Status of RHIC electron lenses

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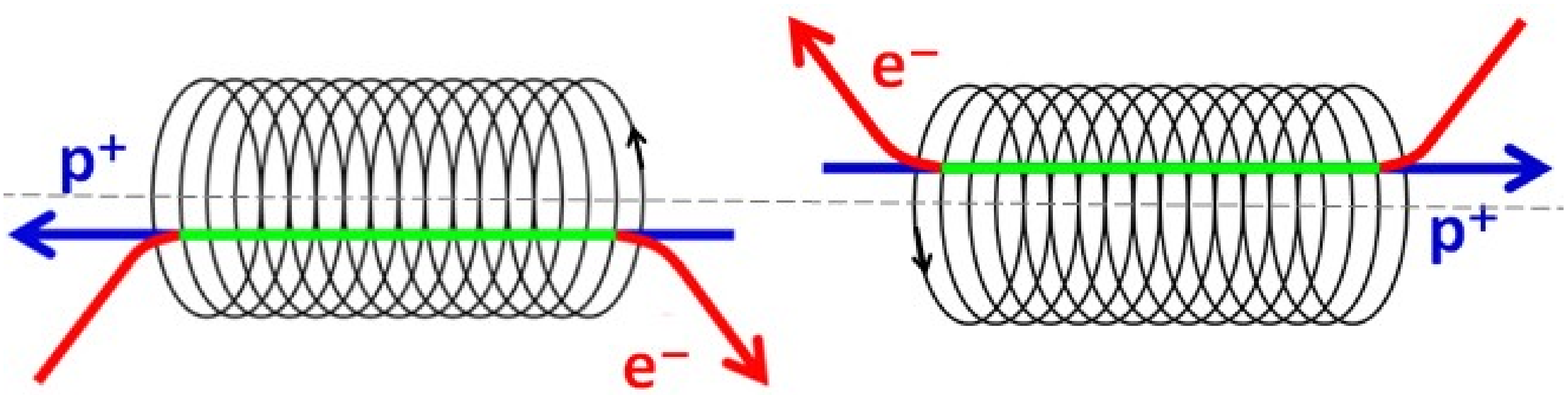
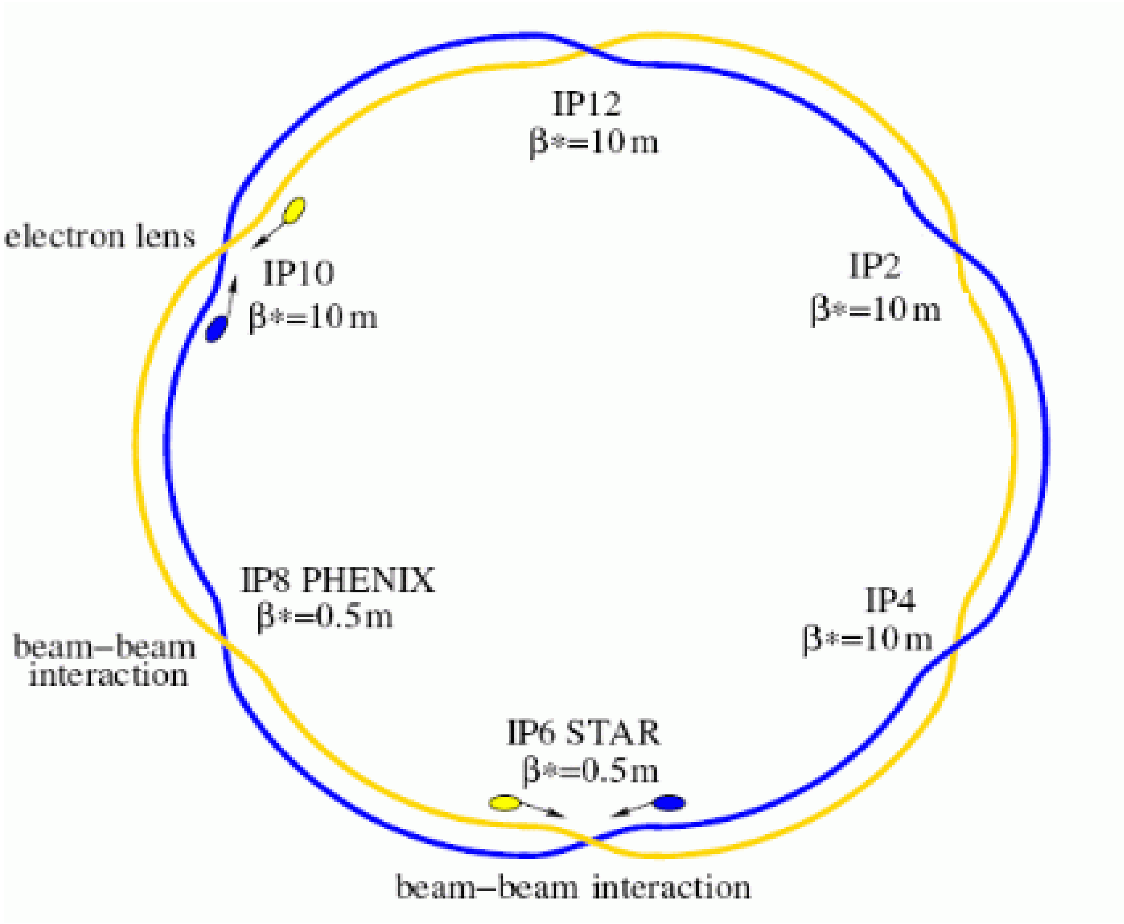


