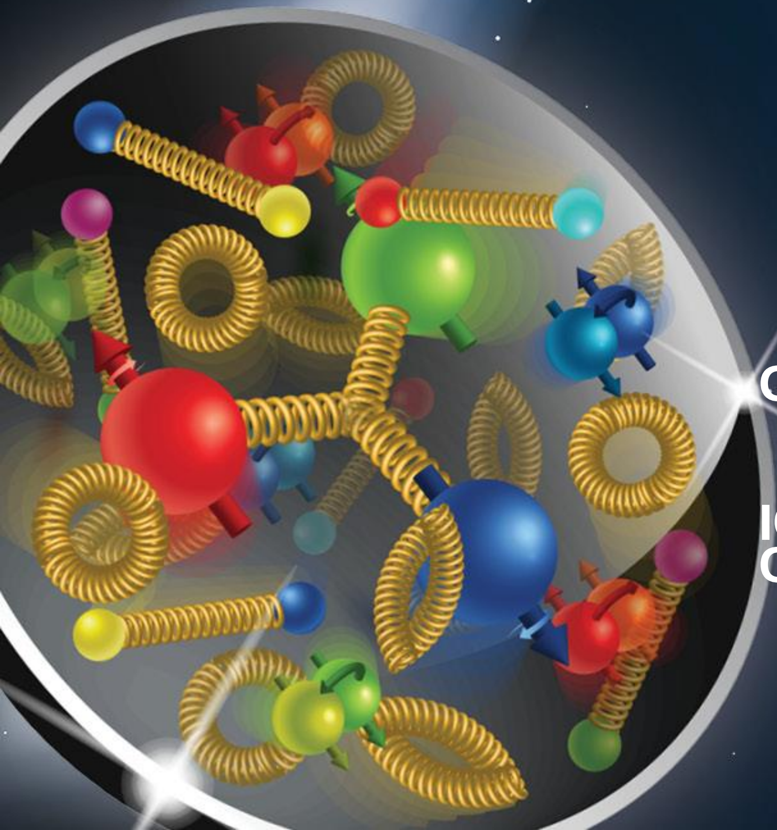
Systematic study of beam-beam effects in electron ion colliders by a combination of strong-strong and weak-strong simulations



Yun Luo

On behalf of eRHIC beam-beam study team

ICFA Mini-Workshop on Dynamic Apertures of Circular Accelerators, Beijing, China, Nov. 1-3, 2017

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY

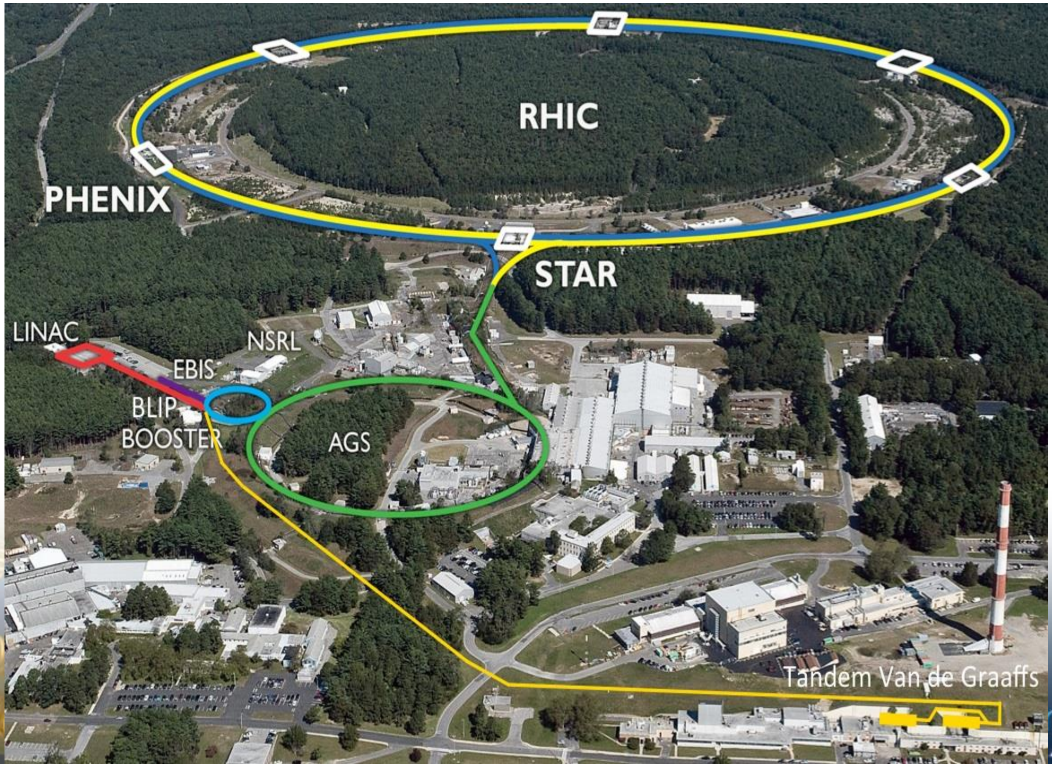
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Introduction to eRHIC Design
- BB Study Strategies for eRHIC
- Head-on Collision Study
- Crabbed Collision Study
- Summary
- Appendix: Additional Considerations

Relativistic Heavy Ion Collider (RHIC)

- RHIC at Brookhaven National Laboratory collides heavy ions and polarized protons since 2000.
- RHIC injectors includes AGS, Booster, Linac and ion sources from EBIS and Tandem Accelerator. Beam top energy: proton 255GeV, ion 100GeV/nucleon.
- Two physics experiments: STAR (IP6) , PHENIX (IP8).

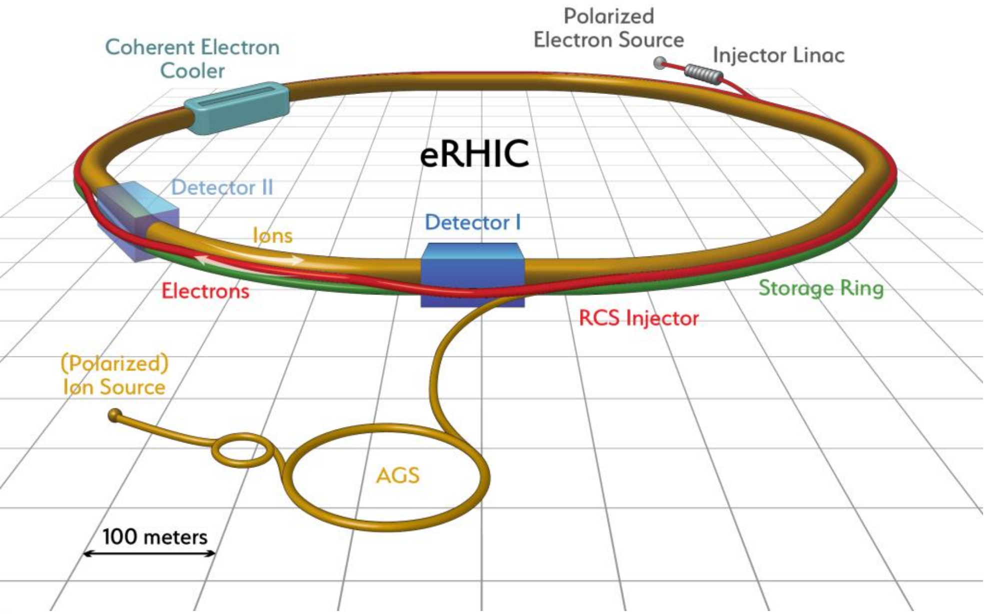


RHIC Upgrade: eRHIC

Main Accelerator Design Goal for eRHIC:

- L ~$\mathbf{10^{33}}$**-**$\mathbf{10^{34}}$ **cm^{-2}s^{-1}**
  (exceeding HERA luminosity by 2 orders of magnitude)
- High electron and proton polarization (>**70%**);
  Realizing complex spin pattern for electrons and protons
- Large acceptance detector
  with detector elements integrated in the accelerator IR for forward particle detection
- Minimizing the construction and operational cost of accelerator

Pre-CDR Design Concept



- Added electron storage ring (**5-18 GeV**)
  - Up to 2.1 A electron current.
  - 10 MW maximum RF power (administrative limit)
- Flat proton beam formed by cooling
- On-energy polarized electron injector
  (**RCS** is a cost-effective injector option)
- **Polarized electron source** and 400 MeV injector linac:
  10nC, 1 Hz

(slide: courtesy of V. Ptitsyn)

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6

Strong-strong and Weak-strong

1) Strong-strong beam-beam simulation

Both bunches represented by million macro-particles
Particle-in-cell method used to solve 2-D Poisson equation

Self-consistent treatment, time consuming & numerical noise

Used to study coherent beam-beam motion and its stability

A must when beam-beam parameter is large

2) Weak-strong beam-beam simulation

Strong bunch represented by 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

Element-by-element tracking with lattice nonlinearities possible

Used to study single particle's long-term stability

Very productive for small beam-beam parameter situation (in most our cases)

Staged Simulation Studies

1) Without full lattice design (**early design stage**):

focus on multi-particle and long-term tracking

focus on slow emittance blow-up, luminosity decay from BB

parameter scans: tunes, bunch intensity, crab cavity, etc.

2) With detailed lattice design :

focus on single-particle tracking and long-term dynamic aperture

element-by-element tracking include lattice nonlinearities

interaction between BB and lattice nonlinearities

re-do parameter scan: tune, bunch intensity, crab cavity, etc.

