Long-range and head-on beam-beam compensation studies at RHIC with lessons for the LHC

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and collaborators from CERN and LARP

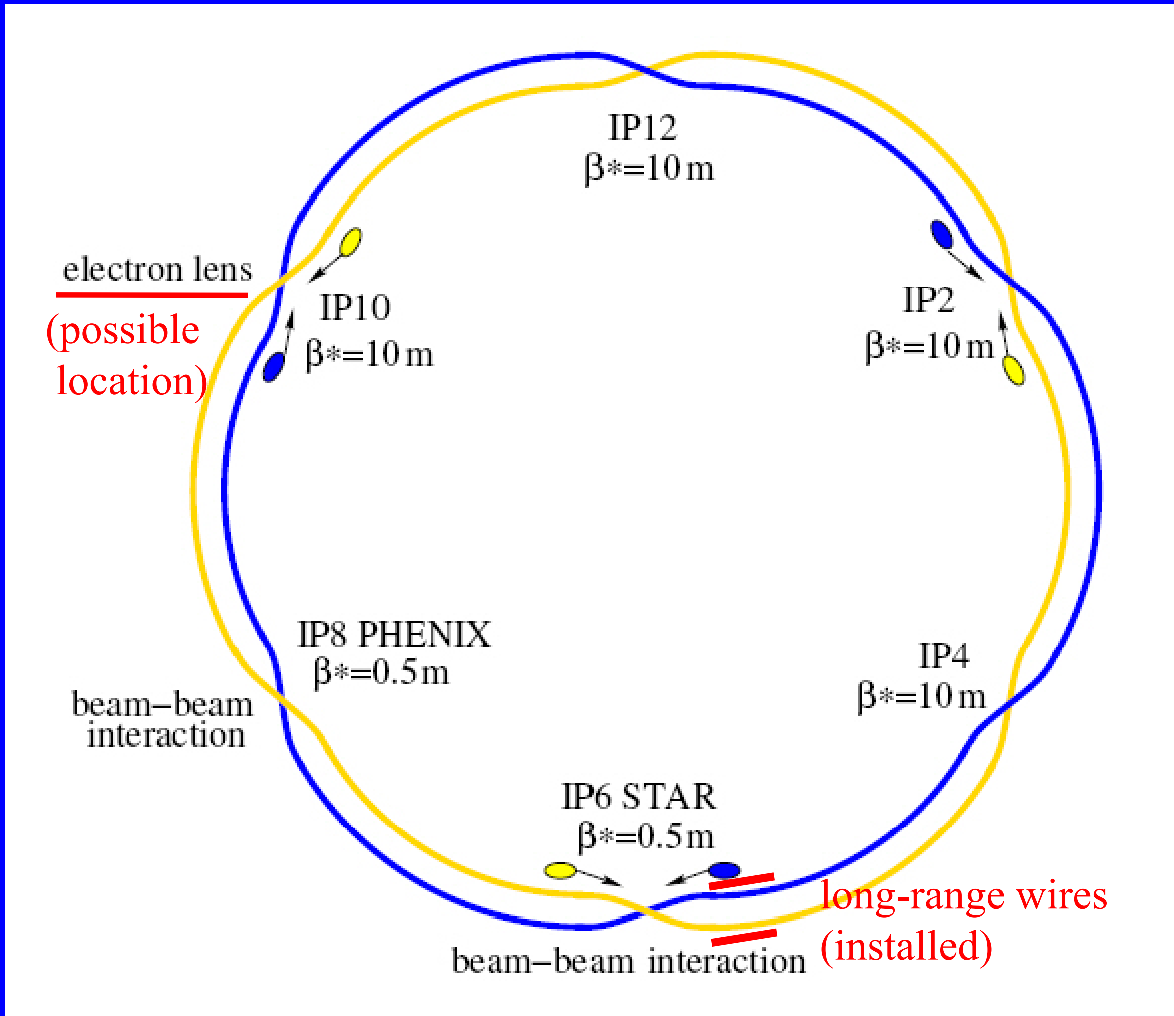
CARE-HHH Workshop 2008 – Scenarios for the LHC upgrade and FAIR
25 November 2008

Outline

1. Long-range beam-beam compensation (LRBBC) studies **(experimental work at RHIC)**

2. Head-on beam-beam compensation (HOBBC) studies at RHIC **(simulation work)**
   - For RHIC
   - For eRHIC (ring-ring)

RHIC beam-beam compensation devices



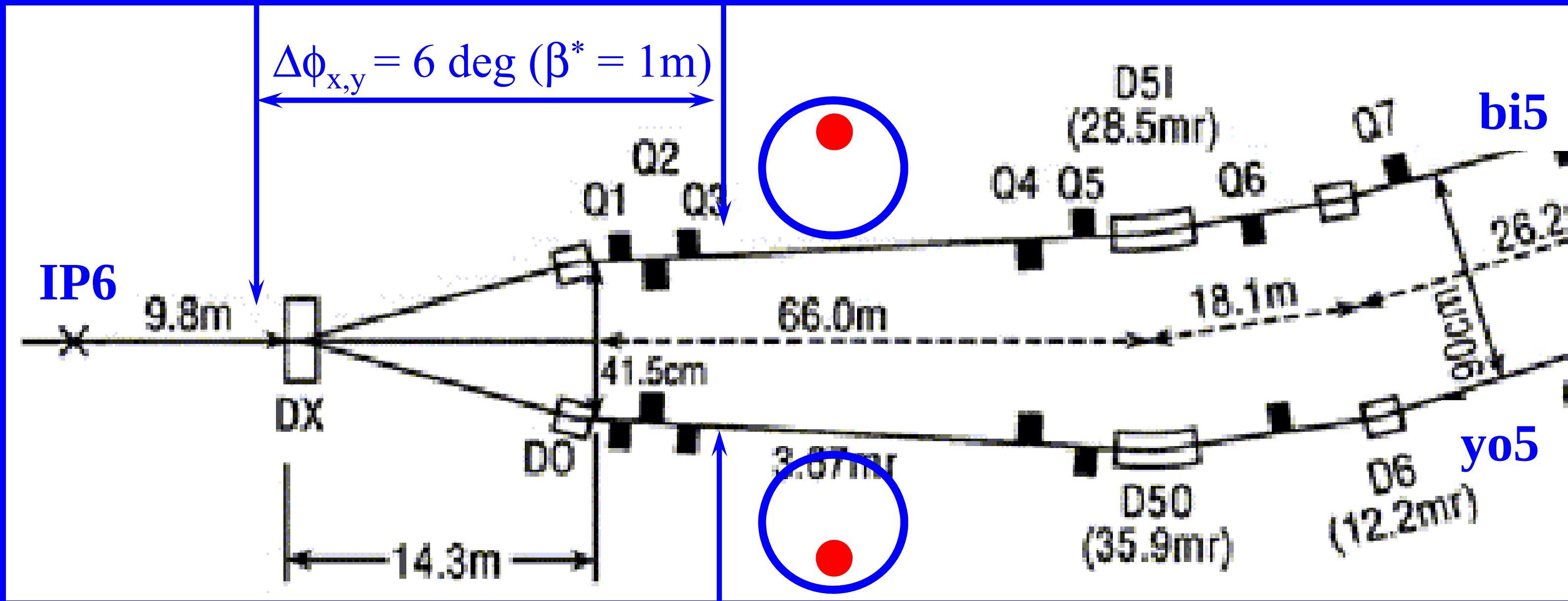
Nominally no long-range beam-beam interactions (dipole first IR).

Long-range beam-beam studies in RHIC

long-range interaction (vertical)

long-range compensation (up)

RHIC Sector 5

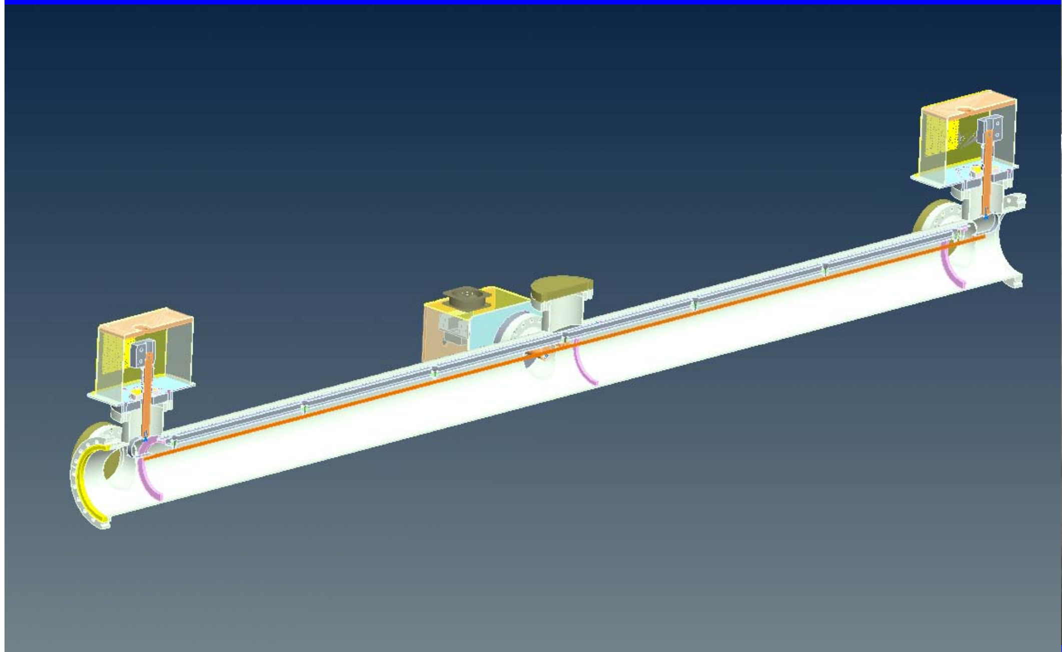


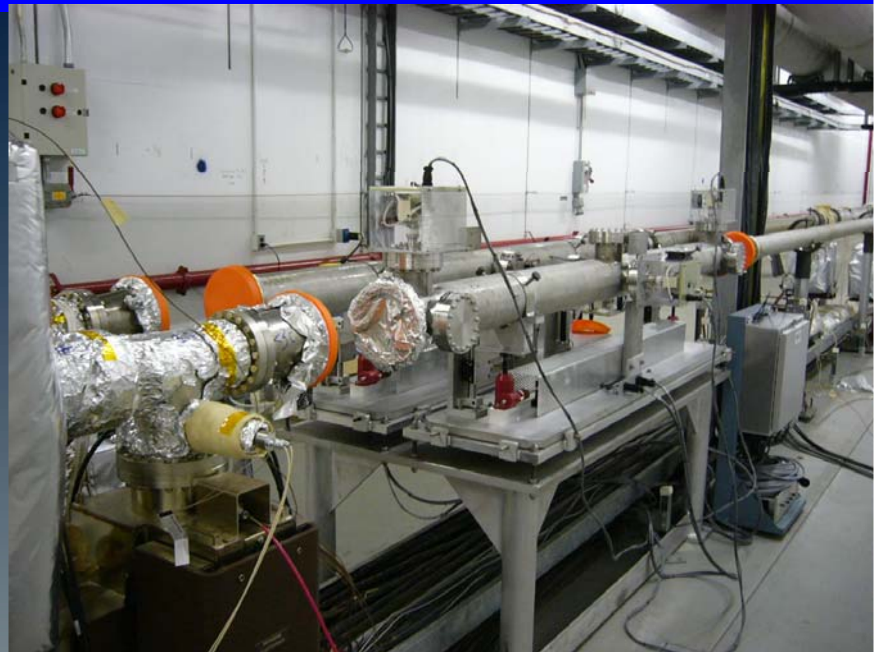
long-range compensation (down)

Small phase advance between long-range beam-beam interaction and possible compensator can only be realized at store.

Long-range experiments with wire

- Long-range beam-beam effects in RHIC only on ramp, possibly with upgrades
- 2 wires installed to study long-range effect
  (collaboration within U.S. LHC Accelerator Research Program)





Vertically movable wires, maximum integrated strength of 125Am (~13 LR interactions with $N_b=2\times10^{11}$).

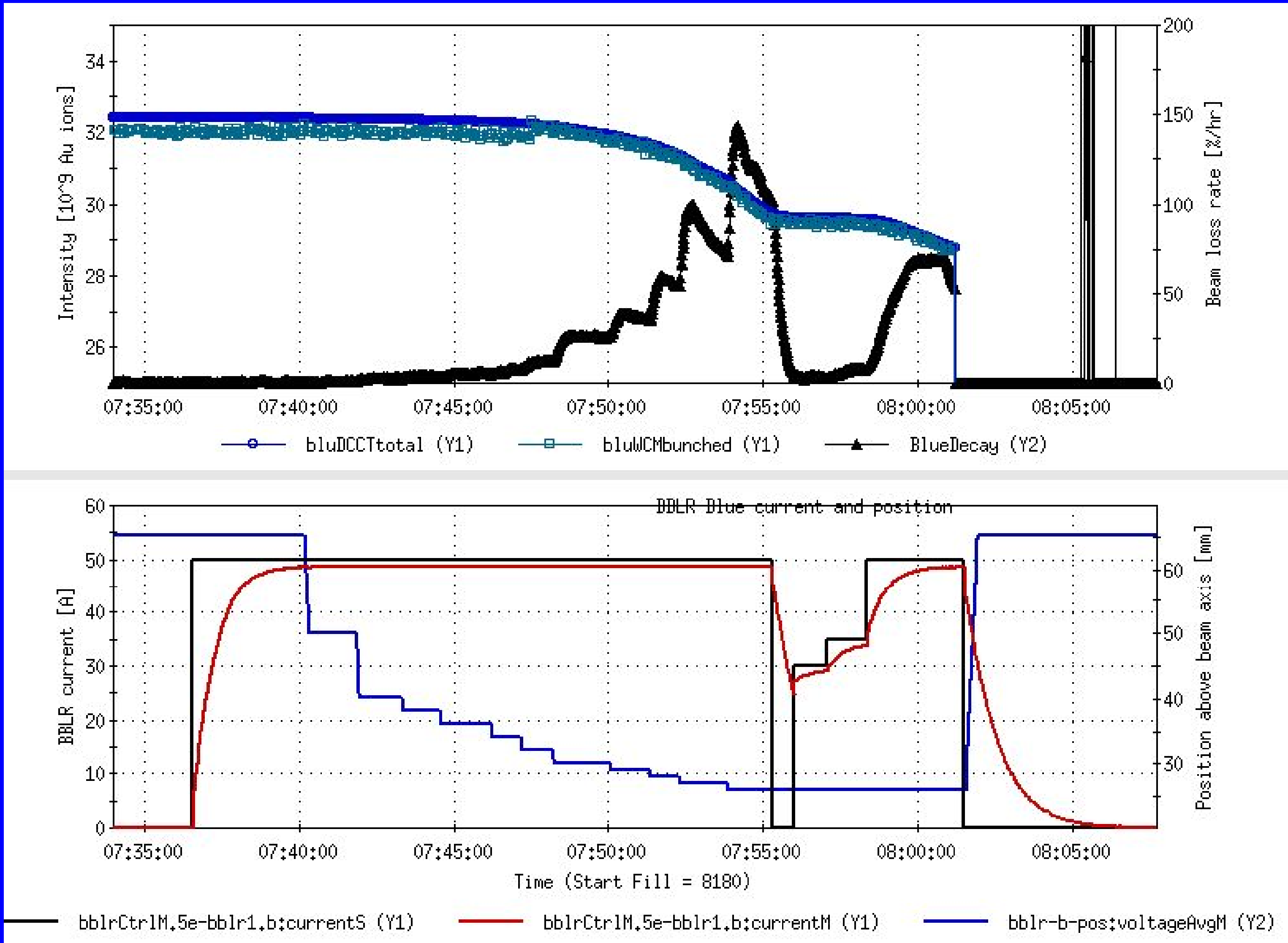
Long-range beam-beam experiments in RHIC