(US LARP CM13, Port Jefferson, NY, Nov. 4-6, 2009)

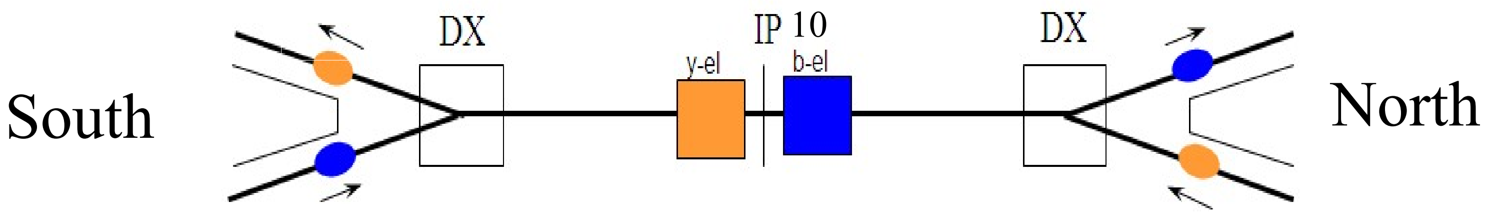
Head-on beam-beam compensation in the RHIC



Proton bunches collide at IP6 and IP8 with beta*=0.5m.

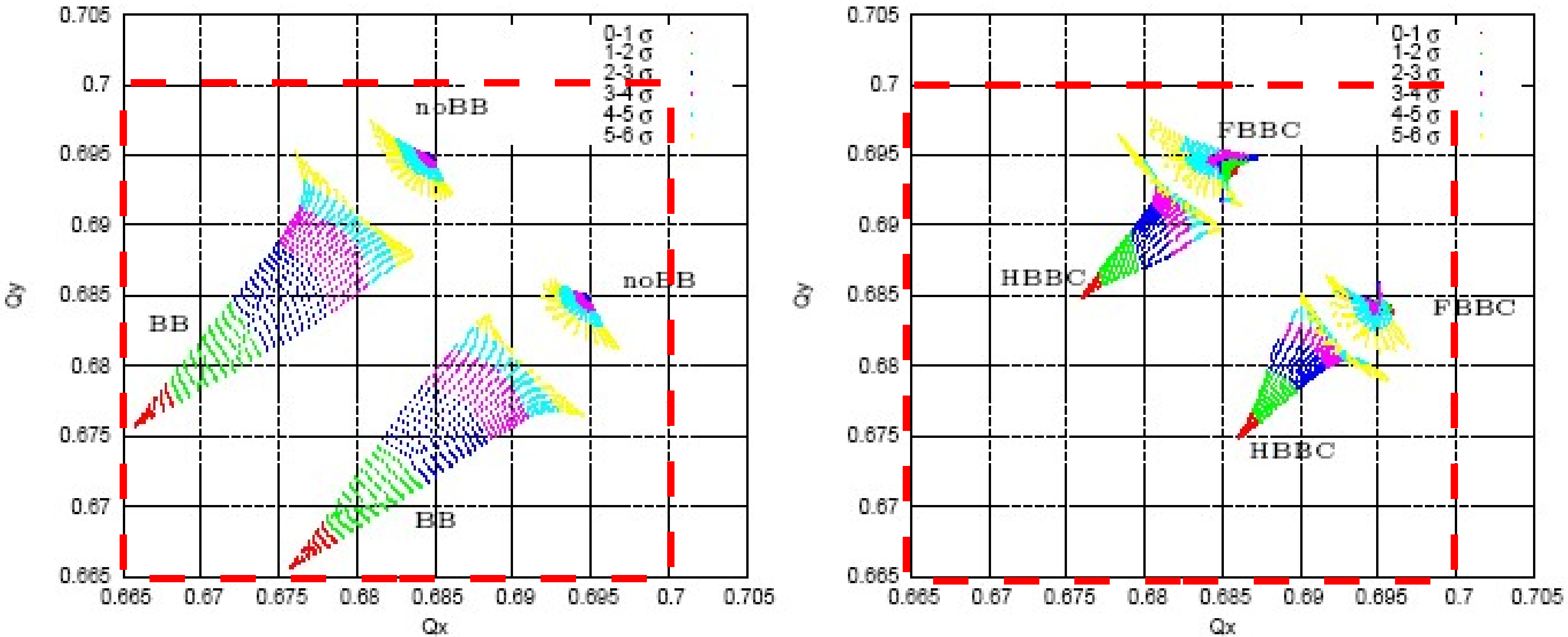
Electron-lenses (e-lens) are to be installed close to IP10 where beta=10m.

