Head-on beam-beam compensation in RHIC
Wolfram Fischer, BNL
Co-authors and Acknowledgements

Co-authors


Acknowledgments – Institutions

FNAL: TEL experience, beam-beam experiments and simulations
US LARP: beam-beam simulation
CERN: beam-beam experiments and simulations

Acknowledgments – Individuals

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Outline – head-on beam-beam compensation

- RHIC goals, Historical survey
  DCI experience, proposals for other machines

- Head-on beam-beam compensation
  ideal, deviations from ideal

- Technology developments for hadron beams
  Tevatron electron lenses, Electron Beam Ion Sources

- RHIC electron lenses
  design, simulations, lattice, hardware, test bench, commissioning
RHIC electron lenses

Motivation

Bunch intensity in 2012 polarized proton physics store

Goal:

Compensate for 1 of 2 beam-beam interactions with electron lenses

Then increase bunch intensity ⇒ up to $2 \times$ luminosity

Need new polarized proton source – under commissioning in 2013, A. Zelenski

$L \mu N_b^2$
Amplitude dependence of beam-beam kick fundamentally different from magnets (strength not monotonically increasing in BB)

Another beam can produce same kick of opposite sign
History of head-on beam-beam compensation (HOBBC)

• Compensation schemes (S. Peggs, Handbook):
  1. Direct space charge compensation (4 beams)
  2. Indirect space charge compensation (electron lenses)
  3. Betatron phase cancellation between neighboring IPs
     (for certain order resonances only)

• Proposals/studies of head-on beam-beam compensation to date:
  • COPPELIA ➔ 4-beam (J.E. Augustine, HEACC, 1969)
  • DCI ➔ 4-beam (G. Arzelia et al., HEACC, 1971) ➔ only real attempt so far
  • CESR ➔ e-lens (R. Talman, unpublished, 1976)
  • SSC ➔ e-lens (E. Tsyganov et al., SSCL-PREPRINT-519,1993)
  • LHC ➔ e-lens (E. Tsyganov et al., CERN SL-Note-95-116-AP, 1995)
  • Tevatron ➔ e-lens (Shiltsev et al., PRST-AB, 1999)
  • $e^+e^-$ collider ➔ 4-beam (Y. Ohnishi and K. Ohmi, Beam-Beam’03, 2003)
Head-on beam-beam compensation in DCI

- Head-on beam-beam compensation was only tested in DCI (starting in 1976)
- 4-beam collider (e⁺e⁻e⁺e⁻) for complete space charge compensation
- Main parameters:
  - Circumference: 94.6 m
  - Energy: 1.8 GeV
  - Beam-beam $\xi$: ~0.05-0.1
  - Luminosity (design): $\sim 10^{32}$ cm$^{-2}$s$^{-1}$
- Luminosity fell short by ~100x compared to expectations (2-, 3-, and 4-beam $L$ about the same)

Conclusion

The present status of the space charge compensation does not permit a gain in luminosity with double ring operation, apart from a factor 2 that could be achieved with two independent rings, as soon as the upper ring will be better conditioned from the vacuum point of view.
Coherent beam motion in DCI

- Luminosity shortfall in DCI attributed to coherent instabilities (Derbenev, Chau, Potau – later Podobedov and Siemann)
- Considered tune-split and feedback

from Podobedov & Siemann:

- beam-size increase at even-order resonances of high order
- regions of stability in simulations 3-5 times wider than observed

FIG. 10. rms beam size in DCI normalized to the nominal size for region I: $Q \sim 0.865$, $\xi = 0.0218$. Even order resonances up to 30th order are plotted with widths calculated using the $m$ dependence in Eq. (20) and a coefficient three times larger.

