RHIC Performance

with Stochastic Cooling for Ions

and Head-on Beam-Beam Compensation for Protons

Wolfram Fischer, Brookhaven National Laboratory

for all of the RHIC team

11 May 2016, Busan
Contents

1. A short history and outlook of RHIC
   species, energies, polarization,
   luminosity, low-energy operation

2. Au+Au with stochastic cooling
   bunch intensity
   stochastic cooling

3. p↑+p↑ with head-on beam-beam
   compensation
   bunch intensity, polarization
   lattice + electron lenses
Relativistic Heavy Ion Collider – main parameters

- Start of operation: 2000
- Circumference: 3.8 km
- Max dipole field: 3.5 T
- Species: p$^+$ to U (including asymmetric)
- Energy: Au 100 GeV/nucleon, p$^+$ 255 GeV
- Experiments: STAR, PHENIX (→ sPHENIX)
1. Creation and study of the Quark Gluon Plasma (A+A)

**QGP close to perfect liquid**

The QGP is a strongly coupled nearly “perfect” liquid (\(\eta/s\) near the quantum limit \(1/4\pi\)). RHIC’s cooler QGP is (on average) closer to perfection than the 40% hotter QGP produced at LHC.

[2015 NSAC Long Range Plan for Nuclear Science]
RHIC science programs

1. Creation and study of the Quark Gluon Plasma (A+A)

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The QGP is a strongly coupled nearly “perfect” liquid ($\eta/s$ near the quantum limit $1/4\pi$). RHIC’s cooler QGP is (on average) closer to perfection than the 40% hotter QGP produced at LHC.

2. Origin of the proton spin ($p^{\uparrow}+p^{\uparrow}$)

$$\frac{1}{2} = \text{Spin of all Quarks} + \text{Spin of Gluons} + \text{Angular Momentum of all Quarks} + \text{Angular Momentum of Gluons}$$

[2015 NSAC Long Range Plan for Nuclear Science]
RHIC science programs

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QGP close to perfect liquid
The QGP is a strongly coupled nearly “perfect” liquid ($\eta/s$ near the quantum limit $1/4\pi$). RHIC’s cooler QGP is (on average) closer to perfection than the 40% hotter QGP produced at LHC.

2. Origin of the proton spin ($p^\uparrow+p^\uparrow$)

RHIC result: not zero (2009 data only)
RHIC – all running modes to date (2001 to 2016)
RHIC – all running modes to date

2001 to 2016

2015

C. Liu, TUPMW039
RHIC – all running modes to date

2001 to 2016

C. Liu, TUPMW039

2015

2016

Species combination
- p↑+p↑
- p↑+Al
- p↑+Au
- d+Au
- h+Au
- Cu+Cu
- Cu+Au
- Au+Au
- U+U

Center-of-mass energy $\sqrt{s_{NN}}$ [GeV]

Average store luminosity $L_{NN}$ [$10^{20}$ cm$^{-2}$s$^{-1}$]

Luminosity [10$^{20}$ cm$^{-2}$s$^{-1}$]
RHIC – all running modes to date

2001 to 2016

2015

C. Liu, TUPMW039

2019/20

(see next talk on NICA)

nominal injection energy

Center-of-mass energy $\sqrt{s_{NN}}$ [GeV]

Average store luminosity [10$^{30}$ cm$^{-2}$s$^{-1}$]

Species combination

- $p^+p^+$
- $p^+p^{+}\text{Al}$
- $p^+p^{+}\text{Au}$
- $d+\text{Au}$
- $h+\text{Au}$
- $\text{Cu}+\text{Cu}$
- $\text{Cu}+\text{Au}$
- $\text{Au}+\text{Au}$
- $\text{U}+\text{U}$
Low Energy RHIC electron Cooling (LEReC)

A. Fedotov
(not to scale)

Energies $E$ : 1.6, 2.0 (2.65) MeV
Avg. current $I_{avg}$ : 27 mA
Momentum $\delta p/p$ : $5 \times 10^{-4}$
Luminosity gain : 4×
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1st bunched beam electron cooler planned operation in 2019/2020
RHIC Au+Au operation with stochastic cooling

Main luminosity limit: intrabeam scattering
RHIC Run-14  Delivering RHIC-II Au+Au luminosity
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2007, Beginning of RHIC-II upgrade
RHIC Run-14  Delivering RHIC-II Au+Au luminosity