DC electron beam has the same Gaussian transverse profile as the proton beam.



[Y. Luo and W. Fischer, "Outline of using an electron lens for the RHIC …", BNL C-AD/AP/284 (2007)]

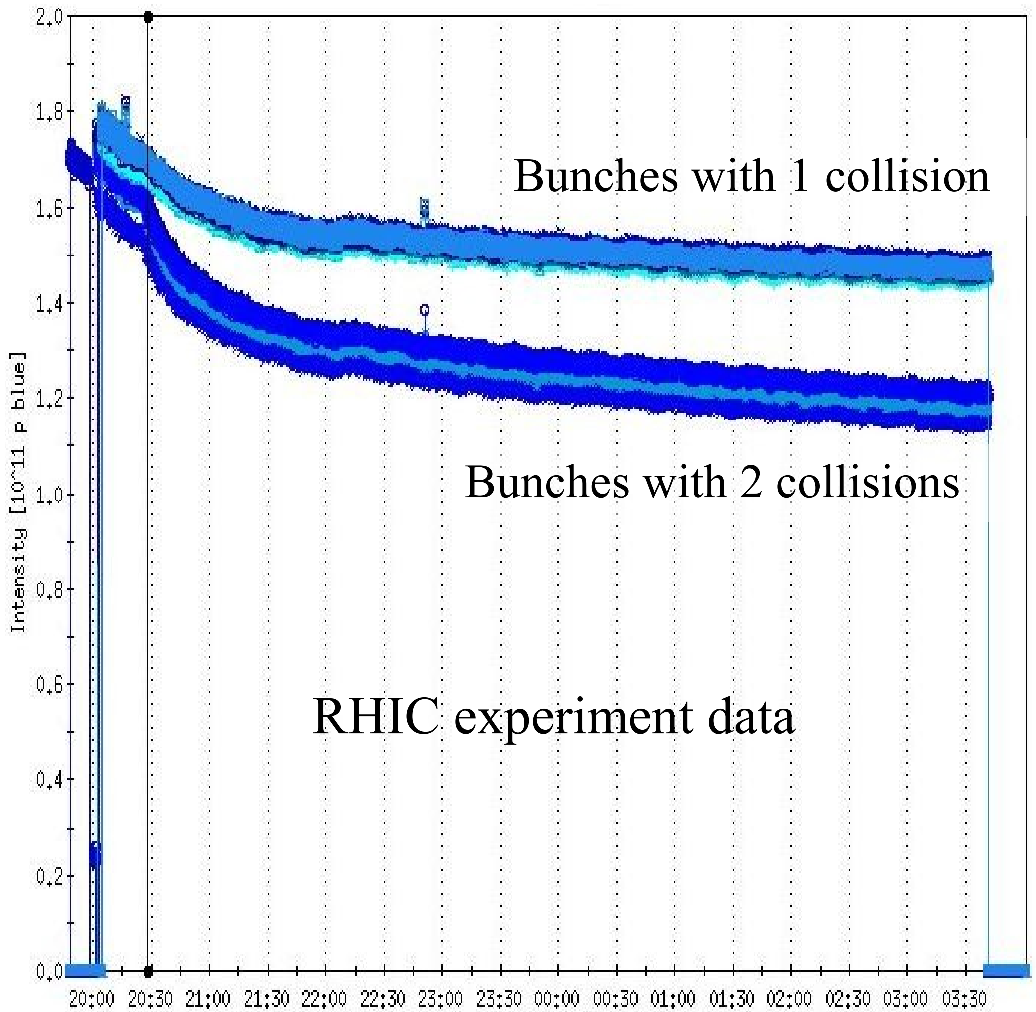
HOBBC effectively reduces the tune footprint



Motivation of HOBBC:
The working point of the polarized proton run in the RHIC is constrained between [2/3, 7/10]. HOBBC effectively reduce the footprint and gives the possibility to increase bunch intensity and therefore the luminosity.

[Y. Luo, W. Fischer, and N. Abreu, “Stability of single particle motion with head-on beam-beam compensation in the RHIC”, BNL C-AD/AP/310 (2008).]