Simulation Codes

- Weak-strong Codes

- SimTrack: a compact C++ code for particle orbit and spin tracking
  Y. Luo, NIM A (2015) 95-103; Y. Luo ; 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 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
- SimTrack (Y. Luo , BNL) also can be used for strong-strong BB simulation

Machine and Beam Parameters

	Unit	Proton	Electron
Circumference	m	3833.845	3833.845
Energy	GeV	**275**	**10**
Bunch population		1.11	3.05
Number of bunches		330	330
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	

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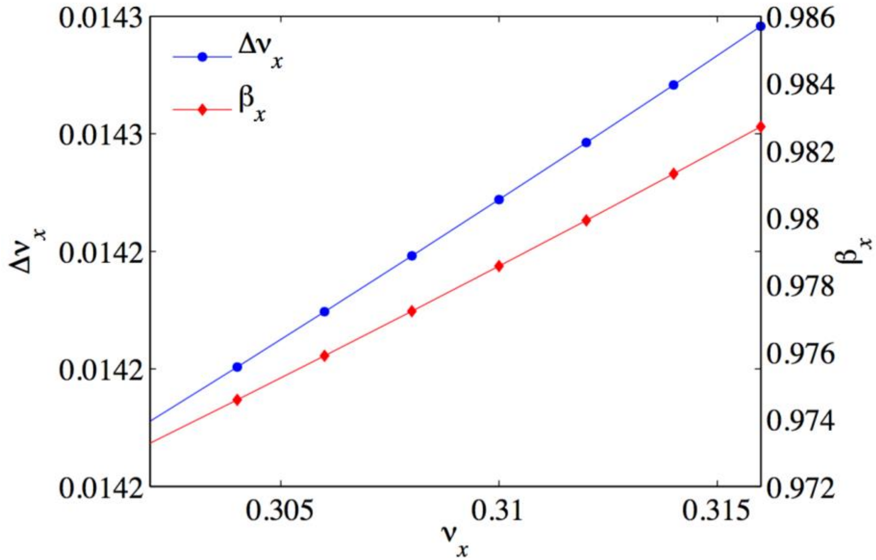
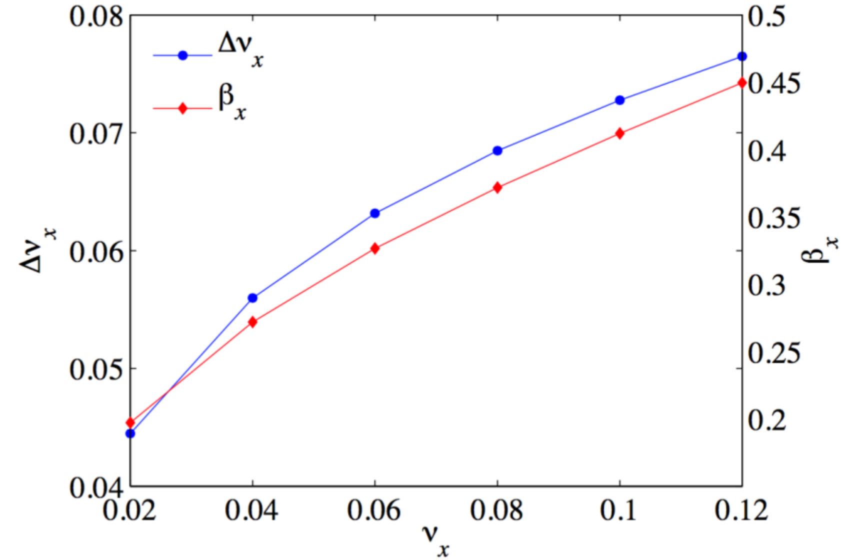
Dynamic Beta Effects

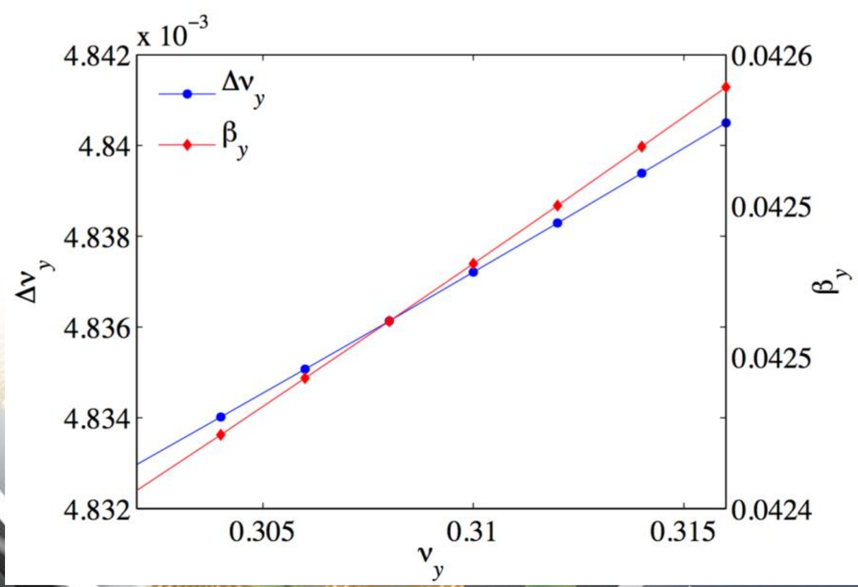
Y. Luo

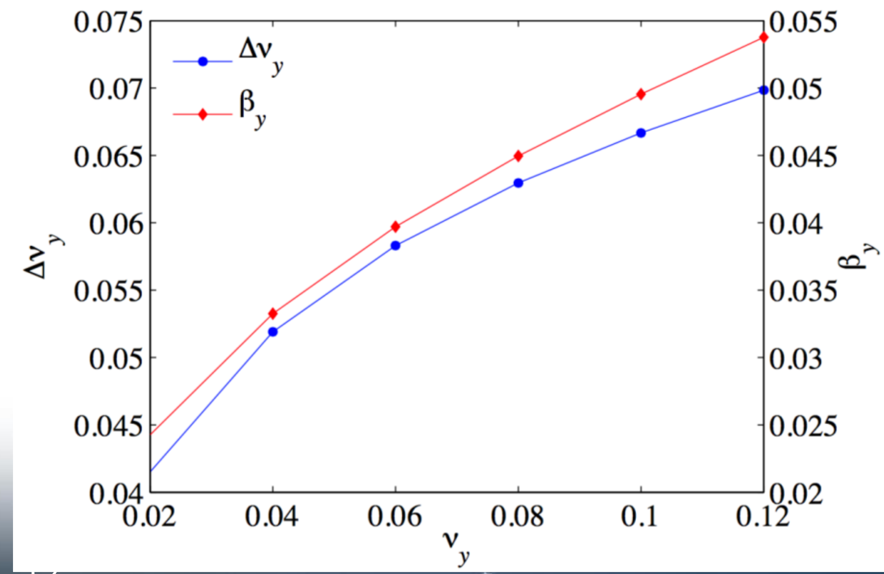
Proton tune scan



Electron tune scan





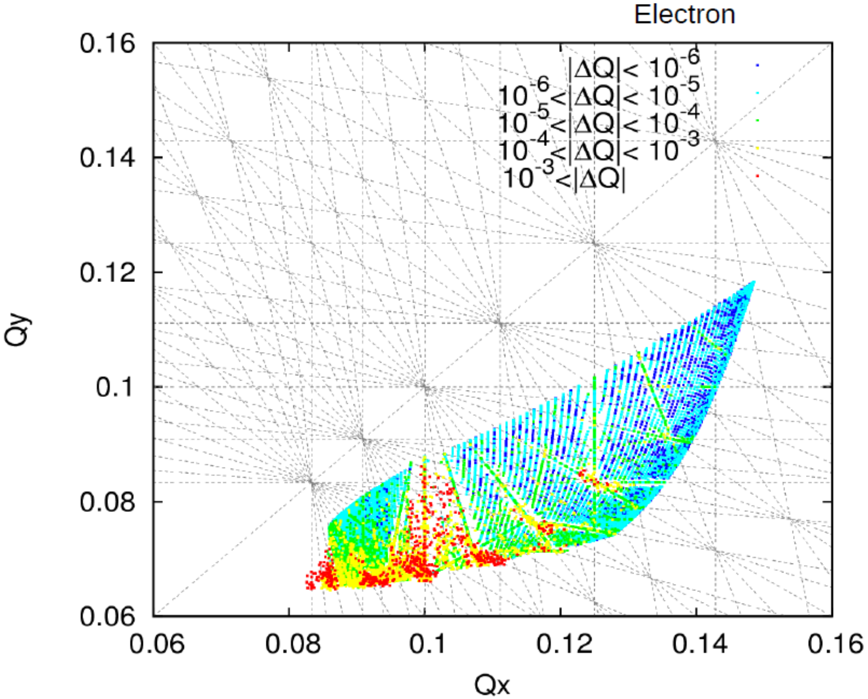


Tune Footprint /Tune Diffusion

Y. Luo

Electron ring

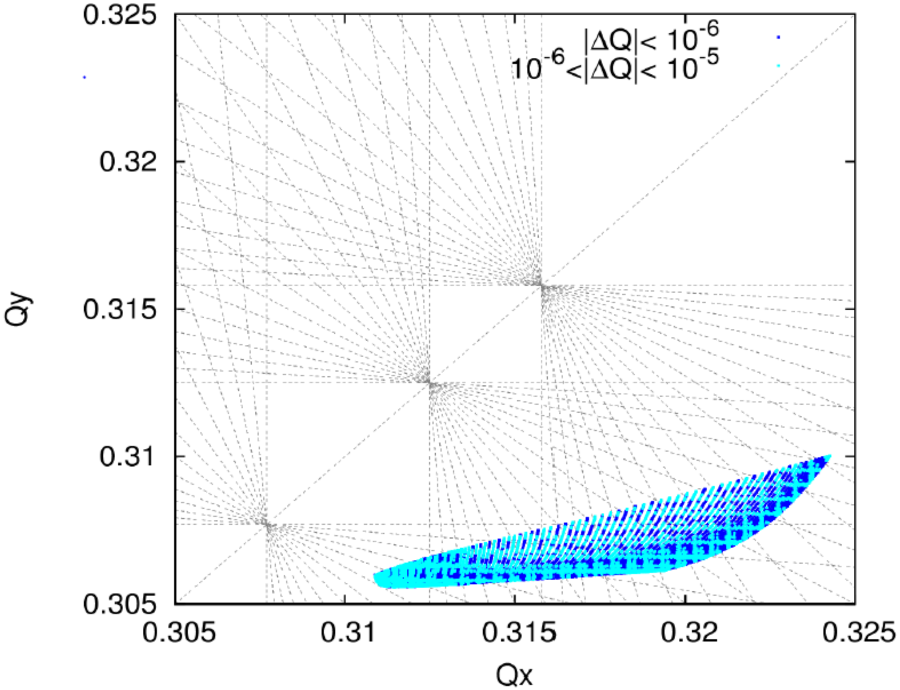
$\xi_x = 0.092, \ \ \xi_y = 0.083$



Electron design tunes (0.08, 0.06)

