Strong-strong simulation of electron-proton beam-beam interaction in eRHIC

Beam-Beam Effects in Circular Colliders
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Electron Ion Collider – eRHIC

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eRHIC

C. Montag

- High-luminosity electron-ion collider based on existing RHIC facility
- Electron-proton luminosities of 10^{33} - 10^{34} $cm^{-2}s^{-1}$
- Center-of mass energy 30 – 140 GeV
- Arbitrary spin patterns (up-down) in both beams
- 22 mrad full crossing angle
- Crab cavities
- Flat beams

eRHIC Concept

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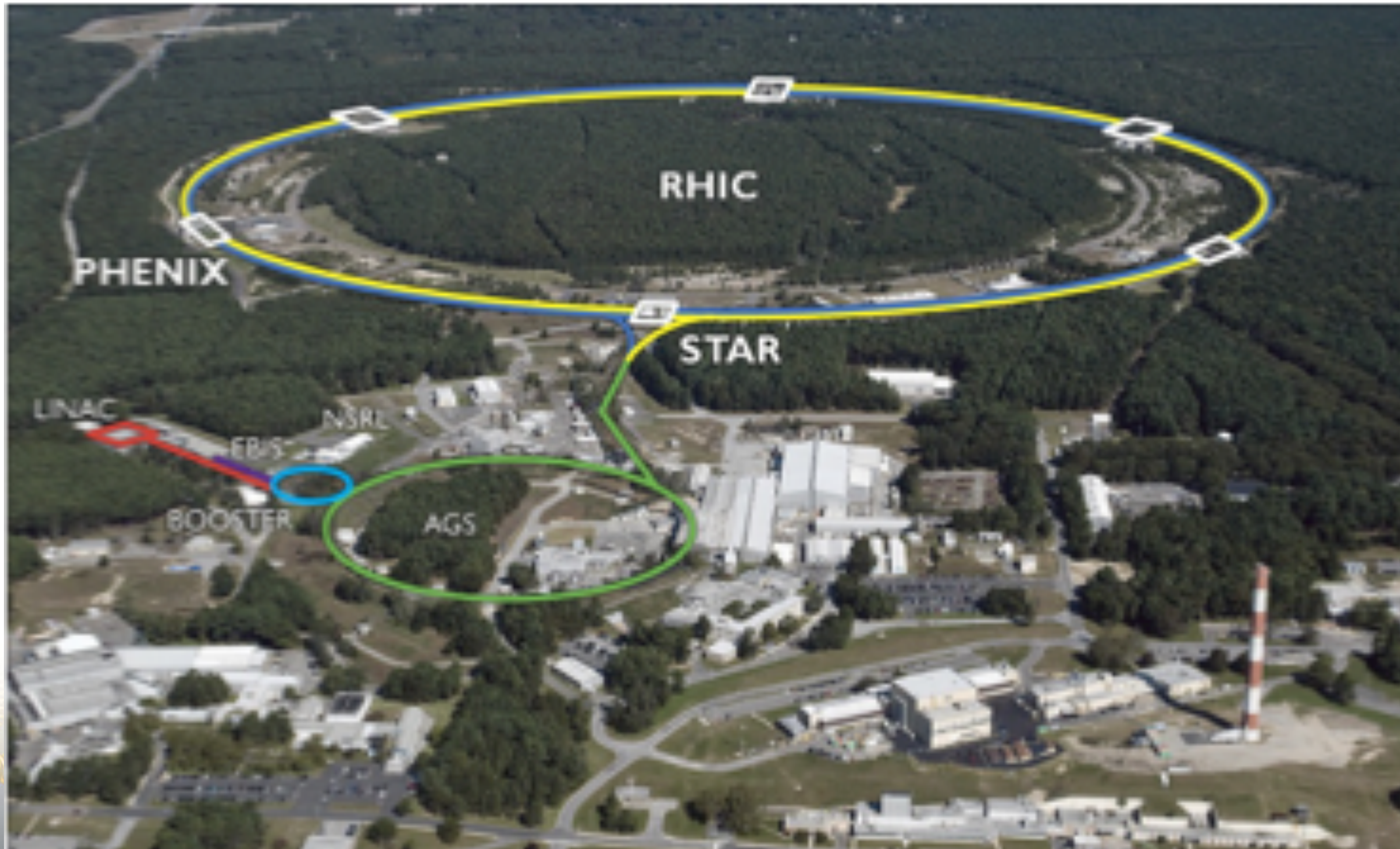
- Install a 5-18 GeV electron storage ring in existing RHIC tunnel
- 3.8 km circumference
- 381 m tunnel curvature radius



e-Au and e-p Energy Combinations

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- Large center-of-mass energy range
- Discrete number of individual beam energies

		Hadrons (GeV/u)		
		50	100	275
Electrons, GeV	5	p, Au	p, Au	
	7.5	Au		
	10		p	p
	15		Au	
	18	Au	Au	p

Beam-Beam Performance of Other Colliders

		KEKB		PEP-II		TEVATRON		RHIC	HERA		eRHIC	
		e-	e+	e-	e+	p+	p-	pp	p+	e-	p+	e-
Circumference (m)		3016		2200		6280		3834	6336		3884	
Energy (GeV)		8	3.5	9	3.1	980	980	255	920	30	275	10
Bunch intensity (10^{10})		4.7	6.4	5.2	8	26	9	18.5	7	3	11.1	30.5
Number of bunches		1585		1732		36	36	111	180	189	330	
Beam current (mA)		1188	1637	1960	3026	70	24	257	90	40	458	1260
Emittance (nm)	hor	24	18	48	24	3	1	13	5	20	16	24
	ver	0.61	0.56	1.8	1.8	3	1	13	5	3.5	6.1	3.5
beta* (cm)	hor	120	120	50	50	28	28	65	245	60	94	62
	ver	0.59	0.59	1.2	1.2	28	28	65	18	26	4.2	7.3
RMS bunch length (cm)		0.65	0.65	1.1	1	50	45	60	8.5	0.83	7	0.43
RMS energy spread (10^{-3})		0.7	0.7	0.61	0.77	0.14	0.14	0.15	0.2	0.91	0.65	0.47
Beam-beam parameter (per IP)	hor	0.102	0.127	0.07	0.051	0.012	0.012	0.0073	0.0012	0.019	0.014	0.092
	ver	0.09	0.129	0.05	0.073	0.012	0.012	0.0073	0.0009	0.045	0.005	0.083
Luminosity (10^{33} $cm^{-2}s^{-1}$)		21		12		0.431		0.245	0.075		2.9	
Full crossing angle (±mrad)		11		0		0		0	0		11	

2 IPs are assumed for eRHIC. If operating with 1 IP, the beam-beam parameters can be larger

eRHIC Machine and Beam Parameters Used for Beam-Beam Simulations

	Unit	protons	electrons
Circumference	m	3833.845	3833.845
Energy	GeV	275	10
Bunch population	10^{11}	1.11	3.05
Radiation damping time	turns		2000/4000
Emittance	nm	16/6.1	24.4/3.5
Beta at IP	m	0.94/0.042	0.62/0.073
Bunch length	cm	7	1
Beam-beam parameter		0.014/0.005	0.092/0.083
Betatron tune		31.310/32.305	34.08/31.06
Synchrotron tune		0.002	0.025
Energy spread		0.00065	0.001
Crab cavity RF frequency	MHz	336	336
Crossing angle	mrad	22	
Luminosity	10^{33} cm^{-2}s^{-1}	2.9	