HOBBC and the RHIC luminosity increase



If 1 of 2 collisions can be compensated then bunch intensity can be doubled with same beam-beam parameter.

This would yield theoretically a factor 4 , expect in practice about a factor 2, of luminosity increase.

Increase of bunch intensity requires

1) Upgrade of the polarized proton source. Approximately 3-year effort. Already started

2) Upgrades in RHIC improvements to deal with larger stored energy, collimation, dump, and so on.

Courtesy of W. Fischer

RHIC electron lenses – funding and schedule

25 Jun 2009	Received $4M (including $1M for labor) through ARRA (American Recovery and Reinvestment Act of 2009)
Aug 2009	Solenoids including power supply ready to order
Jan 2010	Gun and collector ready to order
Feb 2010	Beam transport system ready to order
May 2010	Diagnostics ready to order
Nov 2010	Solenoid acceptance test
Mar 2011	Control system specified
Jun 2011	Begin tunnel installation
Dec 2011	Tunnel installation complete

So far: hired 1 electrical engineer, 1 post-doc position open.

Courtesy of W. Fischer

Physics & Simulation study of HOBBC in the RHIC

Luminosity increase with HOBBC

Dose HOBBC work ?
How much increase to luminosity ?

-> principle check (√)
-> stability of single particle motion (√)
-> multi-particle tracking, lifetime and emittance (√)
-> tolerance of noises and errors (will start)

Numeric simulation and code improvement

-> Realistic tracking lattice model (√)
-> Symplectic optics tracking with all nonlinearities (√)
-> 6-D BB treatment since beta* ~ bunch length (√)
-> Benchmark the observed RHIC lifetime (going on)

Improvement to the RHIC tracking lattice model

We included following items into the tracking lattice model:

1) With BB and HOBBC
   bunch center tunes->(0.67, 0.68),
   first order chrom->(1,1)
2) Multipole errors in IR quads and bends
   big reduction to DA
3) Multipole errors in main arc dipoles and quads
4) Nonlinear corrections
   IR nonlinear,
   second order chromaticities,
   3Qx RDT
5) Residual closed orbit, rms ~ 0.3mm
6) Tune ripples (10 Hz)
7) Physical aperture
8) Artificial betatron phase shifters

Treatment of beam-beam interaction

6-D BB treatment already implemented in SixTrack

Not fully tested. So far LHC / RHIC DA studies used 4-D
Big difference in lifetime tracking between 4-D and 6-D

Then we wrote a stand-alone C++ functions of 6-D BB treatment

(thanks to Y-J., Kim)

-> bunch-marked 6-D BB kicks with BBSIM (√)
-> bunch-marked particle loss rate with BBSIM (√)
-> Compare the results with SixTrack 6-D BB (going on)
-> Including betatron coupling effect in BB treatment (going on)

Modeling of electron lens (√)

3-D strong-strong BB simulation (Ji Qiang)

Observables and Indicators with short term tracking

Advantage

Fast, taking less computing time especially in parameter scan

Analytical tools in short term tracking

Tune footprint / Frequency map / Lyapunov exponent
Action diffusion / Resonance driving terms / BTF

Dynamic aperture in long term tracking

10^6 turns in 5 phases angles in x-y plane
Doesn't give information about motion of low amplitude particle

Are they relevant to BB lifetime ?

Since they are not directly connected to the BB lifetime

Lifetime tracking with 10^4 macro-particles

Simulation capacity

10^7 turns - > 2 mins. of real time
10^4 macro-particles
SixTrack is the fastest tracking code so far

Shortcoming

very time consuming
short-term tracking should be used before

Some Issues

-> Numeric and statistic errors
-> Generation of initial particle coordinates
    Gaussian distribution ,
    Hollow Gaussian distribution
-> Hard to detect emittance change even in 10^7 turns