proton ring

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



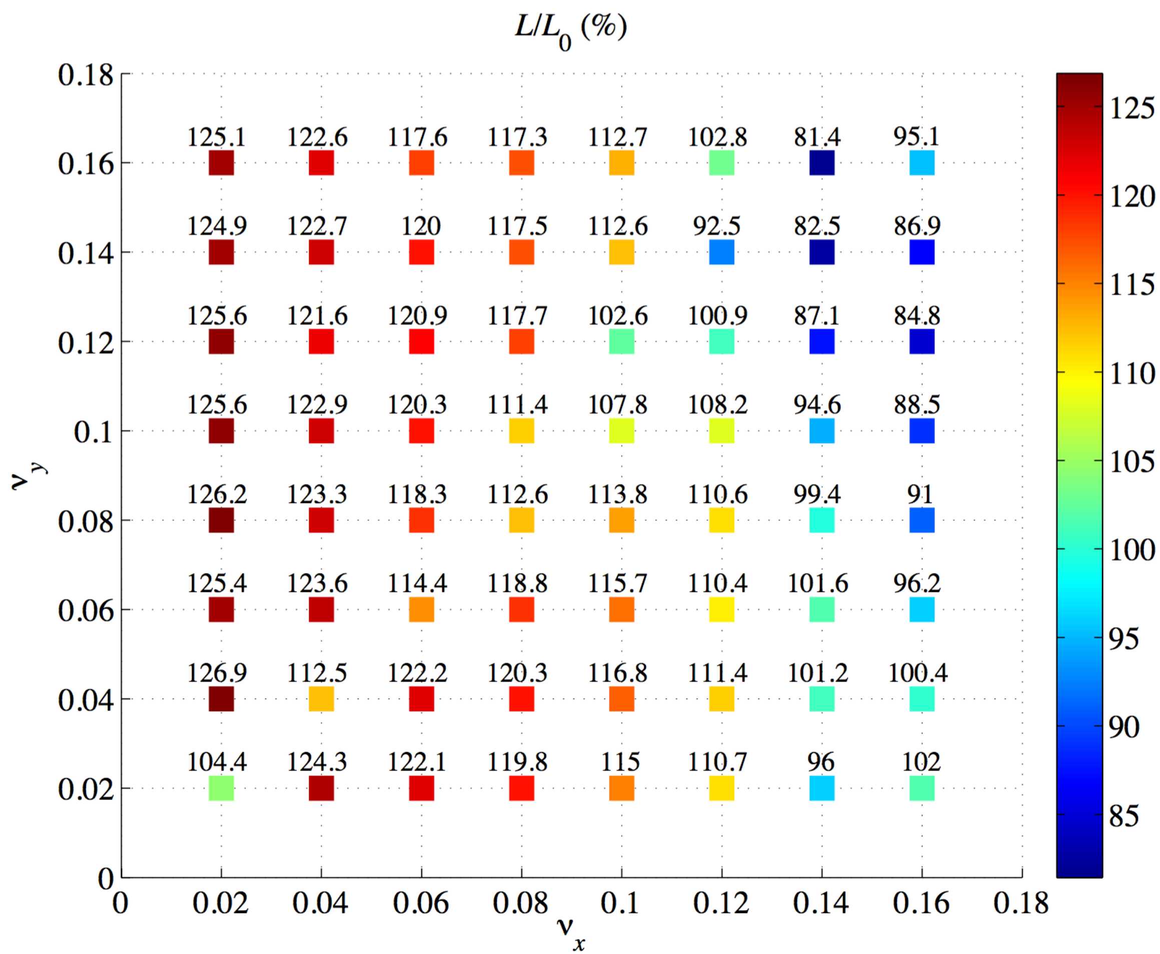
Proton design tunes are (0.310, 0.305)

Weak-strong: tune scan

Electron tune scan, 50k turns

Y. Luo

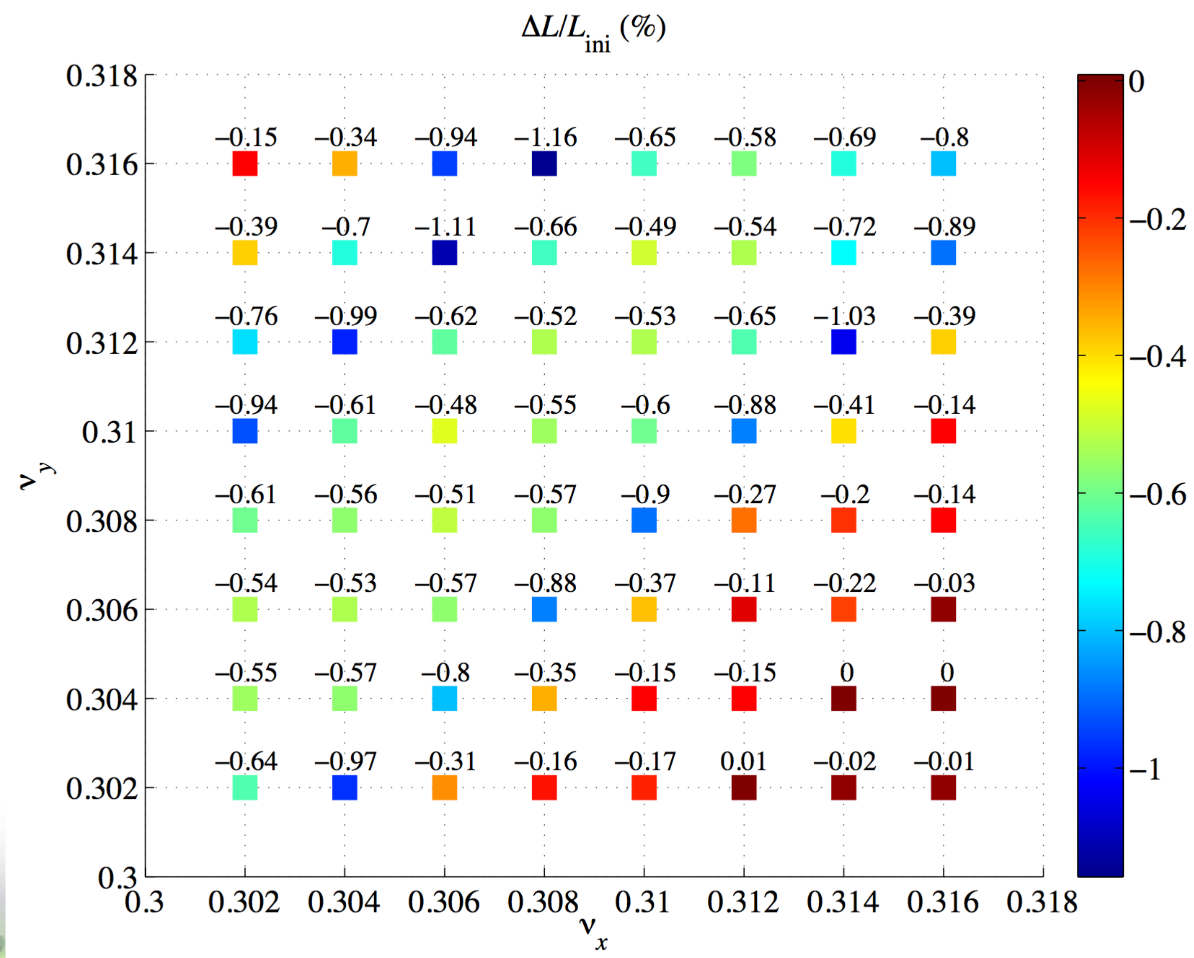
Relative luminosity: $L/L_0, \quad L_0 = 2.9\times10^{33}\ \mathrm{cm^{-2}s^{-1}}$