Weak-Strong and Strong-Strong Simulations

Weak-strong:

- Strong bunch is represented by a rigid Gaussian and weak bunch – by macro-particles;
- Exact analytical solution for beam-beam force, time efficient, no numerical noise;
- However not a self-consistent treatment;
- **Used to study single particle's long-term stability.**

Codes:

- SimTrack: a compact C++ code for particle orbit and spin tracking
  Y. Luo, NIM A (2015) 95-103; Y. Luo e.a., PRSTAB 15, 051004 (2012); Y. Luo e.a., PRSTAB 19, 021001 (2016)
- EPIC: a two-pass weak-strong code to mimic strong-strong simulation with asymmetric bunch length.
  Y. Hao, Beam-beam effect study in ERL based eRHIC, Ph.D Thesis, Indiana University, 2008
- C. Montag, Beam-beam Simulations with Realistic Crab Crossing for the eRhic Ring-Ring Electron Beam. IPAC-2016.

Strong-strong:

- Both bunches are represented by a large number of macro-particles;
- Particle-in-cell method used to solve 2-D Poisson equation;
- Self-consistent treatment, time consuming, with numerical noise;
- **Used to study coherent beam-beam motion and its stability.**

Codes:

- BBSS (K.Ohmi, KEK)
  K.Ohmi, Simulation of beam-beam effects in a circular e+e- collider. Phys. Rev E 62, 5 (2000).
- BeamBeam3D (J.Qiang, LBNL)
  https://web.fnal.gov/collaboration/COMPASS/Documents/scidac08beambeam.pdf