Latest dynamic aperture calculation

job_ID	Np	BB conditions	BB treatment	delatp	15	30	45	60	75	minimum
24	2.0e11	IP6/8	4D	0.	6.3	6.1	6.5	6.5	7.9	6.1
25	2.5e11	IP6/8	4D	0.	7.9	6.3	6.3	7.1	7.3	6.3
26	3.0e11	IP6/8	4D	0.	8.6	6.7	5.5	6.5	7.3	5.5
142	2.0e11	IP6/8/10	4D BB / 5 slice e-lens	0.	6.7	7.1	6.7	5.3	6.1	5.3
143	2.5e11	IP6/8/10	4D BB / 5 slice e-lens	0.	6.7	6.1	5.5	5.3	6.3	5.3
144	3.0e11	IP6/8/10	4D BB / 5 slice e-lens	0.	6.3	6.1	5.7	5.5	6.7	5.5
34	2.0e11	IP6/8	4D	0.0005	5.1	4.7	3.8	3.6	4.3	3.6
35	2.5e11	IP6/8	4D	0.0005	4.1	4.1	4.0	3.2	3.2	3.2
36	3.0e11	IP6/8	4D	0.0005	4.1	3.2	2.8	2.6	2.4	2.4
145	2.0e11	IP6/8/10	4D BB / 5 slice e-lens	0.0005	6.5	5.9	5.1	4.5	4.5	4.5
146	2.5e11	IP6/8/10	4D BB / 5 slice e-lens	0.0005	5.9	5.1	4.7	4.3	4.0	4.0
147	3.0e11	IP6/8/10	4D BB / 5 slice e-lens	0.0005	4.5	4.5	3.8	3.8	3.0	3.0
64	2.0e11	IP6/8	6D BB	0.	9.4	8.3	7.9	7.9	8.3	7.9
65	2.5e11	IP6/8	6D BB	0.	9.6	8.4	7.7	7.7	9.0	7.7
66	3.0e11	IP6/8	6D BB	0.	9.4	7.1	7.5	7.7	8.1	7.1
148	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.	7.1	7.5	6.3	6.7	6.1	6.1
149	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.	6.9	6.9	6.1	5.7	7.5	5.7
150	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.	9.4	6.5	6.3	6.1	7.1	6.1
74	2.0e11	IP6/8	6D BB	0.0005	6.7	6.5	6.3	5.7	4.9	4.9
75	2.5e11	IP6/8	6D BB	0.0005	5.5	4.7	4.7	3.6	4.1	3.6
76	3.0e11	IP6/8	6D BB	0.0005	4.9	4.0	3.0	3.0	4.1	3.0
151	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	6.7	5.9	5.3	5.1	4.3	4.3
152	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	6.5	5.9	5.1	5.1	4.5	4.5
153	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	5.7	5.1	4.5	4.3	4.3	4.3

Half compensation improves off-moment particle's dynamic aperture

The crucial task is to further improve the off-momentum DA.

Verify these activities with lifetime tracking.

DA with betatron phase shiftings between IP8 and E-lens

job_ID	Np	BB conditions	BB treatment	deltap	15	30	45	60	75	minimum
without phase shifts										
148	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0	7.1	7.5	6.3	6.7	6.1	6.1
149	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0	6.9	6.9	6.1	5.7	7.5	5.7
150	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0	9.4	6.5	6.3	6.1	7.1	6.1
151	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	6.7	5.9	5.3	5.1	4.3	4.3
152	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	6.5	5.9	5.1	5.1	4.5	4.5
153	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	5.7	5.1	4.5	4.3	4.3	4.3
with phase shifts , (9PI, 11PI) between IP8 and E-lens										
184	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0	6.7	6.9	6.5	6.7	6.1	6.1
185	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0	6.3	6.5	6.3	6.7	6.3	6.3
186	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0	5.9	5.9	5.9	6.3	6.7	5.9
187	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	6.7	6.7	6.1	5.3	5.1	5.1
188	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	6.1	6.1	6.3	5.1	4.7	4.7
189	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	6.3	5.7	5.7	4.5	4.7	4.5

No significant improvement in off-momentum DA.
The phase shifter was for on-momentum particles.
Will scan on-momentum phase offset from PI.
Will insert off-momentum betatron phase shifters.

DA in the the scan of momentum deviation

job_ID	Np	BB conditions	BB treatment	deltap	15	30	45	60	75	minimum
148	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0	7.1	7.5	6.3	6.7	6.1	6.1
154	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0001	7.1	6.9	6.3	5.5	5.9	5.5
155	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0002	6.9	6.7	6.1	5.1	5.5	5.1
156	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0003	6.7	6.5	5.5	5.3	4.9	4.9
157	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0004	6.7	6.1	5.5	5.5	4.7	4.7
151	2.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	6.7	5.9	5.3	5.1	4.3	4.3
149	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0	6.9	6.9	6.1	5.7	7.5	5.7
158	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0001	7.1	6.5	6.3	5.3	6.1	5.3
159	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0002	7.1	6.7	5.9	5.5	5.1	5.1
160	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0003	6.7	6.5	6.3	5.3	4.9	4.9
161	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0004	6.7	6.1	6.3	5.1	4.7	4.7
152	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	6.5	5.9	5.1	5.1	4.5	4.5
150	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0	9.4	6.5	6.3	6.1	7.1	6.1
162	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0001	6.7	6.1	5.9	4.9	6.5	4.9
163	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0002	6.3	6.5	5.5	4.7	4.5	4.5
164	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0003	5.9	5.3	4.9	5.5	4.7	4.7
165	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0004	6.3	5.3	4.5	4.5	4.3	4.3
153	3.0e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	5.7	5.1	4.5	4.3	4.3	4.3