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2014, End of RHIC-II upgrade

Luminosity [10^{26} \text{ cm}^{-2} \text{s}^{-1}]
RHIC Run-14

Delivering RHIC-II Au+Au luminosity

Increase in initial luminosity result of larger bunch intensity

2007, Beginning of RHIC-II upgrade

2014, End of RHIC-II upgrade

Luminosity $[10^{26} \text{ cm}^{-2} \text{s}^{-1}]$

Time [h]
RHIC Run-14

Delivering RHIC-II Au+Au luminosity

Increase in luminosity lifetime result of 3D stochastic cooling, high peak luminosity not useful without cooling (IBS), losses burn-off dominated

Increase in initial luminosity result of larger bunch intensity

2007, Beginning of RHIC-II upgrade

2014, End of RHIC-II upgrade

Luminosity [10^{26} cm^{-2} s^{-1}]

Time [h]

0 6 12 18 24 30 36 42 48
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

H. Huang, K. Gardner, K. Zeno, RF, et al.
Au bunch intensity evolution

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\( \gamma \)-jump, octupoles at transition
Au bunch intensity evolution

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H. Huang, K. Gardner, K. Zeno, RF, et al.
The Au bunch intensity evolution is shown in the graph. The main limits are:
- Injectors output
- Transition instability in RHIC (e-clouds)
- Presently Landau cavity RF amplifiers

The equation for the intensity evolution is:

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

\(N_b(t)\) and \(\varepsilon(t)\) are related to the bunch intensity and the interaction parameter, respectively.
Au bunch intensity evolution

main limits:
- injectors output
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H. Huang, K. Gardner, K. Zeno, RF, et al.
**Au bunch intensity evolution**

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

- **γ**-jump, octupoles at transition
- 111 bunches
- scrubbing with protons
- 43 bunches
- EBIS, Booster 4→2→1, AGS 8→4→2 merge

**main limits:**
- injectors output
- transition instability in RHIC (e-clouds)
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- \( \gamma \)-jump, octupoles at transition
- 111 bunches
- scrubbing with protons
- 43 bunches
- EBIS, Booster 4→2→1, AGS 8→4→2 merge
- AGS 12→6→2 merge

Main limits:
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H. Huang, K. Gardner, K. Zeno, RF, et al.
3D stochastic cooling for heavy ions

longitudinal pickup

transverse kicker cavity (half side with waveguides)

transverse pickups, FO

fibre-optic links

longitudinal kicker

microwave links

longitudinal kicker

5-9 GHz, cooling times ~1 h

horizontal and vertical pickups

horizontal kicker (open)

vertical kicker (closed)

M. Brennan, M. Blaskiewicz, F. Severino, PRL 100 174803 (2008); K. Mernick PRSTAB, PAC, EPAC
intensities (left scale)
beam loss rates (right scale)
burn-off rates (right scale)
emittances (BH, BV, YH, YV)
luminosity PHENIX
luminosity STAR

Au+Au operation in 2016
8 h

Time [hh:mm]
Au+Au operation in 2016

1. One experiment (STAR) with max leveled $L$ (use transverse offset for leveling)
other experiment (PHENIX) without max $L$
Au+Au operation in 2016

1. One experiment (STAR) with max leveled $L$ (use transverse offset for leveling) other experiment (PHENIX) without max $L$

2. Operate close to burn-off limit (all beam losses due to collision)
Au+Au operation in 2016

1. One experiment (STAR) with max leveled $L$ (use transverse offset for leveling) other experiment (PHENIX) without max $L$

2. Operate close to burn-off limit (all beam losses due to collision)

3. Reduced initial cooling reduces $L$ in PHENIX, preserves intensity, and allows for longer leveled stores for STAR
Ion beams with cooling – tolerance for emittance growth

- Bunch intensity $N_b$, was limited by transition instability in RHIC
  - (1) high peak current – (2) also triggers e-clouds, (3) no synchrotron motion, (4) chromaticity does not change fast enough through transition

- Can tolerate emittance growth at transition as long as it does not lead to intensity loss (need all ions for burn-off)