Proton tune scan, 1M turns

Y. Luo

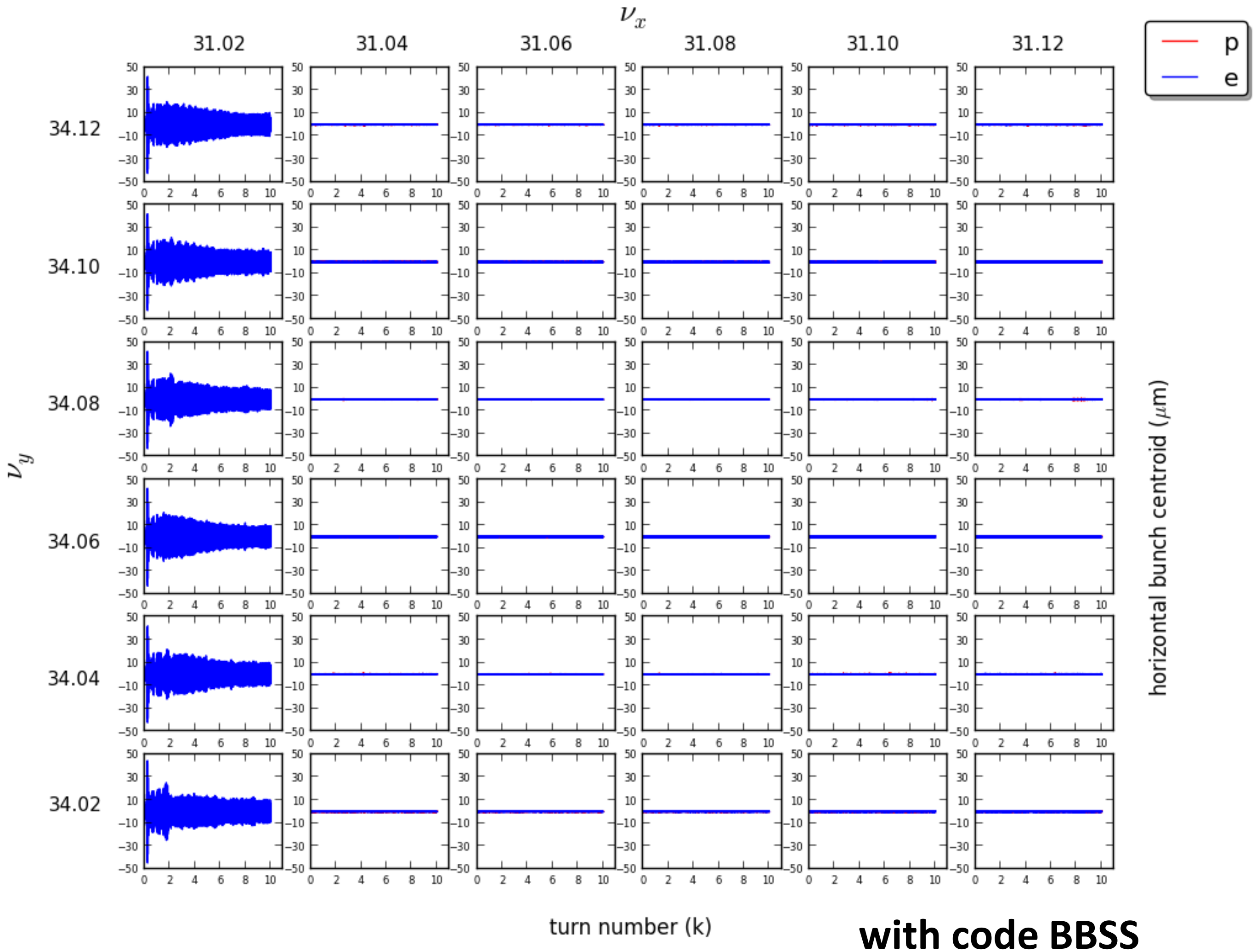
Luminosity decay: $\Delta L / L_{ini}$, $\Delta L = L_{fin} - L_{ini}$, L_{ini} - first 10k turns, L_{fin} - last 10k turns



Strong-strong: tune scan

G.Bassi, A.He, W.Guo

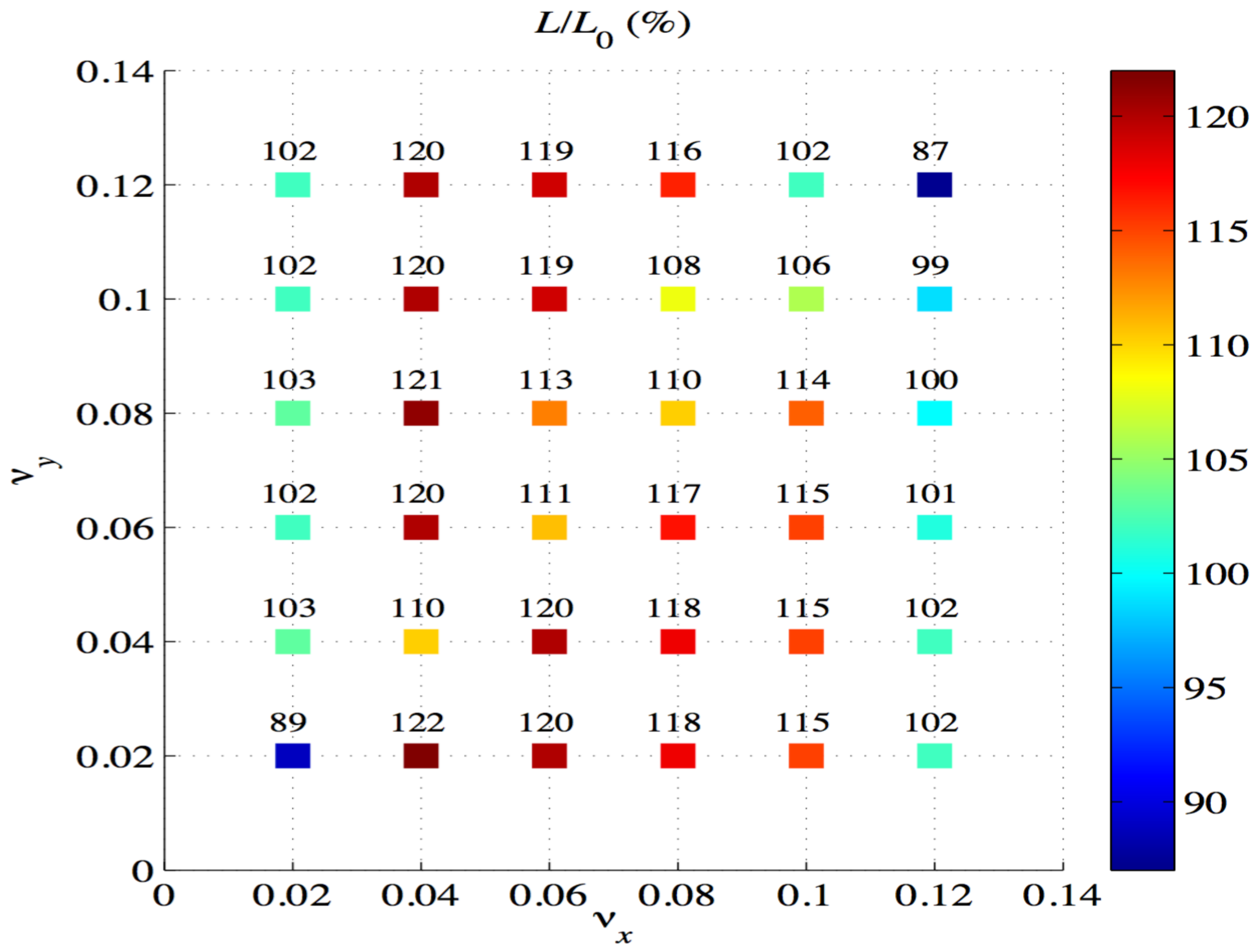
Electron tune scan: Horizontal beam centroid motion <x>



with code BBSS

Electron tune scan: luminosity

G.Bassi, A.He, W.Guo

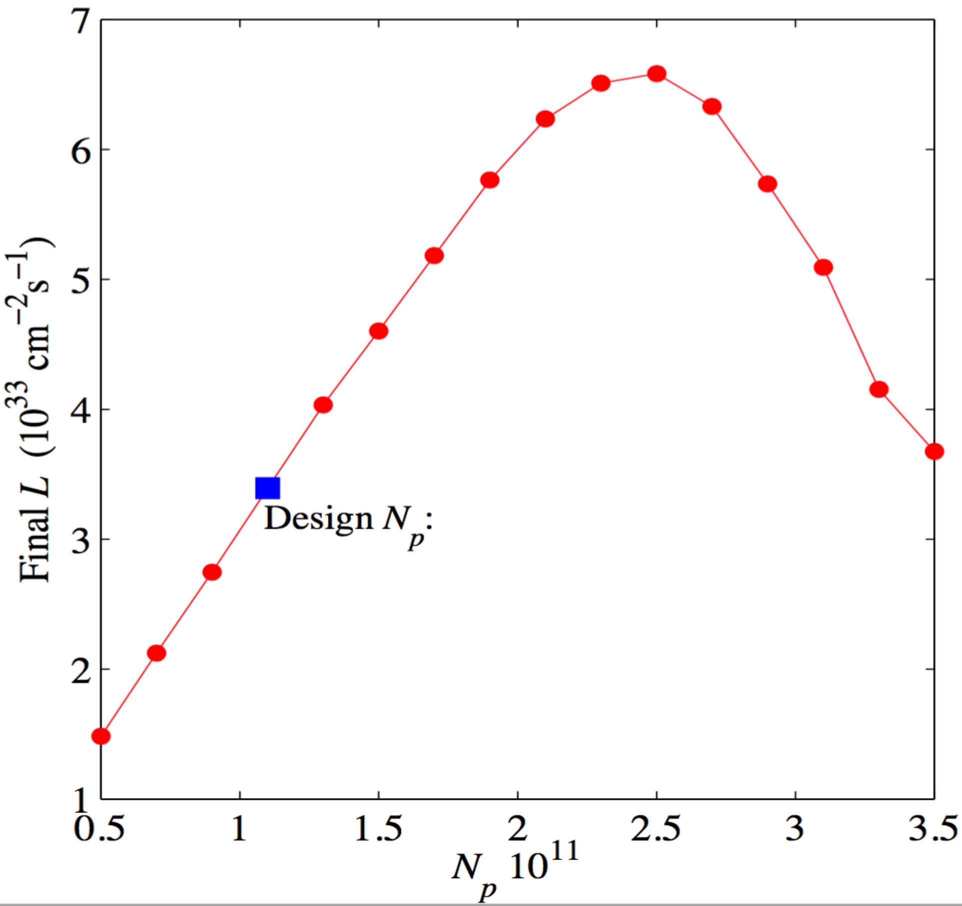


Beam-beam Limit: weak – strong simulation

Y. Luo

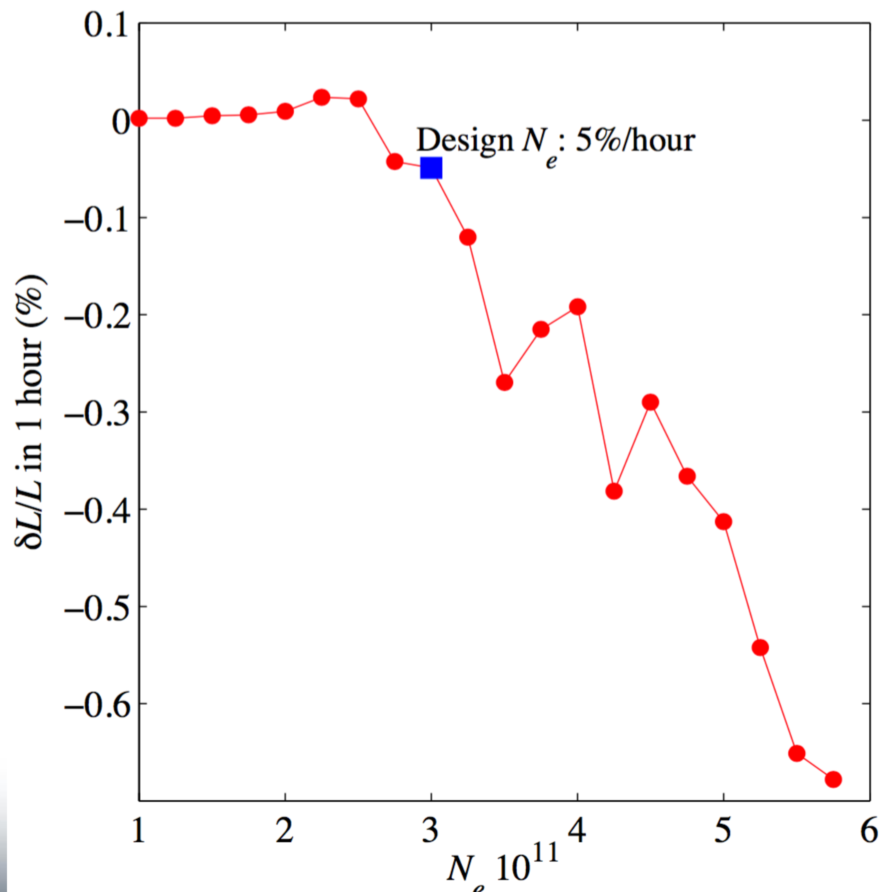
Proton intensity scan

Final luminosity after 50k turns.