Measurements are beam lifetime observations with variations in

- separation
- strength (wire current)
- other parameters (tune, chromaticity)

- 2005: long-range with p-beam at injection
- 2006: long-range with p-beam at store
- 2007: long-range with Au-beam & wire at store
- 2008: only (parasitic) test d-beam & wire (short p-run)
- 2009: will likely have p-beam available (short p-run again)

Scan with d-beam in 2008 (01/28/08, fill 9664)



Long-range beam-beam studies at RHIC

Summary of long-range beam-beam measurements in RHIC

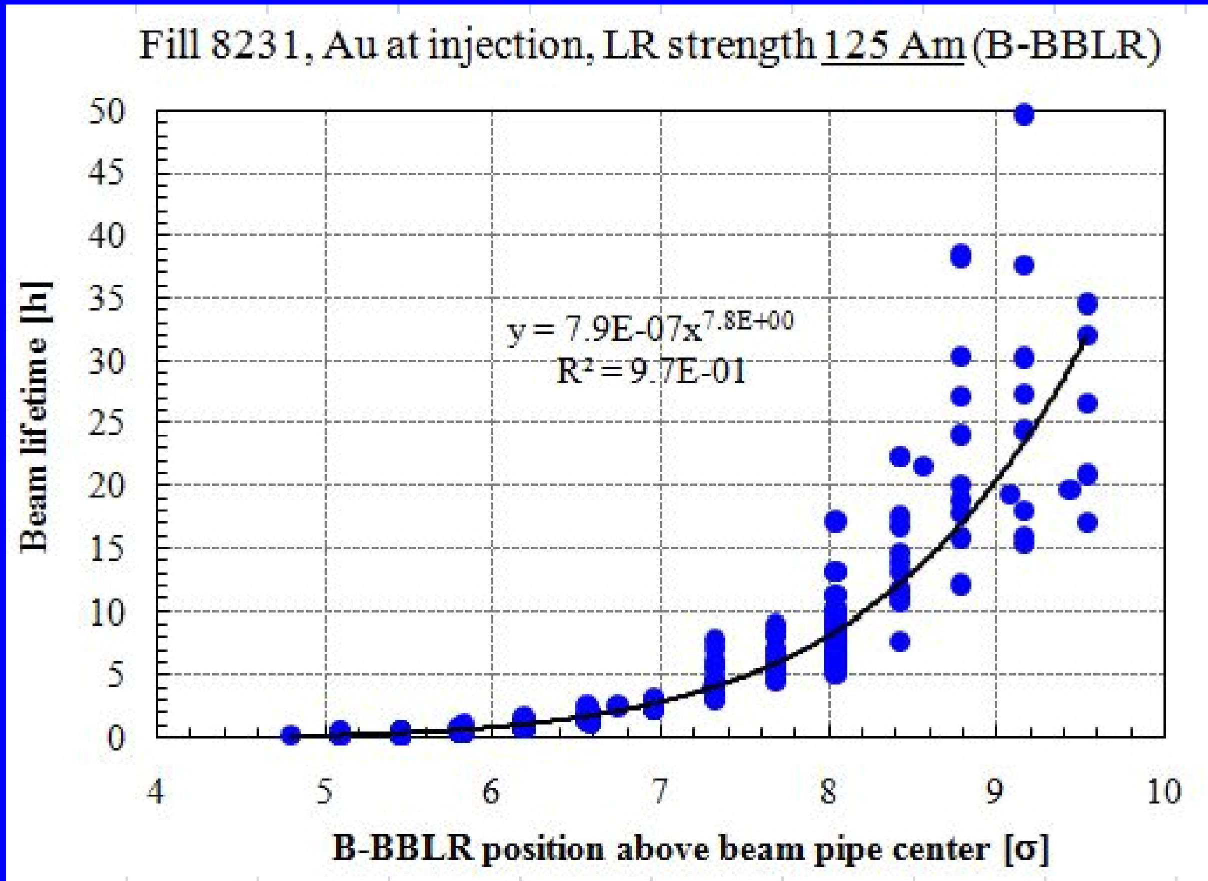
date	fillno	ring	scan	species	elativistic	no of bunches	Blue hor tune [...]	Blue ver tune [...]	Yellow hor tune [...]	Yellow ver tune [...]	LR lo[illegible]	LR strength [Am]	LR separation [mm]
04/28/05	6981	B & Y	1	p	25.963	1/ring	0.7331	0.7223	0.7267	0.7234	[illegible]	5.3	B beam position scanned
04/28/05	6981	B & Y	2	p	25.963	1/ring	0.7351	0.7223	0.7282	0.7233	IP4	5.8	B beam position scanned
04/28/05	6981	B & Y	3	p	25.963	1/ring	0.7383	0.7247	0.7271	[illegible]	IR4 DX	8.6	Y beam position scanned
04/28/05	6981	B & Y	4	p	25.963	1/ring	0.7394	0.7271	[illegible]	[illegible]	IR4 DX	8.9	Y beam position scanned
04/05/06	7707	B & Y	1	p	106.597	10/ring					IR6 DX (sector 5)	6.7	B beam position scanned
04/05/06	7707	B & Y	2	p	106.597	10/ring					IR6 DX (sector 5)	6.7	Y beam position scanned
04/12/06	7747	B & Y	1	p	106.597	8 B/10 Y					IR6 DX (sector 5)	7.9	B beam position scanned
04/12/06	7747	B & Y	2	p	106.597	8 B/10 Y					IR6 DX (sector 5)	7.0	Y beam position scanned
05/03/06	7807	B & Y	1	p	106.597	12/ring	[illegible]	[illegible]	[illegible]	0.6966	IR6 DX (sector 5)	8.2	Y beam position scanned
03/13/07	8231	B	1	Au	10.520	6	0.2327	[illegible]			B-BBLR	12.5	B-BBLR position scanned
03/13/07	8231	B	1	Au	10.520	[illegible]	[illegible]	[illegible]			B-BBLR	125.0	B-BBLR position scanned
03/27/07	8405	B	1	Au	107.369	[illegible]	[illegible]	0.2270			B-BBLR	125.0	B-BBLR position scanned
04/25/07	8609	B	1	Au	[illegible]	23	[illegible]	[illegible]			B-BBLR	12.5	B-BBLR position scanned
04/25/07	8609	B	2	Au	[illegible]	23	0.2340	[illegible]			B-BBLR	125.0	B-BBLR position scanned
04/25/07	8609	Y	1	[illegible]	[illegible]	[illegible]			0.2280	0.2350	Y-BBLR	12.5	Y-BBLR position scanned
04/24/07	8609	Y	2	[illegible]	[illegible]	23			0.2280	0.2350	Y-BBLR	125.0	Y-BBLR position scanned
05/09/07	8727	B	[illegible]	Au	[illegible]	23	0.2200	0.2320			B-BBLR	12.5	B-BBLR position scanned
05/09/07	8727	B	2	Au	[illegible]	[illegible]	0.2200	0.2320			B-BBLR	125.0	B-BBLR position scanned
05/09/07	8727	Y	1	[illegible]	107.369	23			0.2320	0.2280	Y-BBLR	12.5	Y-BBLR position scanned
05/09/07	8727	Y	2	[illegible]	[illegible]	23			0.2320	0.2280	Y-BBLR	125.0	Y-BBLR position scanned
05/09/07	8727	Y	3	Au	[illegible]	[illegible]			[illegible]	0.2280	Y-BBLR	125 - 0	-29
05/09/07	8727	Y	4	Au	107.369	[illegible]			[illegible]	[illegible]	Y-BBLR	125.0	-29
05/09/07	8727	Y	5	[illegible]	[illegible]	23			[illegible]	0.2280	Y-BBLR	125 - 0	-29
01/28/08	9664	B	1	d	[illegible]	12	0.2288	[illegible]			B-BBLR	125.0	B-BBLR position scanned
01/28/08	9664	B	2	d	[illegible]	[illegible]	[illegible]	[illegible]			B-BBLR	75 - 125	26

25 long-range measurements (scans)

- 2 strengths (12.5 and 125 Am)
- 3 species (p, Au, d)
- 2 energies
- 2 tune ranges
- chromaticity scan

RHIC long-range measurements

Beam lifetimes τ fitted to $\tau = A\, d^{\,p}$. Fitted exponents p varies from 1.5 to 16.

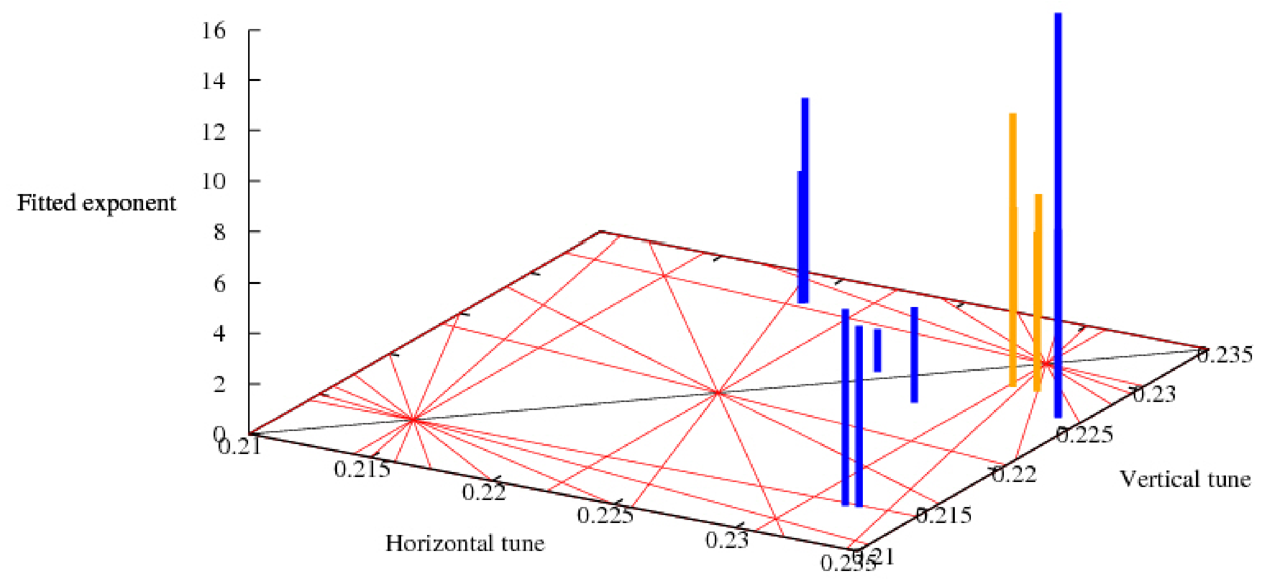


SPS found τ □ d^5 [measurement 11/09/04]

Tevatron found τ □ d^3 [reported in F. Zimmermann, LTC 11/24/04]

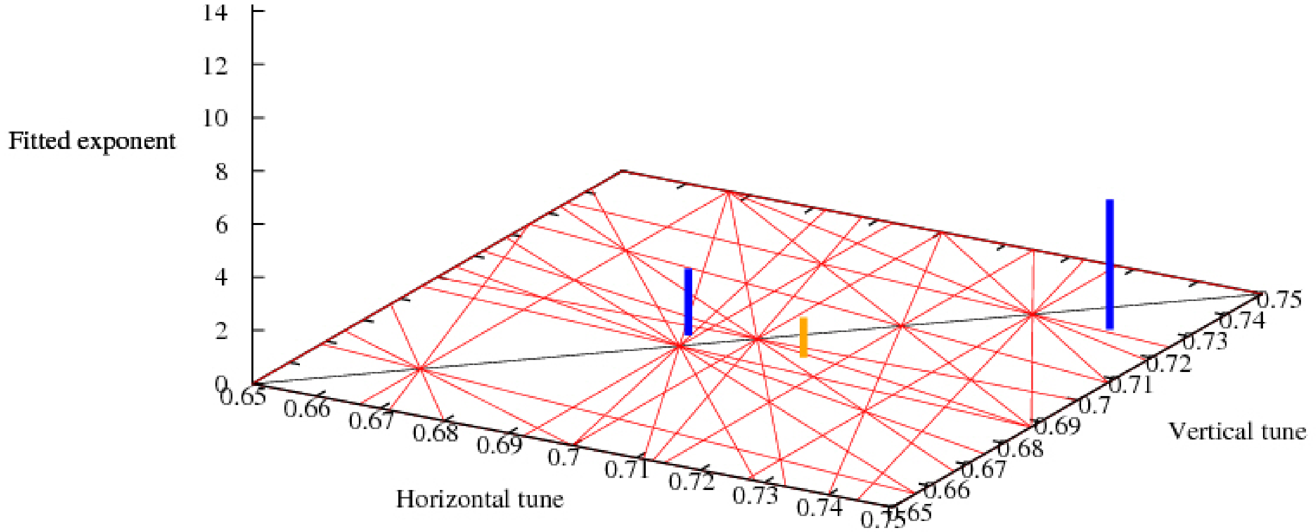
Long-range beam-beam studies at RHIC

Beam lifetimes τ fitted to $\tau = A\, d^{\,p}$. Fitted exponents p varies from 1.5 to 16.