Beam-beam compensation with electron lens

2-beam coherent instabilities not an issue with electron lenses:

No feedback loop with compensating electron beam
(single pass effects – require sufficient rigidity of electron beam required, see S. White)

Also: beam-beam parameter $\xi$ in hadron colliders order of magnitude smaller than in lepton colliders

RHIC electron lens
**Single-pass compensation:**

1. Same amplitude dependent force in p-beam and e-beam lens, and
2. Phase advance between p-beam and e-beam lens is \( \Delta \Psi = k \pi \), and
3. No nonlinearities between p-beam and e-beam lens
HOBBC with electron lens – phase space view

Exact compensation if:

1. Same amplitude dependent force in p-beam and e-beam lens, and
2. Phase advance between p-beam and e-beam lens is $\Delta \psi = k\pi$, and
3. No nonlinearities between p-beam and e-beam lens
HOBBC with electron lens – Hamiltonian view

$$H(J_x, x) = 2 Q_x J_x + V_{p\ p}(x_n) + V_{p\ e}(x_n) \quad (1\text{-D only})$$

$$V(J_x, \Phi_x)|_{p\ -p} = -\frac{N_p r_0}{\gamma} \int_0^{J_x \beta_{ip}^*/2\sigma_{p,ip}^2} V(J_x, \Phi_x)|_{p\ -e} = \frac{N_e r_0}{\gamma} \int_0^{J_x \beta_{e-lens}/2\sigma_e^2}$$

$$\times \frac{d\alpha}{\alpha} (1 \ - \ e^{-2\alpha \cos^2(\Phi_x + \phi_{x,p\ -e})}).$$

$$V_{p\ p}(x_n) + V_{p\ e}(x_n) = 0 \quad \text{if:}$$

1. Same amplitude dependent force in p-beam and e-beam lens

$$N_p = N_e^* \quad \text{and} \quad \frac{N_{p,ip}^*}{2} = \frac{N_{e,\text{lens}}^*}{2}$$

2. Phase advance between p-beam and e-beam lens is $$\Delta \Psi = k\pi$$, and

$$x_p \ e \quad x_{p\ e} = k$$

3. No nonlinearities between p-beam and e-beam lens

Deviations from ideal head-on compensation

1. Deviations from: Same amplitude dependent force in p-beam and e-beam lens
   - e-beam current does not match p-beam intensity
   - e-beam profile not Gaussian
   - e-beam size ≠ p-beam size
   - time-dependence (noise) of e-beam and p-beam parameters

2. Deviations from: Phase advance between p-beam and e-beam lens is $\Delta \psi = k\pi$
   - linear phase error in lattice
   - long bunches ($\sigma_s > \beta^*$)

2. Deviations from: No nonlinearities between p-beam and e-beam lens
   - sextupoles, octupoles, magnetic triplet errors between p-p and e-p

Studied all tolerances with simulations [Y. Luo et al, PRSTAB 15, 041001 (2012)]
Phase advance and resonance driving terms

- E-lens profile and current => reduces tune spread
- $\Delta \psi = k\pi$ phase advance => minimizes resonance driving terms


- Installed additional power supplies in all planes (B+Y; hor+ver) that allow for shifting phase between IP8 (p-p) and IP10 (p-e)
- Also required change of integer tunes
  B: (28,29) => (27,29)
  Y: (28,29) => (29,30)

C. Montag

FIG. 3. 10th order horizontal beam-beam resonance widths under different beam-beam conditions. The vertical axis is in units of the incoherent beam-beam tune shift $\xi_{1\text{IP}}$ with one IP.

Effect of long bunches on HOBB

short bunch, $\sigma_s=0$

long bunch, $\sigma_s=0.2$ m, $\beta^*=0.5$ m

significant deviations from short-bunch case ($\sim 30\%$) for $r \approx \sigma$ and large $r'$
Effect of long – bunches on HOBBC

no HOBBC, RHIC case

 HOBBC, -10 deg phase error

significant part uncompensated (~60%) for r ≈ 0 and large r’
E-lenses technology – Tevatron electron lenses