Electron intensity scan

Luminosity loss percentage in 1 hour (averaged from 1M turn tracking).



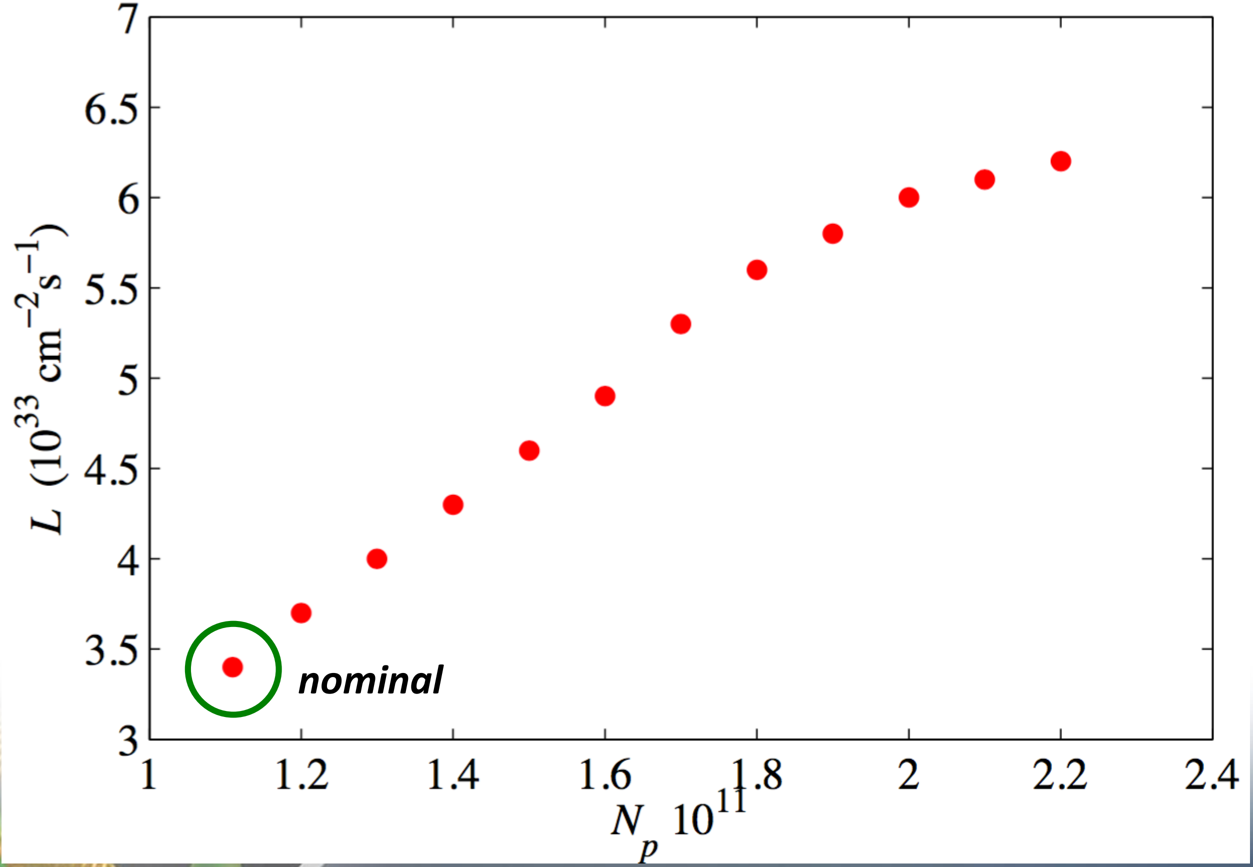
Beam-Beam Limit: strong-strong simulation

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

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

G.Bassi, A.He

Luminosity vs. proton bunch population

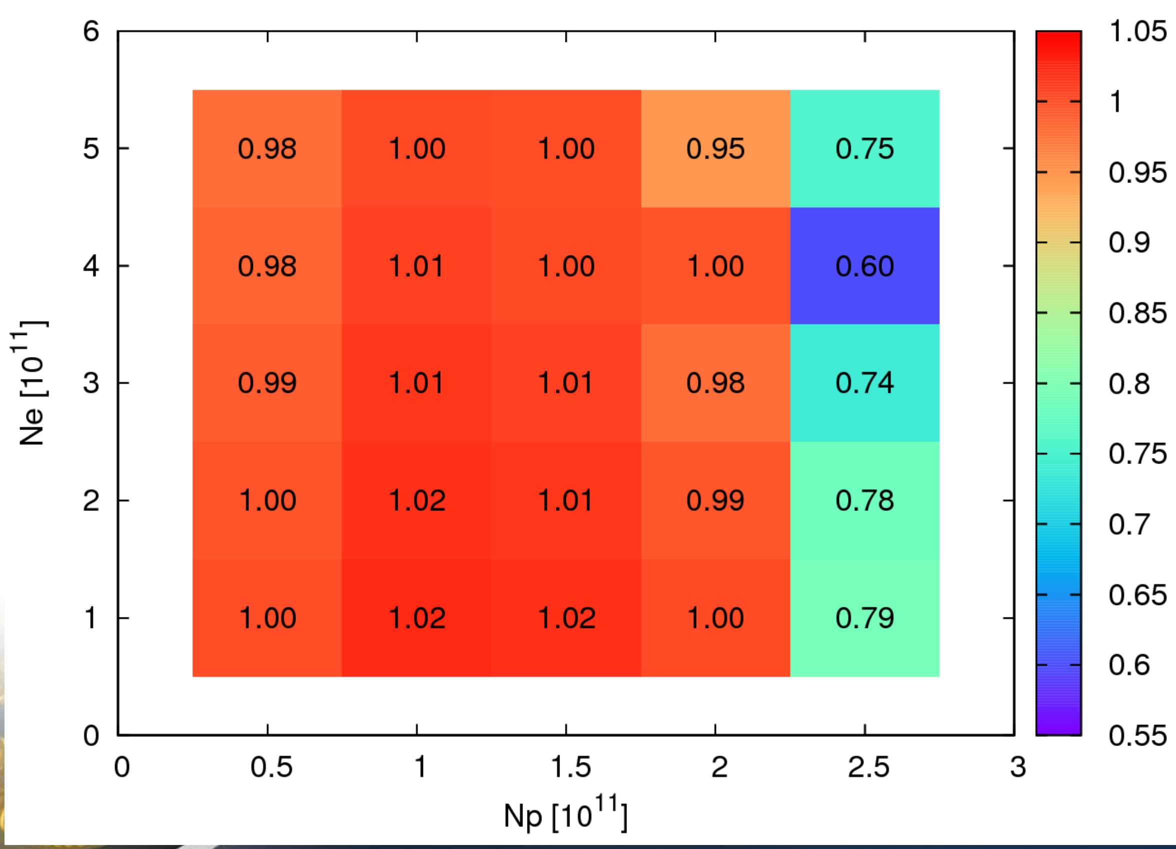


Beam-Beam Limit: 2-D bunch intensity scan

Define $$\kappa = \frac{L(N_p, N_e)}{L(N_{p0}, N_{e0})} \frac{N_{p0}}{N_p} \frac{N_{e0}}{N_e}$$

Y. Luo

If there is no emittance blow-up, κ will remain constant.



with SimTrack

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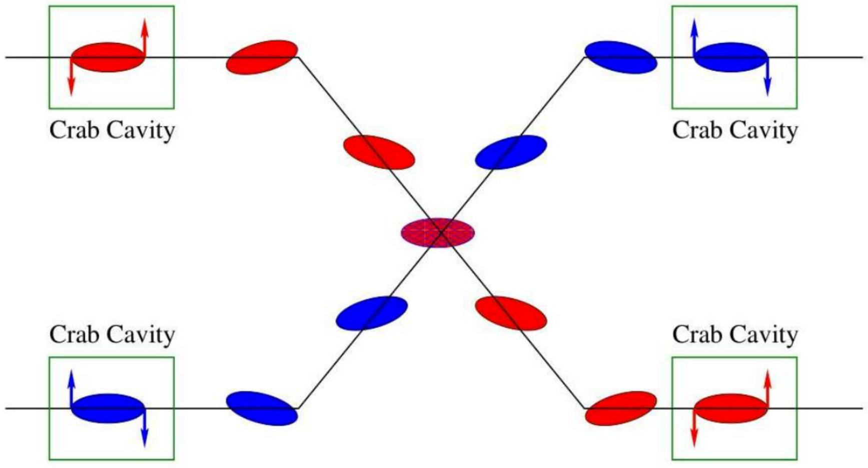
Scheme of Local Crabbing

- To compensate the geometric luminosity loss due to a **horizontal crossing angle of 22mrad**, and to avoid the long-range beam-beam interaction, crab cavities are to be used to make sure the electron and proton bunches collide head-on at IP.
- **Local crabbing scheme** is to be adopted. Two sets of crab cavities are located on both sides of IP, with a π/2 horizontal betatron phase advances to IP.

