

Six-dimensional weak-strong simulations of head-on compensation in RHIC

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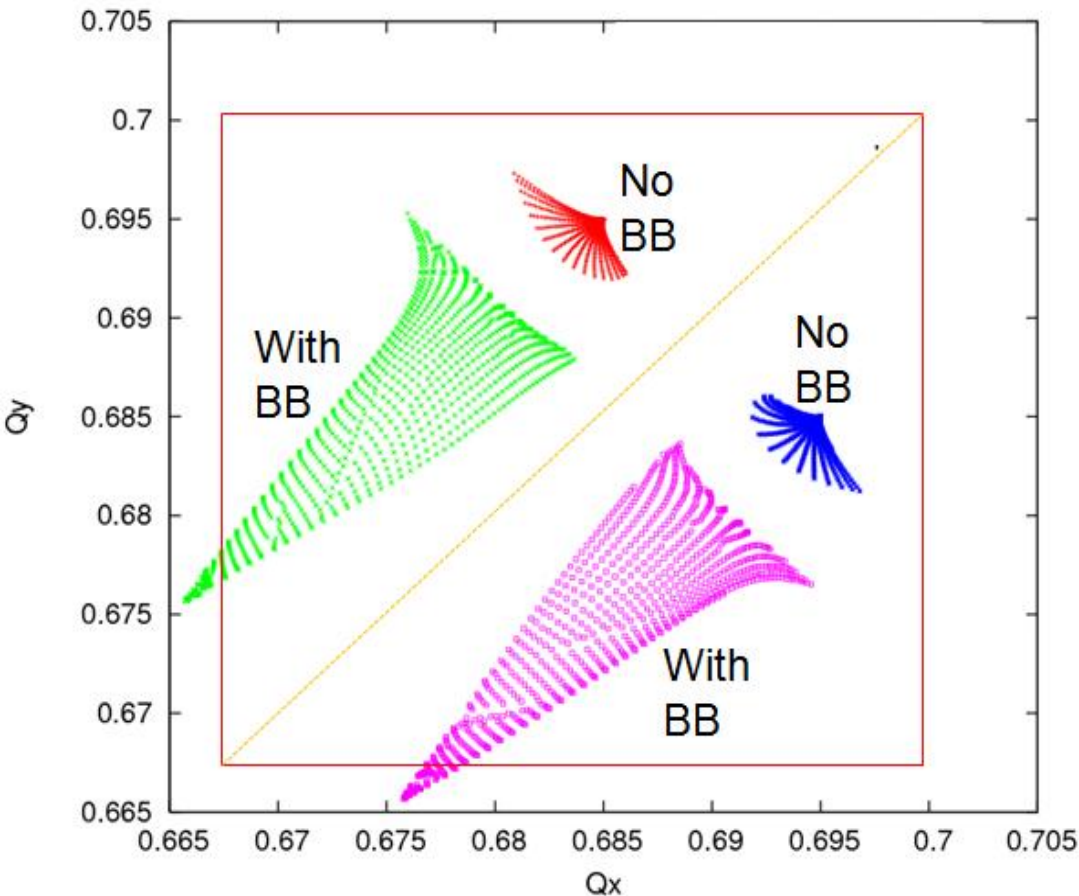
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Here we focus on weak-strong beam-beam simulation results for RHIC head-on beam-beam compensation. For strong-strong simulation results, please see S. White's talk.

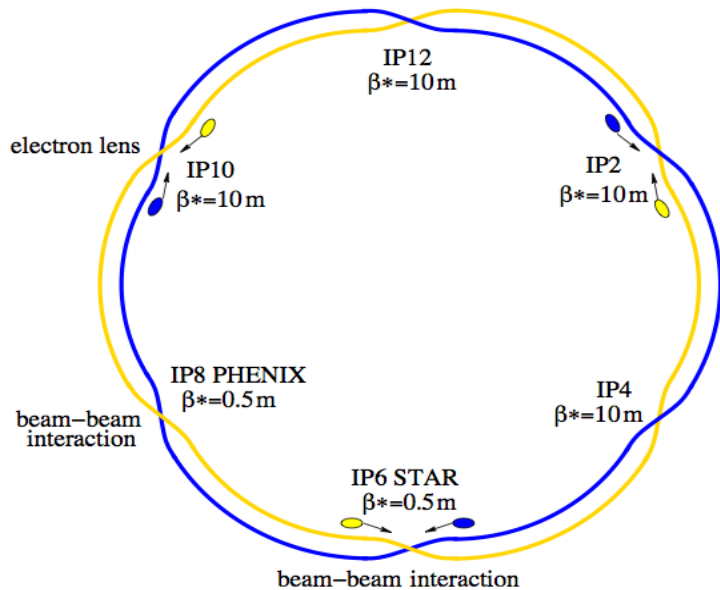
Introduction



Tune footprints with $N_p = 2.0 \times 10^{11}$
with beam-beam parameter 0.02.

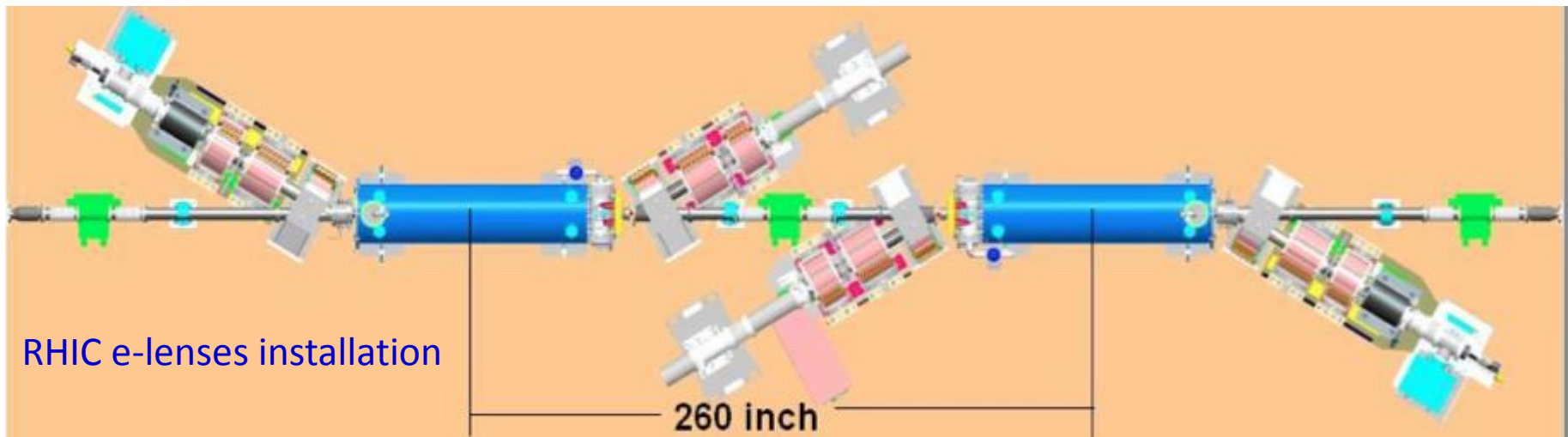
- ❑ To further increase Luminosity in the RHIC polarized proton run we are continuing to increase bunch intensity and decrease β^* .
- ❑ With the newly upgraded polarized proton source, the maximum bunch intensity at store in RHIC will increase from currently 1.7×10^{11} up to 3.0×10^{11} . The beam-beam parameter will exceed 0.025.
- ❑ Current RHIC working point is constrained between $2/3$ and $7/10$. There is not enough tune space between $2/3$ and $7/10$ to hold the large beam-beam tune spread when the proton bunch intensity is higher than 2.0×10^{11} .