eRHIC Weak-Strong Beam-Beam Simulations

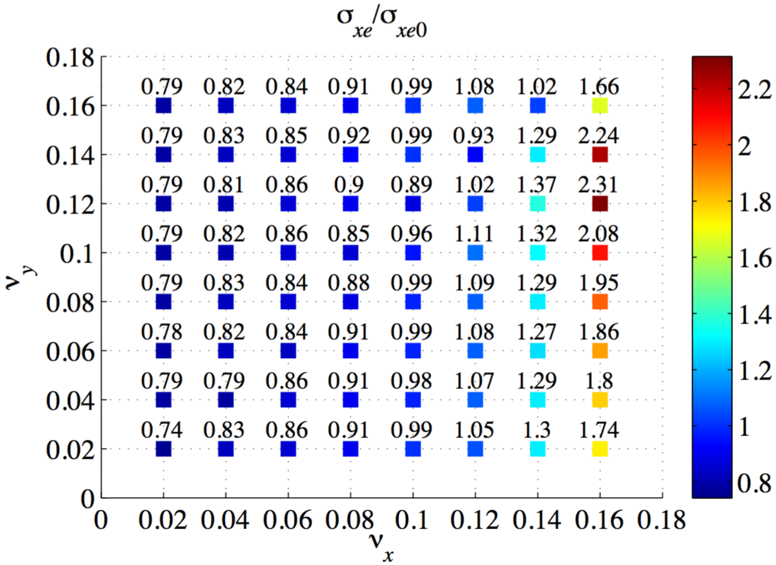
Beam size vs betatron tunes

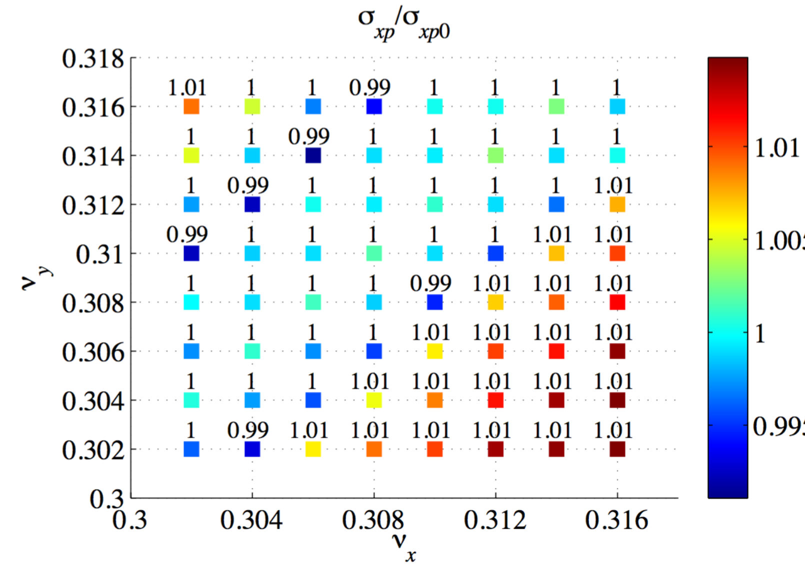
Y.Luo

Electron tune scan

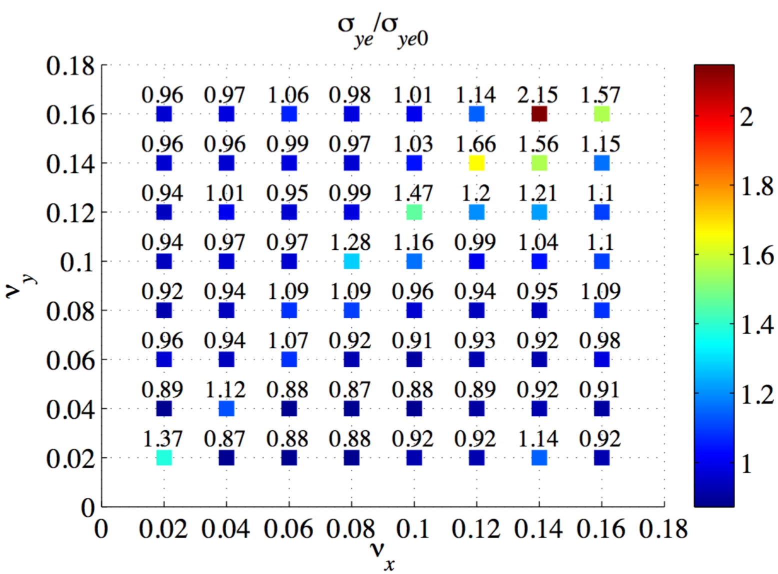
Proton tune scan

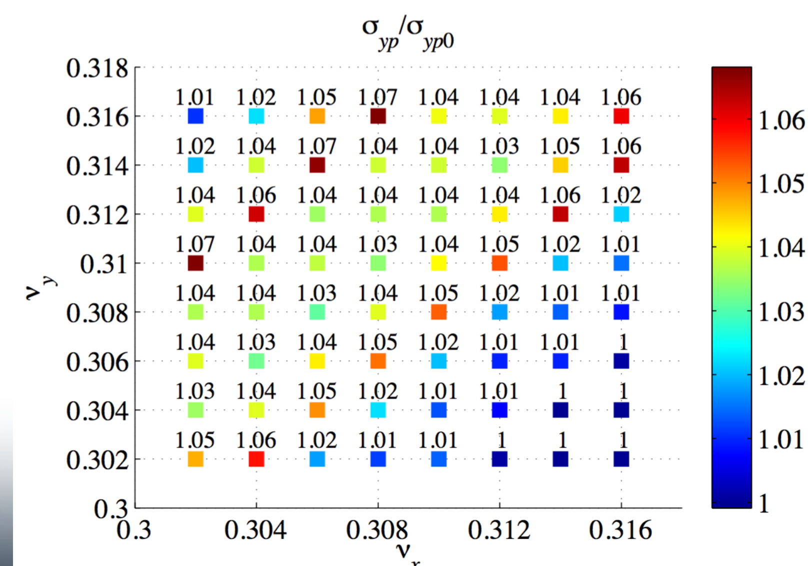
horizontal





vertical





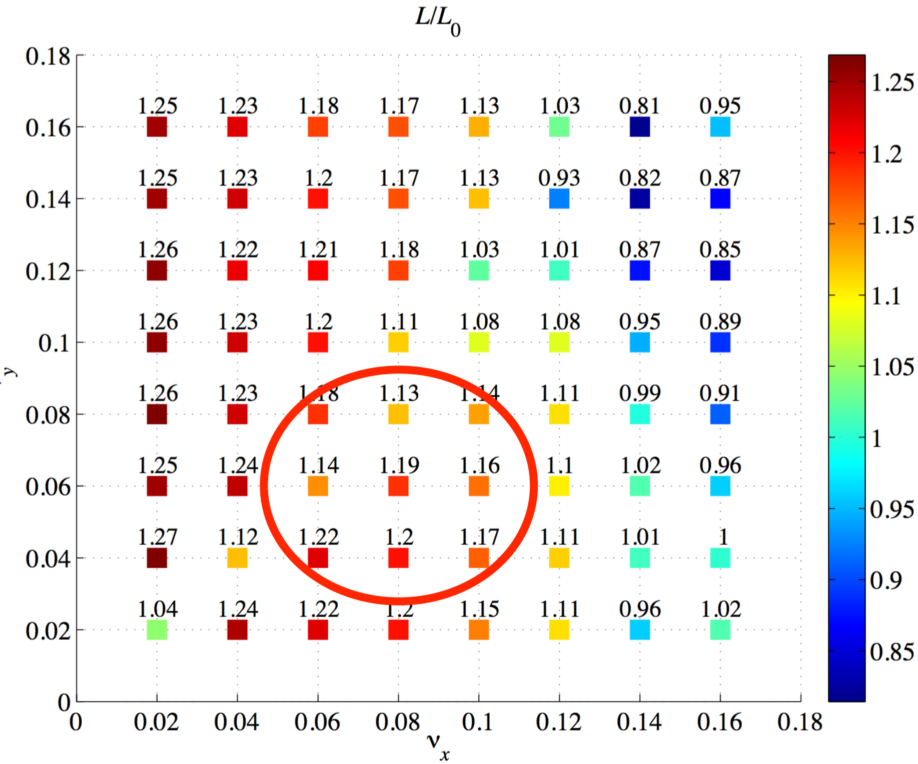
eRHIC Weak-Strong Beam-Beam Simulations
Luminosity vs betatron tunes

Y.Luo

Electron tune scan, 50k turns

Relative luminosity:

$$L / L_0, \quad L_0 = 2.9 \cdot 10^{33}\ \mathrm{cm^{-2}s^{-1}}$$

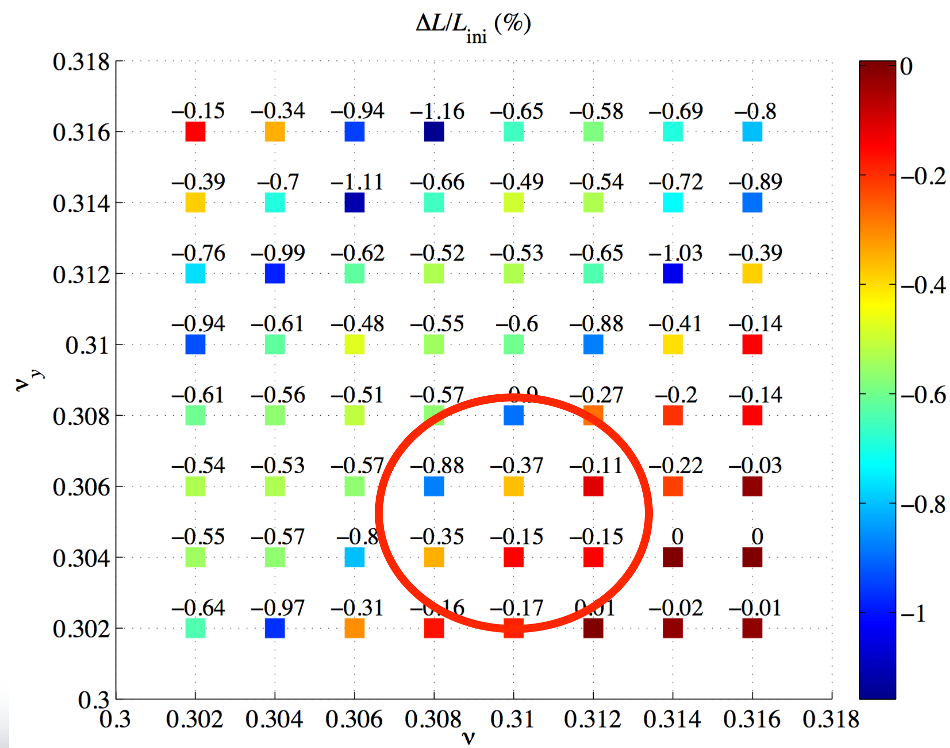


Proton tune scan, 1M turns

Relative luminosity decay:

$$\Delta L / L_{\mathrm{ini}}, \quad \Delta L = L_{\mathrm{fin}} - L_{\mathrm{ini}}$$

$$L_{\mathrm{ini}} - \text{first 10k turns}, \quad L_{\mathrm{fin}} - \text{last 10k turns}$$



