are included (quantity is per lens):

- dual-plane beam position monitors (2)
- e-p beam overlap monitor based on back-scattered electrons (1) [65]
- differential current monitor (1)
- beam loss monitor drift tubes (8)
- collector temperature sensor (1)
- profile monitor (YAG screen) (1)
- profile monitor (pin-hole) (1)
- ion collector (1)

The layout of the vacuum system with the drift tubes is shown in Fig. 11. A total of 8 drift tubes allow for changes in the electron beam energy, the removal of ions in the interaction region, and the split drift tube 4 for the removal of backscattered electrons [69]. These can be trapped with a low main field B_s and high fringe fields. Figure 12 shows a detail with a BPM, 2 drift tubes, cables, feedthroughs and a heat sink to cool the cables that can heat up when the proton beam deposits rf energy in the structure.

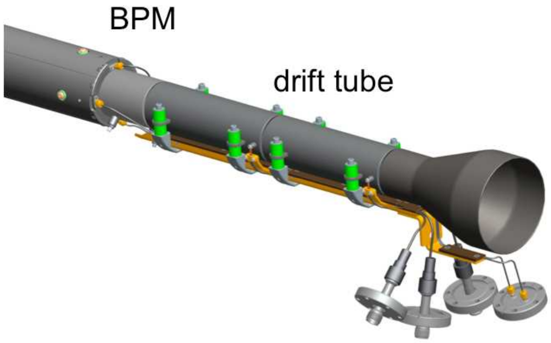

Figure 12: Beam position monitor and drift tubes with high-voltage stand-offs and cable.

The BPMs only see a signal with a pulsed beam. The proton beams are bunched and a fill pattern can be created so that a bunch in one beam is detected when there is a gap in the other beam. The electron beam needs to be pulsed (100 Hz or 80 kHz) to be visible. The BPMs are used to bring the electron and proton beams in close proximity. The final alignment is done with the beam-overlap monitor based on backscattered electrons [65]. Alignment was found to be a critical parameter in the Tevatron electron lenses, and the beams have to be aligned within a fraction of the rms beam size, which is as small as 310 μm (Tab. 1). Figure 13 shows the beam overlap monitor.

The differential current monitor, drift tubes, ion collector, and collector temperature sensor all monitor the electron beam loss in the lens. The YAG screen and pin-hole profile monitors can only be used in a low power mode. The extracted ion current is monitored in a collector [59].

TEST BENCH RESULTS

The test bench (Figs. 15 and 16) uses the location and the superconducting solenoid of the BNL EBIS test stand. Of the RHIC electron lenses the following components were installed: a gun and collector, a GS1 solenoid with power supply, a movable pin hole detector, a movable YAG screen with camera, and an electron halo detector.

The test bench work is complete and the following items were demonstrated [68, 72–74]:

- The gun operated in 80 kHz pulsed mode and DC mode, and reached 1 A of DC current with a current ripple of $\Delta I/I = 0.075$%.
- The gun perveance with a La$_6$B cathode was measured as 0.93 μAV$^{-3/2}$.
- The collector temperature and pressure was measured with the 1 A DC current and found to be within expectations.
- The Gaussian transverse electron beam profile was verified.
- The machine protection system was prototyped.
- Part of the controls software was tested.

After completion of the test bench the components were removed and installed in the RHIC tunnel and service building.