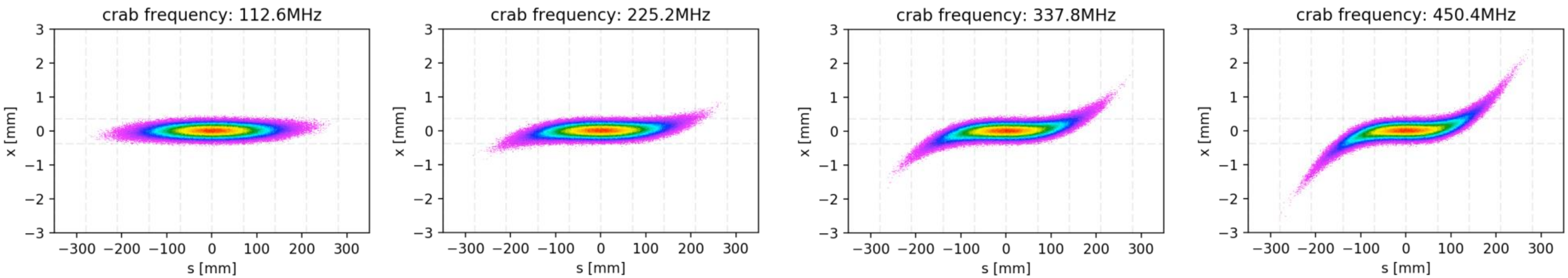


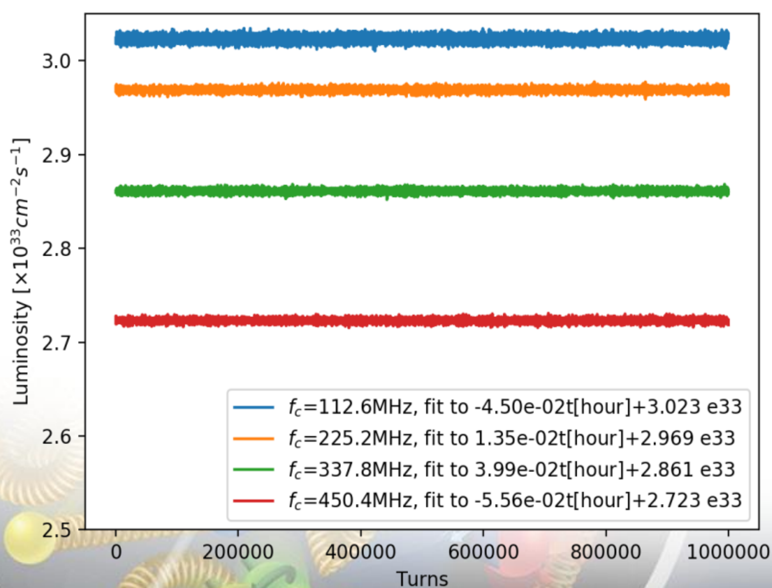
The voltage of crab cavity:

$$\hat{V}_{rf} = -\frac{cE_s}{4\pi f_{rf}\sqrt{\beta_x^* \beta_{cc}}}\theta_c$$

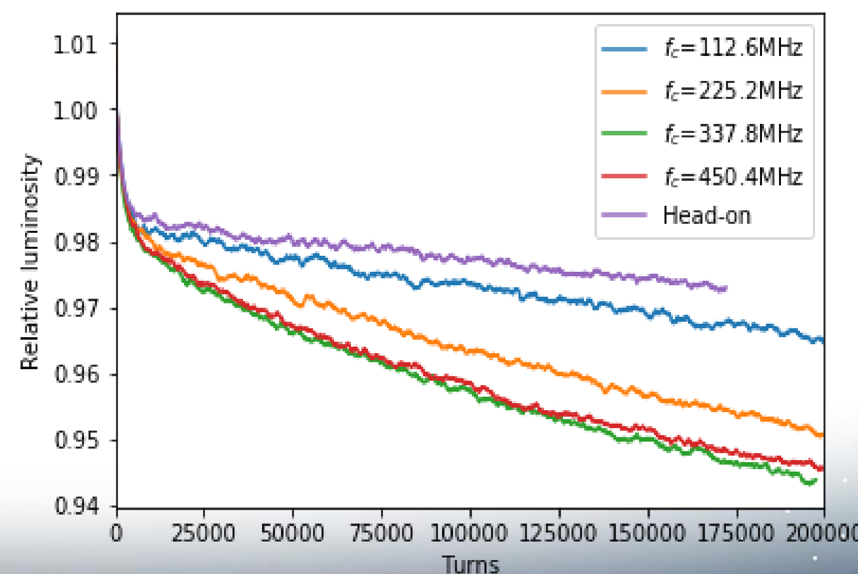
Crabbing with different frequencies

Y.Hao, Y. Luo





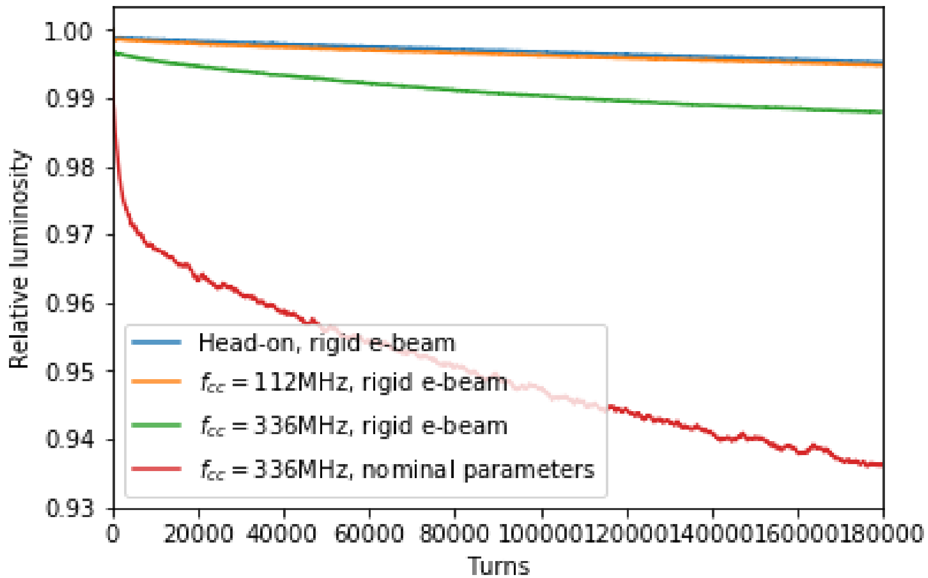
Weak-strong simulation (SimTrack)

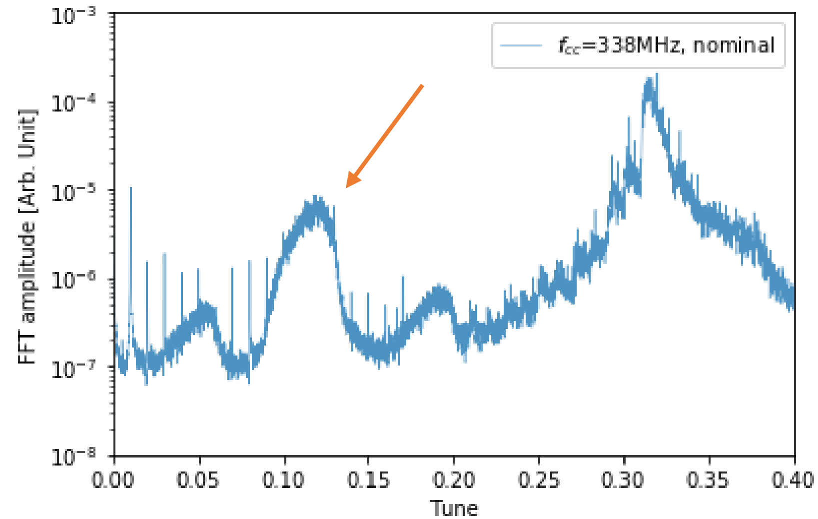


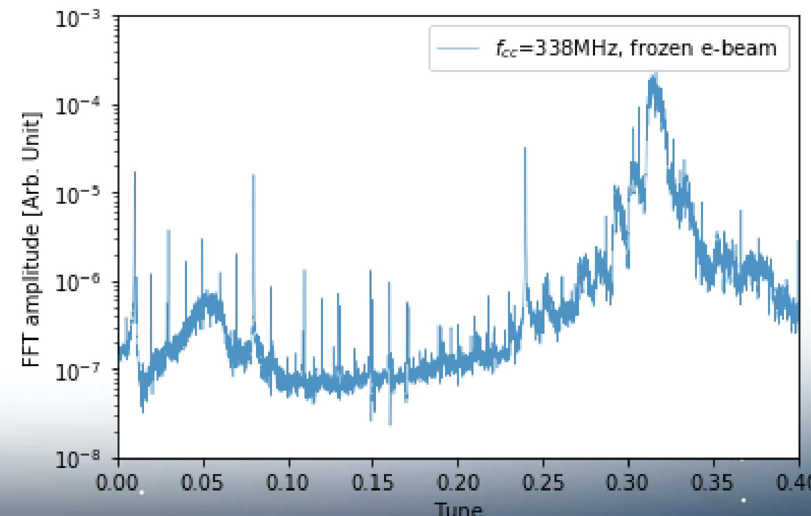
Strong-strong simulation (BeamBeam3D)

Crab Crossing Resonance (I)