2 lenses in Tevatron:
• Energy: 5/10 kV
• Current: 0.6/3 A
• pulsed, 200 ns rise time [RHIC: also DC]
• Length: 2 m
• e-beam radius: 2.3 mm [RHIC: 0.3 mm]

• Operationally used as gap cleaner (very reliable)
• Shown to have increased beam lifetime of pbar bunches affected by PACMAN effect (by factor 2 at beginning of store, mostly tune shift)
• Have learned sensitivity to parameters (relative beam position – important, e-beam shape – important, current – $10^{-3}$ variations ok)
• Experiments with Gaussian gun (Sep. 2009, Jul 2010) (alignment and losses, tune shifts, coherent modes, tune space scan with e-lens)

[V. Shiltsev et al., PRST-AB 2, 071001 (1999); PRL 99, 244801 (2007); PRSTAB 11, 103501 (2008); New J. Phys. 10, 043042 (2008)]
E-lens technology – BNL Electron Beam Ion Source

Operated for NASA Space Radiation Laboratory in 2011-12 with
He⁺, He²⁺, Ne⁵⁺, Ne⁸⁺, Ar¹⁰⁺, Kr¹⁸⁺, Ti¹⁸⁺, Fe²⁰⁺, Xe²⁷⁺, Ta³³⁺, Ta³⁸⁺

Operated for RHIC in 2012 with
U³⁹⁺ (not possible previously), Cu¹¹⁺, Au³¹⁺

<table>
<thead>
<tr>
<th>quantity</th>
<th>unit</th>
<th>RHIC</th>
<th>Test EBIS achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>e-beam current</td>
<td>A</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>e-beam energy</td>
<td>keV</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>ion trap length</td>
<td>m</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>trap charge capacity</td>
<td></td>
<td>10¹¹</td>
<td>11</td>
</tr>
<tr>
<td>charge yield (Au)</td>
<td></td>
<td>10¹¹</td>
<td>5.5 (10 A)</td>
</tr>
<tr>
<td>pulse length</td>
<td>μs</td>
<td>≤40</td>
<td>20</td>
</tr>
<tr>
<td>yield Au³²⁺</td>
<td>10</td>
<td>3.4</td>
<td>&gt; 1.5</td>
</tr>
</tbody>
</table>

RHIC electron lenses – Basic design decisions

1. Electron lenses in IR10
   smallest distance to IP8 head-on beam-beam interaction (nonlinearities), available space

2. Both lenses in common area
   main solenoids compensate each other for coupling and spin, $\beta_x = \beta_y$ at e-lens locations
   drawback: $\beta$-functions relatively small ($\leq 10$ m)

3. DC beam for compensation
   avoids noise introduced with HV switching (have pulsed operation for set-up and diagnostics)

4. Superconducting main solenoid
   need high field to match electron and proton beam size

5. Field straightness correctors incorporated in sc main solenoid
   compact solenoid

6. Transport solenoids and orbit correctors warm
   capital cost lower than for sc (sc transport solenoids with break-even time 5-10 years)

7. Diagnostics
   basic diagnostic consists of BPMs and RHIC instrumentation (BTF, lifetime),
e-bam profile monitors, backscattered electron monitor, halo detection
RHIC electron lenses

Compensation overview

SC main solenoid
B = 6 T, I = 440 A
+ 16 more magnets
(fringe fields, correctors)

CS1 = GS1
CS2 = GS2
CSB = GSB

Electron gun

Electron collector

GS1 warm solenoid
GS2 warm solenoid
GSB warm solenoid
GSX/Y
CSX/Y = GSX/Y

Electron collector

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Requirement for electron lens

1. Electron beam size in the main solenoid
   RMS beam size: 0.3 mm - 0.8 mm (issue: relatively small)

2. Gaussian shape of electron beam
   good fit to 3 \( \sigma \) (issue: cathodes have limited size)

3. Straightness of magnetic field in main solenoid
   target of \( \pm 50 \, \mu \text{m} \) after correction (issue: good overlap of e and p beam)

