RHIC Operation and Electron Lens Commissioning

Xiaofeng Gu

for E-lens team and CAD

Thank the HB 2016 Committee for invitation!

July 03 ~ July 08, 2016
The 57th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams
Outline

- Proton Beam Intensity
- Electron Lens introduction
- E-lens Commissioning and Operation
- Run16 Operation with Au-Au
- Summary
RHIC – a High Luminosity (Polarized) Hadron Collider
Operated modes (beam energies):

- **U – U**: 100 GeV/n
- **Au – Au**: 3.8/4.6/5.8/10/14/32/65/100 GeV/n
- **d – Au**: 9.8/19.5/31.2/100 GeV/n
- **Cu – Cu**: 11/31/100 GeV/n
- **p↑ – p↑**: 11/31/100/205/250 GeV
- **H3 – Au**: 100 GeV/n
- **p↑ – Al**: 100 GeV/n
- **p↑ – Au**: 100 GeV/n

Achieved peak luminosities:

- **Au–Au (100 GeV/n)**: $155 \times 10^{26}$ cm$^{-2}$ s$^{-1}$
- **p↑–p↑ (250 GeV)**: $245 \times 10^{30}$ cm$^{-2}$ s$^{-1}$

Performance defined by:

1. Luminosity $L$
2. Proton polarization $P$
3. Versatility (species, $E$)
Intensity Limit during Run13 and Run15 (Polarized Proton)

\[ L(t) = \frac{1}{4\pi} f_0 N \frac{N_b^2(t)}{\varepsilon(t) \beta^*(t)} h(\beta^*, \sigma_s, \theta) \]

20% more proton Intensity 2015
Improved by AGS + Source
15% more intensity available
Limited by AGS brightness

A. Zelenski, H. Huang, K. Gardner, K. Zeno, RF, et al.
Intensities during Run13 and Run15 (Polarized Proton):

- **2013 Proton Intensity**
  - Limited by RHIC during 2013

- **2015 Proton Intensity**
  - 15% more maximum intensity available in AGS with higher emittance and polarization

This talk focuses on how to overcome this limit during 2015.
Proton Beam Intensity Limit in RHIC before Run 15

1. Beam-Beam DA Tracking:
   If intensity >2.0E11, then DA is less than 4 sigma which is not good for the proton beam lifetime in RHIC.

There was an intensity limit in RHIC before Run15.

Reason?

2. 2013 polarized proton run:
   If average intensity is greater than 2.0E11, the emittance would blow up and luminosity decreased.

[Yun Luo et al., PRAB19, 041002 (2016)]
Reason->Beam-Beam:

1. Proton-Proton lumi is limited by beam-beam. Oncoming proton beam acts as a nonlinear defocusing force, leads to beam decay, emittance increase;

2. Bunches with 2 collision point has more beam decay comparing with 1 collision points (less beam-beam).

3. Tune spread with beam-beam is larger than without beam-beam effect.

Solution->Electron lenses (e-p):

Electron beams provide equal but focusing force to compensate for 1 of 2 beam-beam interactions (p-p), then increase bunch intensity (Luminosity)
1. Tune spread compensation
   => e-p has same amplitude dependent force as p-p
   => provided by electron lens

2. Resonance driving terms compensation
   => phase advance between p-p and e-p is $\Delta \psi = k \pi$
   => provided by lattice (new lattice in 2015, based on ATS – S. White)
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Electron Lens for Beam-Beam Compensation

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

1. Gaussian Beam
2. 1A DC current
3. 78 kHz pulsed beam
4. 5~10 keV
1. Detector  
2. BPM  
3. Electron gun  

1. YAG screen  
2. Collector  
3. CTs
E-gun

1. Thermal cathode

2. IrCe and Tungsten

[Xiaofeng Gu et al., NIMA, Volume 743 (2014)]
Collector, YAG, Pinhole and BPM
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Collector, YAG, Pinhole and BPM
Electron beam backscattering detector (eBSD)
Superconducting Solenoid

1. 6T field
2. Field straightness
3. Angle correctors
4. 2.8 m long total

winding at BNL
22 layers, ~25000 turns

shell with correctors
Superconducting Magnet

A maximum ±50 μm deviation of the main solenoid field lines within ±800 mm

1. Tolerance ±50 μm
2. Three different fields
3. ±1000 mm good field
4. Without correction
5. With warm magnets

Linear Fit ±0.85 m Subtracted

Blue Ring

Z_Pos_MagFrame (mm)
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1. Modulator current indicates 78 kHz is running.

2. Blue and Yellow were running 78 kHz pulse mode with 1A simultaneously within RHIC beam abort gap;

3. Parasitic to RHIC beam provides more commissioning time;

4. Blue e-lens 78 kHz was running for 14 hours during 2013;
1. Current 70 mA
2. Beam profile from YAG is a Gaussian
3. Profile does not change with current
4. Current 1150 mA.
5. Pinhole profile is Gaussian
Transverse e-Beam Alignment With Au Beam (2014)

- Two methods to do transverse position and angle alignment: BPM or eBSD (detector)
  
  [P. Thieberger, PRSTAB 19, 041002 2016]

- BPMs in both lenses to bring e- and A- beam in proximity (transverse electron beam position for blue and yellow, electron beam angle steering for yellow)

- Backscattered electron detector to maximize overlap
Transverse e-Beam Alignment With Au Beam (2014)

- Two methods to do transverse position and angle alignment: BPM or eBSD (detector) [P. Thieberger, PRSTAB 19, 041002 2016]

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**BPMs, E-beam, E-lens**

**eBSD, ion beam and Lisa**

[Peter Thieberger et al., PRAB19, 041002 (2016)]
Lattice improvements

E-lens requires $\pi$ phase advance from lens to one colliding IP.