← Tune range [0.21,0.235]
(heavy ions)

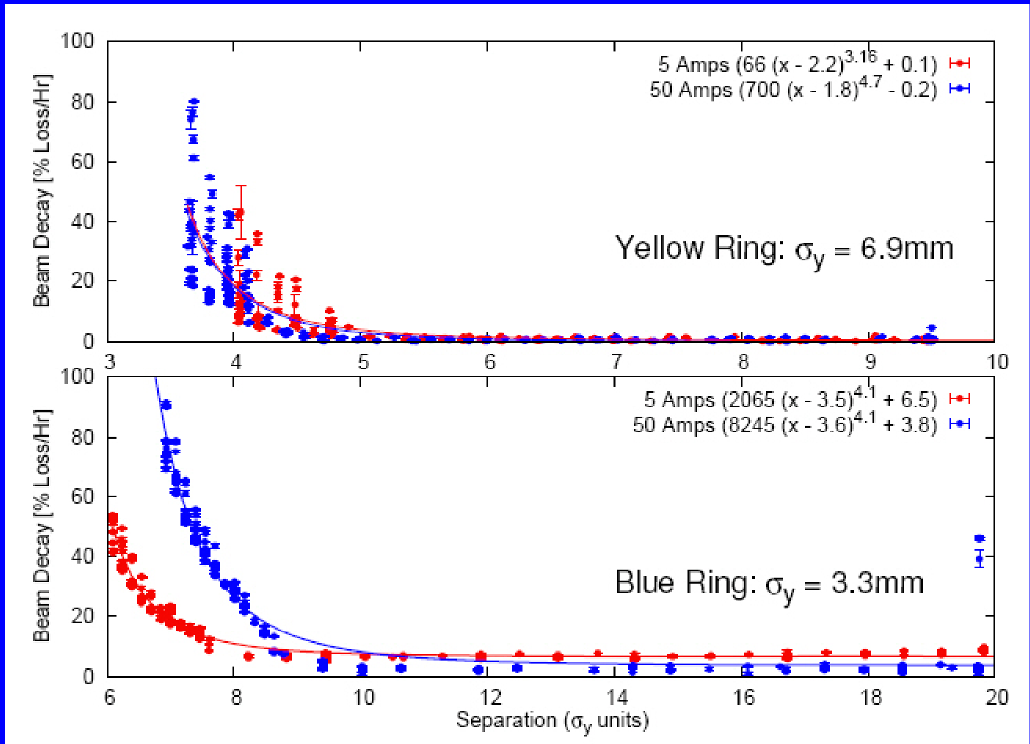
Tune range [0.65,0.75] →
(protons)

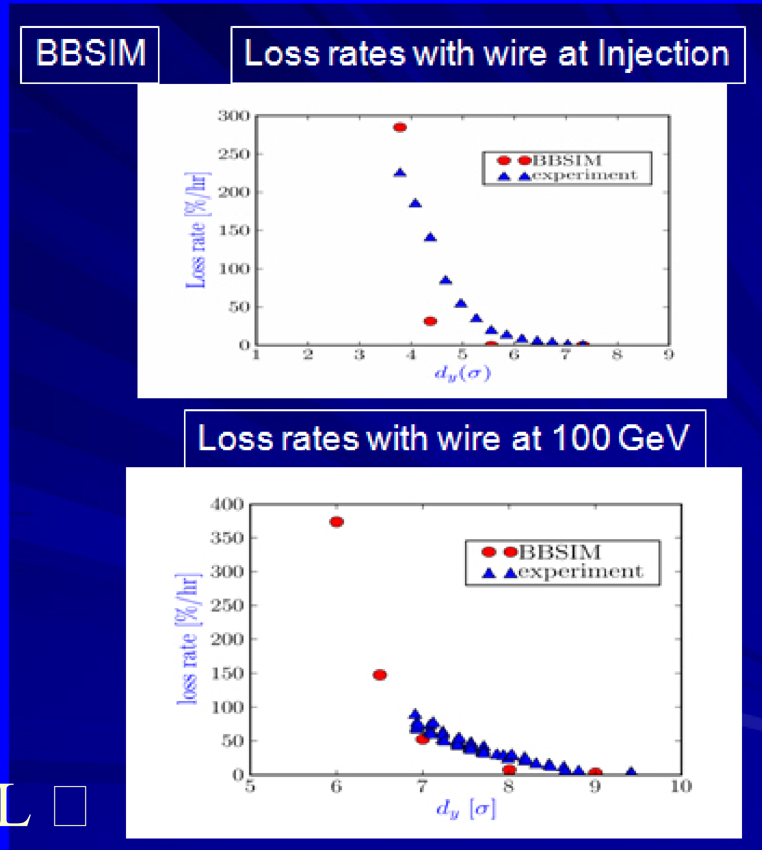


Wolfram Fischer

Long-range measurement and simulation

Experiments so far: distance, current and chromaticity scans with Au, for comparison with simulations



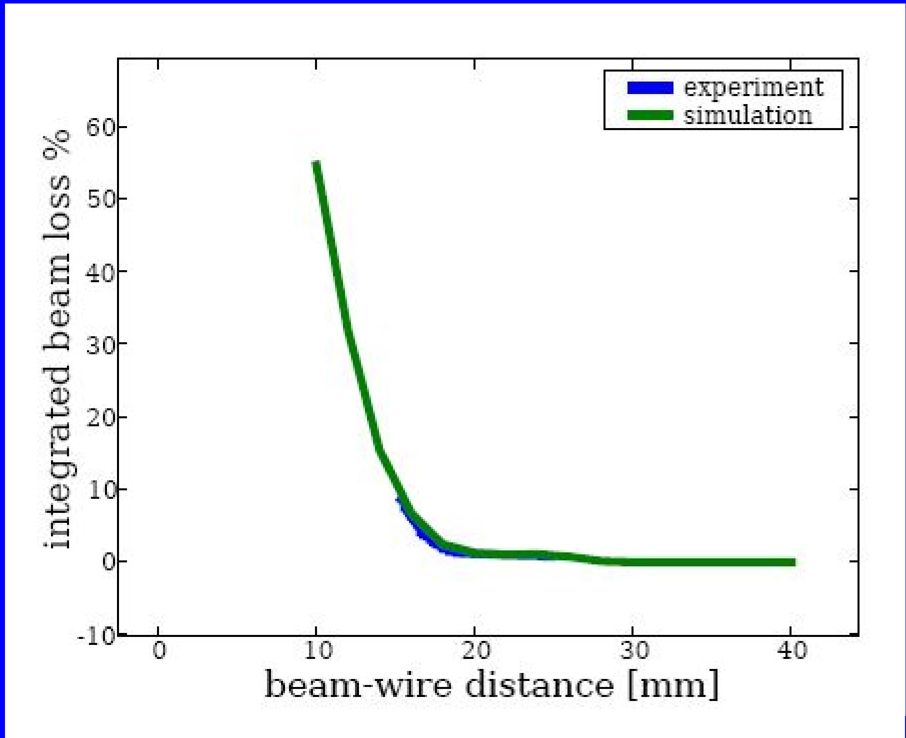


H.J. Kim, T. Sen, FNAL □

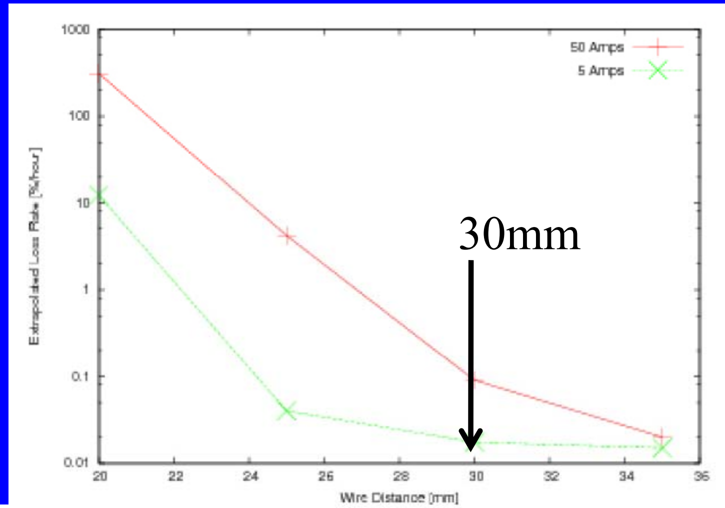
Onset of large losses reproduced within 1σ.

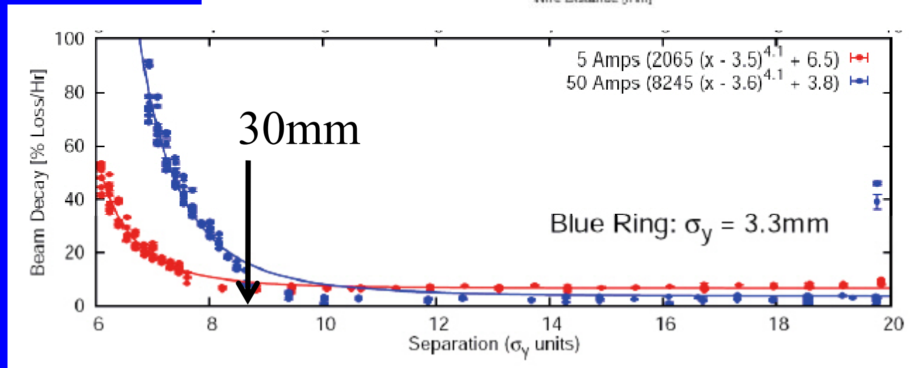
Long-range measurement and simulation

Simulation by U. Dorda for
Au beam with wire 12.5Am



Simulation by A. Kabel for
Au beam with wire 12.5 & 125Am

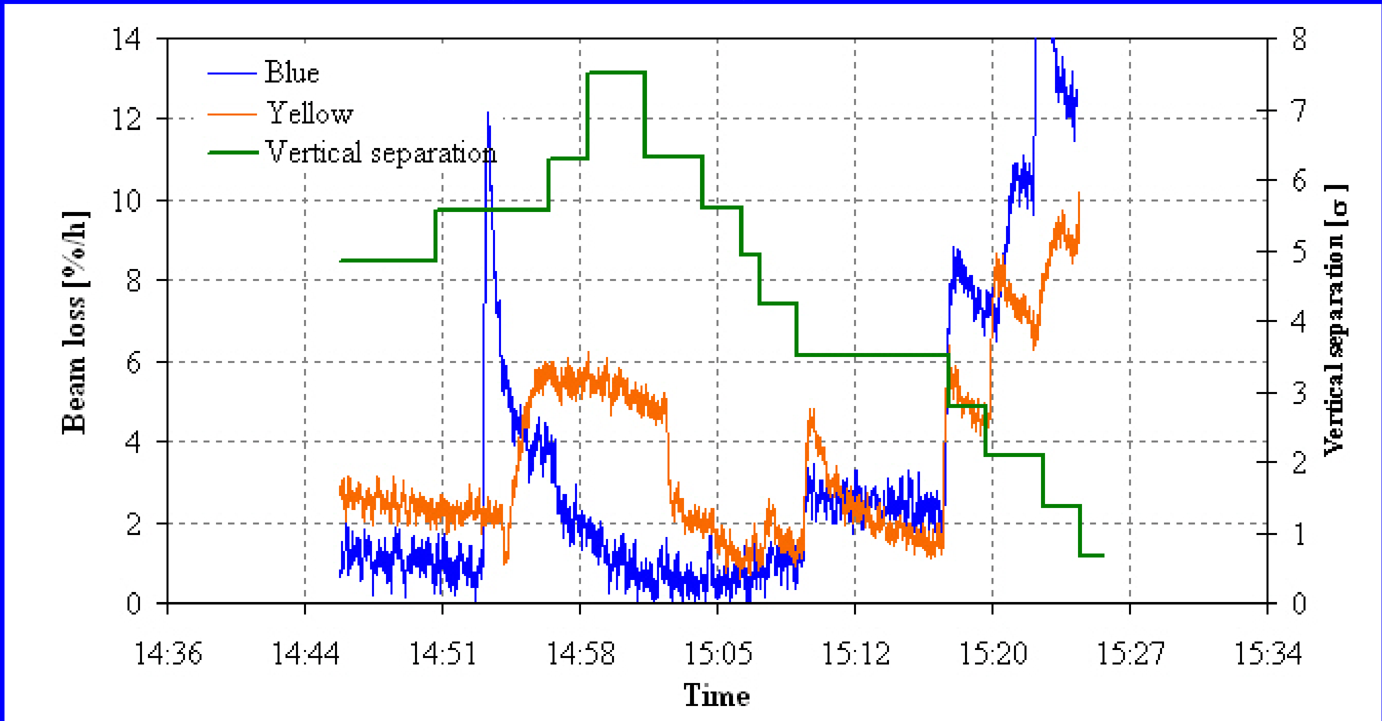




Onset of large losses reproduced within 1σ.

Minimum beam separation

Collision at s = 10.6 m, Yellow beam moved vertically (after 15:00)
Tunes B (0.739,0.727) Y (0.727,0.738)



Onset of losses from long-range interaction seen in experiments:

- at 4σ for single beam LR interaction (picture above)
- between 5-9σ with wire (strong dependence on WP and chromaticity)

[N. Abreu, "Beam-beam with a few long-range encounters at long distance", BEAM'07.]

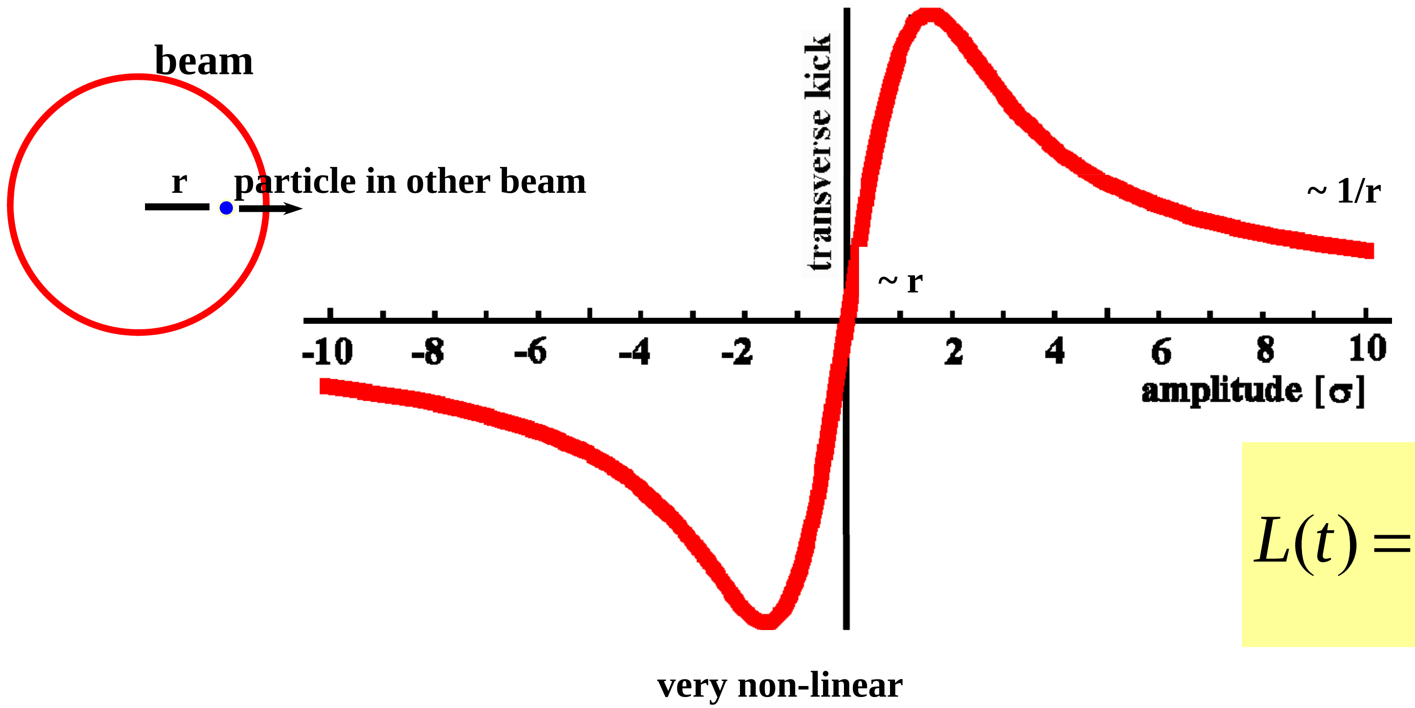
Planned test with RHIC BBLR wires in 2009