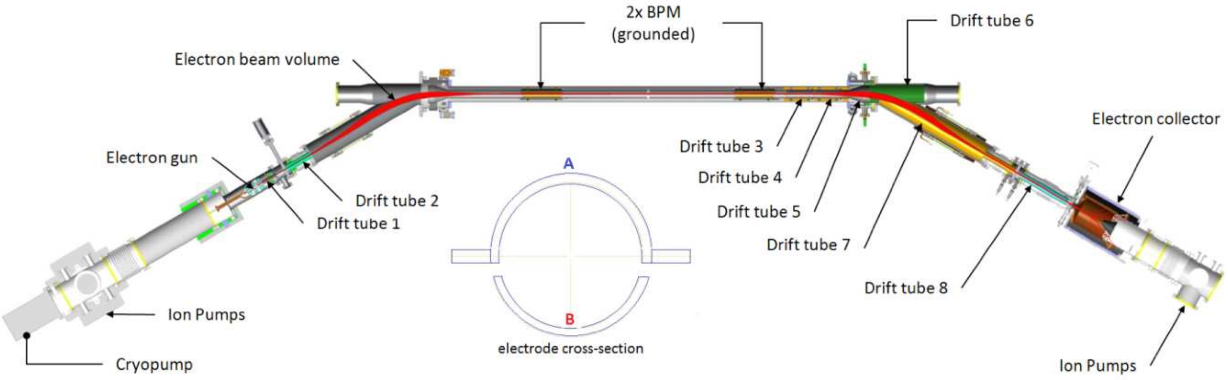

Figure 11: Layout of the drift tube system and cross section of the drift tube 4, which is split for the removal of trapped electrons [69].

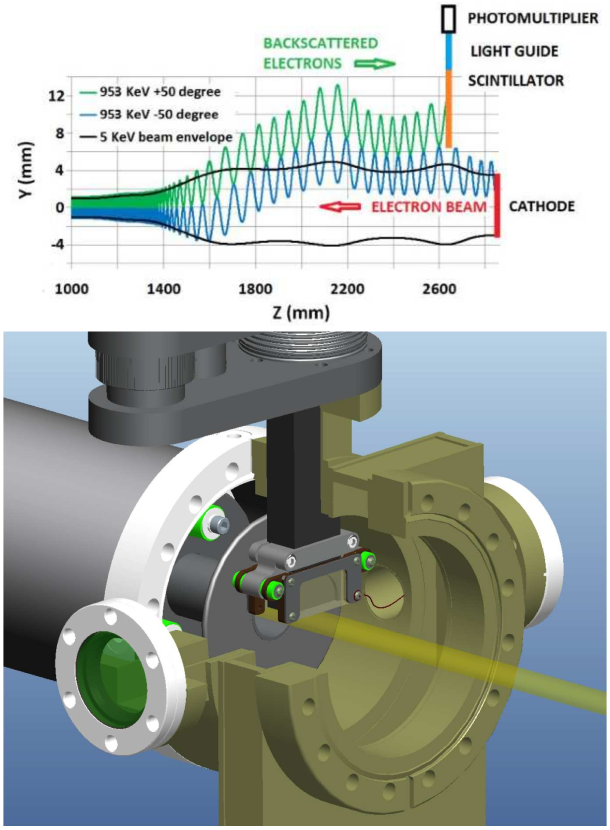

Figure 13: Beam overlap monitor using backscattered electrons [65]. The top view is a schematic with 2 trajectories of backscattered electrons arriving at the gun above the primary electron beam. The bottom view shows the positioning mechanism of the detector.

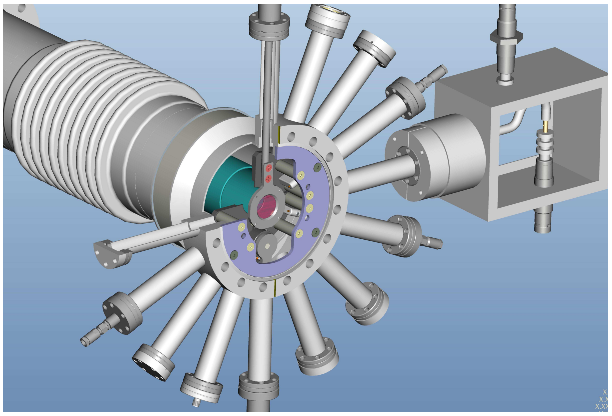

Figure 14: Instrument holder in front of the collector. Visible are the halo detector, YAG screen (inserted), and pin hole detector (retracted).

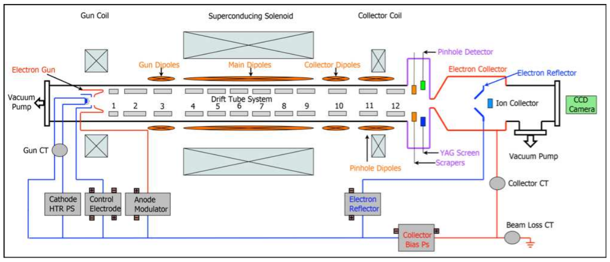

Figure 15: Schematic of the electron lens test bench layout.