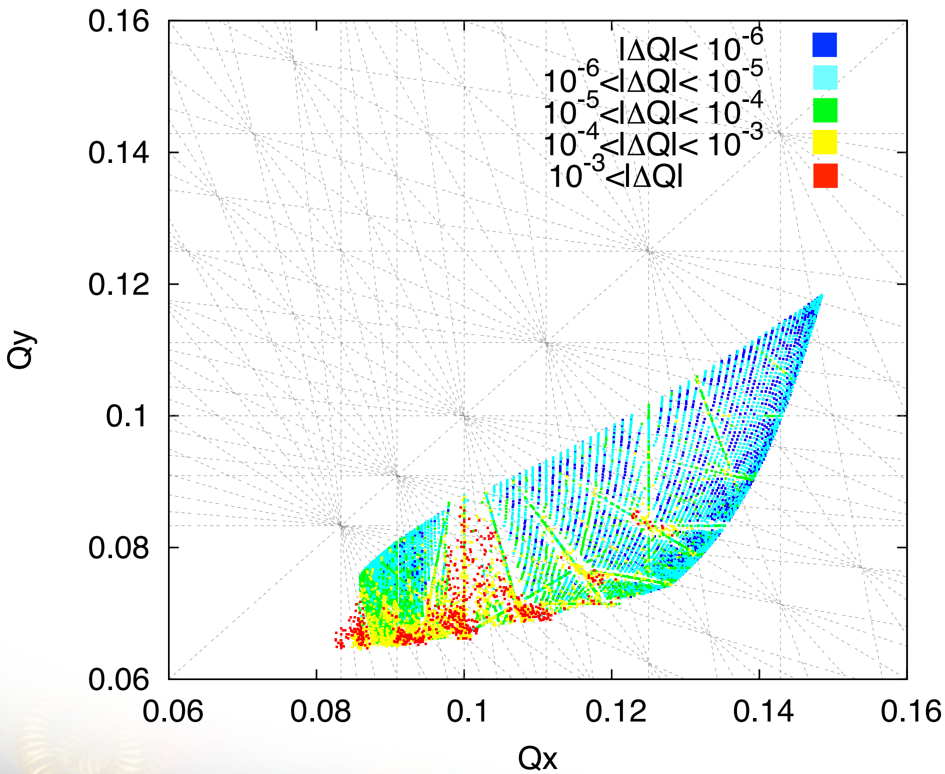
eRHIC Weak-Strong Beam-Beam Simulations
Frequency maps

Y.Luo

2048 turns

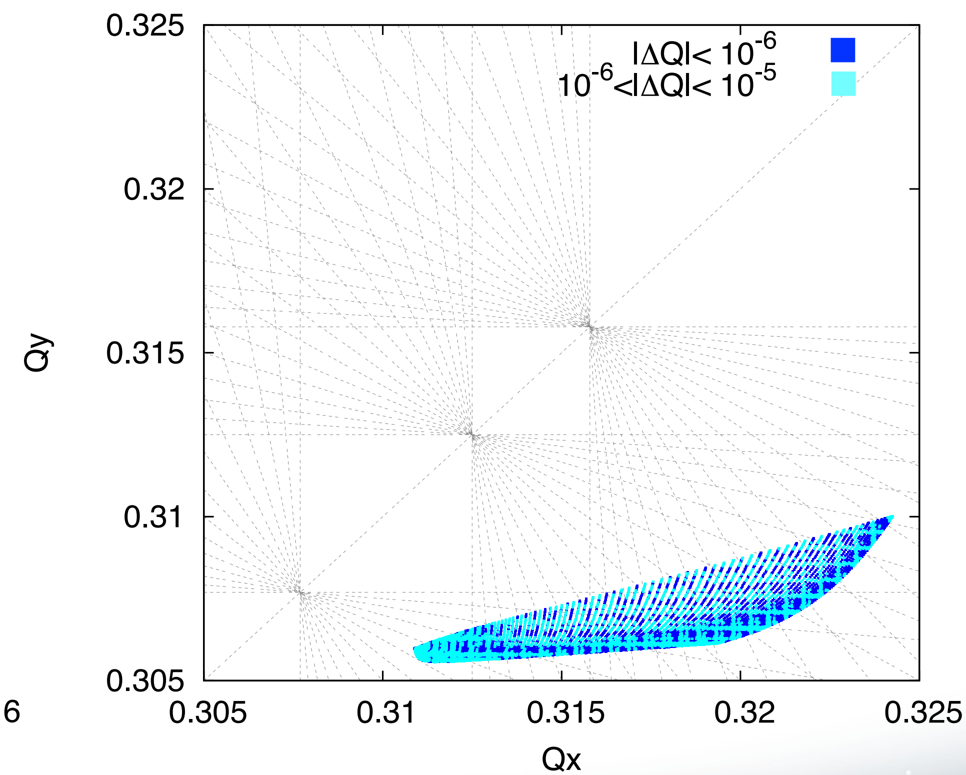
Electron tune footpint

$\xi_x = 0.092, \; \xi_y = 0.083$



Proton tune footpint

$\xi_x = 0.014, \; \xi_y = 0.005$



BBSS Strong-Strong Code:
convergence studies

G.Basssi

Optimal simulation parameters have been determined for the strong beam-beam simulations by comprehensive convergence studies of the BBSS code.

The optimal parameters have been found to be:

- 1 million macroparticles for both proton and electron beams.

- 15 longitudinal slices for the proton beam

  2 longitudinal slices for the electron beam

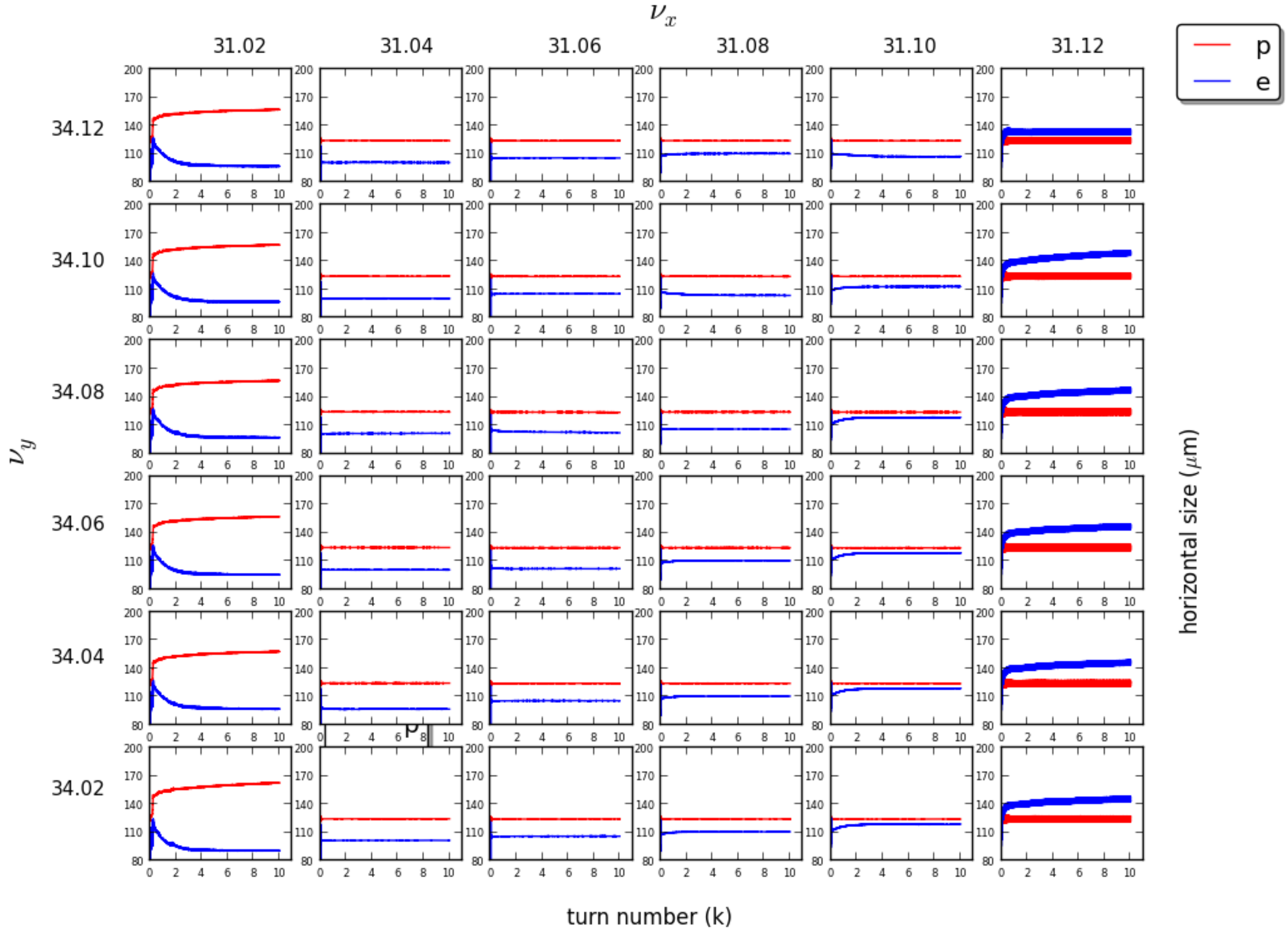
  (ratio $\approx \sigma_{z,p}/\sigma_{z,e}$ = 7).