Y.Hao



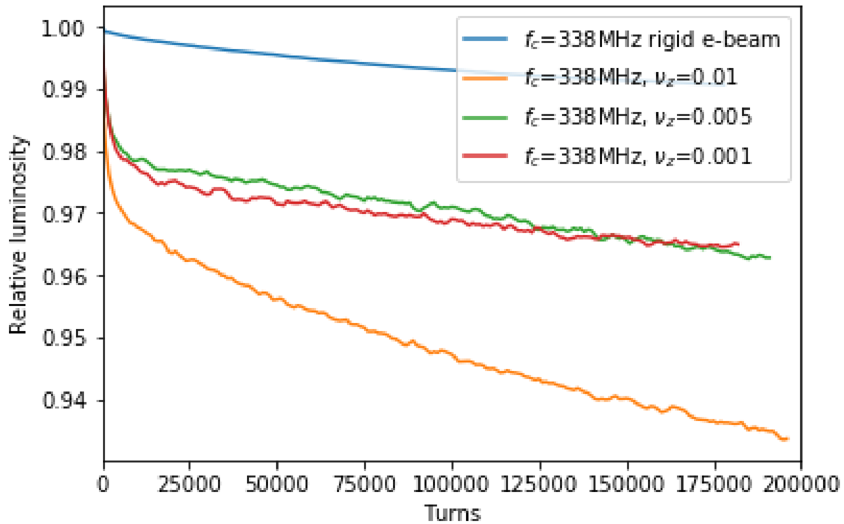


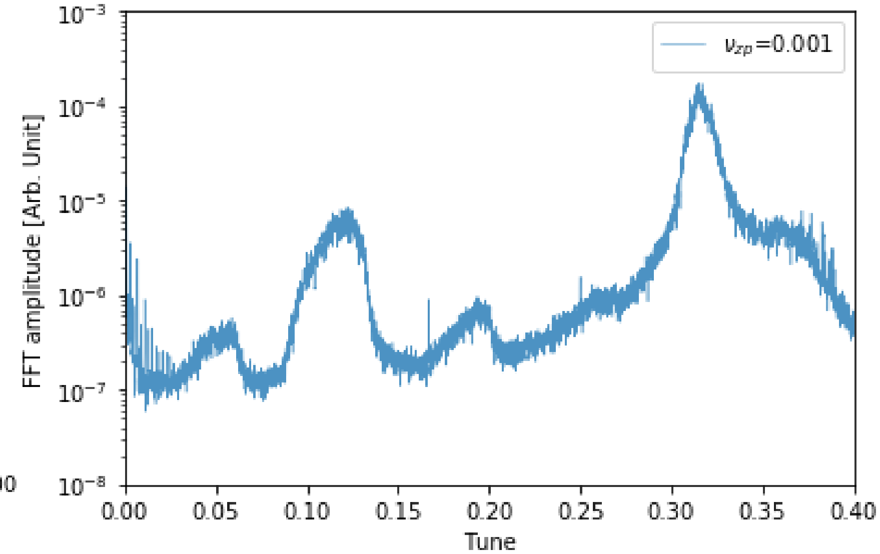


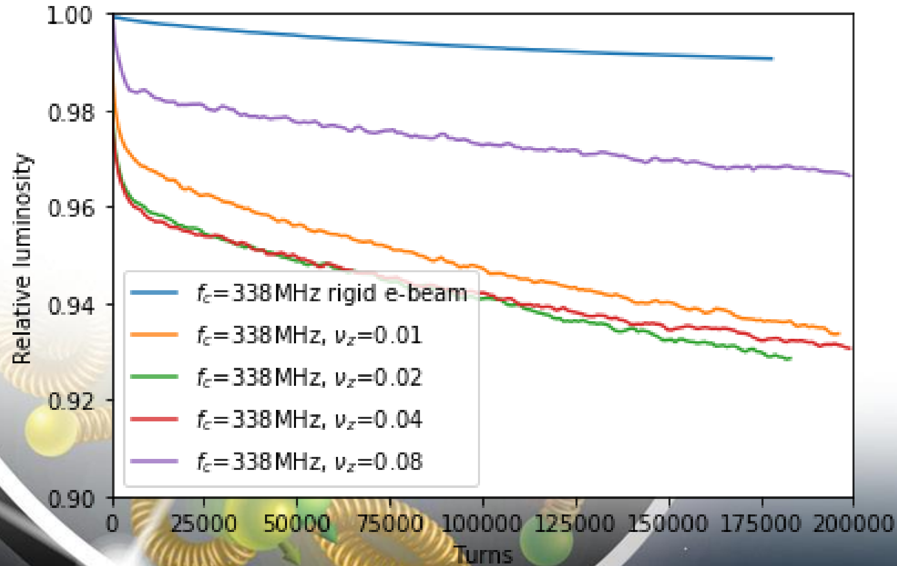
By comparing with the ‘frozen’ electron case, we believe there is physics reason that cause the lumi-degradation observed in the strong-strong simulations.

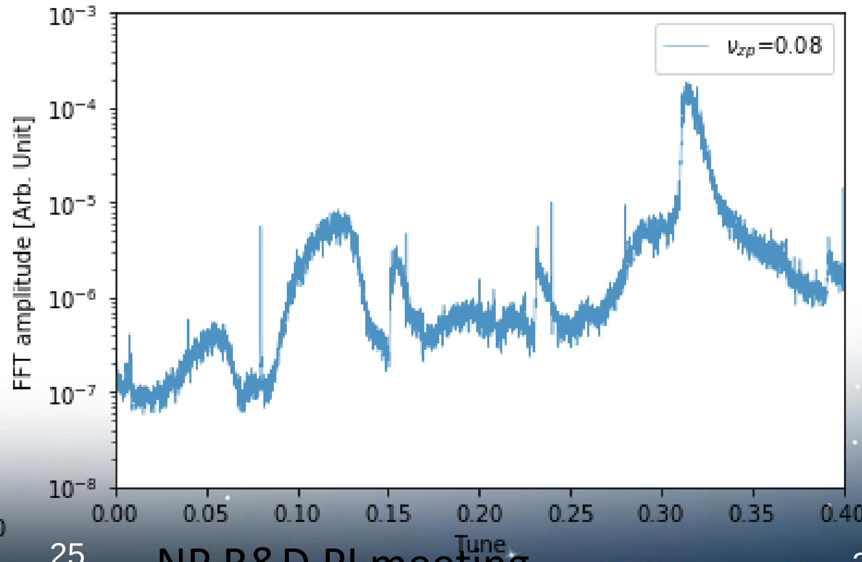
Crab Crossing Resonance (II)

Y.Hao





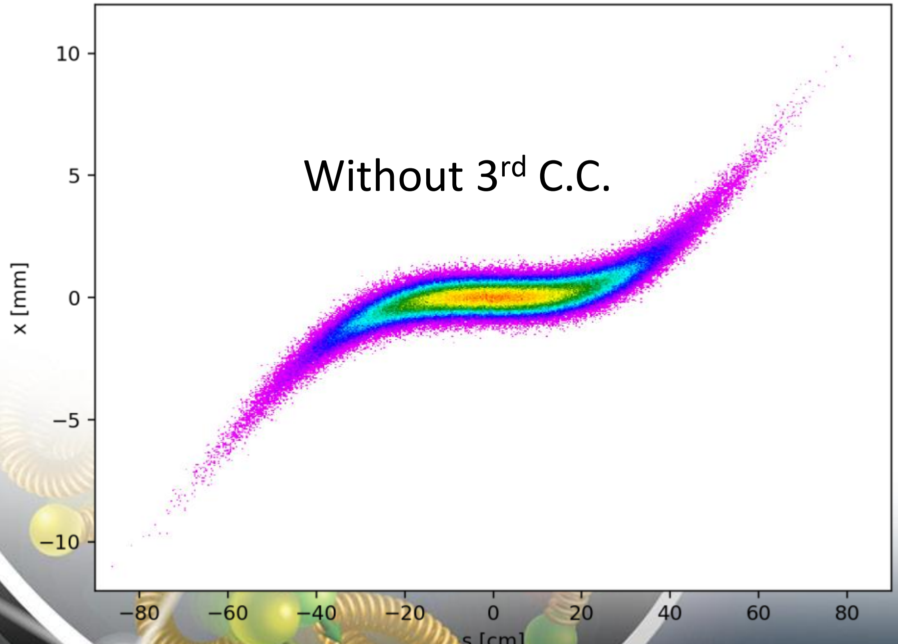


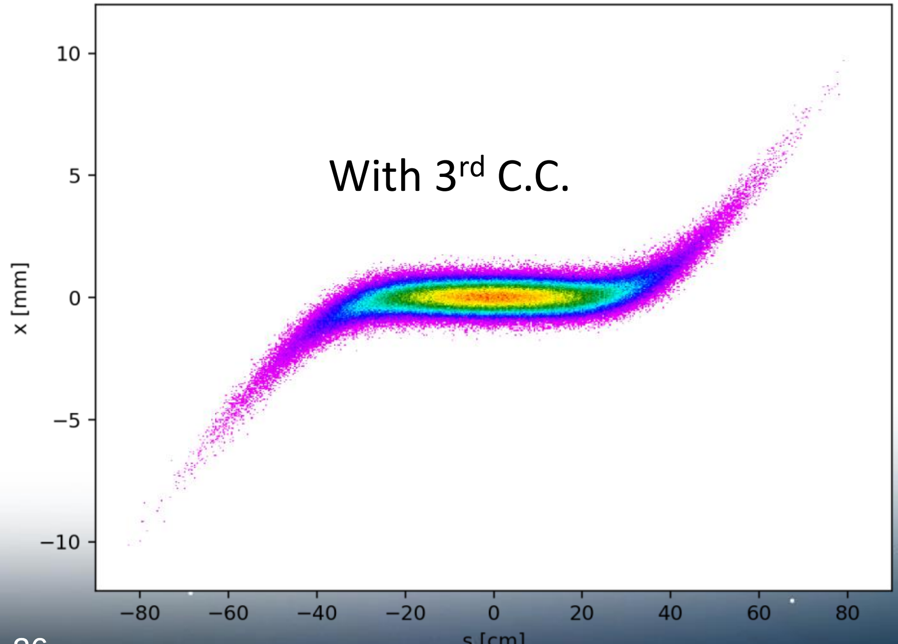


3rd Harmonic Crab Cavities

Y.Hao, Y. Luo

- To compensate the sine shape of crab cavity voltage, it is possible to add a third order harmonics. The foundational crab cavity frequency can be 112MHz, the 3rd harmonics will be 336MHz.
- Simulation results show that we can **gain 5% more luminosity by adding 3rd harmonic crab cavities to proton ring**. The optimum ratio of crabbing angles for the fundamental and 3rd harmonics crab cavities are **1.16 : (-0.16)**