STATUS AND OUTLOOK

For the ongoing RHIC Run-13 the hardware of both lenses is partially installed (Fig. 5). The Blue lens has a complete electron beam transport system, although instead of the superconducting main solenoid designed for the electron lens a spare solenoid of the BNL EBIS is installed. This magnet is a 2 m long superconducting solenoid with a maximum field strength of 5 T, but without an iron yoke and therefore field lines that are not straight enough for beam-beam compensation. It does, however, allow for propagation of the electrons from the gun to the collector even at a field as low as 1 T. The low field is necessary in order to minimize the effect on the proton spin as long as the second superconducting solenoid is not yet powered. The Blue lens also has a full complement of instrumentation with the exception of the overlap monitor based on backscattered electrons. All drift tubes are grounded. In

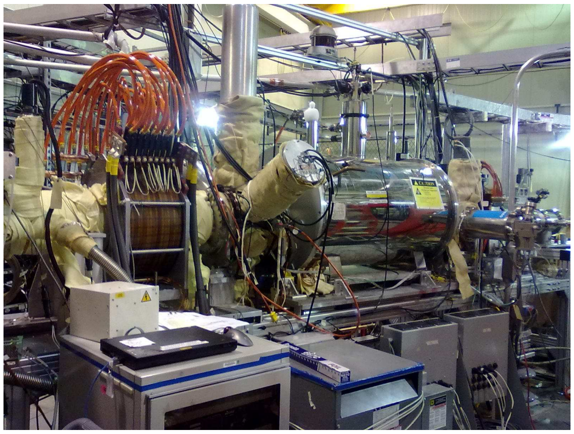

Figure 16: RHIC electron lens test bench. The electron beam travels from left to right, GS1 is visible.

this configuration all warm magnets can be commissioned as well as the electron beam in pulsed mode. The two dual plane BPMs inside the superconducting solenoid, the YAG screen profile monitor and pin hole detector can be tested. Interaction with the proton beam is in principle possible.

The Yellow lens has one of the new superconducting solenoids installed, but with a straight beam pipe without BPMs or drift tubes (i.e. the vacuum system of the electron gun and collector is not connected to the proton beam vacuum system). This configuration allows for commissioning of the superconducting main solenoid and all superconducting correctors, as well as all warm magnets. The Yellow lens is shown in Fig. 10.

The second superconducting solenoid is set up in the Superconducting Magnet Division as a test bed for the field straightness measurement system. As of the submission time of this paper the following items were done: A new lattice was commissioned for both rings that has a phase advance of a multiple of π between IP8 and the electron lens. For this new phase shifter power supplies were installed in both rings and both transverse planes. A bunch-by-bunch loss monitor became available, and bunch-by-bunch BTF measurements are being tested. The derivation of the incoherent beam-beam tune spread in the presence of coherent modes from transverse BTF measurements is under investigation [81]. In the Blue lens a field of 1 T in the superconducting solenoid was established. All warm solenoids were tested at operating currents, and all GSB and CSB solenoids ran concurrently with RHIC polarized proton operation.

In the summer of 2013 the second superconducting main solenoid will be installed, and the field straightness of both magnets will be measured in place and corrected. After that the installation will be completed for both lenses, including the overlap detector based on backscattered electrons.

In 2014 RHIC is likely to operate predominantly with heavy ions. The beam-beam effect with heavy ions is too small for compensation but all electron beam operating modes (pulsed and DC) can be established, and the electron beam can interact with the ion beam. The first compensation test can be done in polarized proton operation.

SUMMARY

Partial head-on beam-beam compensation is being implemented in RHIC. One of two beam-beam interactions is to be compensated with two electron lenses, one for each of the two proton beams. This allows for an increase in the bunch intensity with a new polarized proton source [37], with the goal of doubling the average luminosity in polarized proton operation.

The components of two electron lenses have been manufactured, and partially installed. The current installation allows for commissioning of the warm magnets, electron beam, and instrumentation in the Blue lens. In the Yellow lens the new superconducting solenoid and the warm magnets can be commissioned. First tests with ion beams are anticipated for the following year, after which the compensation can be commissioned for polarized proton operation.

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