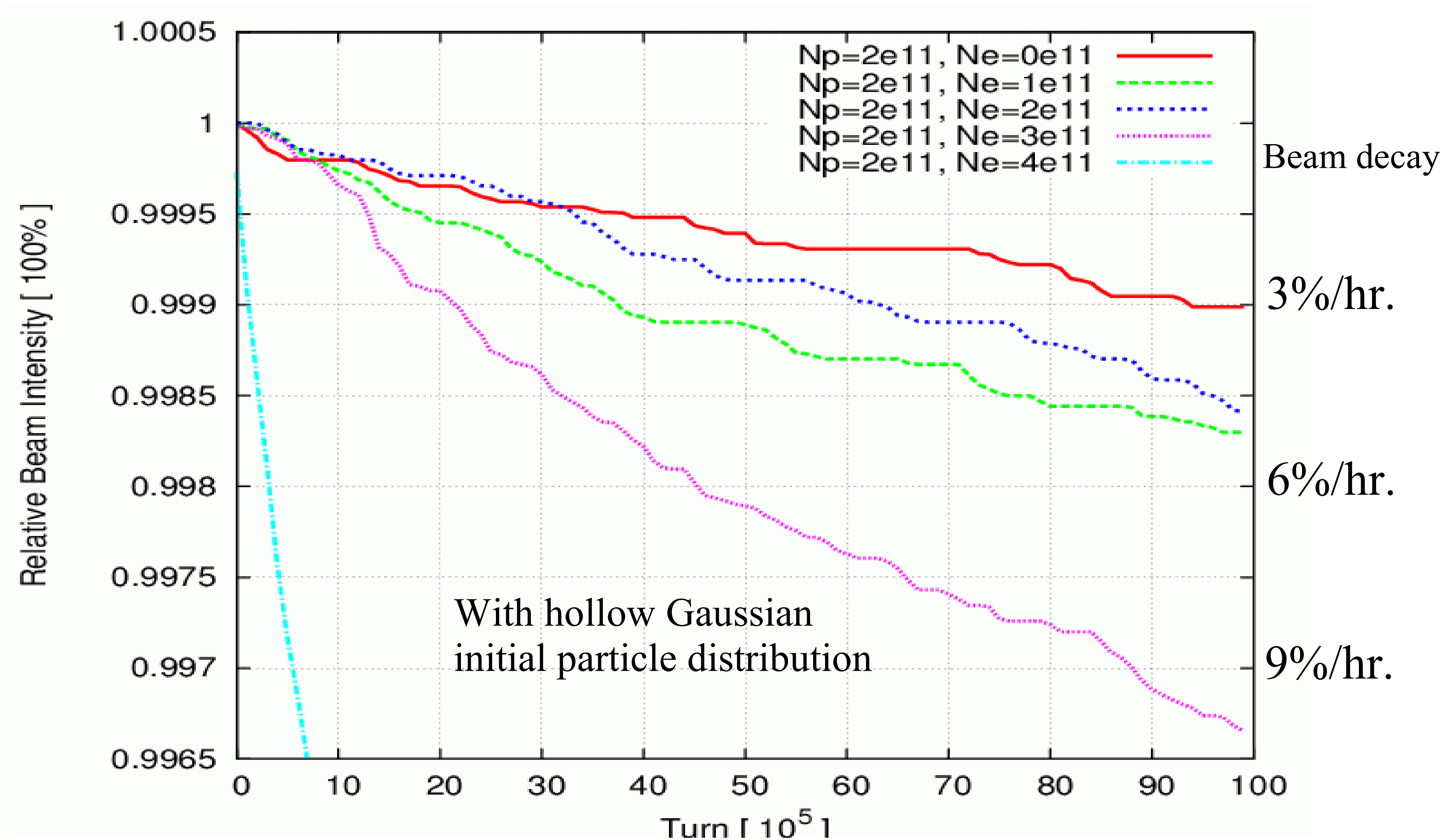
With HOBBC, reduction in the off-momentum DA is seen.