- Useful feature during electron lens commissioning with Au beams experiments tolerated intermittent emittance growth from electron beam commissioning or quenched solenoids
U+U operation at burn-off limit – allows measurement of $\sigma_{tot}$
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97% of intensity burned off at $L_{max}$
U+U operation at burn-off limit – allows measurement of $\sigma_{tot}$

97% of intensity burned off at $L_{max}$

\[
\frac{dN_B(t)}{dt} = \frac{dN_Y(t)}{dt} = -[\mathcal{L}_6(t) + \mathcal{L}_8(t)] \sigma_{tot}
\]
U+U operation at burn-off limit – allows measurement of $\sigma_{tot}$

97% of intensity burned off at $L_{max}$

Burn-off dominated operation allows for determination of total U+U cross section $\sigma_{tot}$ – and comparison with calculation (mostly QED) published in Phys. Rev. C =>
U+U operation at burn-off limit – allows measurement of $\sigma_{tot}$

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2016 event with increased luminosity \( (L_{\text{avg}} \text{ now } 40\times \text{ design}) \) — shorted quench protection diode
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19 d for exchange of shorted quench protection diode
2016 event with increased luminosity \((L_{avg}\text{ now 40x design})\) – shorted quench protection diode

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2016 event with increased luminosity \( (L_{\text{avg}} \text{ now } 40x \text{ design}) \) —
shorted quench protection diode

Large orbit bumps protect experiments in abort kicker pre-fire

19 d for exchange of shorted quench protection diode
2016 event with increased luminosity \((L_{\text{avg}} \text{ now } 40x \text{ design})\) –
shorted quench protection diode

Large orbit bumps protect experiments in abort kicker pre-fire

Locations of max orbit deviation are momentum collimators for secondary beams generated in collision
\((\text{Au ions with captured } e, \text{ or expelled } n)\)

\(\Rightarrow\) radiation damage to diode \((\sim 15 \text{ kGy})\)

19 d for exchange of shorted quench protection diode
RHIC $p\uparrow+p\uparrow$ operation with head-on beam-beam compensation

Main luminosity limit: beam-beam
Special devices for polarized protons: source, polarimeters, snakes, rotator, flipper

Absolute Polarimeter (H jet)

RHIC pC Polarimeters

Spin flipper

Siberian Snakes

PHENIX (p)

Spin Rotators (longitudinal polarization)

STAR (p)

Spin Rotators (longitudinal polarization)

Solenoid Partial Siberian Snake

Strong AGS Snake

Linac Booster

Pol. H$^-$ Source

200 MeV Polarimeter

AGS Polarimeters

Helical Partial Siberian Snake
p bunch intensity and polarization

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

\[ FOM = LP^4 \sim N_b^2 P^4 \]

main limits:
- injectors output
- polarization
- beam-beam in RHIC

A. Zelenski, H. Huang, K. Gardner, K. Zeno, RF, et al.
p bunch intensity and polarization

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

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p bunch intensity and polarization

AGS warm snake

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

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main limits:
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A. Zelenski, H. Huang, K. Gardner, K. Zeno, RF, et al.
Proton bunch intensity and polarization

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AGS warm snake
polarized source upgrade with sc solenoid

AGS cold snake

main limits:
- injectors output
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AGS tune jumps, RHIC 9 MHz RF
AGS warm snake
AGS cold snake
AGS polarized source upgrade with sc solenoid

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main limits:
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A. Zelenski, H. Huang, K. Gardner, K. Zeno, RF, et al.
**p bunch intensity and polarization**

- **AGS warm snake**
  - polarized source upgrade with sc solenoid

- **AGS cold snake**
  - AGS tune jumps, RHIC 9 MHz RF
  - polarized source upgrade with Atomic Beam Source
  - beam-beam compensation

**Main limits:**
- injectors output
- polarization
- beam-beam in RHIC

**Ultimate goal**

\[
L(t) = \frac{1}{4\pi} \int_0^N N_b^2(t) \frac{d}{d\beta^*} h(\beta^*, \sigma_s, \theta)
\]

**FOM = \(LP^4 \sim N_b^2P^4\)**

A. Zelenski, H. Huang, K. Gardner, K. Zeno, RF, et al.
Head-on beam-beam compensation

Correction in same turn, need to fulfill 2 conditions:
Head-on beam-beam compensation