- Transverse mesh size: 128×128 grid points.

eRHIC Strong-Strong Beam-Beam Simulations
BBSS, head-on collision

G.Bassi, A.He

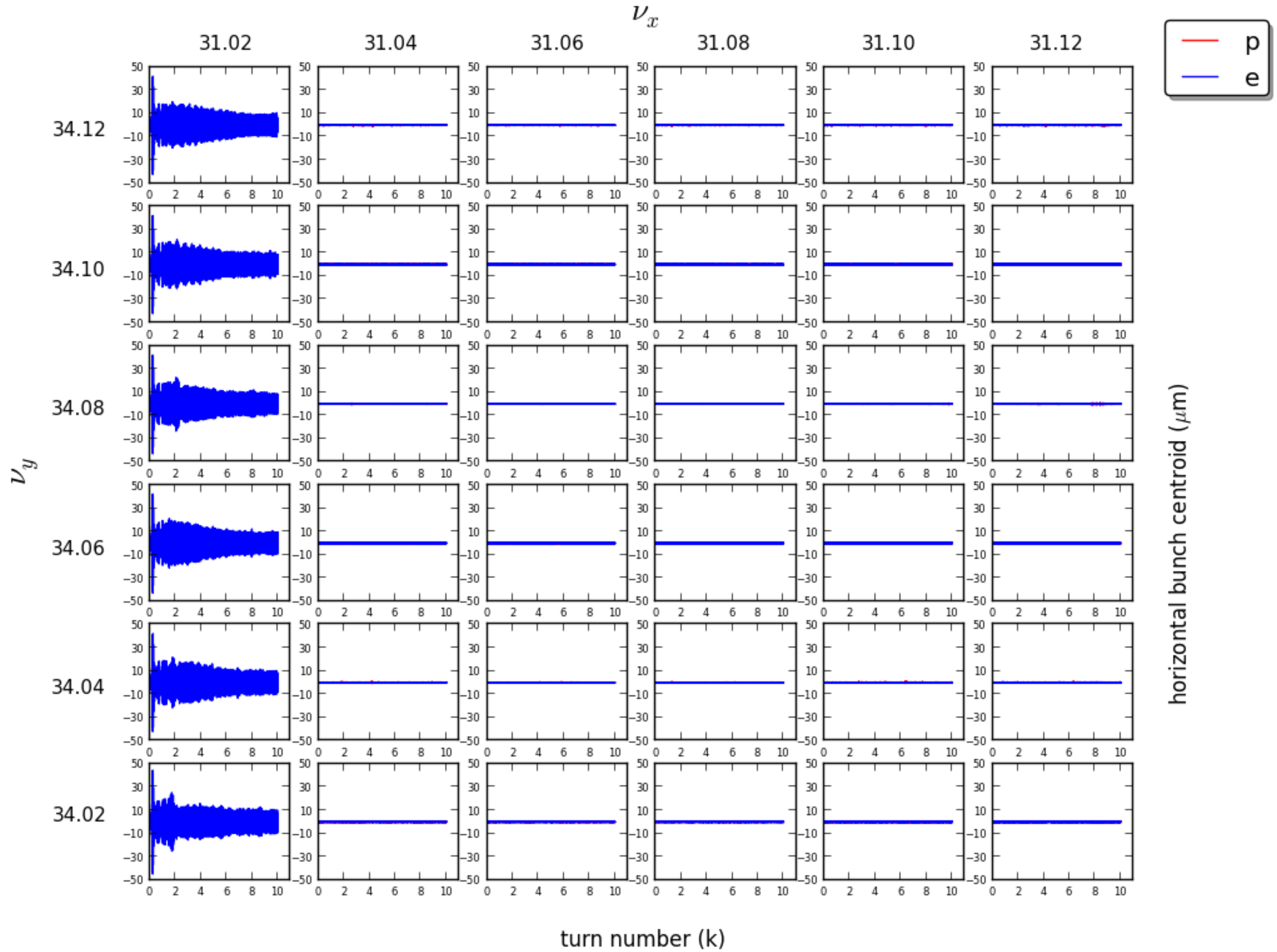
Horizontal beam size vs electron tunes



eRHIC Strong-Strong Beam-Beam Simulations
BBSS, head-on collision

G.Bassi, A.He

Horizontal beam centroid vs electron tunes

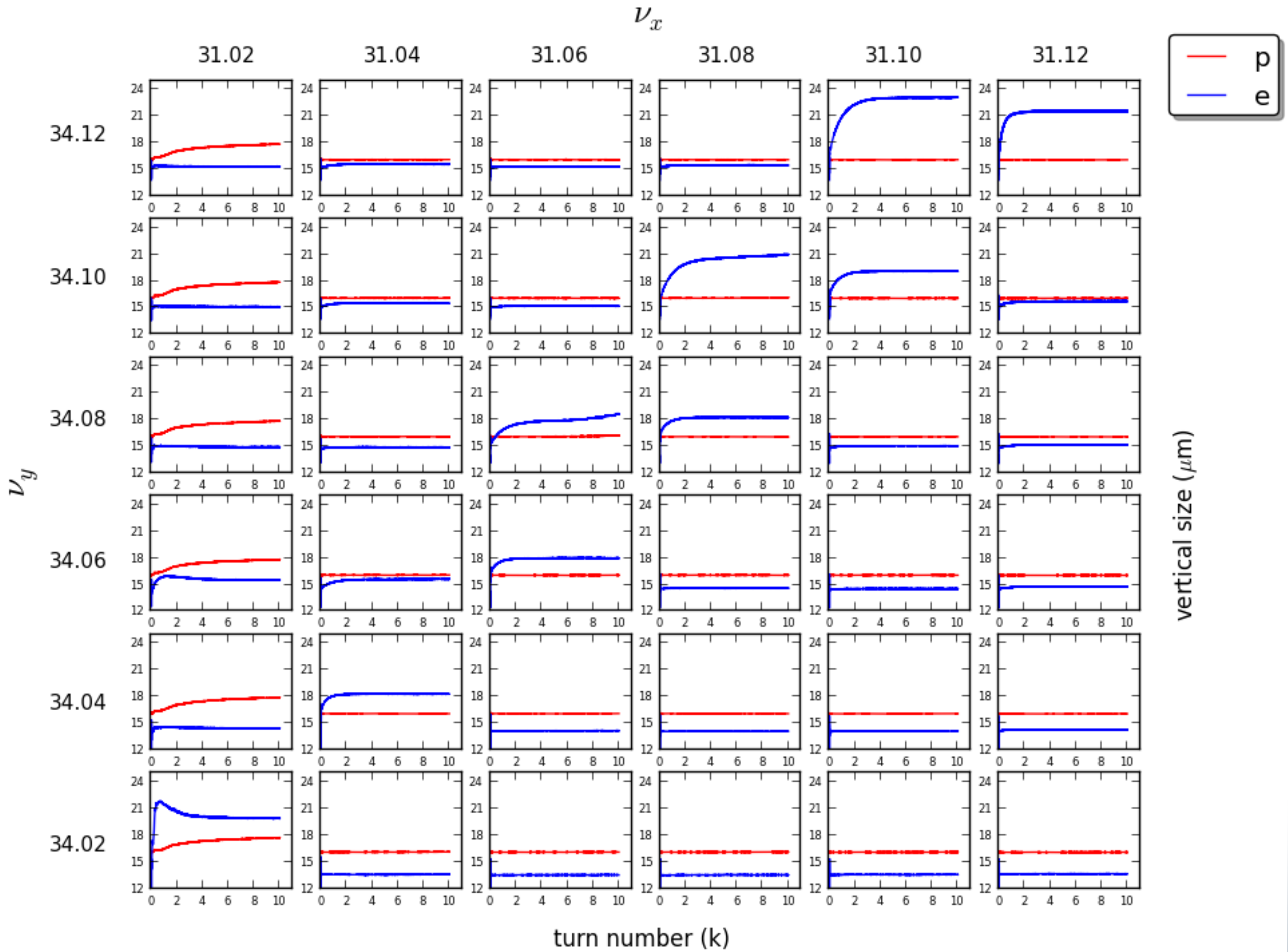


eRHIC Strong-Strong Beam-Beam Simulations