$\pi/2$ phase advance per cell and ‘ATS’ style beta squeeze allow passive compensation of sextupole driving terms.

Optics measured-to-model agreement quite good (10-15% beat beat) without additional correction.

Momentum aperture improved, shown by increase in tolerable radial shift:
Run 12: +/- 0.7 mm radial shift;
Run 15: +/- 1.25 mm radial shift.
1. Turned on for every store (45~60 min.)

2. High reliability: available for all stores after running

3. Blue e-lens limited to ~ 500 mA by onset of e-current instability
   Yellow e-lens operating at > 1 A

[Wolfram Fischer et al., PRL 115, 264801 (2015)]
Note: It is possible that higher beam-beam parameters $\xi$ can be demonstrated in the future, without and with lens ($\xi$ sensitive to orbit, tune, chromaticity etc.)
Electron Lens Operation increases in \( L \) and \( \xi \)

<table>
<thead>
<tr>
<th>quantity</th>
<th>unit</th>
<th>operations (avg. over 10 best stores)</th>
<th>tests for max ( \xi_p ) without e-lens</th>
<th>with e-lens</th>
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</tr>
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<tbody>
<tr>
<td>Bunch intensity ( N_p )</td>
<td>( 10^{11} )</td>
<td>1.6 2.25</td>
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<td></td>
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<td>No of bunches ( k_b )</td>
<td>...</td>
<td>109 111</td>
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<tr>
<td>( \beta_{x,y}^* ) at IP6, IP8 (p+p)</td>
<td>m</td>
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<td>( \beta_{x,y}^* ) at e-lens (p+e)</td>
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<tr>
<td>Lattice tunes ( (Q_x, Q_y) )</td>
<td>...</td>
<td>(0.695,0.685)</td>
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<tr>
<td>RMS emittance ( \epsilon_n )</td>
<td>( \mu \text{m} )</td>
<td>3.3 2.8</td>
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<td></td>
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<tr>
<td>RMS beam size IP6/8 ( \sigma_p^* )</td>
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<td>165 150</td>
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<td>RMS bunch length ( \sigma_s )</td>
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<td>Hourglass factor ( H )</td>
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<td># of beam-beam IPs</td>
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<td>2 2+1*</td>
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<td>Luminosity ( \mathcal{L}_{peak} )</td>
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\( L_{peak} \) 2.5\( \times \) increase \quad \( L_{avg} \) 1.9\( \times \) increase

Note: It is possible that higher beam-beam parameters \( \xi \) can demonstrated in the future, without and with lens (\( \xi \) sensitive to orbit, tune, chromaticity etc.)
Electron Lens Operation

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$L_{peak} 2.5\times$ increase  \quad L_{avg} 1.9\times$ increase

Note: It is possible that higher beam-beam parameters $\xi$ can be demonstrated in the future, without and with lens ($\xi$ sensitive to orbit, tune, chromaticity etc.)
# Electron Lens Operation

Increases in $L$ and $\xi$

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$L_{peak}$ 2.5× increase  
$L_{avg}$ 1.9× increase

Note: It is possible that higher beam-beam parameters $\xi$ can be demonstrated in the future, without and with lens ($\xi$ sensitive to orbit, tune, chromaticity etc.)

$\xi$ +38% w/o and w/ electron lens

effect of new lattice  
effect of electron lens

effect of electron lens

---
Tune spread Compensation with 0BB from e-lens (PP run)

1. e-p collision (only negative beam force), no p-p
2. Incoherent tune vs e-beam current
3. Incoherent tune vs e-beam size
4. e-lens creates as much $\Delta Q = 0.013$ as one beam-beam collision
Demonstration Tune Spread Compensation

1. tune spread without bb and without e-lens
2. tune spread expands with bb
3. tune spread contracts again with bb and e-lens, but only up to ~750 mA (first such direct observation)
4. tune spread is only compressed to the value without bb, even with e-currents up to 1030 mA
Intensity Limit during Run13 and Run15 (Polarized Proton)

\[ L_{\text{peak}} +150\% \quad L_{\text{avg}} +90\% \]
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Intensity RHIC during 2016 Au-Au

25% or more Maximum Intensity Available in AGS

28% more Au Intensity.
Improved by AGS
25% more intensity available
Limited by RHIC RF
Lumi. Limited by detector
Au Bunch Intensity Evolution

\[ L(t) = \frac{1}{4\pi} f_0 N \frac{N_b^2(t)}{\varepsilon(t) \beta^*(t)} h(\beta^*, \sigma_s, \theta) \]

main limits:
- injectors output
- transition instability in RHIC (e-clouds)
- presently Landau cavity RF amplifiers

ultimate goal (25% more)

AGS 12→6→2 merge

H. Huang, K. Gardner, K. Zeno, RF, et al.
1. Average all peak luminosity: 80% more

2. Average all average luminosity: 60% more

3. Excluded 12 extremely low intensity store for Run14 for luminosity.
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1. Head-on beam-beam compensation scheme in operation in 2015, consisting of new lattice (RDT compensation) + e-lenses (DQ compensation) 
   \[ L_{\text{peak}} +150\% \quad L_{\text{avg}} +90\% \]

2. Higher \[ \xi/IP \] possible, presently constrained by injectors (potential for 3~4\times L in future runs)

3. The gold (Au) intensity in the RHIC during the 2016 run exceeded the previously achieved intensity by 28%. \[ L_{\text{peak}} +80\% \quad L_{\text{avg}} +60\% \]

4. There is 20\% (compared with the max. intensity in 2016) more Au intensity available from AGS.
Acknowledgements

Brookhaven National Laboratory

STAR and PHENIX experiments – supported e-lens commissioning

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

Individuals