- Will ask for 3×3 hr dedicated time again
- Would like to test effect on background with protons too (semi-parasitic)
- Parameter scans (distance, strength) with protons
  - Including head-on
  - Different working points than for Au (LHC working point mirrored at 0.5)
- Attempt to compensate one long-range interaction

LRBBC studies at RHIC – lessons for the LHC

1. Strong long-range beam-beam effect confirmed with RHIC data
   (125 Am □ one side of one LHC IR, but beam rigidity is □ 30□ smaller)
2. Beam lifetime sensitive to tune chromaticity
   (can change lifetime by order of magnitude)
3. Distance with onset of large losses can be reproduced in simulations within 1σ
4. Distance smaller than 5σ appear problematic

Head-on beam-beam compensation (HOBBC)



$$L(t) = \frac{1}{4\pi} f_0 N \frac{n^2(t)}{\sigma_{rms}^2(t)}$$

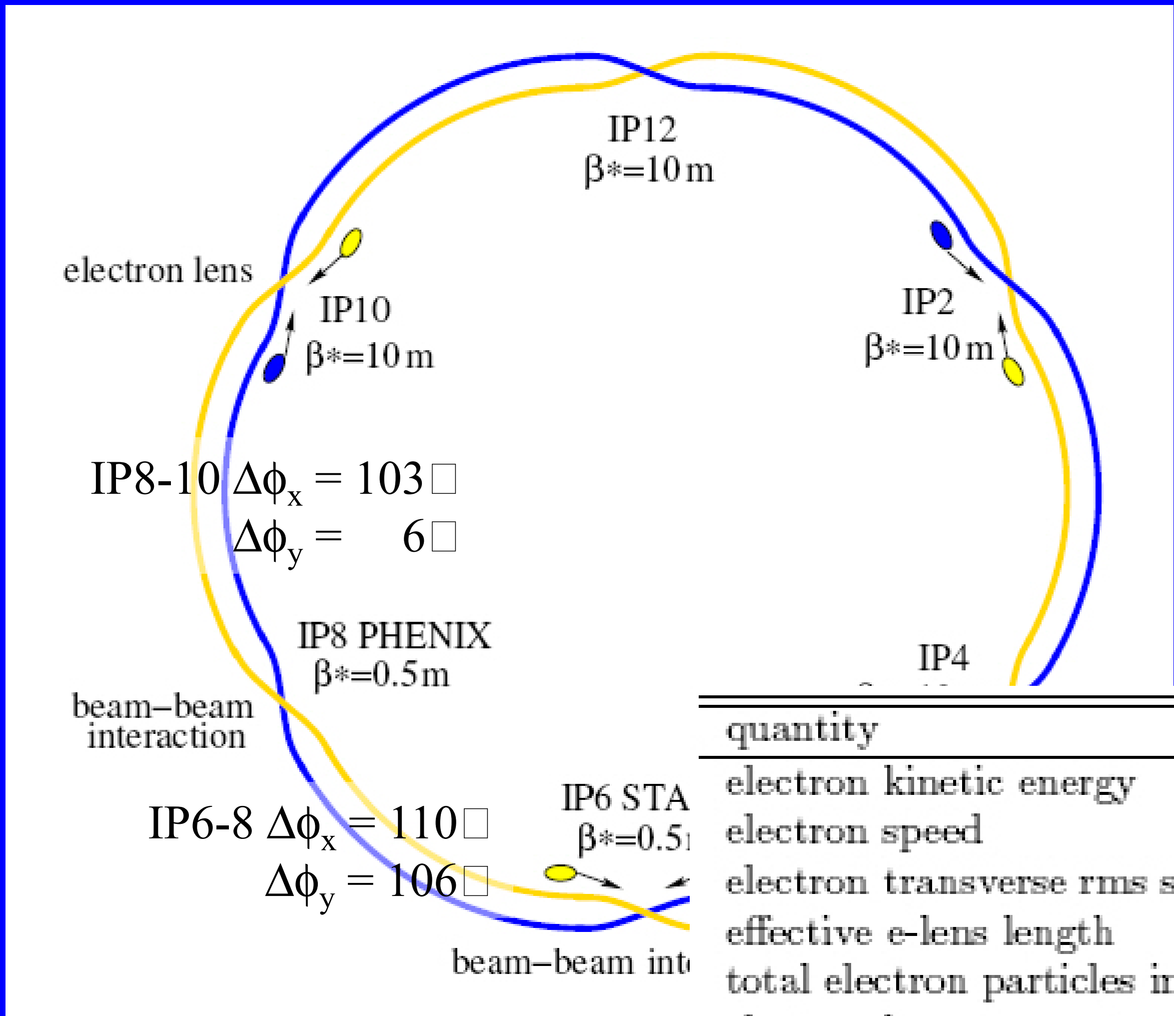
If beam-beam kick is followed by another kick

- **of same amplitude dependence** (e-lens)
- **with inverted sign** (e-lens)
- **multiples of π away and linear transport**

then beam-beam kick is canceled exactly.

Q1: How far can one deviate from ideal?
Q2: Can one reach these limits with the available technology?

HOBBC studies at RHIC

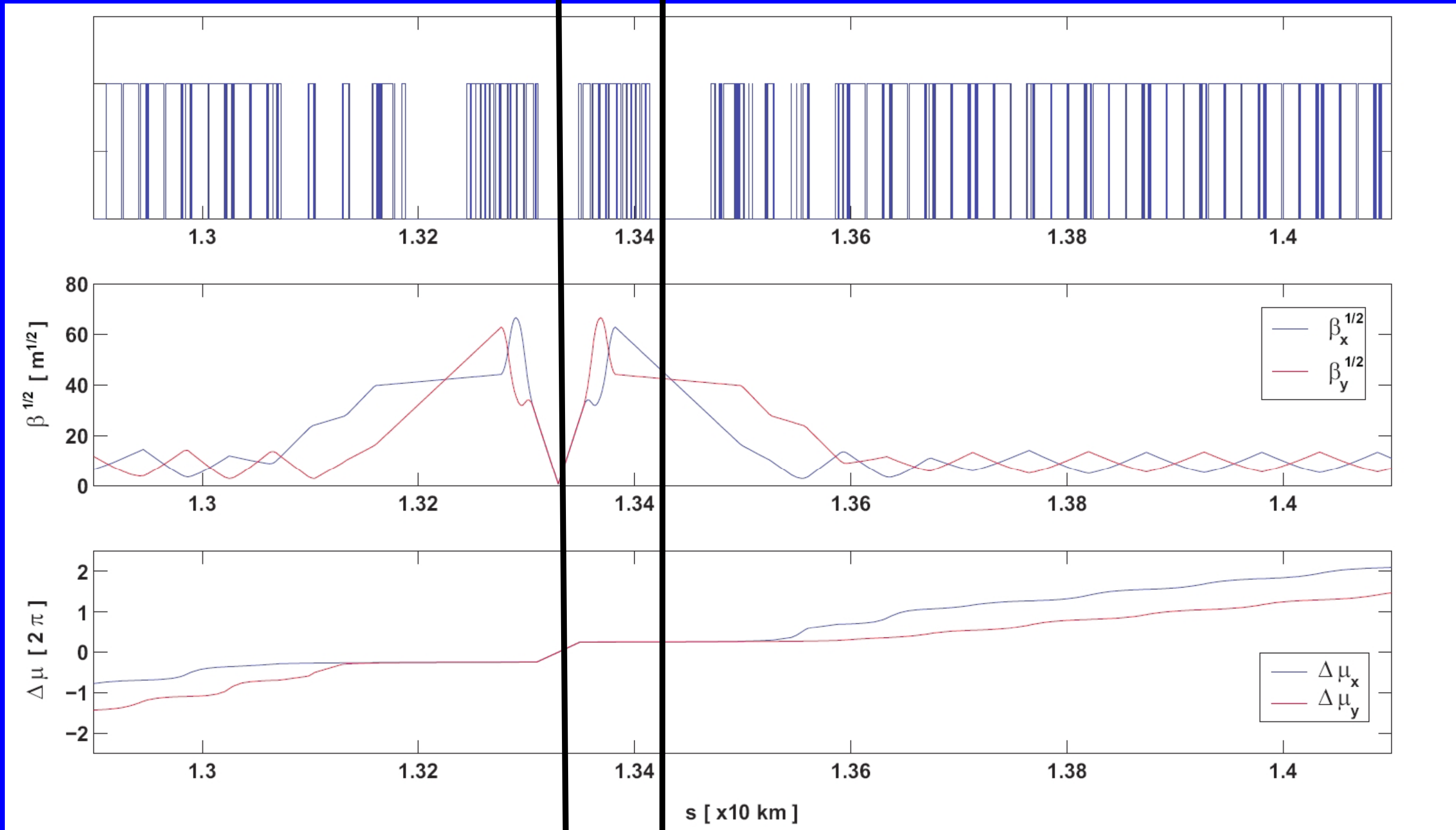


Electron lens parameters adapted from Tevatron

quantity	symbol	unit	value
electron kinetic energy	K_e	keV	5
electron speed	$\beta_e c$	...	0.14c
electron transverse rms size	σ_e	mm	0.433
effective e-lens length	L_{elens}	m	2.0
total electron particles in e-lens	N_e	-	3.5×10^{11}
electron beam current	I_e	A	1.2

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

Beam-beam compensators in LHC



IP

s = 13329 m

$\beta_x = 0.55$ m $\mu_x = 32.049$ [2π]

$\beta_y = 0.55$ m $\mu_y = 29.604$ [2π]

BBLR or e-lens

s = 13433 m

$\beta_x = 1925$ m $\mu_x = 32.303$ [2π]

$\beta_y = 1784$ m $\mu_y = 29.857$ [2π]

$\Delta\mu_x$ = 91□

$\Delta\mu_y$ = 91□

Electron lenses in Tevatron V. Shiltsev et al.

2 electron lenses in Tevatron:

Were proposed to compensate long-range and other effects

- Energy: 5-10 kV
- Length: 2 m
- Current: □ 3A

- Operationally used as gap cleaner (very reliable)
- Shown to increase beam lifetime (by factor 2) of pbar bunches affected by PACMAN effects (mostly tune shift)
- Not used as head-on compensators

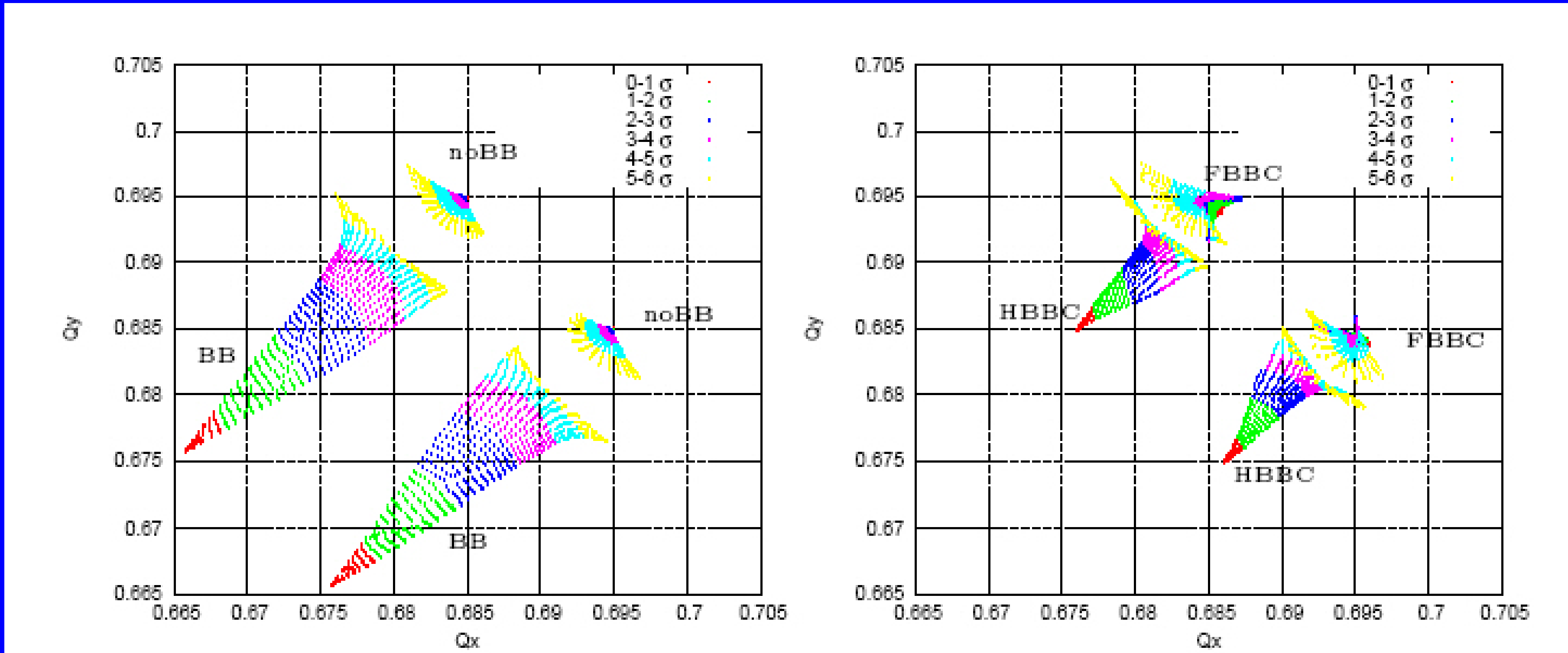
[V. Shiltsev et al., “Tevatron electron lenses: design and operation”, PRST-AB 11, 103501 (2008)]

HOBBC studies at RHIC

- Simulations:
  - Single particle (could be many)
  - Element-by-element tracking
  - Short-term (thousands of turns) and long-term (up to 10M turns)
- Tools:
  - SixTrack + post processing, other programs
- Lattice model:
  - Magnetic field errors in IR dipoles and quadrupoles
  - Weak-strong beam-beam effect (IPs and electron lens)
  - Tune ripple for long-term tracking