BBSS, head-on collision

G.Bassi, A.He

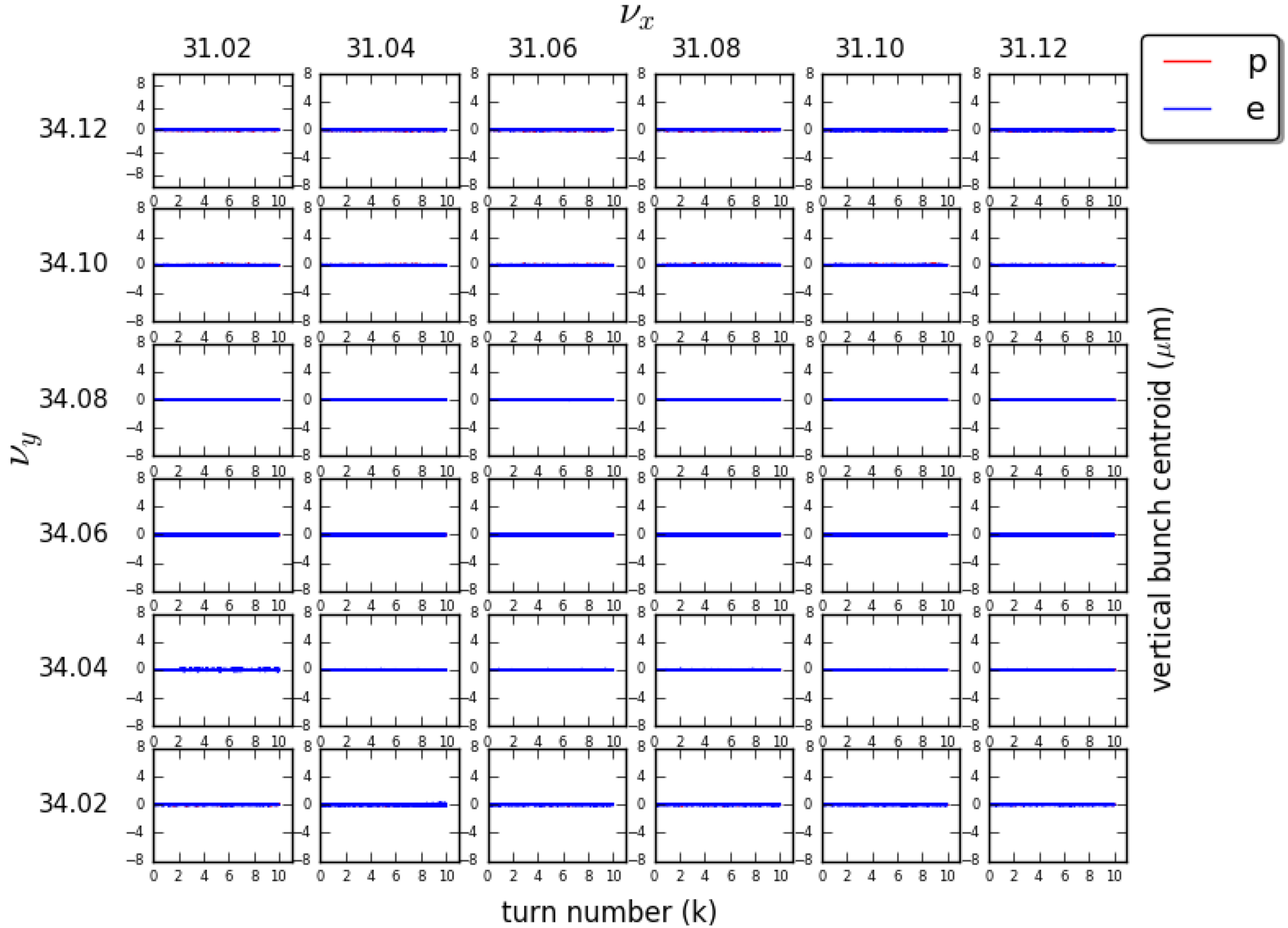
Vertical beam size vs electron tunes



eRHIC Strong-Strong Beam-Beam Simulations
BBSS, head-on collision

G.Bassi, A.He

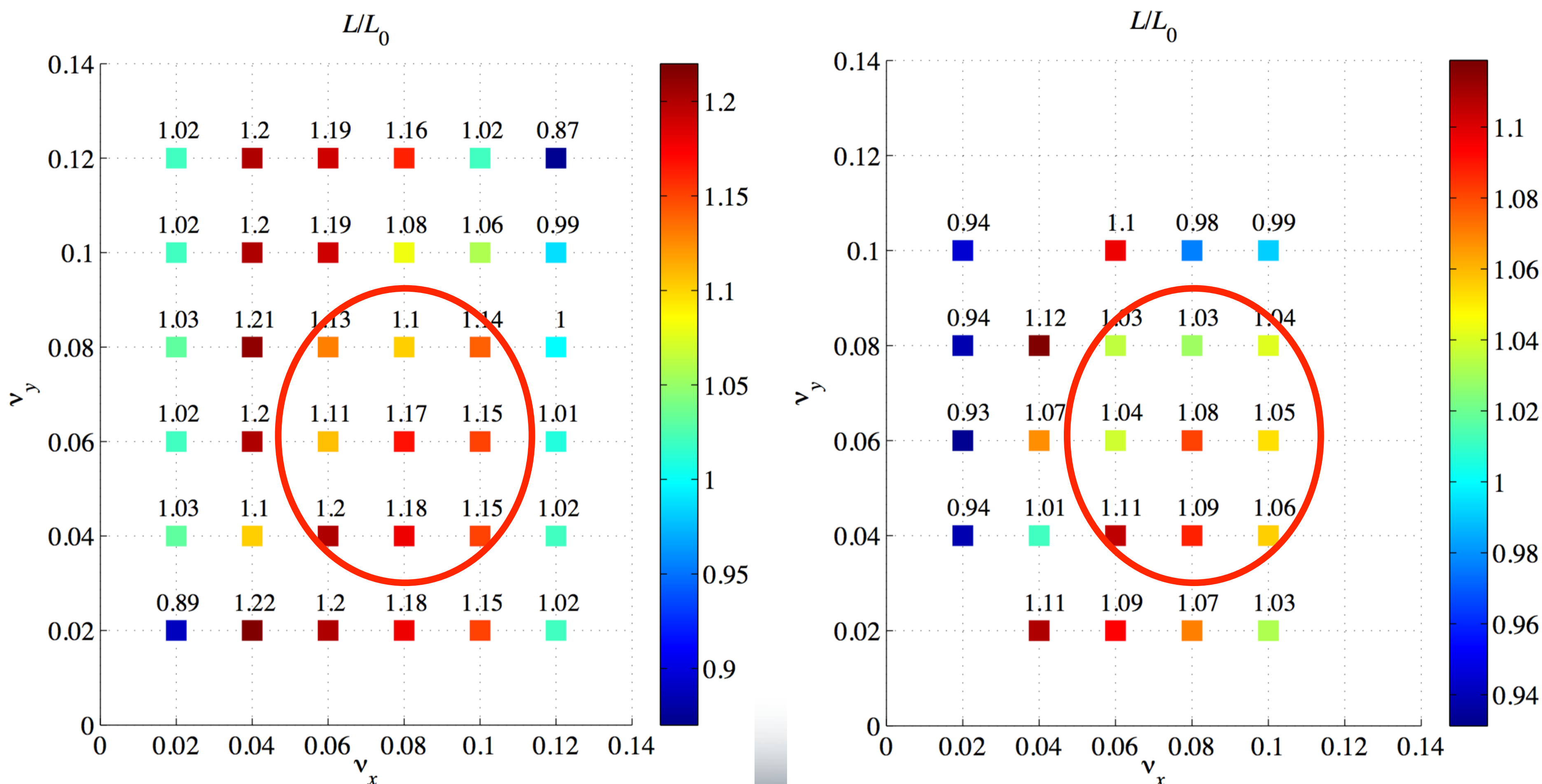
Vertical beam centroid vs electron tunes



eRHIC Strong-Strong Beam-Beam Simulations Luminosity

G.Bassi, A.He **BBSS** **BeamBeam3D** **Y.Hao**