Head-on Beam-beam compensation



Layout RHIC BBC

- Head-on beam-beam compensation (BBC) has been adopted in RHIC for beam-beam tune spread and nonlinear beam-beam resonance driving term (RDT) compensations.
- Two electron lenses (e-lenses) have been installed on either side of IP10, one for compensation in Blue ring, and one for Yellow ring. Proton beams are separated vertically in e-lenses.
- The electron beam should have same transverse profile and beam size as the proton bunches at e-lenses for best cancellation of BB effects.



Beam & optics parameters used in simulation

TABLE I: Lattice and beam parameters used in this study.

Parameter	Value
Ring circumference	3833.8451 m
Energy	250 GeV
Relativistic γ	266
Working point $Q_{x,y}$	(28.67, 29.68)
Linear chromaticities $\xi_{x,y}^{(1)}$	(1, 1)
Second order chromaticities $\xi_{x,y}^{(2)}$	(2800, 2900)
Normalized transverse rms emittance ϵ_n	2.5 mm·mrad
$\beta_{x,y}^*$ at IP6 and IP8	0.5 m
$\beta_{x,y,e-lens}$ at the e-lens	10.0 m
Transverse rms beam size at IP6 and IP8	68 μm
Transverse rms beam size at e-lens	310 μm
Phase advances between IP6 and IP8	(10.6 π , 9.7 π)
Phase advances between IP8 and e-lens	(8.5 π , 11.1 π)
Optimized phase advances between IP8 and e-lens	(9.0 π , 11.0 π)
Harmonic number	360
RF cavity voltage	300 kV
Longitudinal rms bunch area	0.17 eV·s
Bucket height $(dp/p_0)_{max}$	1.1×10^{-3}
Relative rms bunch momentum spread $(dp/p_0)_{rms}$	1.4×10^{-4}
Rms bunch length	0.45 m

Weak-strong BB simulation code

❑ Code : SimTrack (by Y. Luo)

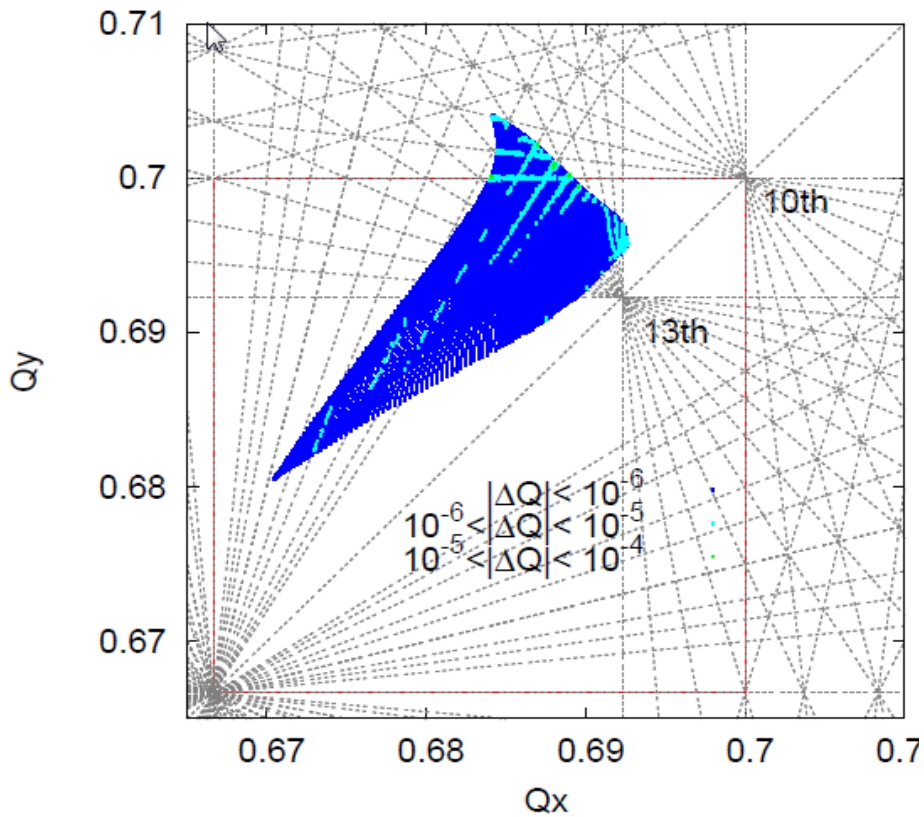
- C++ library: flexible, manageable
- 4th order symplectic integration for magnets
- 6-D synch-beam map for p-p beam-beam
- 4-D beam-beam kickers for e-p beam-beam
- element-by-element tracking
- nonlinear interaction region magnet fields used

❑ Code benchmarking with other codes

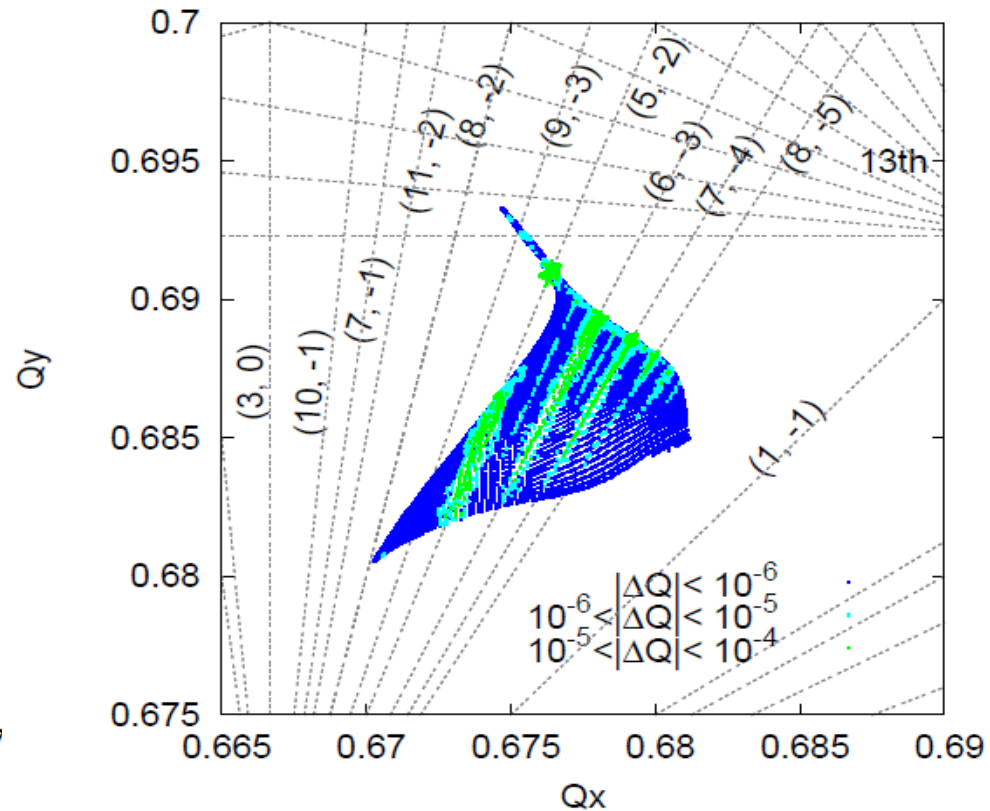
- optics benchmarked with TRACY-II (J. Bengtsson)
- 6-D beam-beam benchmarked with BBSIMC (Y-J. Kim, T. Sen)
- particle loss compared with BBSIMC, LifeTrac (A. Valishev)

Tune footprints w/o BBC

- Plots below show the tune footprints without / with beam-beam compensation. In this example, we used bunch intensity 2.5×10^{11} , normalized emittance 15 Pi mm.mrad .
- We define full beam-beam compensation (FBBC) and half head-on beam-beam compensation (HBBC) to compensate full and half of total beam-beam tune shift.
- Partial head-on beam-beam compensation is to be used in RHIC.