4. Steering electron beam in e-lens
   maximum shifting: \( \pm 5 \, \text{mm} \) in X and Y planes
   maximum angle: 0.1 mrad

5. Stability in electron current
   power supplies stability better than 10^{-3}

6. Overlap of electron and proton beams
   robust real-time measurement with resolution better than 100 \( \mu \text{m} \)
Gun

**Designed for:** current density, profile

3 modes:
- DC (full compensation)
- 100 Hz (positioning)
- 78 kHz (single bunch compensation)

\[ V_{\text{max}} = 10 \text{ kV}, \quad I_{\text{max}} = 1 \text{ A}, \quad P = 1 \times 10^{-6} \text{ AV}^{-3/2} \]

Cathodes: LaB\(_6\) and IrCe (from Budker), 4.1 mm radius, Gaussian profile (2.8 \(\sigma\))

Collector

**Designed for:** Reliability

Water cooled, can take 4x nominal load of 15 kW

\[ \rho_P < 50 \text{ W/cm}^2, \quad T < 125^\circ\text{C} \]
RHIC electron lenses

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4 types: GS1, GS2, GSB, GSX/Y

**Designed for:** 0.3 T min transport field, power consumption (total < 0.5 MW)

**GS1** (gun, collector)
B = 0.8 T, I = 1200 A, P = 58 kW

**GSX/Y**

**GSB** (bend)
B = 0.3 T, I = 770 A, P = 45 kW

**PS in assembly**
(1 each for GS1-CS1, GS2-CS2, GSB-CSB)

**GS2**
B = 0.5 T, I = 730 A, P = 25 kW
RHIC electron lenses Superconducting magnets (R. Gupta)

**Designed for:** solenoid field strength (6T), field straightness (±50 μm)

Stabilizes e-beam
Magnetic compression (need 310 μm rms beam size)

\[ B_{\text{main}} = \sqrt[3]{B_{\text{gun}}} \]

Maximize overlap of p- and e-beams

17 magnets total

0.3 T with reduced \( B_{\text{main}} \)

To correct for straightness
5 hor + 5 ver

**fringe field solenoid**

**anti-fringe field solenoid**

maintain field quality with reduced \( B_{\text{main}} \)

**main solenoid**

**main "trim" solenoid**

**correction**
RHIC electron lenses

- Winding at BNL
- 22 layers, ~25000 turns

Superconducting magnets

- Shell with correctors

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1\textsuperscript{st} solenoid tested cold:

<table>
<thead>
<tr>
<th>quench no</th>
<th>current [A]</th>
<th>field [T]</th>
<th>location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>340</td>
<td>4.64</td>
<td>layer 1</td>
</tr>
<tr>
<td>2</td>
<td>366</td>
<td>5.00</td>
<td>layer 1</td>
</tr>
<tr>
<td>3</td>
<td>380</td>
<td>5.18</td>
<td>layer 1</td>
</tr>
<tr>
<td>4</td>
<td>389</td>
<td>5.30</td>
<td>layer 1</td>
</tr>
<tr>
<td>5</td>
<td>408</td>
<td>5.56</td>
<td>layer 1</td>
</tr>
</tbody>
</table>

2\textsuperscript{nd} solenoid also reached 6 T (all layers good)

- Ground fault developed in layer 1, decided to disable layers 1&2

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RHIC electron lenses

**Designed for:**
- e-beam position
- e-current and losses **halo monitor**
- Drift tubes **ion extraction with DC e-beam**
- e-beam profiles **pin-hole detector, YAG screen**
- Overlap of p- and e-beam
Beam overlap monitor (P. Thieberger):
• p-e beam interaction creates bremsstrahlung (photons) and backscattered electrons
• Backscattered electrons can be detected near gun (above e-beam)
RHIC electron lenses

Test bench 2012

- collector
- instrument holder
  - pin hole detector
  - YAG screen
  - halo monitor