Relative luminosity, 10k turns $L_0 = 2.9 \cdot 10^{33}\ \text{cm}^{-2}\text{s}^{-1}$ **Relative luminosity, 50k turns**

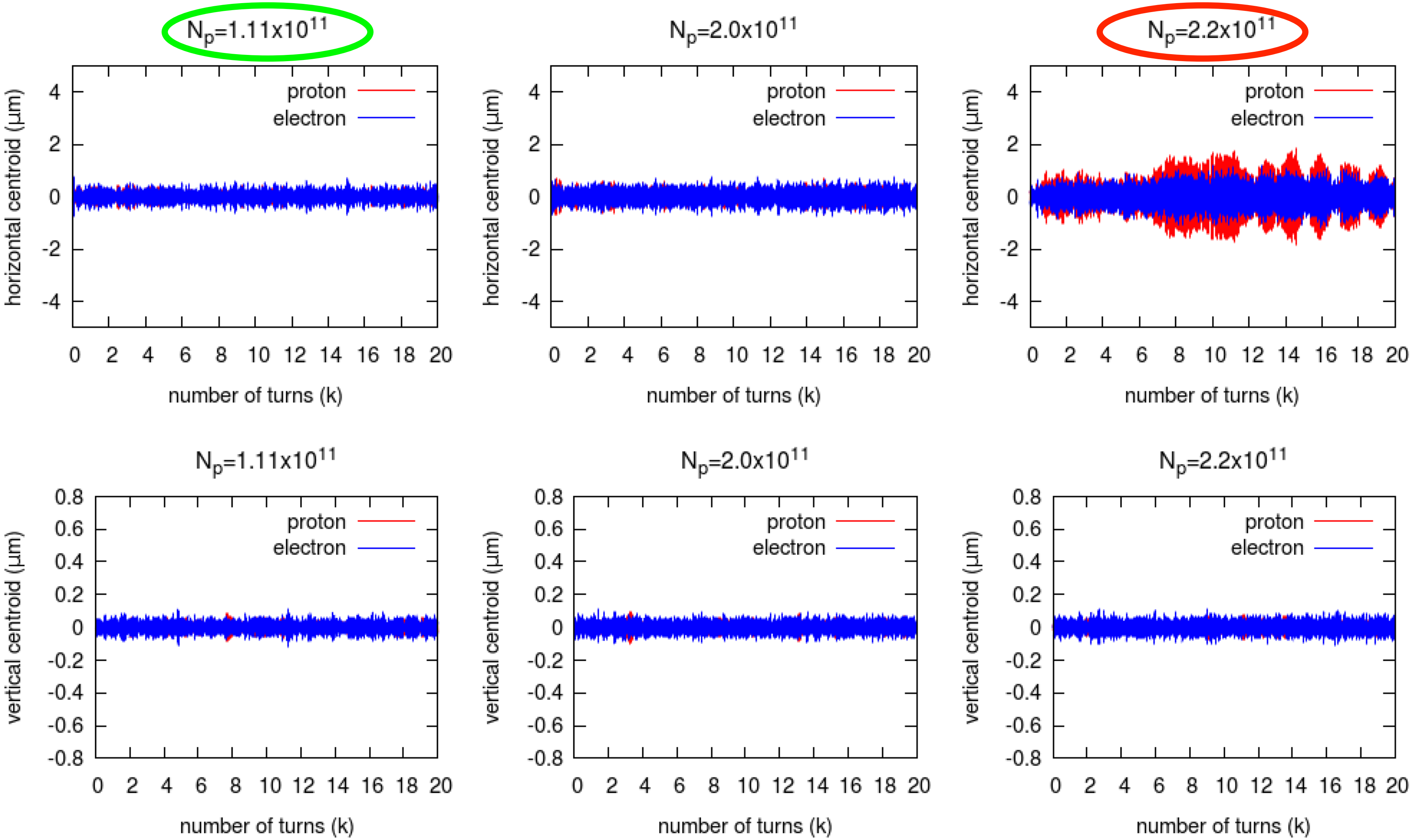


eRHIC Coherent Instability

Strong-Strong Simulations: BBSS, head-on collision

Nominal intensity is factor of 2 lower than the coherent instability threshold

G.Bassi, A.He



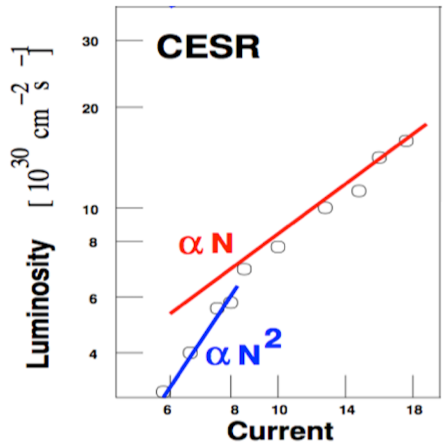
eRHIC Beam-Beam Limit
BBSS and SimTrack Simulations