HOBBC studies at RHIC Y. Luo

E-lens compresses tune footprints

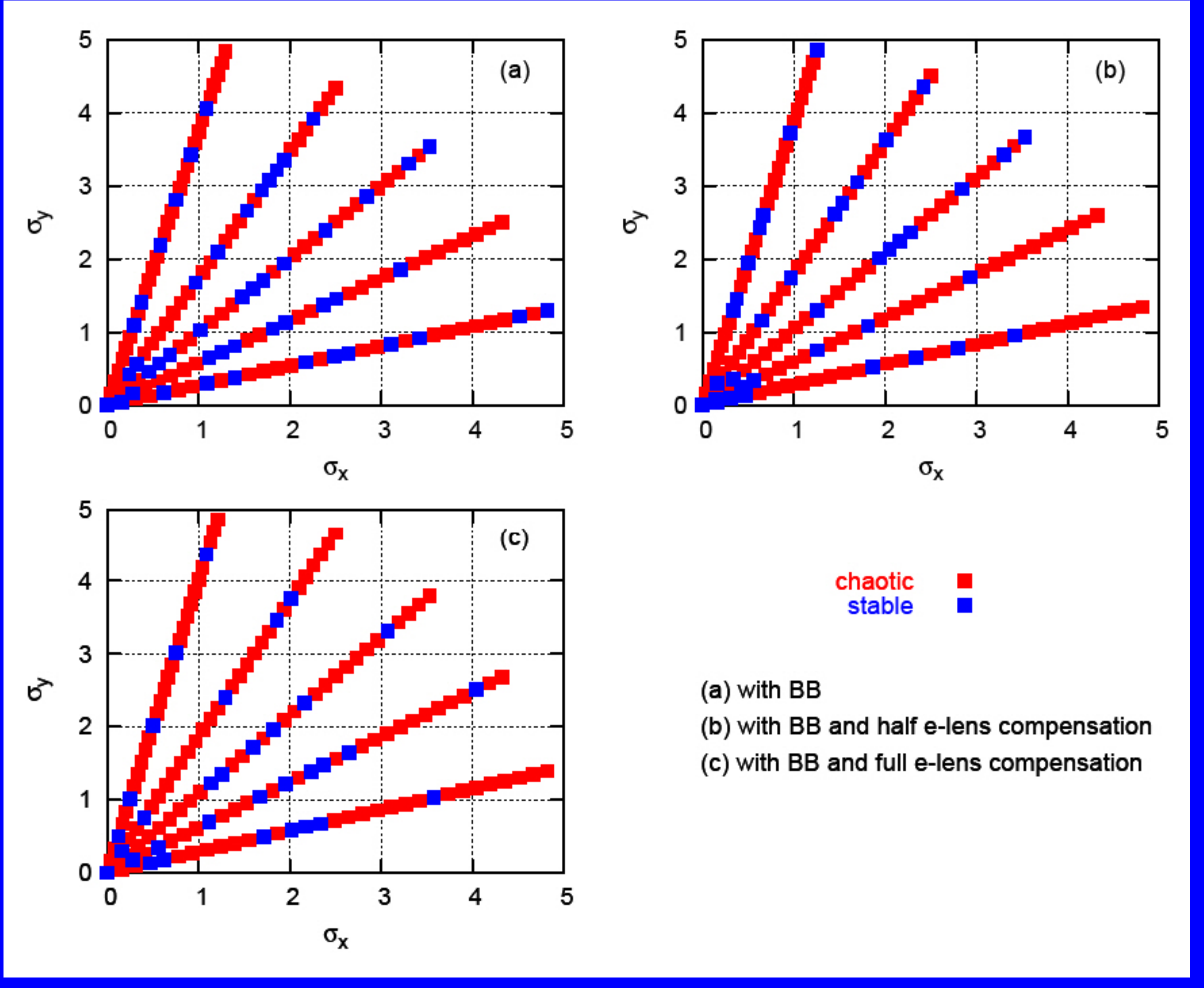


Tune footprint compression is not sufficient for better beam lifetime.

[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 studies at RHIC N. Abreu

Particle chaoticity evaluated with phase space distance of initially close particle pair after 10^6 turns (exponential divergence of chaotic particles)

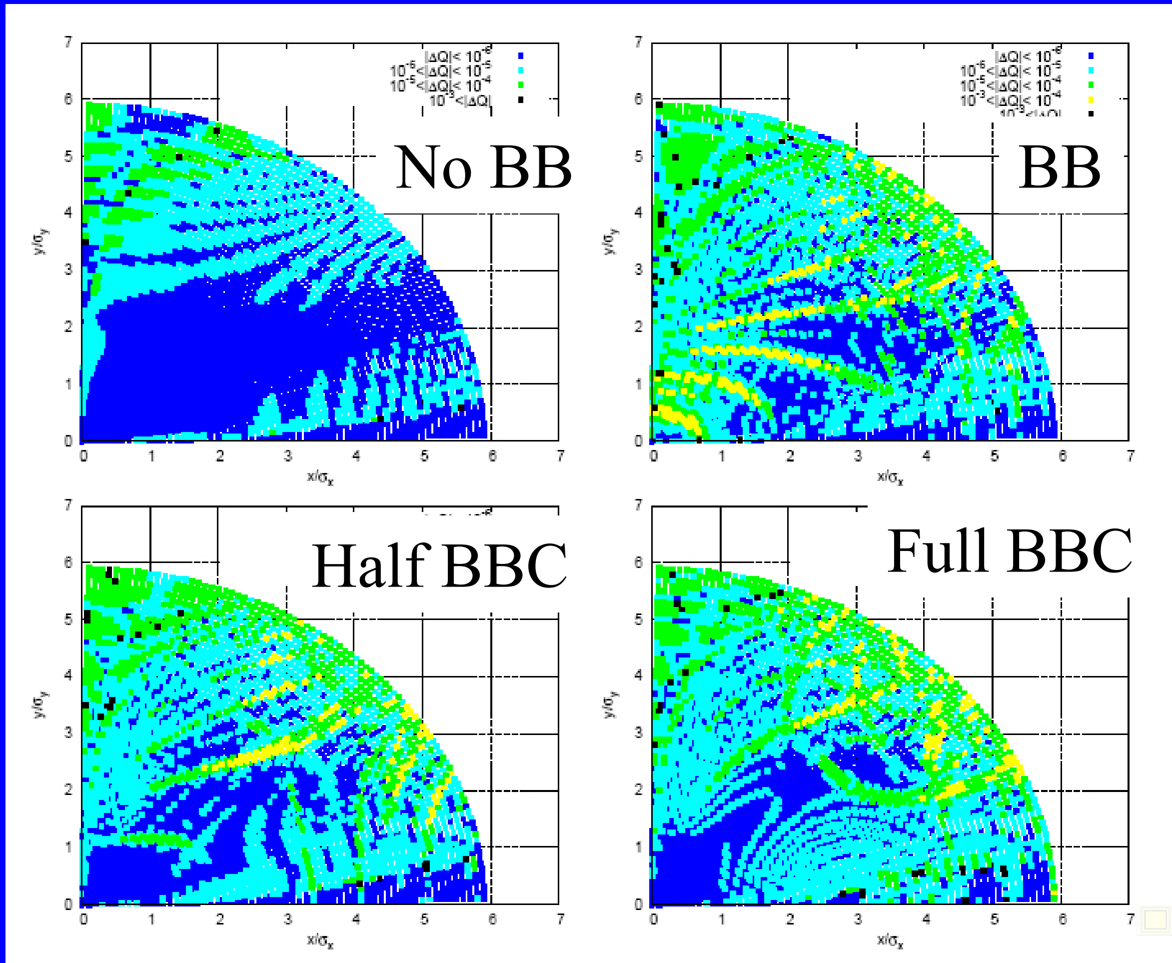


Practically all particles are chaotic with beam-beam interaction

[N. Abreu et al., EPAC08]

HOBBC studies at RHIC Y. Luo

E-lens reduces tune diffusion in core (<3σ), increases in tail (>4σ)



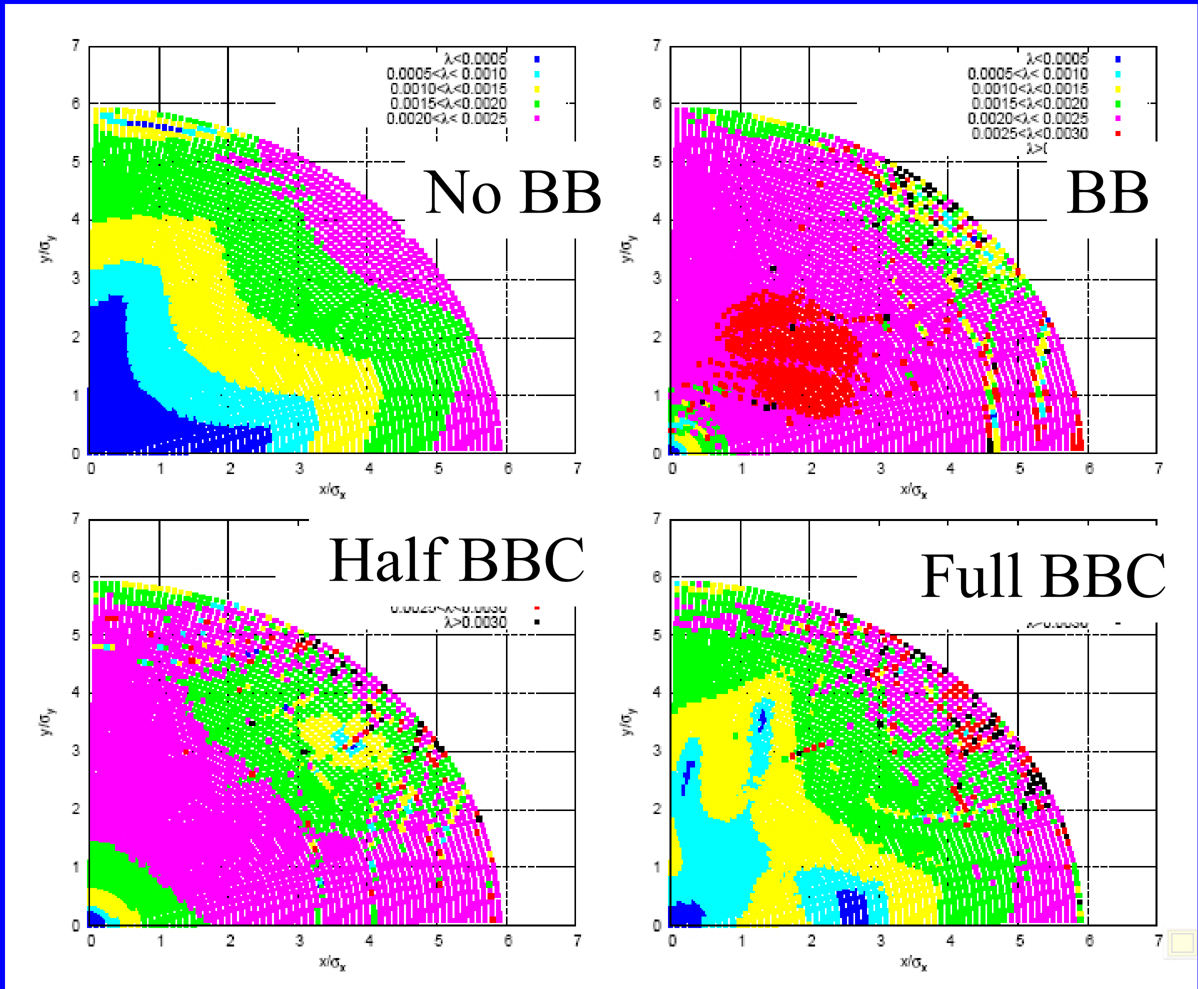
Tune change over
2 successive periods
of 1024 turns

$$|\Delta Q| = \sqrt{|\Delta Q_x|^2 + |\Delta Q_y|^2}$$

[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 studies at RHIC Y. Luo

E- lens reduces chaoticity in core (<3σ), increases in tail (>4σ)



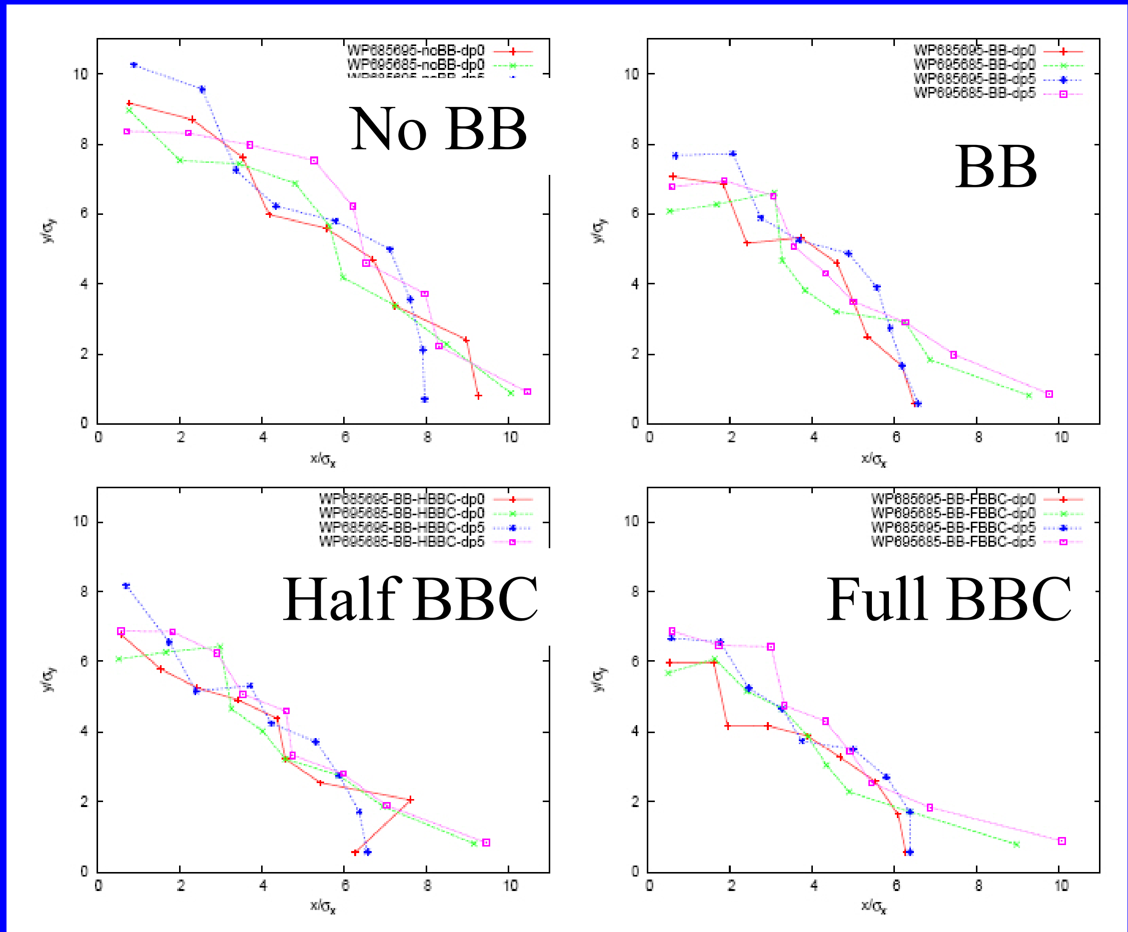
Lyapunov exponent λ calculated over 2048 turns