$N_p = 2.5 \times 10^{11}$, no compensation



$N_p = 2.5 \times 10^{11}$, half compensation

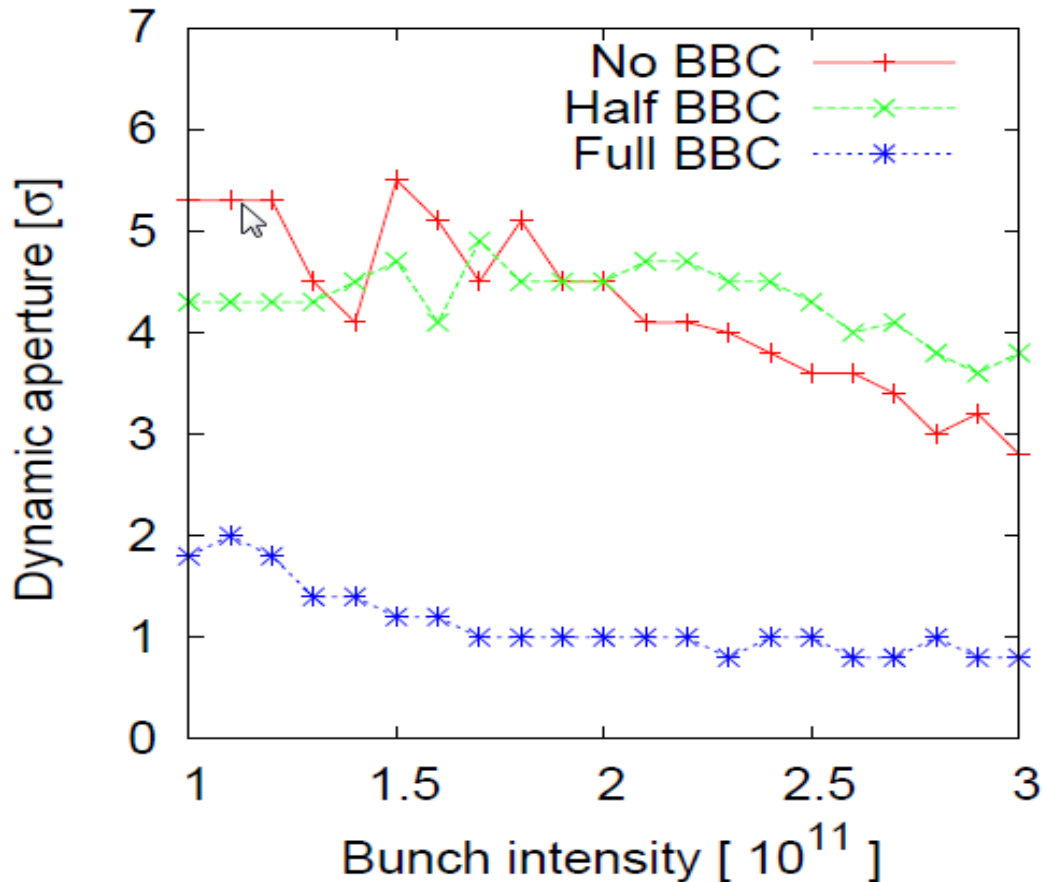
Dynamic Aperture Calculation

In this section, we present DA results:

- without and with BBC
- parameter scans
- phase advances between IP and e-lenses
- second order chromaticity correction

Dynamic aperture has been used to determine single particle's stability in RHIC and results qualitatively agreed well with observations.

DA with and without compensation



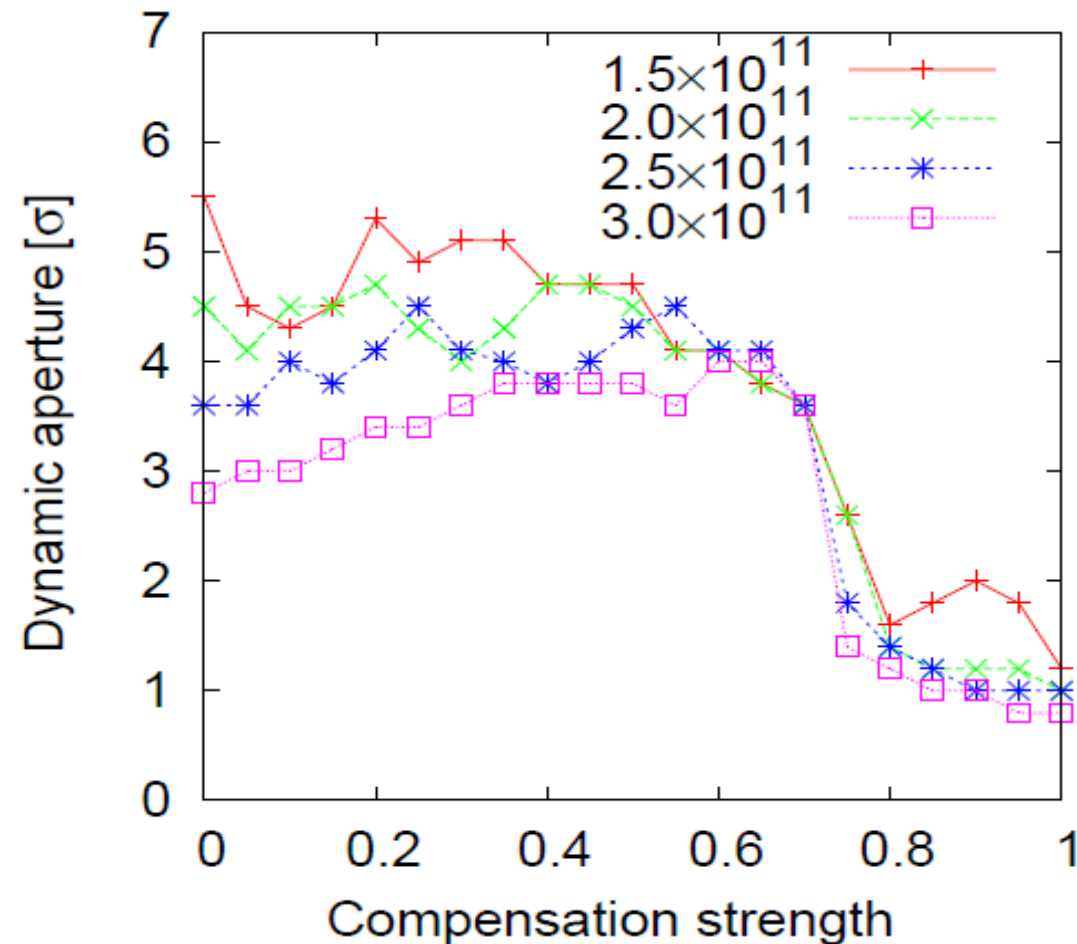
□ In the following simulation, zero-amplitude tunes are always set to (0.67, 0.68) under different BB conditions.

□ Left plot shows that DA without BBC, with FBBC, and HBBC in the scan of proton bunch intensity. Simulation results show that HBBC improves DA when $N_p > 2.5 \times 10^{11}$. FBBC reduces DA for all bunch intensities.

□ Explanation: HBBC moves the tune spread away from 7/10 resonance line.

□ Explanation: FBBC compensates almost all of BB tune spread, its tune footprint is every irregular due to $Q_x=2/3$ resonance. FBBC also gives largest beam-beam RDTs.