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1. \( k\pi \) phase advance minimizes beam-beam resonance driving terms – implemented with ATS type lattice (Simon White, now ESRF)

new lattice with better DA and larger bb param. \( \xi \)
Head-on beam-beam compensation

Correction in same turn, need to fulfill 2 conditions:

1. $k\pi$ phase advance minimizes beam-beam resonance driving terms – implemented with ATS type lattice (Simon White, now ESRF).
2. New lattice with better DA and larger bb param. $\xi$

(2) Same amplitude correction kick as bb kick reduces beam-beam tune spread – implemented with electron lenses (not possible with magnets)
Head-on beam-beam compensation

Correction in same turn, need to fulfill 2 conditions:

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RHIC electron lenses

Overview

Xiaofeng Gu, liaison physicist
RHIC electron lenses

Overview

Xiaofeng Gu, liaison physicist
RHIC electron lenses

Overview
Xiaofeng Gu, liaison physicist

- Warm solenoids
- Electron gun

Diagram showing the path of pions (p) and electrons (e-) through the RHIC electron lenses.
RHIC electron lenses

Overview

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

Xiaofeng Gu, liaison physicist
RHIC electron lenses

Overview

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Xiaofeng Gu, liaison physicist

e^-

cold solenoids

electron gun

electron collector
RHIC electron lenses

Overview

Xiaofeng Gu, liaison physicist

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

Warm solenoids

Electron gun

Orbit steerers

Electron collector

Brookhaven National Laboratory
RHIC electron lenses

**Overview**

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

- **Warm solenoids**

- **Orbit steerers**

- **Electron gun**

- **Electron collector**

Xiaofeng Gu, liaison physicist
### TABLE I. Typical electron lens parameters for 2015 and design values (for up to 250 GeV proton energy).

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<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>2015 value</th>
<th>Design value</th>
</tr>
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<tbody>
<tr>
<td>Distance of center from IP10</td>
<td>m</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>Magnetic length $L_e$</td>
<td>m</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Gun solenoid field $B_g$</td>
<td>T</td>
<td>0.31</td>
<td>$\leq 0.69$</td>
</tr>
<tr>
<td>Main solenoid field $B_m$</td>
<td>T</td>
<td>5.0</td>
<td>2–6</td>
</tr>
<tr>
<td>Cathode radius (2.7σ)</td>
<td>mm</td>
<td>7.5</td>
<td>4.1, 7.5</td>
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<tr>
<td>rms beam size in main solenoid $\sigma_e$</td>
<td>µm</td>
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<td>$\geq 300$</td>
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<tr>
<td>Kinetic energy $E_e$</td>
<td>keV</td>
<td>5.0</td>
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<tr>
<td>Relativistic factor $\beta_e$</td>
<td>...</td>
<td>0.14</td>
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<td>Electron beam current $I_e$</td>
<td>mA</td>
<td>600</td>
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<tr>
<td>Beam-beam parameter from lens $\xi_e$</td>
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<td>0.001</td>
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Technology sources: Tevatron e-lenses (V. Shiltsev et al.), RHIC Electron Beam Ion Source (EBIS) (J. Alessi et al.)
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Technology sources: Tevatron e-lenses (V. Shiltsev et al.),
RHIC Electron Beam Ion Source (EBIS) (J. Alessi et al.)
Head-on bb compensation

Tune distributions from e-lens

tune distribution measured with transverse BTF

complex coherent response $R(Q)$ to small sinusoidal excitation at tune $Q$

non-zero $\text{Im}(R) = \text{non-zero particle distribution}$

current scan ($\sigma_e = 0.55 \text{ mm}$)

size scan ($I_e = 900 \text{ mA}$)
Head-on bb compensation  
Tune distributions from e-lens

tune distribution measured with transverse BTF
complex coherent response $R(Q)$ to
small sinusoidal excitation at tune $Q$
non-zero $\text{Im}(R) = \text{non-zero particle distribution}$

current scan ($\sigma_e = 0.55 \text{ mm}$)

size scan ($I_e = 900 \text{ mA}$)

$\Delta Q = 0.013$

$\xi_{\text{max}} = -0.011$ (max in 2015 RHIC operations)
Head-on bb compensation

tune distribution could not be measured with BTF and p+p collisions due to coherent modes

Head-on bb compensation

tune distribution **could not** be measured with BTF and p+p collisions due to coherent modes


Footprint compression

tune distribution **can be** measured with BTF and p+Al collisions

- proton beam: $(Q_x, Q_y) = (0.685, 0.695)$
- Al beam: $(Q_x, Q_y) = (0.685, 0.695)$

$\Delta Q_x, \Delta Q_y \gg \xi \Rightarrow$ no coherent modes
Head-on bb compensation

Tune distribution could not be measured with BTF and p+p collisions due to coherent modes.