More details: X. Gu et al., IPAC12, paper in preparation
RHIC electron lenses

Test bench results 2012

1. Gun operation in all modes (100 Hz, 78 kHz, DC) – 1 A, $\Delta I/I_{\text{rnd}} = 0.075\%$ OK
2. Measured gun perveance (I vs. U): $0.93 \, \mu \text{AV}^{-3/2}$ OK
3. Measured collector temperature and pressure with high load OK
4. Commissioning of pin hole detector and YAG screen done
5. Verified transverse Gaussian profile OK
6. Prototype of machine protection system done
7. Test of software controls done

More details: X. Gu et al., IPAC12, paper in preparation
Installation for 2013

**EBIS spare solenoid**
- allows for electron transport from gun to collector with 2 Tm integrated strength
- does not allow for beam-beam compensation
  (field lines not straight enough)

**Electron lens main solenoid #1**
- straight beam pipe (Y-pipes not ready)
- allows for commissioning of all solenoid magnets
- does not allow for electron beam commissioning
RHIC Electron lenses

lead of sc solenoid

drift tube

Y-pipe

water-cooled bus for warm solenoids

Yellow e-lens in RHIC tunnel

ps for warm solenoids
RHIC electron lenses - commissioning

2013 polarized proton run

• Commission new lattice ($\Delta \psi_{x,y} = k\pi$)
• Commission new p-beam diagnostics
  (single bunch BTF, single bunch beam loss rates)
• Commission Yellow lens superconducting solenoid
• Commission Blue and Yellow lens warm magnets
• Commission Blue lens electron beam and instrumentation

Summer 2013 shut-down

• Install Blue superconducting solenoid
• Measure/correct Blue and Yellow field straightness in tunnel
• Complete installation
  (Yellow vacuum system, backscattered electron detectors)

2014 run

• Commission both lenses with ion/proton beams
Summary – RHIC head-on beam-beam compensation

• Simple principle
  – reverse beam-beam kick with beam of opposite charge

• Need to control deviation from ideal compensation scheme
  – phase advance, lattice nonlinearities, bunch length, e-beam position and shape, noise in all parameters

• To date one attempt at DCI (unsuccessful because of coherent modes), and a number of proposals (including hadron colliders SSC, Tevatron, RHIC, and LHC)

• Electron lens technology well established today
  Tevatron electron lenses, EBIS and similar devices

• RHIC electron lens test bench demonstrated required e-beam, lenses mostly installed, hardware under commissioning
Additional slides
Effect of long bunches on beam-beam

phase advance near IP w/o BB
(phase averaging usual beneficial)

differential eqs. for \((r,r')\) for BB with long bunches

\[
\frac{dr}{dt} = cr'
\]

\[
\frac{dr'}{dt} = \frac{2N_p r_p c(1 + \beta_{p1}/\beta_{p2})}{\sqrt{2\pi}\beta_{p1}\gamma_{p1}\sigma_s} \times \\
\times \exp \left[ -\frac{c^2((\beta_{p1} + \beta_{p2})t - \beta_{p1}\delta t)^2}{2\sigma_s^2} \right] \times \\
\times \frac{1}{r} \left[ 1 - \exp \left( -\frac{r^2}{2\sigma_p^2(\beta_{p1} c(t - \delta t))} \right) \right]
\]

change of \((r,r')\) for \(r=1\sigma_p, r'=0\)

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Effect of long bunches on HOBB (II)

short bunch, $\sigma_s=0$

long bunch, $\sigma_s=0.2\,\text{m}$, $\beta^*=0.5\,\text{m}$ and $\sigma_t$ late arrival

significant deviations from short-bunch case ($\sim100\%$) for $r \approx \sigma$ and large $r'$
Effect of long bunches on HOBB with e-lens

short e-lens (1.55m off IP)

long bunch, $\sigma_s = 0.2\text{m}$, $\beta^* = 0.5\text{m}$

small deviations from short-lens case ($\sim3\%$) for $r \approx \sigma$ and large $r'$