Compensation strength



□ We define compensate strength:

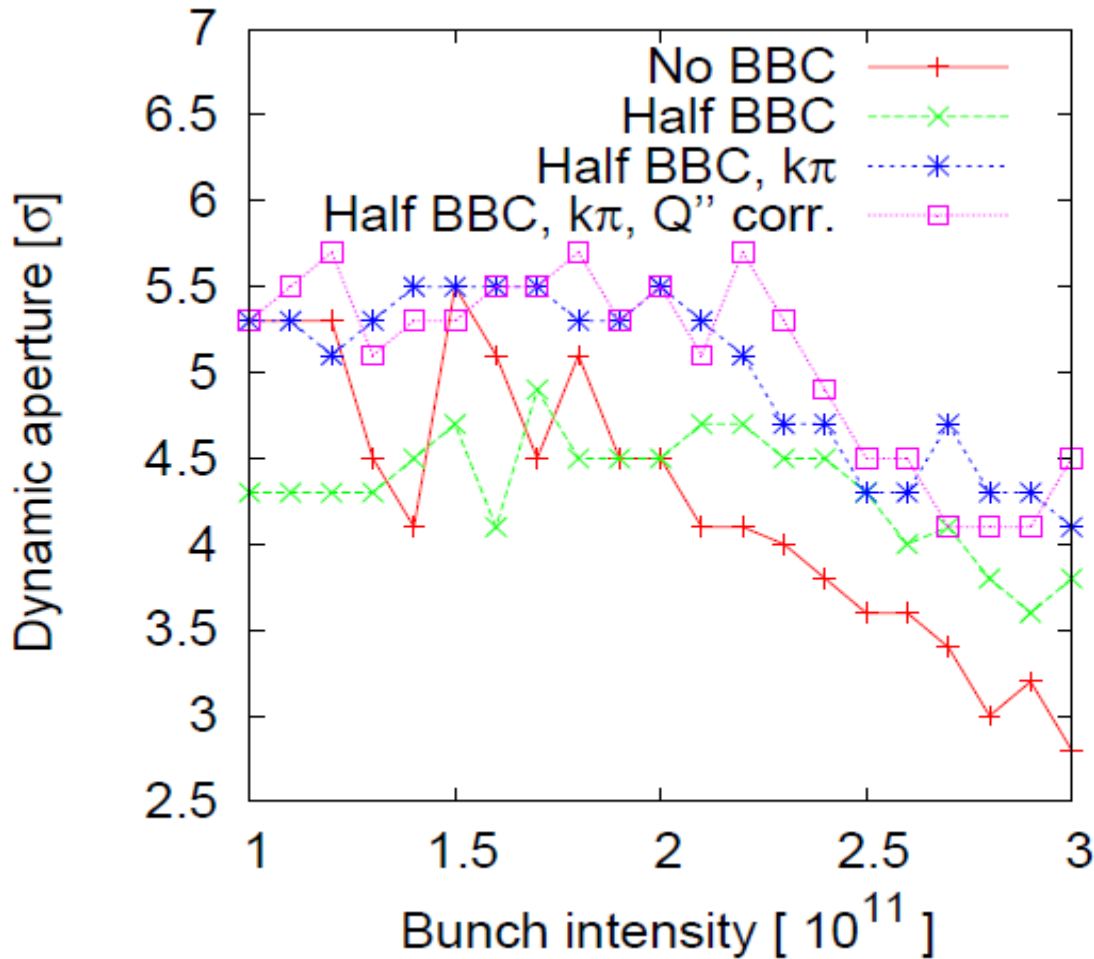
$$\kappa = (N_e^*/2N_p)/(\sigma_e/\sigma_{p,e-lens})^2$$

Here we adjust N_e^* to change κ .

□ Simulation results show that for all of the bunch intensities, DA begins to drop sharply when compensation strength exceeds 0.7.

□ The optimized compensation strength for $N_p = 2.5 \times 10^{11}$ and 3.0×10^{11} is around 0.5-0.6.

Phase adjustment and Q'' correction

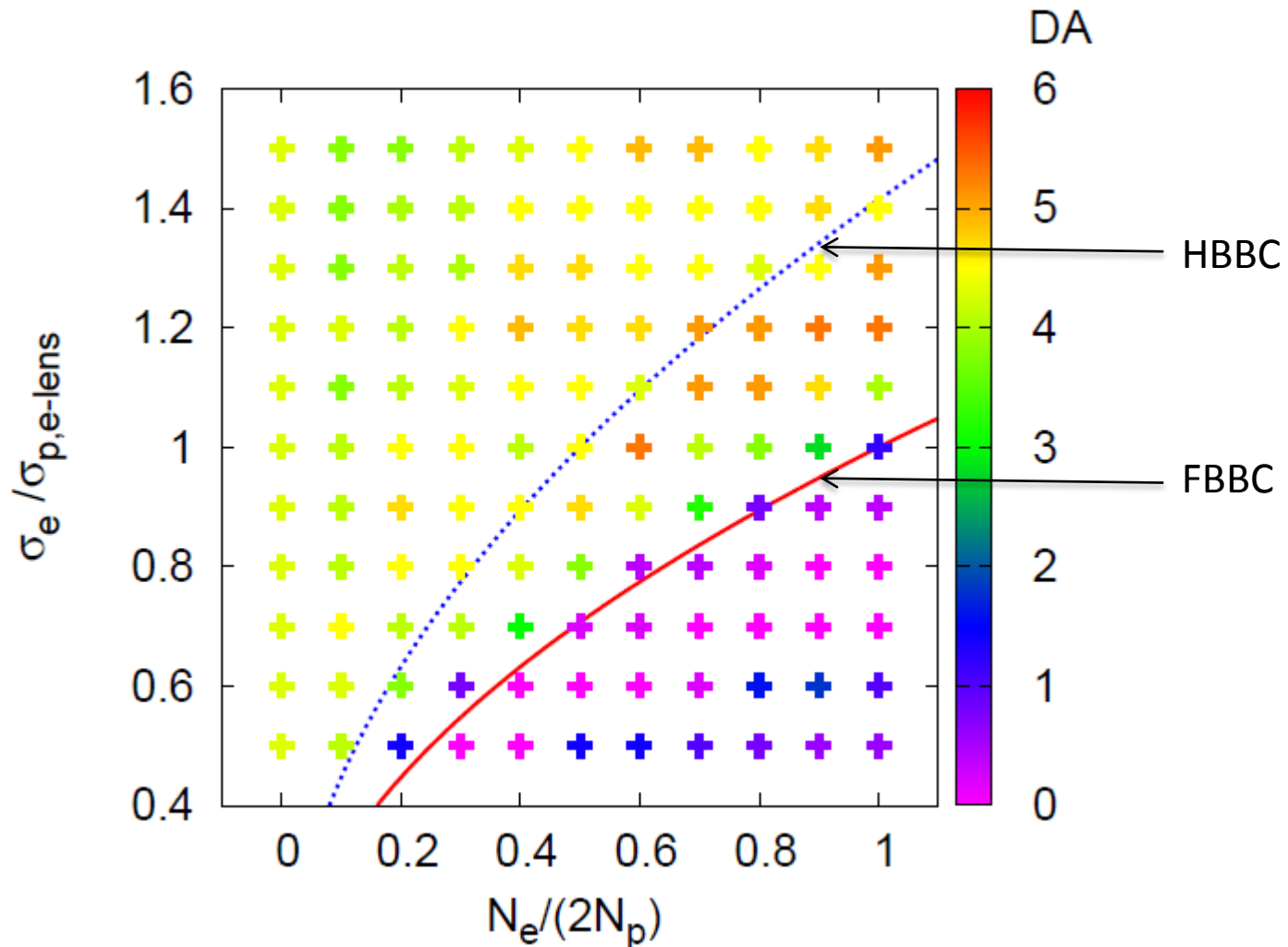


□ Two shunt power supplies are added to the main arc quadrupoles between IP8 and IP10 to adjust the phase advances between IP8 and e-lens to be $K * \pi$ for cancellation of IP8 's contributions to beam-beam RDTs with the e-lens .