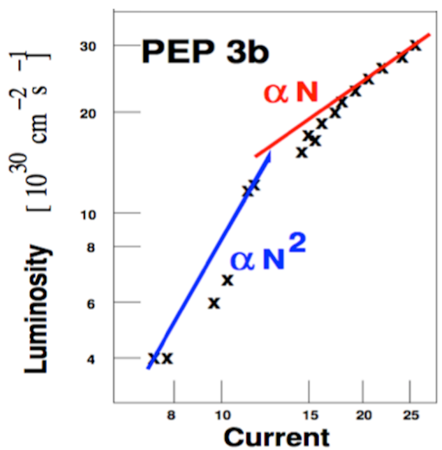
G.Bassi, Y.Luo

- Synchrotron radiation
- Coupling of oscillations
- Equilibrium between excitation and damping determines $\xi_{\lim}$

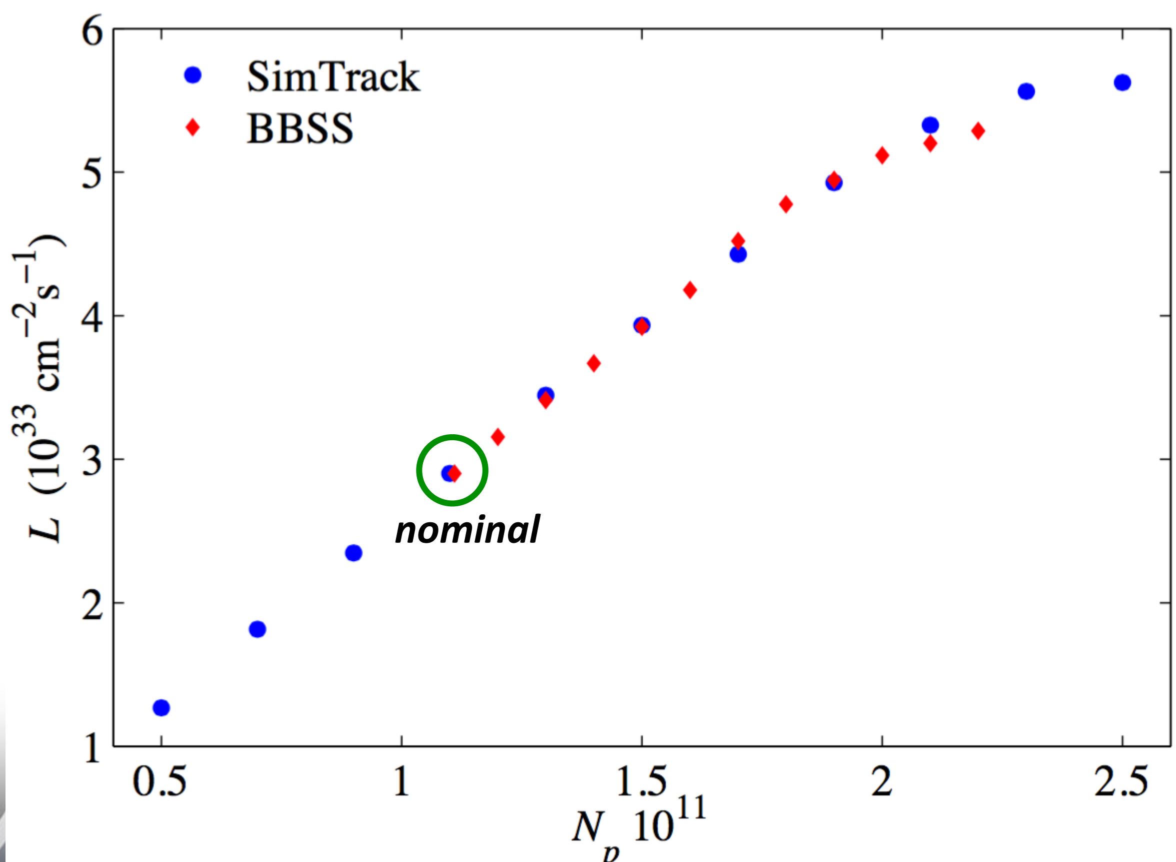
$$\text{electrons:}\quad Q_{x0} = 0.08,\quad Q_{y0} = 0.06$$

$$\text{protons:}\quad Q_{x0} = 0.310,\quad Q_{y0} = 0.305$$





Luminosity vs. proton bunch population



Summary and Conclusion

- Coherent and incoherent beam-beam effects are studied using weak-strong (SimTrack) and strong-strong codes (BBSS and BeamBeam3D).
- Optimal simulation parameters have been determined for the strong beam-beam simulations by comprehensive convergence studies of the BBSS code.
- Optimal tune working points have been found using weak-strong and strong-strong simulations:
  $Q_x = 0.31, Q_y = 0.305$ for protons
  $Q_x = 0.08, Q_y = 0.06$ for electrons
- Threshold intensity of the coherent instability has been found using strong-strong simulations: $N_p = 2.2 \cdot 10^{11}$ (2 times larger than nominal).
- Two simulation codes (BBSS and SimTrack) show that the beam-beam limit exceeds the nominal intensity almost 2 times.
- For the nominal eRHIC parameters, neither significant emittance growth nor coherent instability was observed in the simulation results at the optimal working points (head-on collision, single interaction point).

More Beam-Beam Studies

More results of beam-beam simulations for eRHIC are presented in the following talks:

- Beam-beam - Beam-beam interaction with crossing angles

- Beam-beam effects with multiple interactions points in eRHIC

- Effects of electron bunch replacement in eRHIC

- Proton beam emittance growth due to strongly disrupted electron beam in eRHIC

- Filling patterns for 2 interaction regions
- Parasitic beam-beam effects
- Radiation damping time + beam-beam
- Numerical effects in strong-strong beam-beam simulation
- Crossing collision + crab cavities

Thank you for your attention!

Beam-Beam Effects

Electromagnetic fields of a colliding beam act on particles like a very special electromagnetic lens:

- highly non-linear (forces depend on the particle distribution);
- time-dependent (the particle distribution is changed due to beam-beam interaction).

Beam-beam effects result in:

- shifting betatron tunes;
- changing effective beta function at the interaction point (dynamic beta);
- changing transverse emittance of the beams;
- coherent instabilities;
- decreasing luminosity.

Studying and modeling beam-beam effects:

- field-particle interaction + non-linear dynamics + multi-particle dynamics.
- analytical approach is limited to simplified cases.
- computer simulation is the main tool.