Tune distribution can be measured with BTF and p+Al collisions.
Proton beam: \((Q_x, Q_y) = (0.685, 0.695)\); Al beam: \((Q_x, Q_y) = (0.685, 0.695)\); \(\Delta Q_x, \Delta Q_y \gg \xi\) \(\Rightarrow\) no coherent modes.
Head-on $bb$ compensation

Tune distribution **could not** be measured with BTF and $p+p$ collisions due to coherent modes


Tune distribution **can be** measured with BTF and $p+Al$ collisions

Proton beam: $(Q_x, Q_y) = (.685,.695)$; $Al$ beam: $(Q_x, Q_y) = (.685,.695)$; $\Delta Q_x, \Delta Q_y \gg \xi$ => no coherent modes

Footprint compression

Graph showing graph with different settings.
Head-on bb compensation

tune distribution could not be measured with BTF and p+p collisions due to coherent modes


tune distribution can be measured with BTF and p+Al collisions

proton beam: $(Q_x, Q_y) = (0.685, 0.695)$; Al beam: $(Q_x, Q_y) = (0.685, 0.695)$; $\Delta Q_x, \Delta Q_y \gg \xi \Rightarrow$ no coherent modes
Head-on bb compensation

Tune distribution could not be measured with BTF and p+p collisions due to coherent modes (works in simulations – P. Görgen et al. NIM A 777, pp. 43-53 (2015))

Footprint compression

Tune distribution can be measured with BTF and p+Al collisions

Proton beam: \((Q_x, Q_y) = (0.685, 0.695)\); Al beam: \((Q_x, Q_y) = (0.685, 0.695)\); \(\Delta Q_x, \Delta Q_y >> \xi \Rightarrow \) no coherent modes

\[ \Delta Q \text{ reduction from e-lens} \]

\[ 2x \text{ bb} \]

\[ \text{no bb} \]
Head-on bb compensation

tune distribution could not be measured with BTF and p+p collisions due to coherent modes

tune distribution can be measured with BTF and p+Al collisions
proton beam: \((Q_x, Q_y) = (.685,.695);\) Al beam: \((Q_x, Q_y) = (.685,.695);\) \(\Delta Q_x, \Delta Q_y \gg \xi\) => no coherent modes

Footprint compression

Can only reduced BB tune spread (black curve is limit)
e-lenses in operation with collisions at 2 experiments

- Luminosities
- IPM emittances
- e-lens e-beam currents
- Backscattered electron rates
- Luminosities [10^30 cm^-2 s^-1]
- RMS Emittance [mm.mrad]
- e-lens current [mA]
- eBSD rate
e-lenses in operation with collisions at 2 experiments
1. e-lenses turn on before collision
(112 stores with both lenses without a single turn-on failure)
e-lenses in operation with collisions at 2 experiments

1. e-lenses turn on before collision
   (112 stores with both lenses without a single turn-on failure)

2. luminosities

3. IPM emittances

4. e-lens e-beam currents

   backscattered electron rates
e-lenses in operation with collisions at 2 experiments

1. e-lenses turn on before collision
   (112 stores with both lenses without a single turn-on failure)

2. Beams into collision at PHENIX, collimators to store positions
   (requires PHENIX collisions)
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   (112 stores with both lenses without a single turn-on failure)

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3. Beams into collision at STAR and e-lenses. e-lenses prevent emittance growth and/or beam loss for large beam-beam param. $\xi$
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3. Beams into collision at STAR and e-lenses
   e-lenses prevent emittance growth and/or beam loss for large beam-beam param. $\xi$