□ Global second order chromaticity correction is applied to improve the off-momentum dynamic aperture.

□ Simulation results show that the phase adjustment between IP8 and e-lens, and second order chromaticity correction improve the dynamic aperture of HBBC.

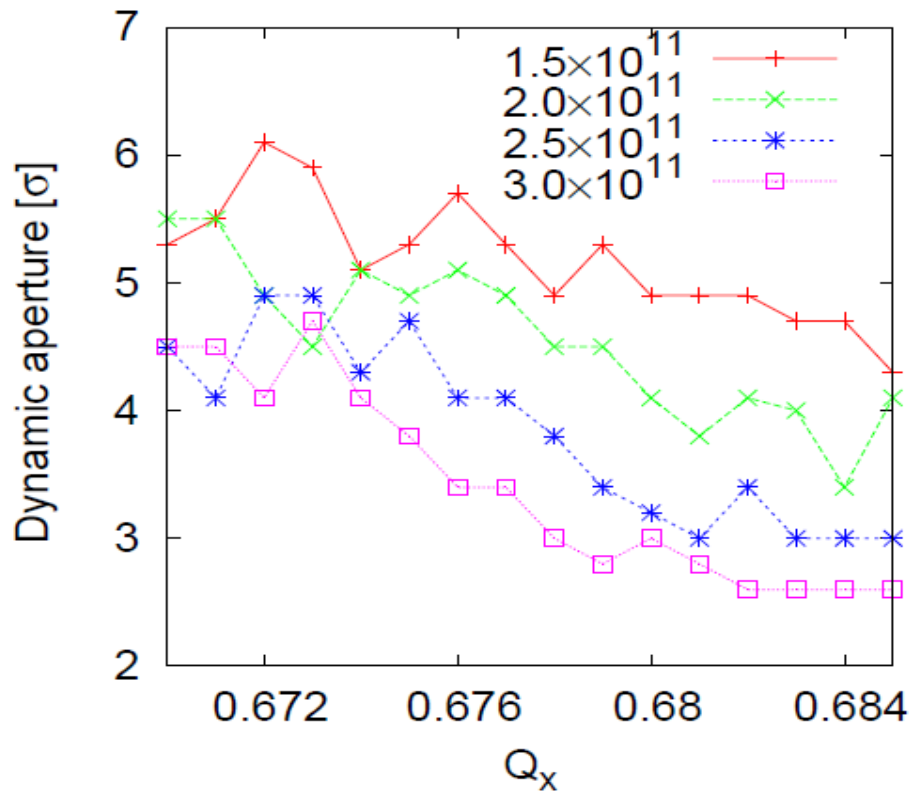
Electron beam size



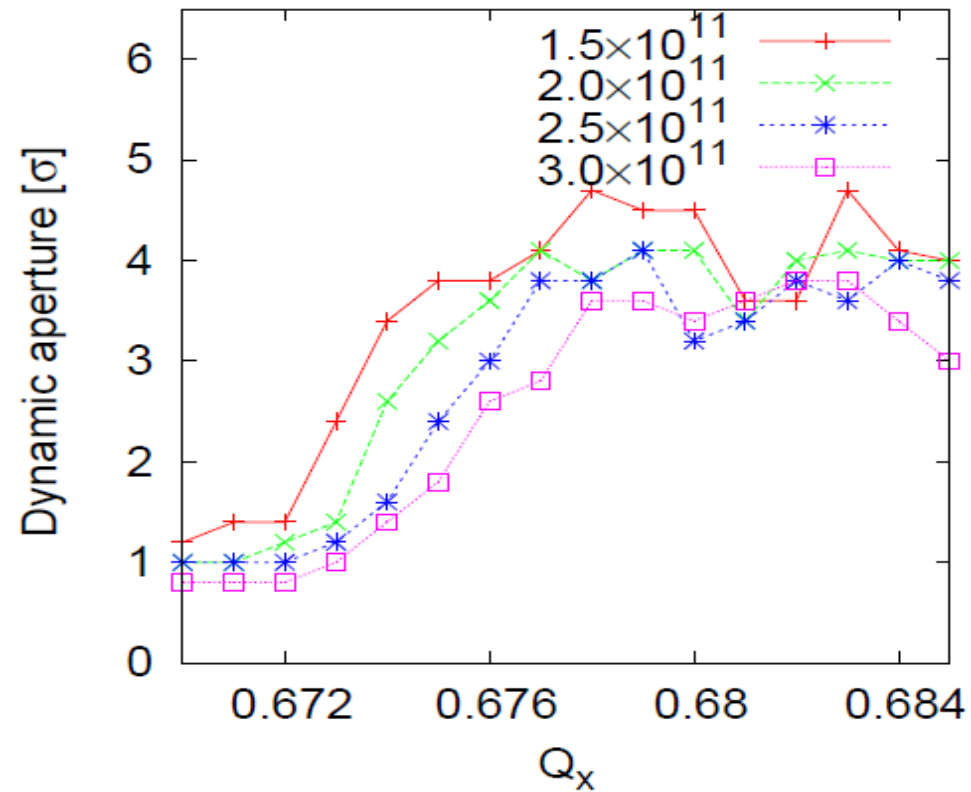
□ A 2-D scan of electron current and electron beam size shows that the maximum DA with head-on beam-beam compensation is around half beam-beam compensation with the electron beam size slightly larger than the proton beam's.

Tune scan with compensation

- With BBC, the tune footprint becomes smaller and therefore it is possible to scan the proton working point between 2/3 and 7/10 to maximize DA.
- Simulation shows that HBBC prefers lower tunes while FBBC prefers higher tunes. The maximum DA of FBBC is smaller than that of HBBC in the tune scan.



HBBC tune scan



FBBC tune scan

Particle Loss Rate Calculation

In this section, we present multi-particle long-term tracking results with head-on beam compensation in RHIC:

- challenges in multi-particle tracking
- new approaches & algorithms
- some particle loss rate calculation

Challenges in multi-particle tracking

❑ Beam-beam study tools

- single particle tracking:

tune diffusion, action diffusion, dynamic aperture (DA), etc.

- multi-particle tracking:

beam lifetime, emittance growth

❑ Dynamic aperture versus lifetime

- DA doesn't give information about emittance

- DA is not directly connected to beam lifetime

- online measurement of DA is tedious

- beam decay, emittances, luminosity are measured online

❑ Challenges in multi-particle tracking

- Limited computing time : have to reduce particle number, tracking turns

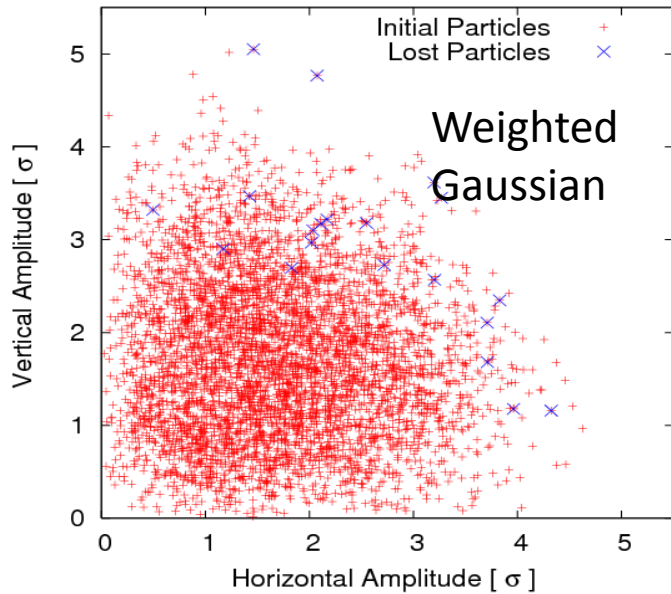
- Limited resolution in tracking results:

for example, for RHIC multi-particle tracking, 2×10^6 turns (24 seconds)

to detect 1% / hour beam decay → resolution: 0.007% in particle loss

to detect 20% emittance increase over 10 hours → resolution: 0.02% in emittance

Techniques & Algorithms



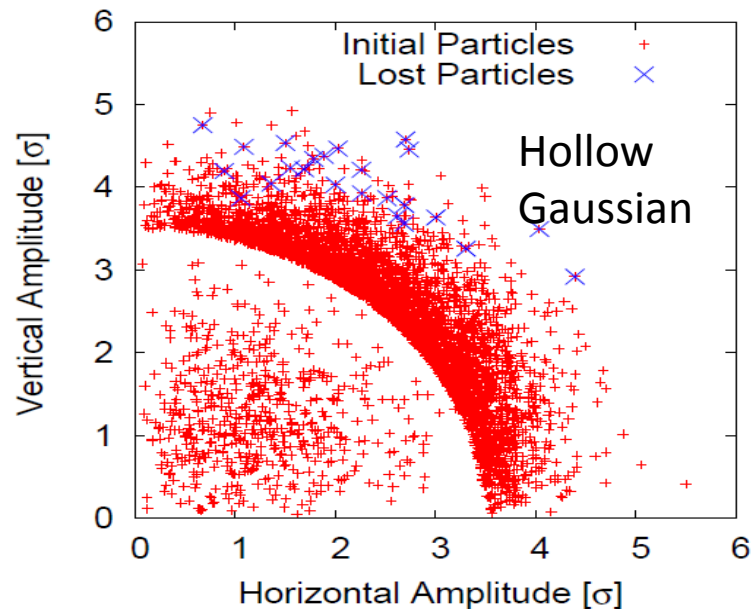
- For limited multi-particle number (4800), we use
 - 1) weighted particle distribution (LifeTrac)
 - 2) Hollow Gaussian particle distribution (BBSIMC)

- For hollow Gaussian distribution, only track particles with amplitudes above certain transverse and longitude boundaries. Particles inside that boundaries are considered stable and don't track.

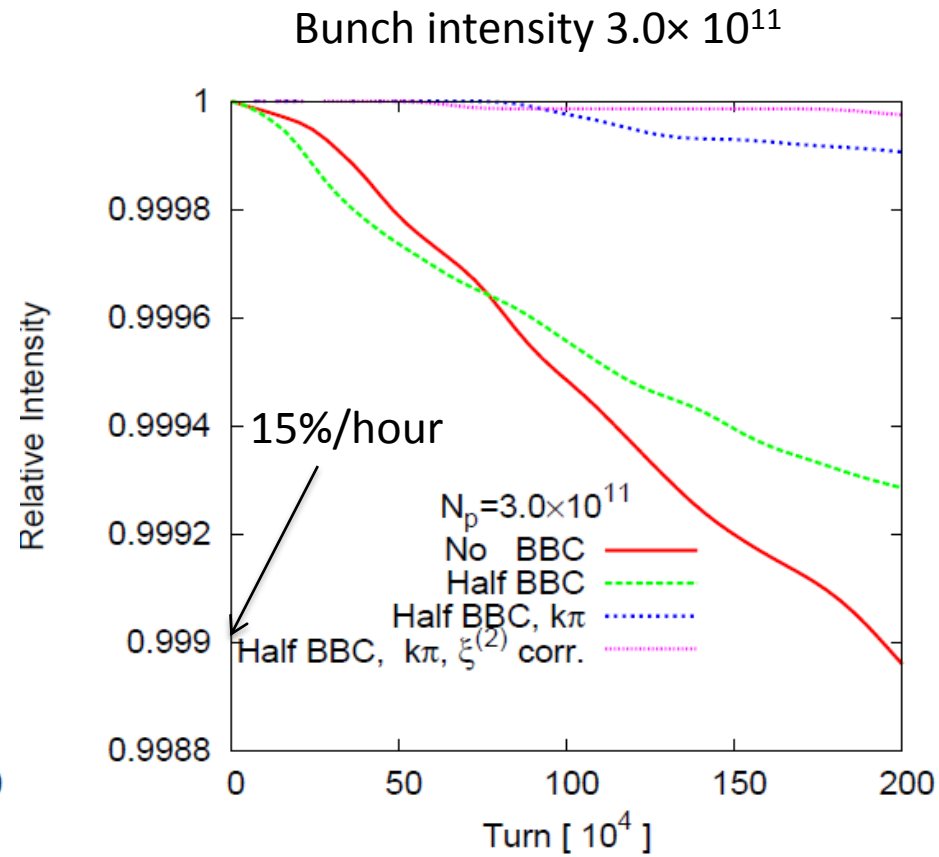
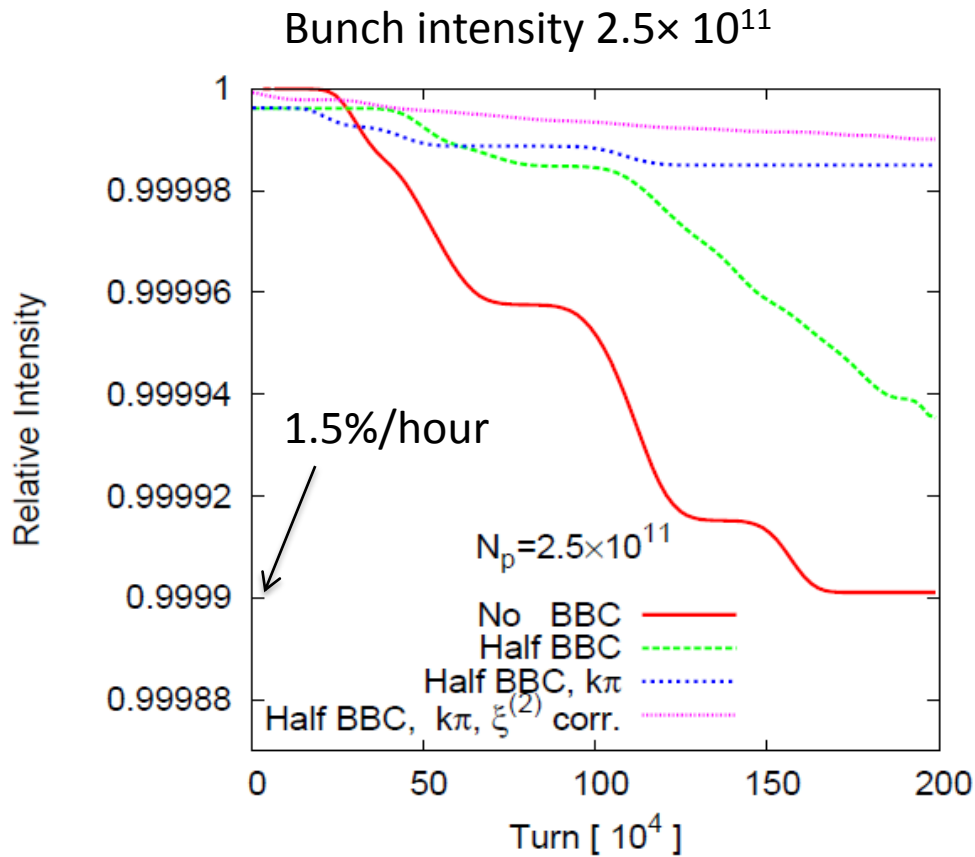
- For example, HBBC with bunch intensity $Np= 2.5 \times 10^{11}$, 4800 macro-particles, over 2×10^6 turns. Following table shows the calculated beam decays with three initial particle distributions:

Table 1: Particle Losses with Different Initial Distributions

Case	$N_{represent}$	N_{lost}	beam decay
Plain Gaussian	4800	1	2.9%/hr
Hollow Gaussian	66269	16	3.4%/hr
Weighted Gaussian	70108	20	4.0%/hr



Particle loss rates



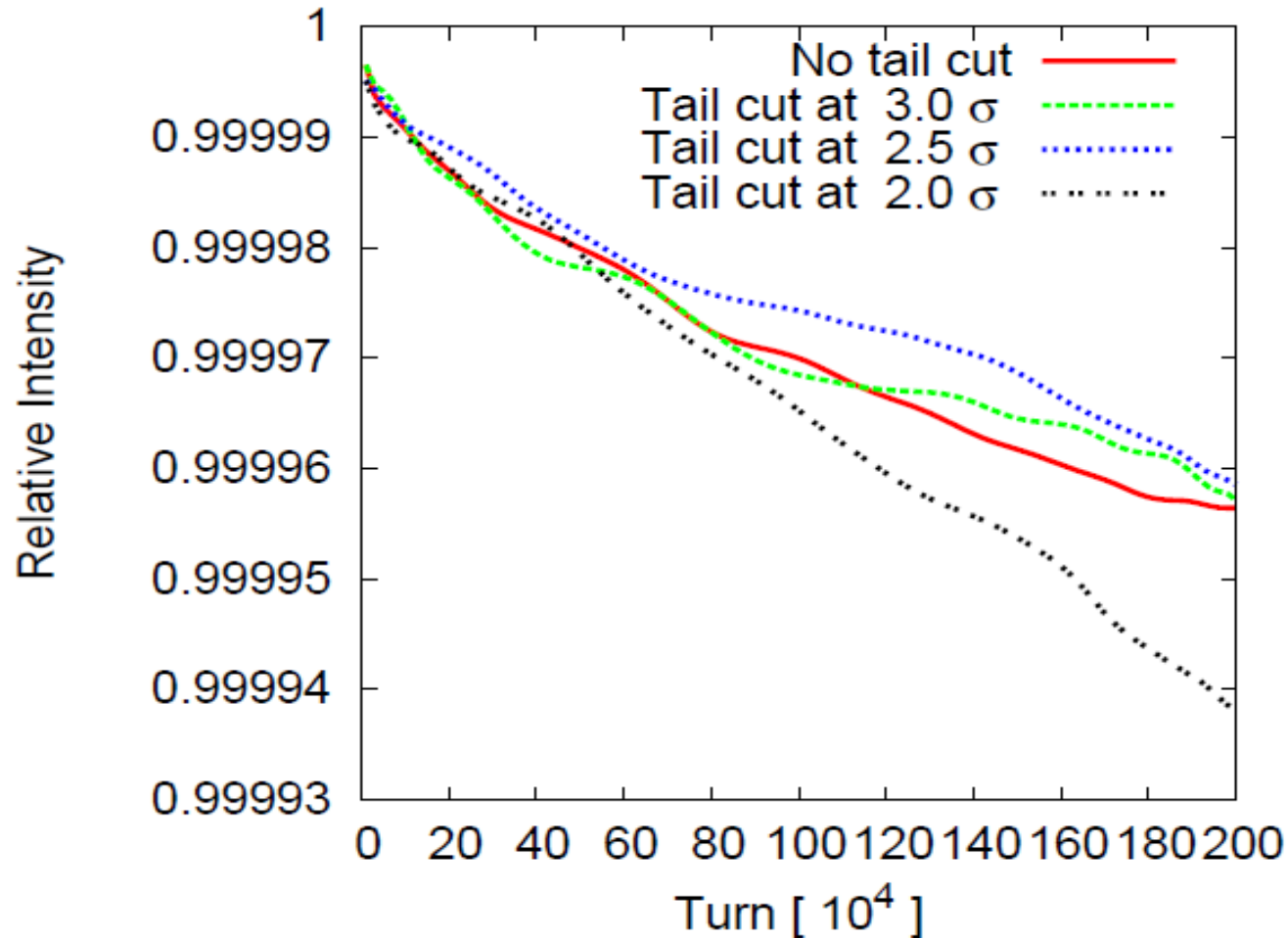
□ Multi-particle simulation results confirm the results from DA tracking: HBBC improves the beam lifetime of half beam-beam compensation. And the phase adjustment between IP8 and e-lens, and second order chromaticity correction further increase the proton beam lifetime.

Sensitivity Study

In this section, we present the sensitivity of head-on beam-beam compensation on the beam imperfections and beam noises:

- truncated Gaussian electron distribution
- offsets between electron and proton beams
- noises in electron beam current

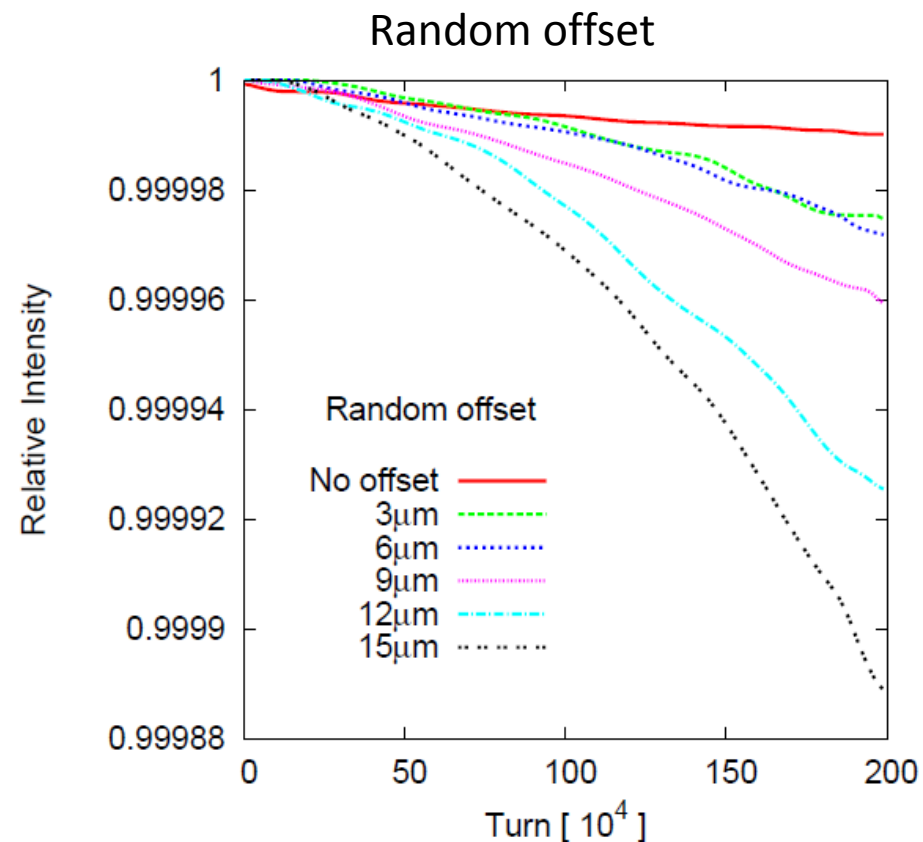
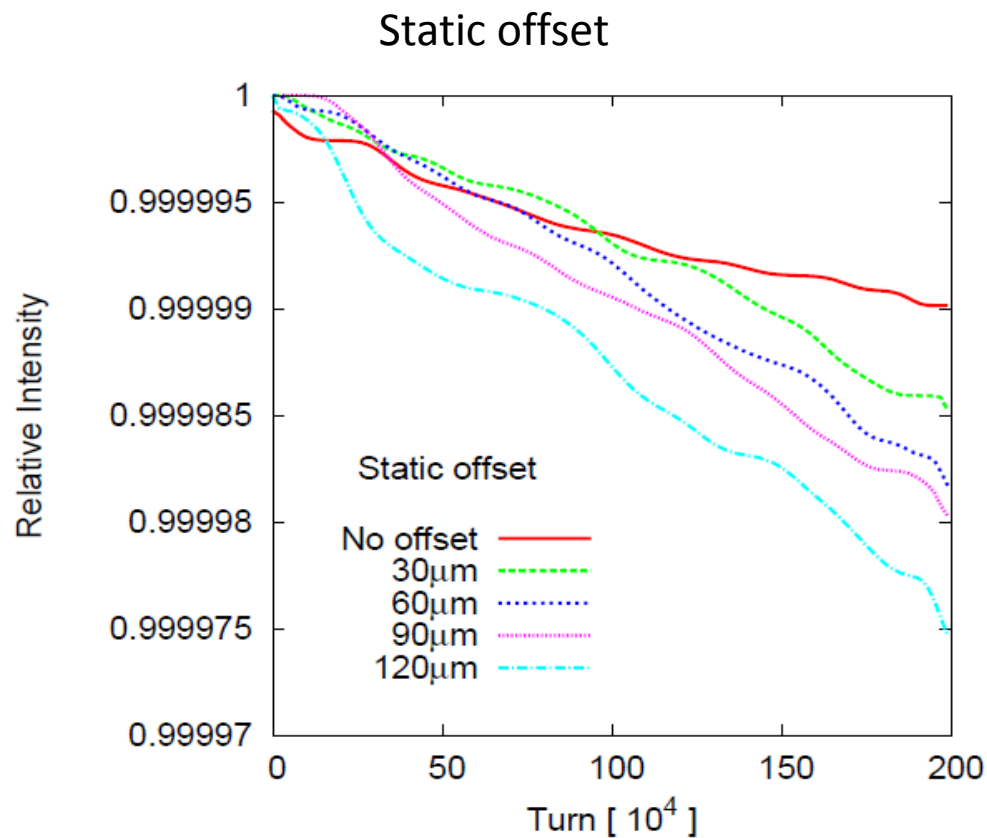
Truncated Gaussian Tail