$$\lambda(n) = \frac{1}{n} \ln \frac{|\vec{X}(n) - \vec{X}(0)|}{d_0}$$

[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 studies at RHIC Y. Luo

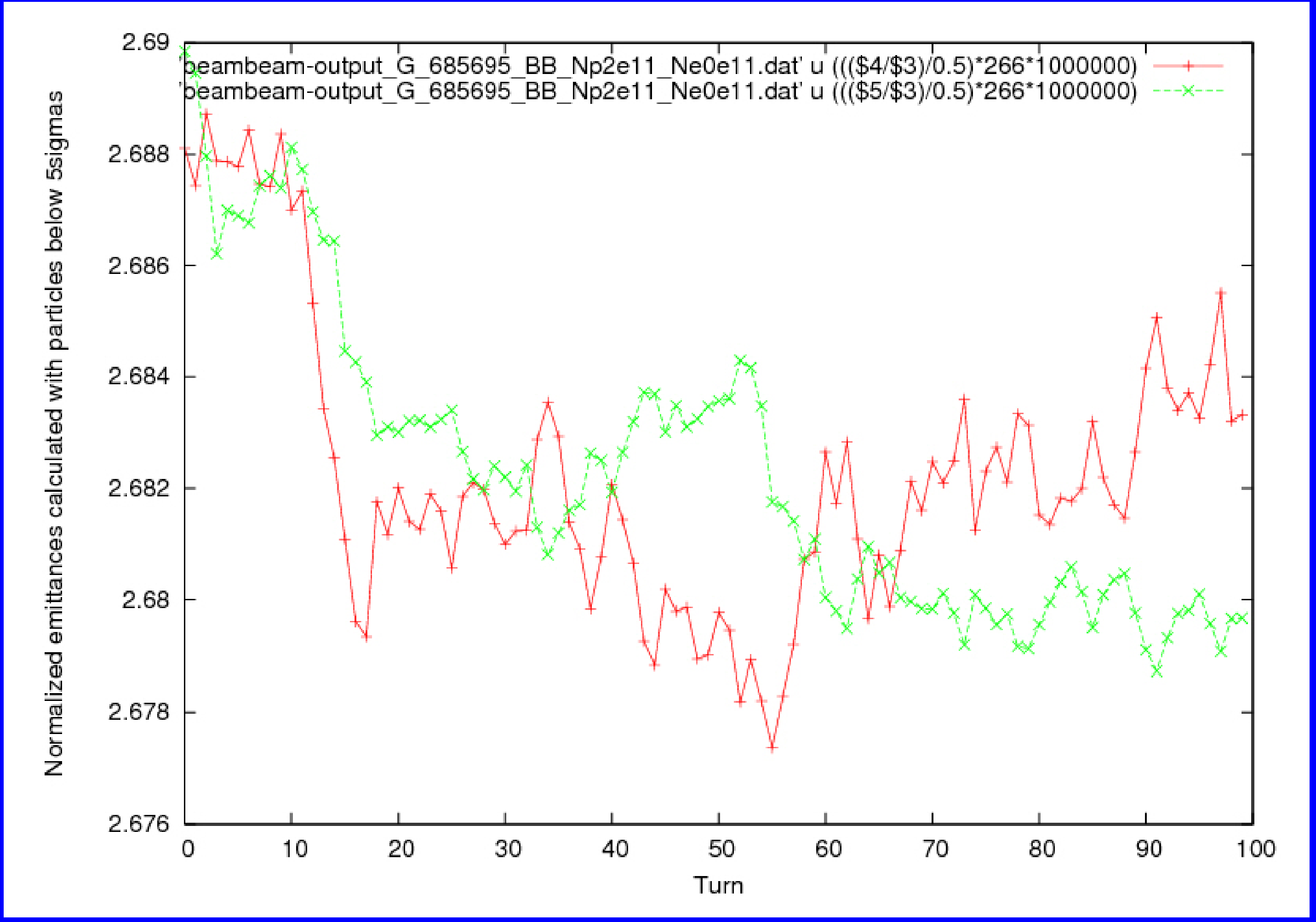
Dynamic aperture cannot be used to evaluate electron lenses (tests large amplitudes where head-on beam-beam is weak).



[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).]

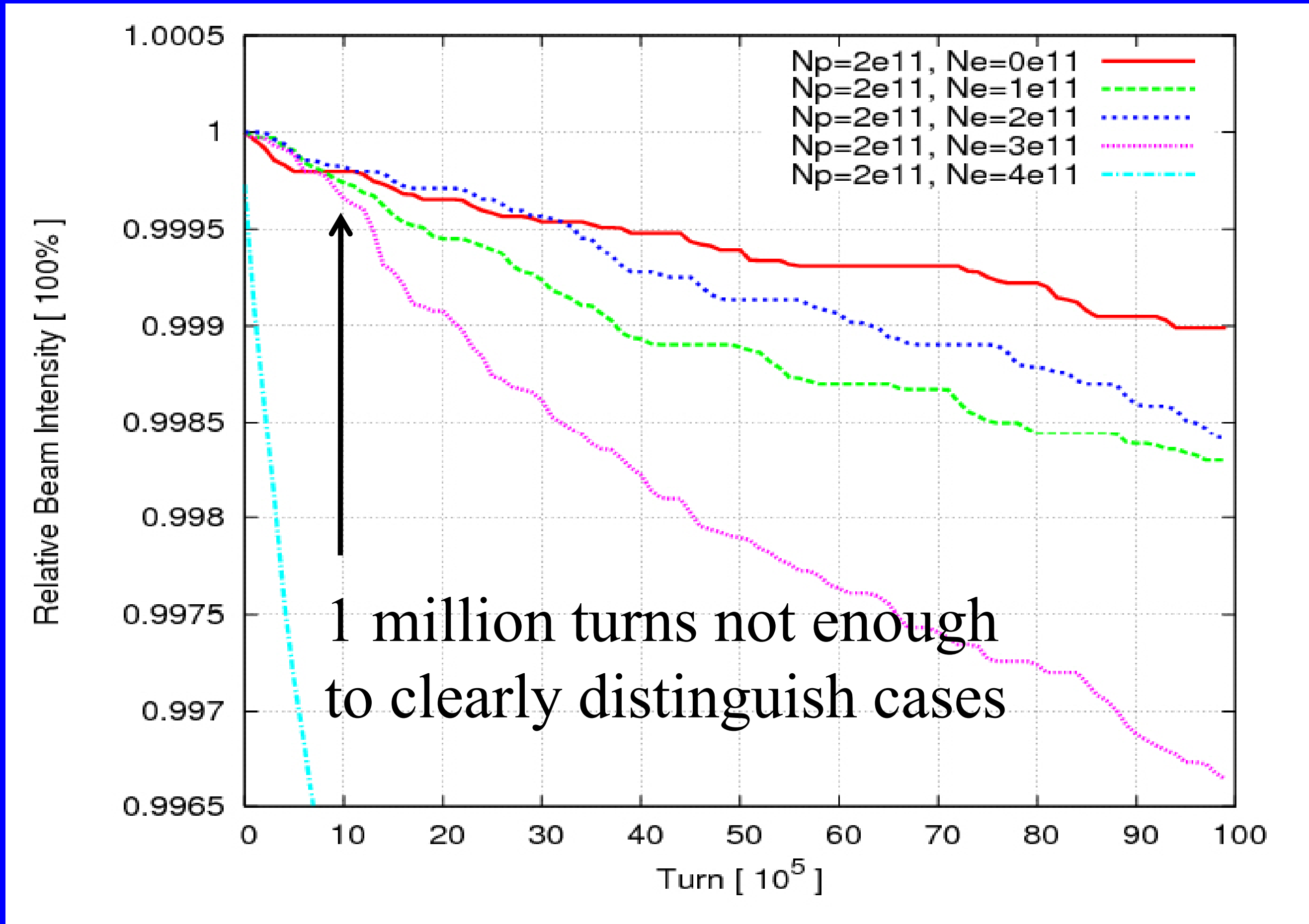
HOBBC studies at RHIC Y. Luo

Emittance in long-term tracking is still a noisy signal with several 10k particles.



HOBBC studies at RHIC Y. Luo

Beam lifetime simulation for increasing bunch intensity N_b

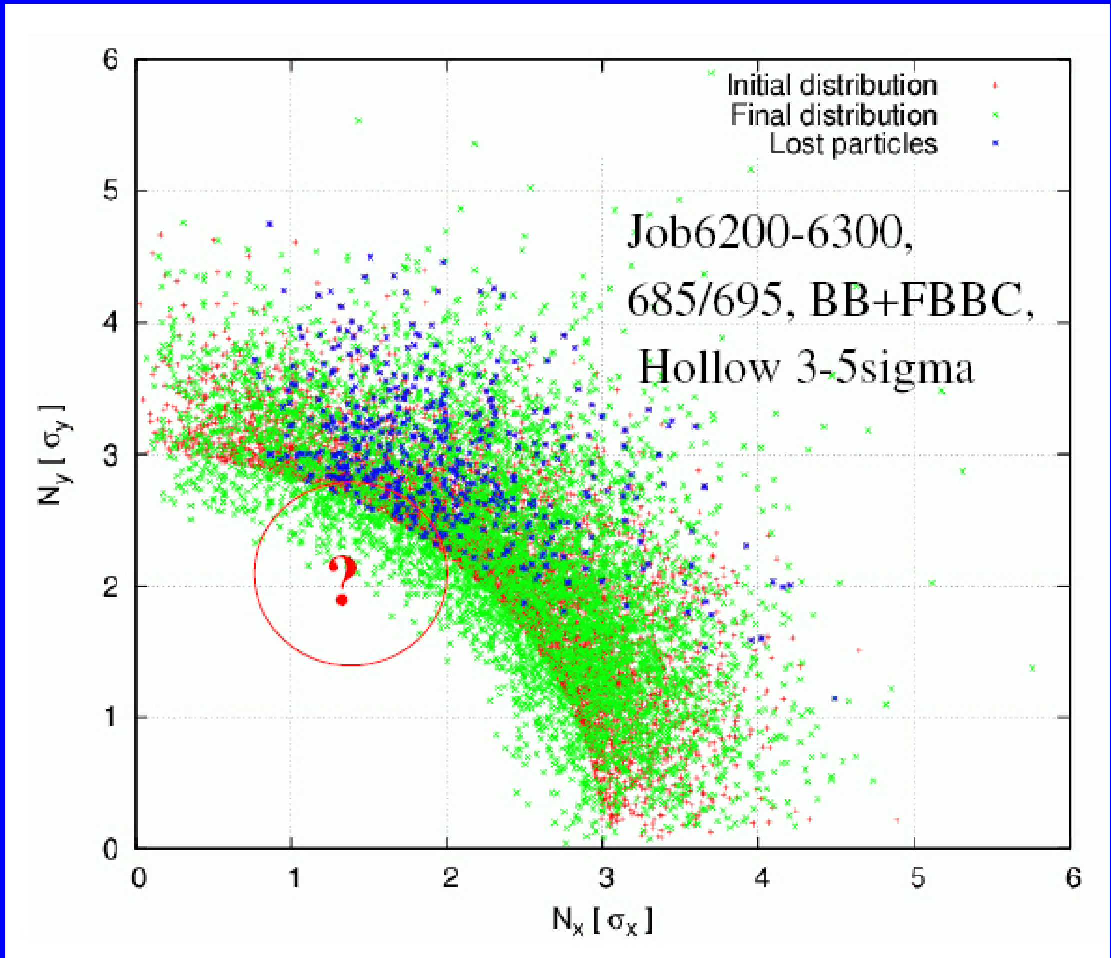


More than 10 million turns results in numerical noise problems.

[PhD thesis F. Schmidt]

HOBBC studies at RHIC Y. Luo

Beam lifetime simulations currently use 6400 particles, distributed over 2.5-6 σ (equivalent to 34k particles in Gaussian distribution)



← Study to determine size of stable core

Conclusions from e-lens simulations so far

1. Established methods used to evaluate magnet errors fail for electron lenses:
   - All particles are chaotic (i.e. no chaotic boundary)
   - Dynamic aperture not a good a measure for head-on beam-beam problems since beam-beam force becomes small at large amplitudes

2. None of the short-term evaluations gives a reliable answer for long-term behavior
   - Tune footprints, tune diffusion maps and Lyapunov exponent maps

3. Simulations generally show improvements in particle behavior below 3σ and deterioration above 4σ
   - Not clear if this is acceptable in reality
   - Can this be improved with phase advance adjustment?

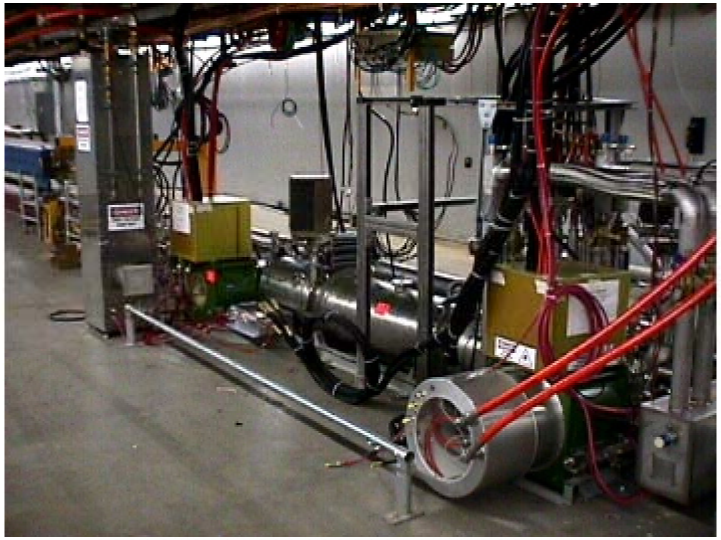
Conclusions from e-lens simulations so far

4. Emittance growth is too noisy in simulations and not useful as a figure of merit

5. Electron lens benefits can be evaluated with beam lifetime simulations
   - Simulations must run over more than 1 million turns

6. Need about 30 years of CPU time with single 2.4 GHz processor (100 cases, 6400 particles, 10 million turns)
   - Looking into using clusters at BNL (Blue Gene/P – 8000 cores) and/or LBL (NERSC – 40000 cores)
   - Could also use LHC@HOME (180,000 volunteer screen savers) but QMUL (server host) has not yet installed special SixTrack version [had excellent support for this from E. McIntosh and F. Schmidt at CERN]

HOBBC – Mini-Workshop on E-lens Simulations



Tevatron electron lens TEL-1 in the tunnel.