4. Lenses are gradually turned off when lattice alone can sustain bb parameter $\xi$
Head-on bb compensation

Initial emittance and 5 min later, beam loss over 5 min

Increase in bb parameter $\xi$ with lens

2 data sets:
(1) 2015 ops
(2) tests for max $|\xi|$
### Head-on bb compensation 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>
<th>with e-lens e-lens — 2015 —</th>
</tr>
</thead>
<tbody>
<tr>
<td>bunch intensity $N_p$</td>
<td>$10^{11}$</td>
<td>1.6 2.25</td>
<td>2.6 2.15 2.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>no of bunche $k_b$</td>
<td>...</td>
<td>109 111</td>
<td>48 111 30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_{x,y}^*$ at IP6, IP8 (p+p)</td>
<td>m</td>
<td>0.85 0.85</td>
<td>— 0.85 —</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_{x,y}^*$ at e-lens (p+e)</td>
<td>m</td>
<td>10.5 15.0</td>
<td>— 15.0 —</td>
<td></td>
<td></td>
</tr>
<tr>
<td>lattice tunes ($Q_x, Q_y$)</td>
<td>...</td>
<td>(0.695, 0.685)</td>
<td>— (0.695, 0.685) —</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rms emittance $\epsilon_n$</td>
<td>$\mu$m</td>
<td>3.3 2.8</td>
<td>3.5 2.4 1.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rms beam size IP6/8 $\sigma_p^*$</td>
<td>$\mu$m</td>
<td>165 150</td>
<td>170 150 125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rms beam size e-lens $\sigma_p$</td>
<td>$\mu$m</td>
<td>— 630</td>
<td>700 645 520</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rms bunch length $\sigma_s$</td>
<td>m</td>
<td>0.63 0.70</td>
<td>0.77 0.70 0.56</td>
<td></td>
<td></td>
</tr>
<tr>
<td>hourglass factor $H$</td>
<td>...</td>
<td>0.74 0.75</td>
<td>0.78 0.81 0.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>beam-beam param. $\xi_p/IP$ 0.001</td>
<td></td>
<td>-5.8 -9.7</td>
<td>-9.1 -10.9 -12.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td># of beam-beam IPs</td>
<td>...</td>
<td>2 2+1*</td>
<td>2 2+1* 2+1*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>luminosity $L_{peak}$</td>
<td>$10^{30}$ cm$^{-2}$s$^{-1}$</td>
<td>46 115</td>
<td>72 115 40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>luminosity $L_{avg}$</td>
<td>$10^{30}$ cm$^{-2}$s$^{-1}$</td>
<td>33 63</td>
<td>— — —</td>
<td></td>
<td></td>
</tr>
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</table>

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.)
Head-on bb compensation

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<tr>
<th>quantity</th>
<th>unit</th>
<th>operations (avg. over 10 best stores)</th>
<th>tests for max</th>
<th>2 data sets:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2012 2015</td>
<td>without e-lens e-ler 2015</td>
<td>(1) 2015 ops</td>
</tr>
<tr>
<td>bunch intensity $N_p$</td>
<td>$10^{11}$</td>
<td>1.6 2.25</td>
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<td>beam-beam param. $\xi_p/IP$</td>
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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.)
### Head-on bb compensation

| quantity                    | unit | 2012 | 2015 | 2015 | tests for max $|\xi|$ |
|-----------------------------|------|------|------|------|----------------|
| bunch intensity $N_p$       | $10^{11}$ | 1.6  | 2.25 | 2.6  | 2.15           |
| no of bunches $k_b$         |      | 109  | 111  | 48   | 111            |
| $\beta^*_{,y}$ at IP6, IP8 (p+p) | m    | 0.85 | 0.85 | —    | 0.85           |
| $\beta^*_{,y}$ at e-lens (p+e) | m    | 10.5 | 15.0 | —    | 15.0           |
| lattice tunes $(Q_x, Q_y)$  |      | (0.695, 0.685) | (0.695, 0.685) | —    | —              |
| rms emittance $\epsilon_n$ | $\mu$m | 3.3  | 2.8  | 3.5  | 2.4            |
| rms beam size IP6/8 $\sigma^*_p$ | $\mu$m | 165  | 150  | 170  | 150            |
| rms beam size e-lens $\sigma_p$ | $\mu$m | —    | 630  | 700  | 645            |
| rms bunch length $\sigma_s$ | m    | 0.63 | 0.70 | 0.77 | 0.70           |
| hourglass factor $H$        |      | 0.74 | 0.75 | 0.78 | 0.81           |
| beam-beam param. $\xi_p$/IP | 0.001 | —    | —    | —    | —              |
| # of beam-beam IPs          |      | 2    | 2+1* | 2    | 2+1*           |
| luminosity $L_{peak}$       | $10^{30}$ cm$^{-2}$ s$^{-1}$ | 46   | 115  | 72   | 115            |
| luminosity $L_{avg}$        | $10^{30}$ cm$^{-2}$ s$^{-1}$ | 33   | 63   | —    | —              |