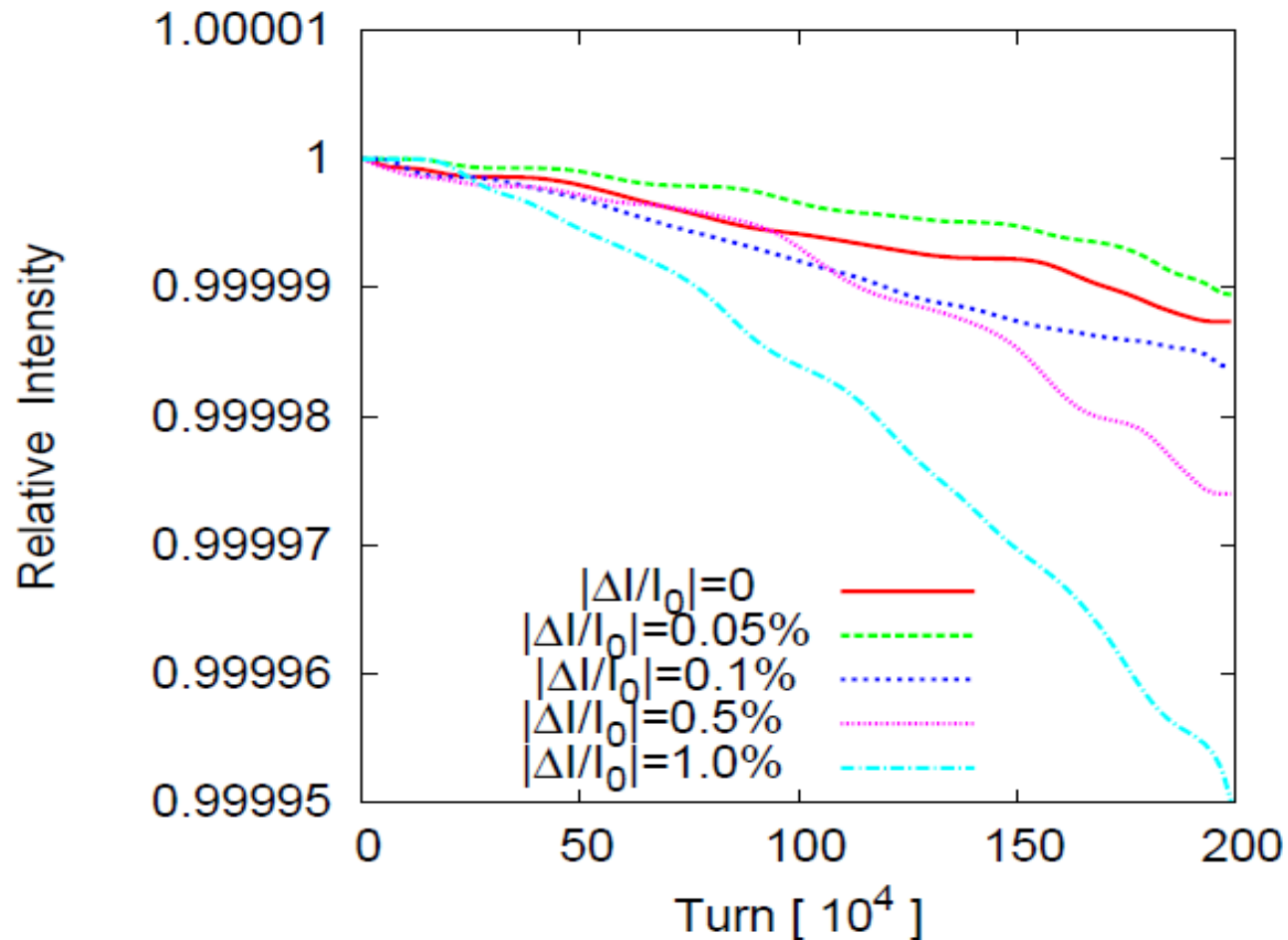
- ❑ RHIC e-lens gun design and real measurement show that the electron beam has a Gaussian tail cut off at 2.8 . This is determined by electric field distribution on cathode.
- ❑ Simulation shows that Gaussian tail cut at 2.8 from the current electron gun design is acceptable.

Offset of electron and proton beams

- ❑ Over-lapping of the electron and proton beams in the e-lens plays a crucial role in the head-on beam-beam compensation.
- ❑ Based on particle loss rate calculations, we set the static offset error tolerance to be $30\ \mu\text{m}$ which is a tenth of a rms beam size in the e-lens, and the random offset tolerance to be $9\ \mu\text{m}$ which requires stability of bending magnet's power supply better than 0.01%.



Noise in electron current



- ❑ Due to the instability of the power supplies of the electron gun, there is noise in the electron beam current.
- ❑ Based on particle loss rate calculation, we require that the stability of the power supplies of the electron gun should be better than 0.1% .

Summary

- We presented the 6-D weak-strong simulation results for the head-on beam-beam compensation in RHIC. Dynamic aperture, particle loss rate, and sensitivity are calculated.
- Calculated dynamic aperture and particle loss rate show that half beam-beam compensation improves proton beam's beam lifetime. And phase advance adjustment between IP8 and e-lens, and second order chromaticity correction further increase the proton beam lifetime.
- In the following months we will repeat simulations with the real RHIC e-lens lattices and focus on the e-lens lattice optimization, nonlinear corrections with head-on beam-beam compensation.