DA in the scan of the first order chromaticities

job_ID	Np	BB conditions	BB treatment	deltap	Q'	15	30	45	60	75	minimum
190	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	(4)	6.3	6.3	5.3	4.7	4.0	4.0
191	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	(3)	6.5	5.9	5.3	5.1	4.1	4.1
192	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	(2)	6.3	6.3	5.3	5.3	4.7	4.7
188	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	(1)	6.1	6.1	6.3	5.1	4.7	4.7
193	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	(0)	6.5	6.3	6.1	5.3	4.5	4.5
194	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	(-1)	6.7	6.3	6.1	5.7	5.9	5.7
195	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	(-2)	6.5	6.3	6.3	5.1	4.7	4.7
196	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	(-3)	6.3	6.7	5.7	5.5	4.5	4.5
197	2.5e11	IP6/8/10	6D BB / 5 slice e-lens	0.0005	(-4)	6.3	6.3	5.7	5.7	4.1	4.1

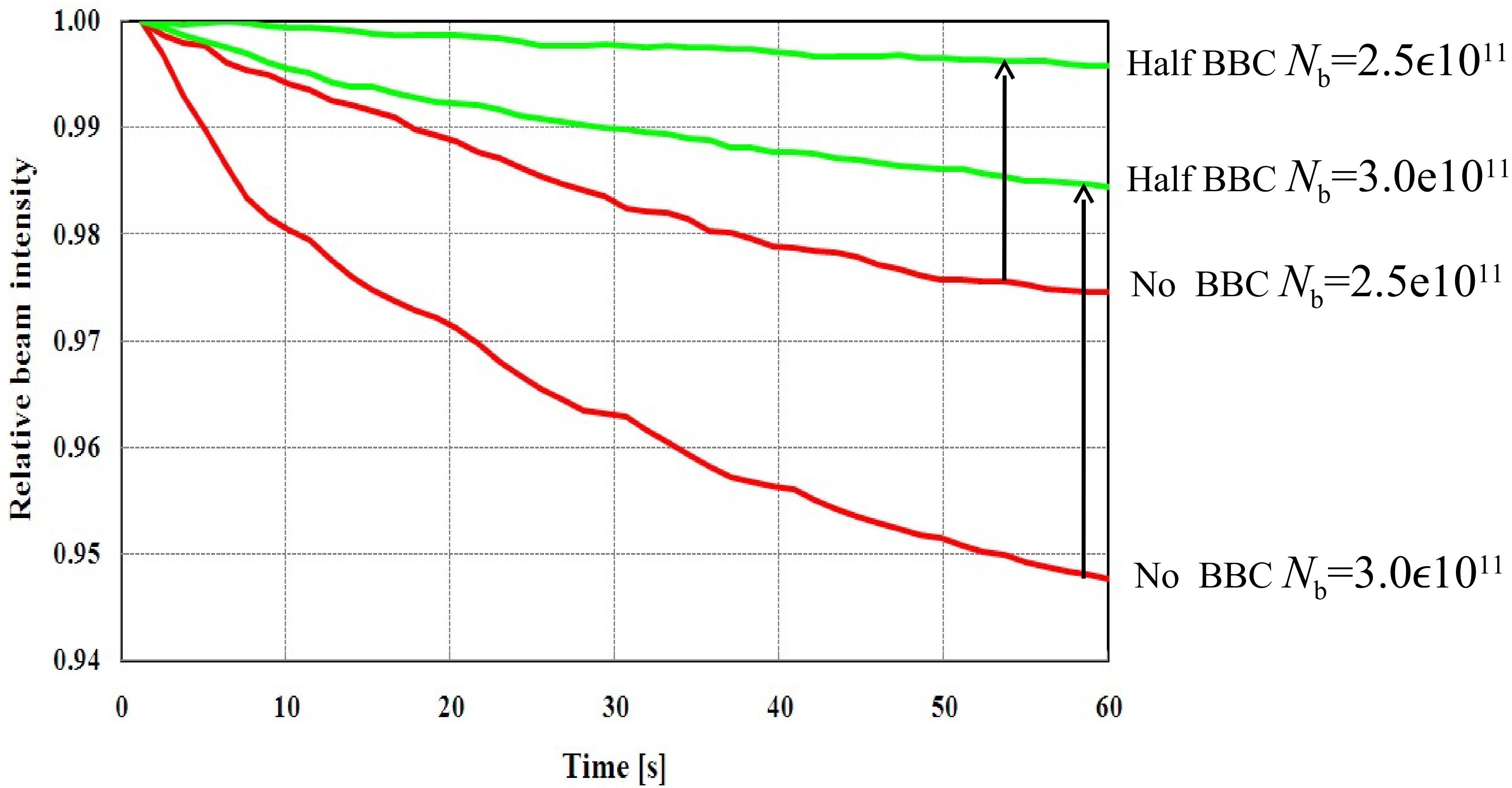
Q'=-1 gives the largest minimum DA.
Will track with second order chromaticity correction.
Will optimize the section chromaticity between IP8 and E-lens.
To conclude if the phase advance matters or not.