$L_{peak}$ **2.5x increase**  
$L_{avg}$ **1.9x 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.)
Head-on bb compensation

| quantity                        | unit | operations (avg. over 10 best stores) | tests for max $|\xi|$ without with e-lens e-lens (2015) |
|--------------------------------|------|---------------------------------------|------------------|
| bunch intensity $N_p$          | $10^{11}$ | 1.6 2.25                           | 2.6 2.15 —      |
| no of bunches $k_b$            | ...  | 109 111                           | 48 111 30       |
| $\beta_{x,y}$ at IP6, IP8 (p+p) | m    | 0.85 0.85                       | — 0.85 —        |
| $\beta_{x,y}$ at e-lens (p+e) | m    | 10.5 15.0                        | — 15.0 —        |
| lattice tunes ($Q_x, Q_y$)     | ...  | (0.695,0.685)                     | — (0.695,0.685) — |
| rms emittance $\epsilon_n$     | $\mu m$ | 3.5 2.4 1.9              | 3.5 2.4 1.9     |
| rms beam size IP6/8 $\sigma_p$ | $\mu m$ | 16 170 150 125              | 170 150 125     |
| rms beam size e-lens $\sigma_p$ | $\mu m$ | — 700 645 520              | 700 645 520     |
| rms bunch length $\sigma_s$    | m    | 0.63 0.70                      | 0.77 0.70 0.56 |
| hourglass factor $H$           | ...  | 0.74 0.75                    | 0.78 0.81 0.86 |
| beam-beam param. $\xi_p/IP$    | 0.001 | —9.1 —9.7 —12.6             | —9.1 —12.6 —    |
| # of beam-beam IPs             |       | 2 2+1*                         | 2 2+1* 2+1*     |
| luminosity $L_{peak}$          | $10^{30}$ cm$^{-2}$s$^{-1}$ | 46 115                        | 72 115 40       |
| luminosity $L_{avg}$           | $10^{30}$ cm$^{-2}$s$^{-1}$ | 33 63                         | — — —           |

$L_{peak}$ 2.5× increase  
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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.)

2 data sets:
(1) 2015 ops
(2) tests for max $|\xi|$
### Head-on bb compensation

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<td>9</td>
</tr>
<tr>
<td>rms beam size IP6/8 $\sigma_p^*$</td>
<td>$\mu$m</td>
<td>16</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>rms beam size e-lens $\sigma_p$</td>
<td>$\mu$m</td>
<td>—</td>
<td>7</td>
<td>0</td>
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2 data sets: (1) 2015 ops (2) tests for max $|\xi|$
Head-on bb compensation

increases in $L$ and $\xi$

2 data sets:
(1) 2015 ops
(2) tests for max $|\xi|$

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.)

Wolfram Fischer
Summary – RHIC upgrades

Continue to run new species combinations at various energies
Summary – RHIC upgrades

Continue to run new species combinations at various energies →
Summary – RHIC upgrades

Continue to run new species combinations at various energies →

Completed stochastic cooling upgrade for A+A, increase in $N_b$
left 7x increase in avg. luminosity
(further 2x luminosity increase planned)
Summary – RHIC upgrades

Continue to run new species combinations at various energies →

Completed stochastic cooling upgrade for A+A, increase in $N_b$
← 7x increase in avg. luminosity
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Summary – RHIC upgrades

Continue to run new species combinations at various energies →

Completed stochastic cooling upgrade for A+A, increase in $N_b$

$\leftarrow$ 7x increase in avg. luminosity

(further 2x luminosity increase planned)

First operational use of head-on beam-beam compensation for $p^{↑}+p^{↑}$ (lattice + e-lenses),
iincrease in $N_b$, 2x increase in avg. $L$ at 100 GeV →

(further 3/4x luminosity increase planned at 100/250 GeV)