U.S. LARP

BROOKHAVEN NATIONAL LABORATORY

FNAL

SLAC

Mini-Worshop on Electron Lens Simulations

BNL, Bldg. 911B, Small Conference Room

3 December 2008

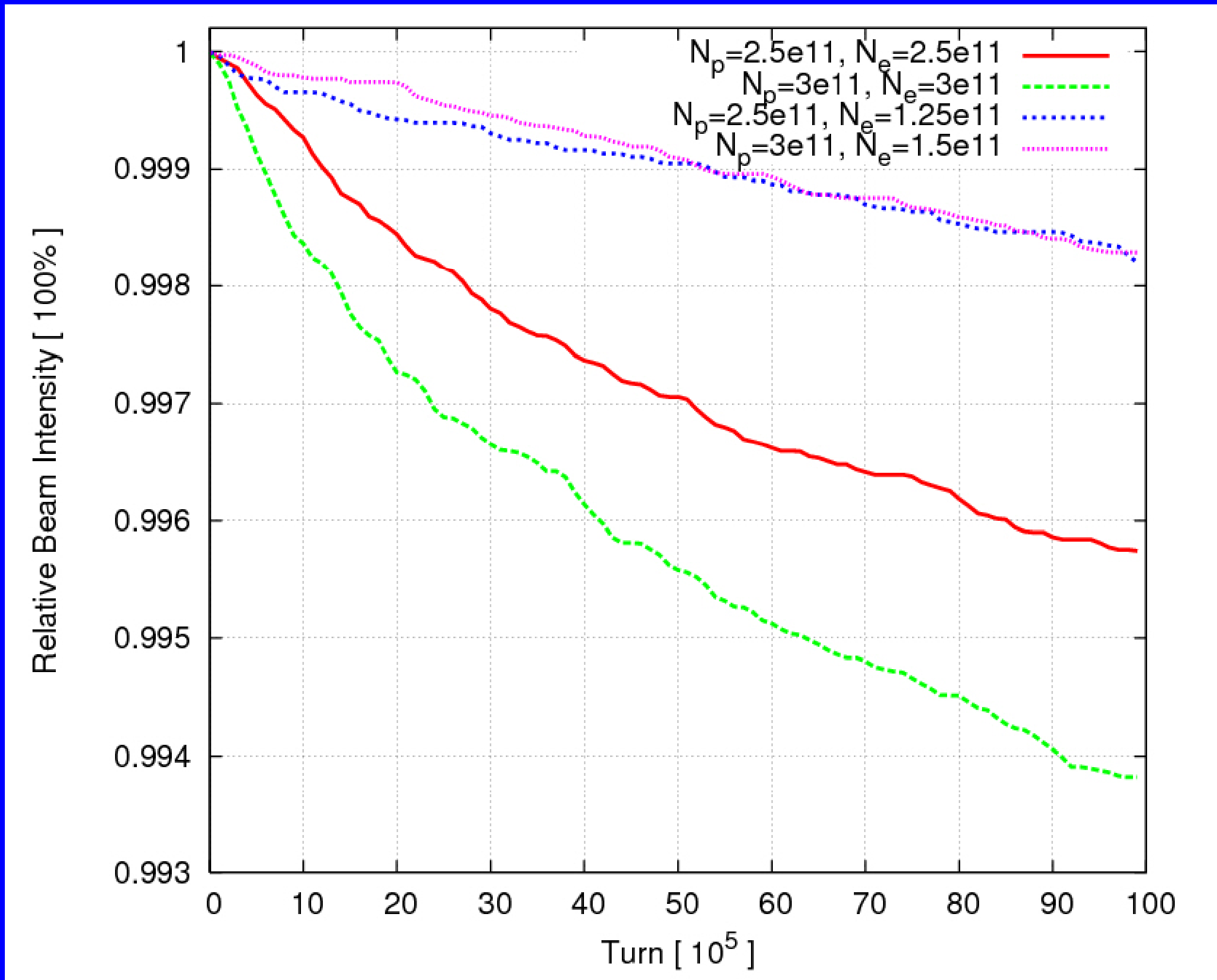
Participants:

Natalia Abreu, BNL
J. Beebe-Wang, BNL
Wolfram Fischer, BNL
Yun Luo, BNL
Christoph Montag, BNL
Guillaume Robert-Demolaize, BNL

How can the luminosity gain from an electron lens be estimated?
What can we conclude from short-term measures? (footprints, tuned diffusion, Lyapunov exponents)
What can we conclude from long-term measures? (dynamic aperture, emittance growth beam lifetime)
How do we benchmark simulations?
Electron lenses in BNL simulations stabilizes particles below 3 sigma, but reduces stability above 4 sigma. Why? (phase advance)
What are the sensitive parameters? (phase advance? current noise? shape? shape noise? position noise?)
What are the insensitive parameters?
Which parameters were found to be sensitive/insensitive during Tevatron electron lens operation?
What effects need to be included in simulations? (magnetic field errors in IRs, magnetic field errors in arcs, tune ripple)
How are Tevatron, RHIC, LHC different?
How are LIFETRAC, BBSIM, SixTrack, PlibB different?
Where do we get enough CPU power for the simulations?

HOBBC studies at RHIC Y. Luo

Scan of electron lens strength



← Half HOBBC
N_b = 2.5, 3□10^{11}
τ = 19.7 h

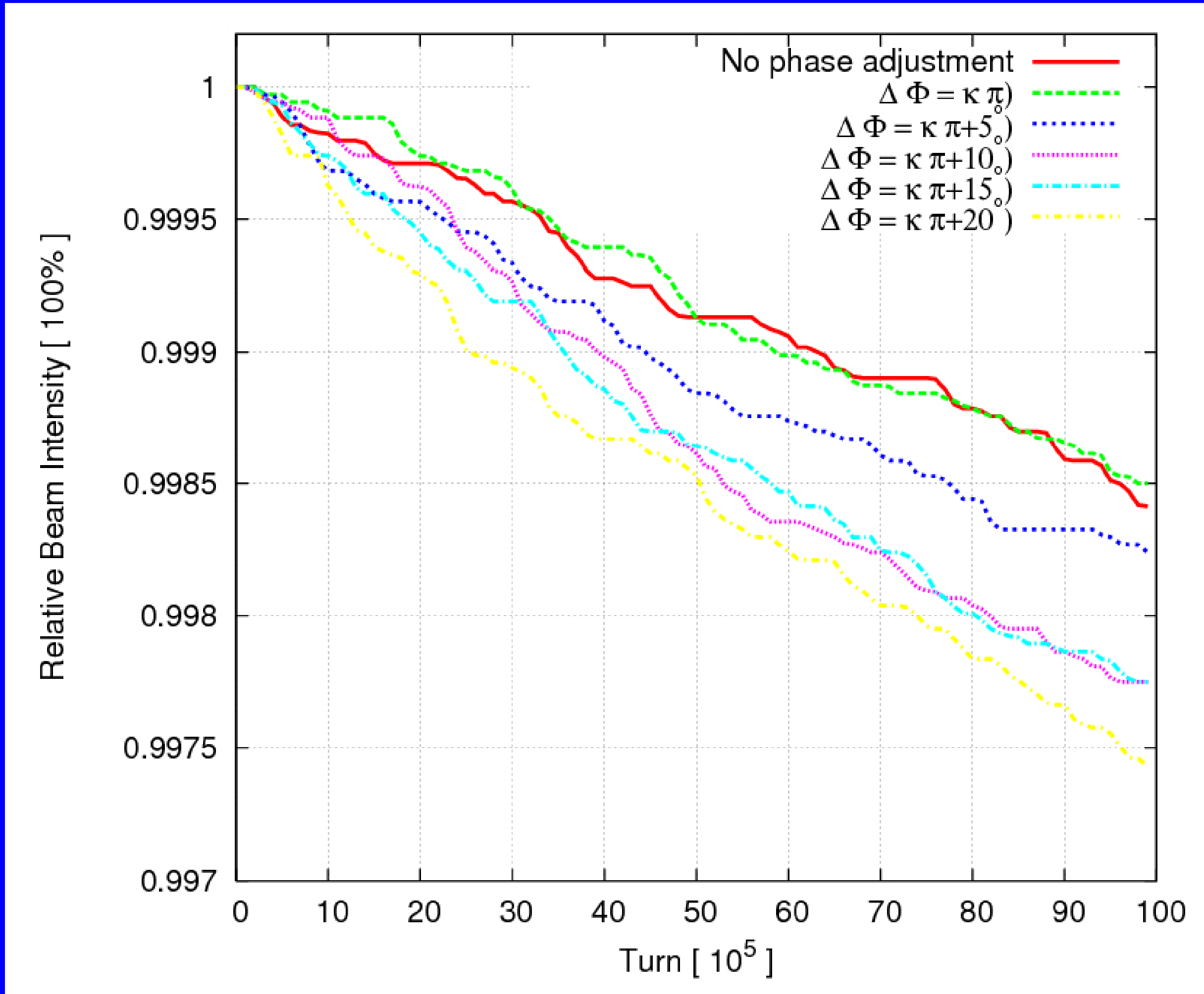
← Full HOBBC
N_b = 2.5□10^{11}
τ = 8.5 h

← Full HOBBC
N_b = 3□10^{11}
τ = 5.7 h

Best results with half compensation (avoids footprint folding).

HOBBC studies at RHIC Y. Luo

Scan of phase advance between IP and electron lens



ideal & RHIC default
$\tau = 23.7$ h

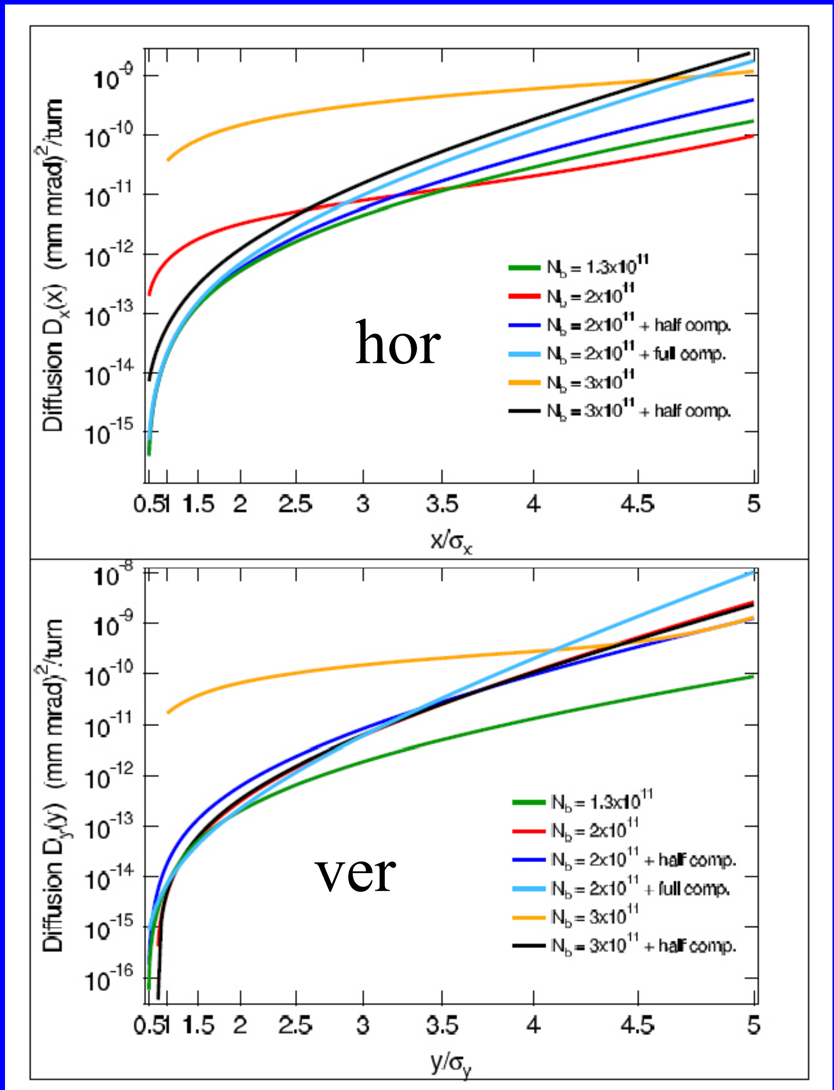
$\Delta\phi_{x,y} = 20$
$\tau = 14.2$ h

Phase advance between IP and e-lens is important.

HOBBC studies at RHIC N. Abreu

Alternative approach to lifetime tracking: use diffusion coefficients.

[T. Sen and J.A. Ellison, PRL 77, V 6, pp. 1051 (1996)]



Diffusion coefficients obtained from

- 64 particles, initially closely spaced
- tracked over 5□10^4 turns

- dε/dt for N_b=1.3□10^{11} is about factor 2 smaller than measured one
- electrons lens stabilizes core, enhances tail diffusion

[N. Abreu et al., EPAC08]

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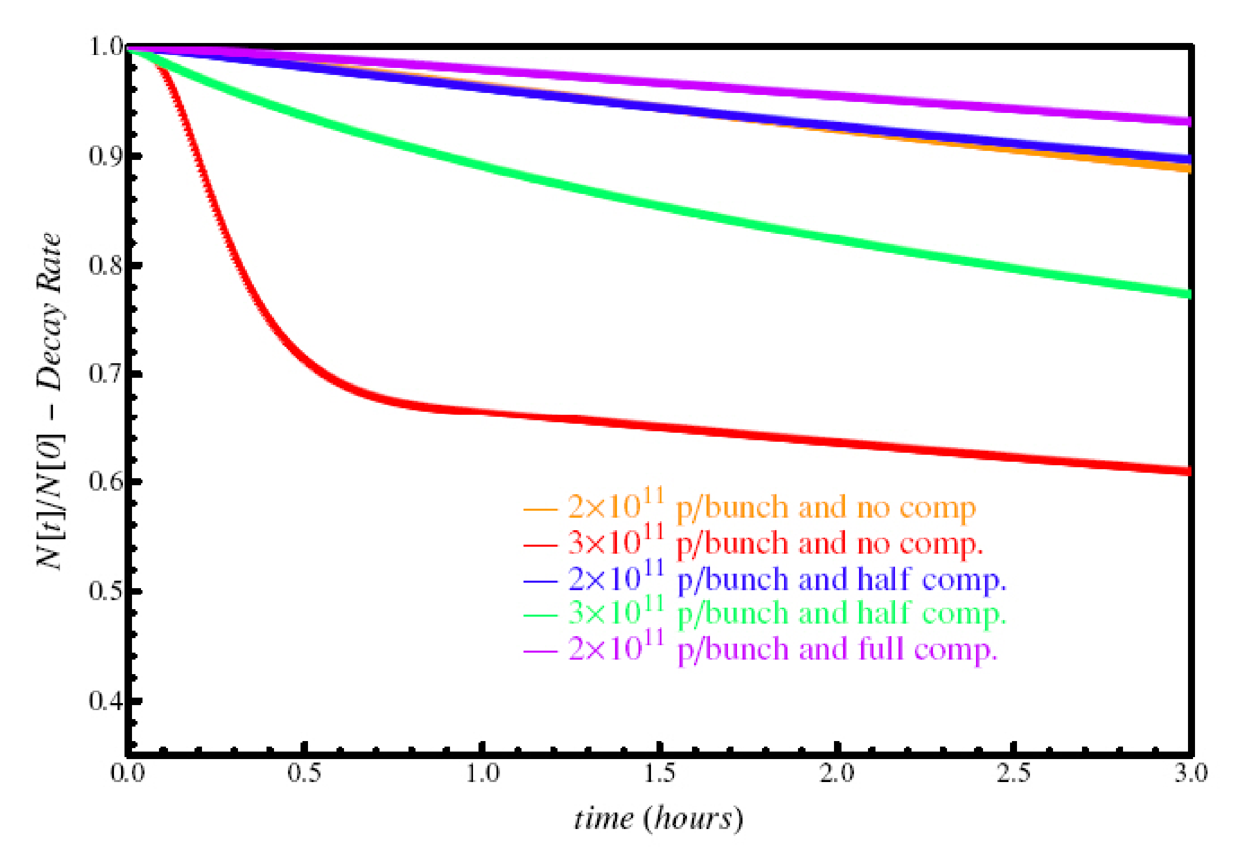
HOBBC studies at RHIC N. Abreu

Beam lifetime calculated with diffusion coefficients at (0.685,0.695)



← $N_b = 2 \square 10^{11}$

← $N_b = 3 \square 10^{11}$+HC

← $N_b = 3 \square 10^{11}$

Similar approach also pursued by H.J. Kim and T. Sen at FNAL using BBSIM.