Particle loss versus compensation strength



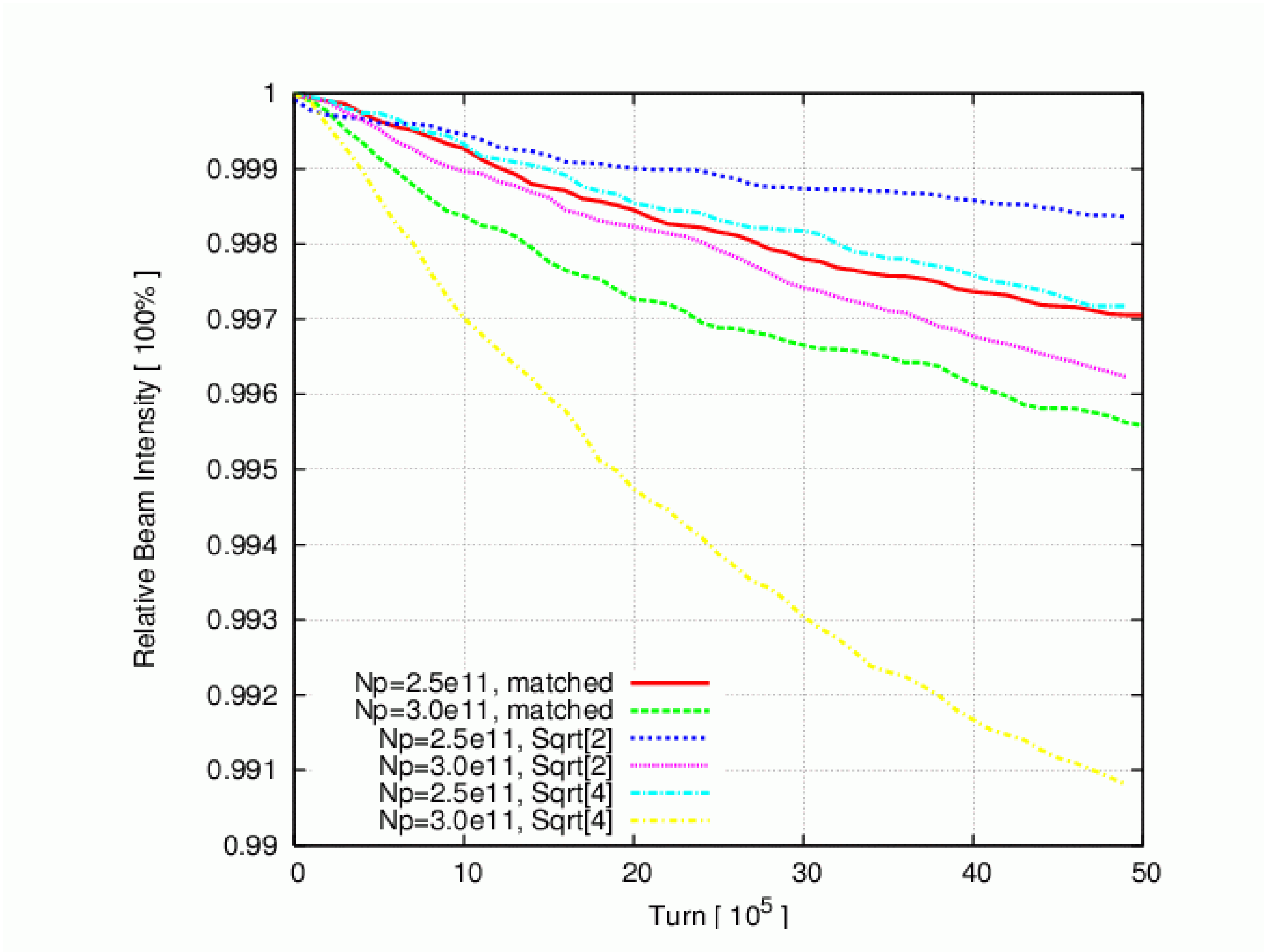
From simulation, more than half HOBBC is not recommended.

Particle loss with increase bunch intensities



HOBBC gives opportunity to increase bunch intensity above 2.0e11.
HOBBC does improve the BB lifetime.

Particle loss with unmatched electron beam sizes



Slightly enlarged electron beam size improves lifetime for Np=2.5e11 / 3.0e11.

Summary

- Previous simulation results show that the HOBBC improves the beam-beam lifetime with bunch intensity Np=2.5e11 and 3.0e11.

- Re-do lifetime calculation in the scan of parameters (such as tunes, phase shifts, compensation strengths, electron beam profile and so on) based on 6-D weak-strong BB treatment will be used.

- Will start simulations to check the tolerance of noises and errors (such as alignment, Gaussian tail cut-off, current vibration, 10 Hz tune modulation and so on) in the compensation.

- At the same time benchmark the simulated lifetime with the RHIC operation. Predicate BB lifetime of future RHIC operation. Answer how much luminosity increase HOBBC can yield.

- Further improve the 6-D BB treatment, such as including betatron coupling. Comparisons between different codes.