[N. Abreu et al., "Stochastic boundary, diffusion, emittance growth and lifetime calculation for RHIC", BNL C-A/AP note in preparation]

HOBBC studies at RHIC – Lessons for LHC

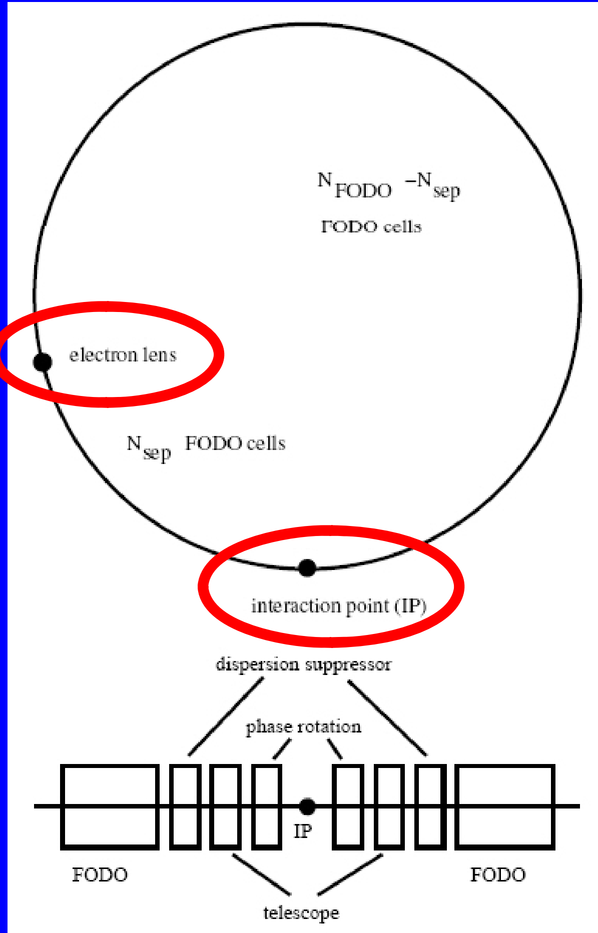
- Electron lenses could increase luminosity (□2□?) in LHC if
  1. Luminosity is limited by head-on beam-beam effect
  2. N_b/ε can be increased above observed beam-beam limit
  3. Electron lenses were successfully implemented in RHIC
- Location reserved for BBLR could also house e-lens
  - About equal β-functions in both planes (good)
  - 90□ phase advance to next IP (not good but may be ok for other IP)
  - May compete with long-range compensation

HOBBC studies for eRHIC (ring-ring) C. Montag

Main limit for eRHIC ring-ring luminosity: beam-beam on electrons

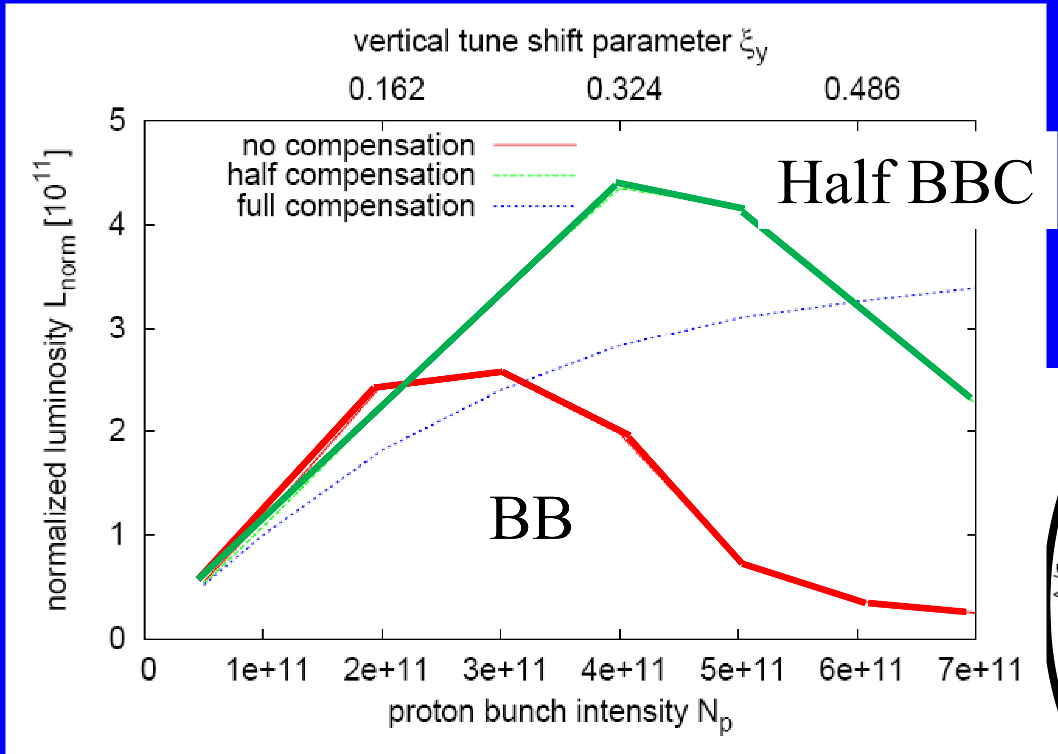
		High energy setup	
		p	e
Energy, GeV	GeV	250	10
Number of bunches		165	55
Bunch spacing	ns	71	71
Particles / bunch	10^{11}	1.00	2.34
Beam current	mA	208	483
95% normalized emittance	π mm·mrad	15	
Emittance ε_x	nm	9.5	53.0
Emittance ε_y	nm	9.5	9.5
βx^*	m	1.08	0.19
βy^*	m	0.27	0.27
Beam-beam parameter ξ_x		0.015	0.029
Beam-beam parameter ξ_y		0.0075	0.08
Bunch length σ_z	m	0.20	0.012
Polarization	%	70	80
Peak Luminosity	10^{33}, $cm^{-2}s^{-1}$	0.47	
Average Luminosity	10^{33}, $cm^{-2}s^{-1}$	0.16	
Luminosity Integral /week	pb^{-1}	96	

Could be mitigated through e-lens for electron beam

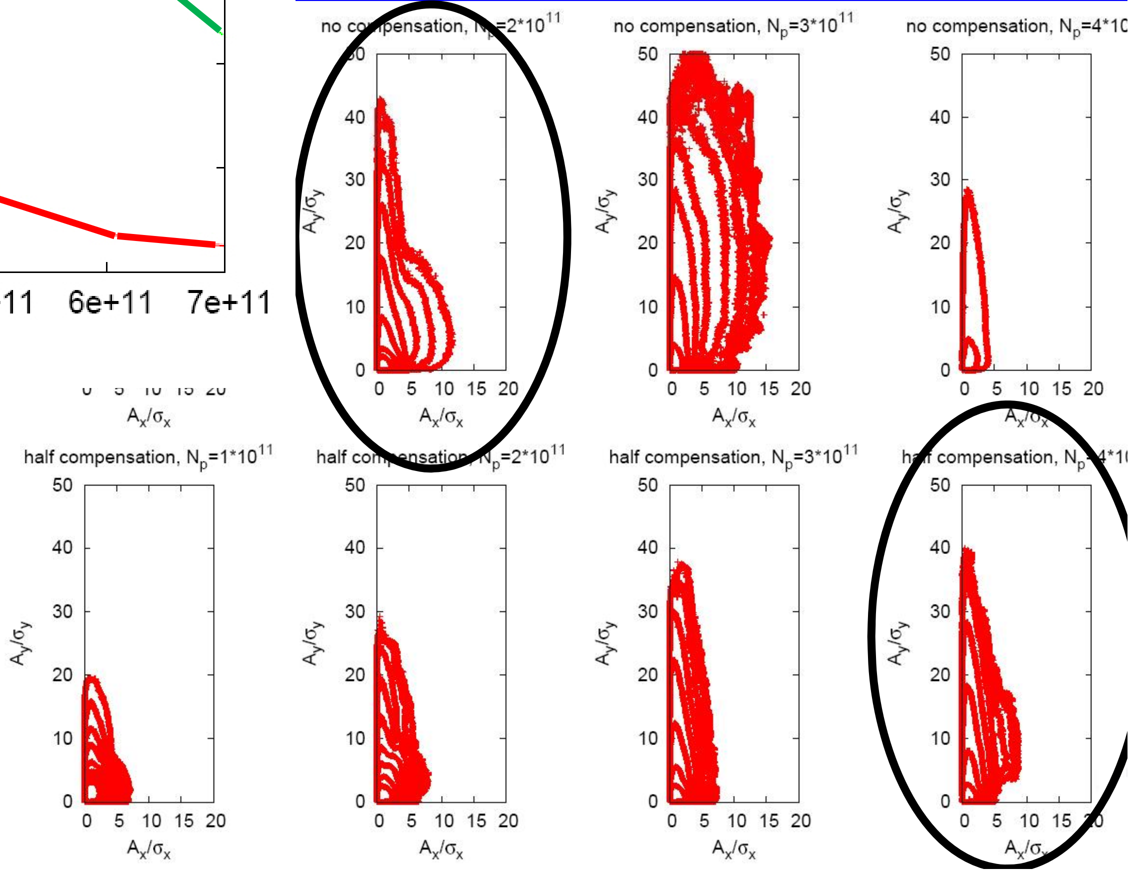


[eRHIC Accelerator Position Paper for NSAC 2007]

HOBBC studies for eRHIC (ring-ring) C. Montag



← Core size increase (1st beam-beam limit) at 2□ larger beam-beam ξ and e-lens



About same transverse tails → (2nd beam-beam limit) at 2□ larger beam-beam ξ and e-lens

HOBBC studies for eRHIC (ring-ring) C. Montag

- Expect doubling of eRHIC ring-ring luminosity with e-lens if luminosity is limited by either 1st (core size) or 2nd (transverse tails) beam-beam limit in e-beam
- Best effect at about ½ compensation
- Luminosity much less dependent on working point
- In simulation is compensation is
  - Robust against intensity mismatch
  - Robust against beam size mismatch
  - Sensitive to phase advance errors between IP and e-lens ($\Delta\phi \leq 2$□)

Head-on beam-beam compensation in an electron-ion or electron-positron collider ring

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(Dated: October 13, 2008)

In a collider the luminosity is typically limited by the beam-beam effect. Once the beam-beam limit is reached, the luminosity no longer increases linearly with the bunch intensity in either beam, but begins to saturate and even drop again if the beam-beam tuneshift is increased further. To overcome this limitation in the electron ring of an electron-ion or electron-positron collider, we investigate a compensation scheme based on an electron lens.

PACS numbers: 29.20.db, 29.27.-a, 29.27.Bd

[paper in preparation]

Summary

- Long-range experiments
  - Beam lifetime measurements with p-beam and wire still outstanding
  - Onset of large losses reproduced within 1σ for a number of measurements and with different parameters
  - Onset of losses from long-range interaction seen in experiments:
    - at 4σ for single beam LR interaction
    - between 5-9σ with wire (strong dependence on WP and chromaticity)
- Head-on beam-beam compensation
  - Could about double (?) luminosity in RHIC/eRHIC-rr and LHC (LHeC?)
  - Technology of electron lenses tested in Tevatron operation (but not used for head-on compensation)
  - Evaluations likely needs to rely on beam lifetime simulations, covering a few minutes real time
  - Simulations need to give tolerances for: phase advance between IP and e-lens; current, profile and orbit errors, …
  - Tevatron lenses could be adapted for RHIC

RHIC LRBBC and HOBBC documentation

http://www.rhichome.bnl.gov/AP/BeamBeam/biblioRHIC.html

RHIC Beam-Beam Reports

53. N.P. Abreu, W. Fischer, Y. Luo, and G. Robert-Demolaize, "Diffusion simulation and lifetime calculation at RHIC", report in preparation.

52. N.P. Abreu, W. Fischer, Y. Luo, and G. Robert-Demolaize, "Stochastic boundary, diffusion, emittance growth and lifetime calculation for RHIC e-lens", report in preparation.

51. C. Montag and W. Fischer, "Head-on beam-beam compensation in an electron-ion or electron-positron collider ring", report in preparation.

50. H.J. Kim, T. Sen, N.P. Abreu, and W. Fischer, "Simulations of wire compensator in RHIC", proceedings of the 42th ICFA Advanced Beam Dynamics Workshop on High Intensity High Brightness Hadron Beams HB2008, Nashville, TN (2008).

49. Y. Luo, G. Robert-Demolaize, N. Abreu, and W. Fischer, "Multi-particle weak-strong simulation of head-on beam-beam compensation in the RHIC", proceedings of the 2008 European Particle Accelerator Conference, Genoa, Italy (2008).

48. H.J. Kim, T. Sen, N.P. Abreu, and W. Fischer, "Studies of wire compensation and beam-beam interaction in RHIC", proceedings of the 2008 European Particle Accelerator Conference, Genoa, Italy (2008).

47. N.P. Abreu, W. Fischer, Y. Luo, and G. Robert-Demolaize, "The effect of head-on beam-beam compensation on the stochastic boundaries and particle diffusion in RHIC", proceedings of the 2008 European Particle Accelerator Conference, Genoa, Italy (2008).

46. Y. Luo, W. Fischer, N. Abreu, E. Beebe, J. Beebe-Wang, C. Montag, M. Okamura, A. Pikin, and G. Robert-Demolaize, "Head-on beam-beam compensation with electron lenses in the Relativistic Heavy Ion Collider", proceedings of the 2008 European Particle Accelerator Conference, Genoa, Italy (2008).

45. Y. Luo, W. Fischer, and N. Abreu, "Stability of single particle motion with head-on beam-beam compensation in the RHIC", BNL C-A/AP/310 (2008).

44. W. Fischer, O. Brüning, J.-P. Koutchouk, F. Zimmermann, T. Sen, V. Shiltsev, K. Ohmi, M. Furman, Y. Cai, and A. Chao, "Summary of LARP Mini-Workshop on Beam-Beam Compensation 2007", BNL C-A/AP/291; ICFA Beam Dynamics Newsletter No. 44, pp. 220-225; proceedings of BEAM'07, CERN-2008-005, CARE-Conf-08-004-HHH (2008).

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- Y. Alexahin, V. Kamerdzhiev, H.-J. Kim, T. Sen, A. Valishev, V. Shiltsev (FNAL)
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