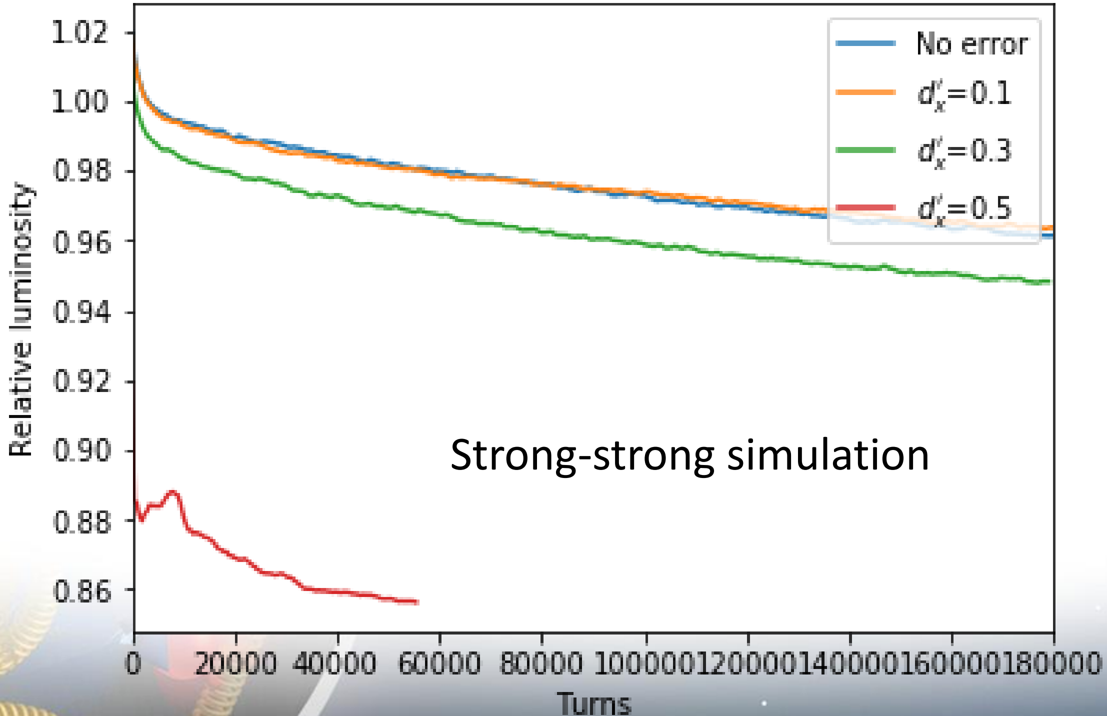




Dispersion at C.C.

Y.Hao, Y. Luo

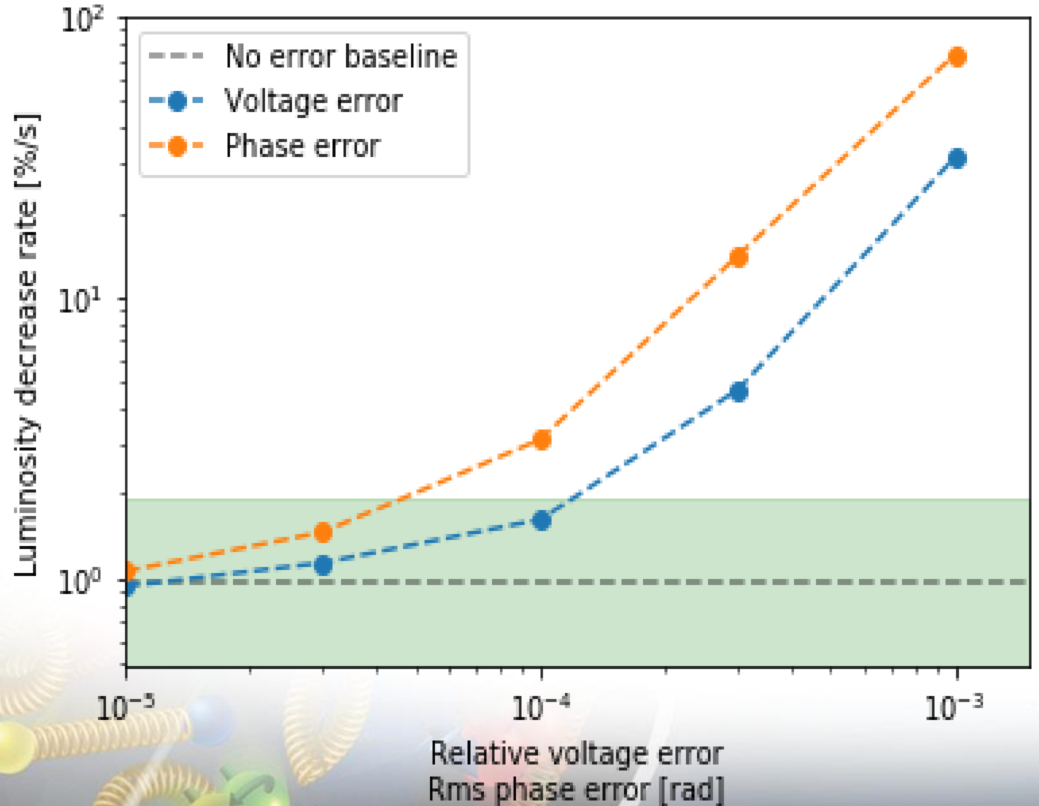
- The effects of dispersion **Dx and D’x at crab cavities** are studied with both weak-strong and strong-strong simulations.
- D’x plays an important role to emittance growth and luminosity evolution.
- Simulation results show that the tolerance for **D’x should be less than 0.5**.

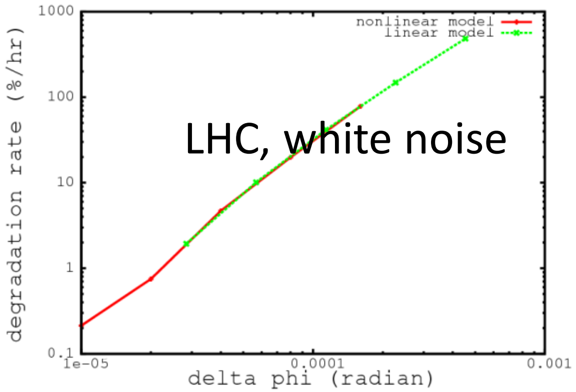


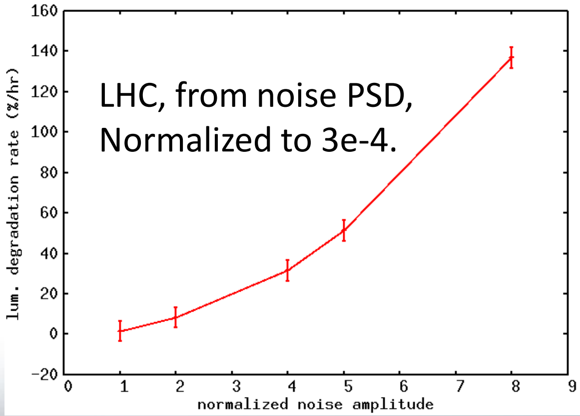
Noises in Crab Cavity

J. Qiang

From studies of LHC Hi-lumi , the PSD of the noise of LLRF control is very important to achieve reasonable results. Need to understand the most driving frequencies for EIC.







Summary

- Both weak-strong and strong-strong beam-beam simulation are used to study the beam-beam effects in the future electron-ion collider design of eRHIC.
- We sstudied the beam-beam interaction related beam and optics parameters. The simulation results show that the present design parameters are reasonable and the design luminosity is achievable.
- The present design tunes of both rings are in the good working point area. The design bunch intensities and the beam-beam parameters are well below the beam-beam limits.
- More studies are going on to understand and determine any possible beam-beam related beam emittance growth or beam lifetime reduction.

Backup slides

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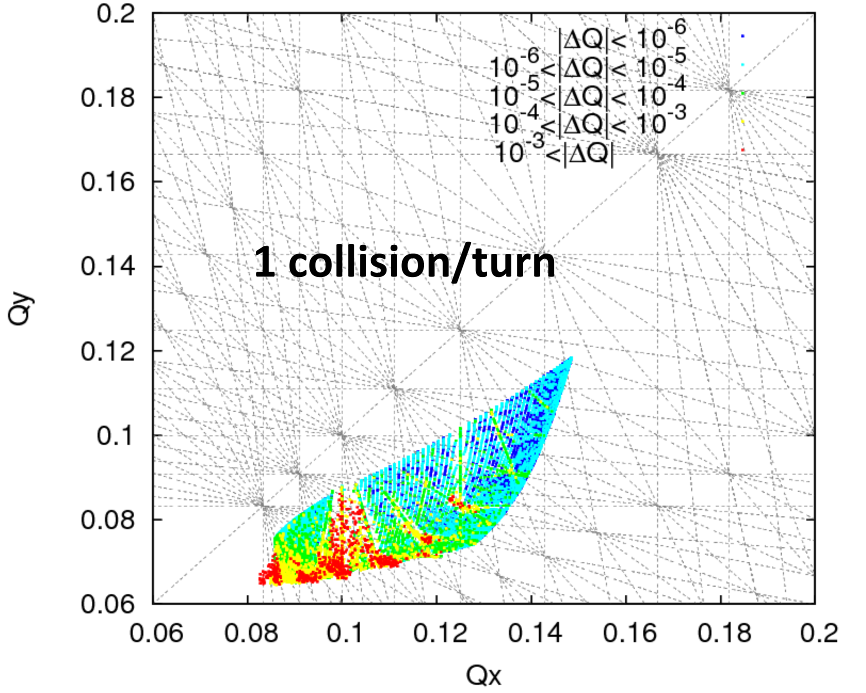
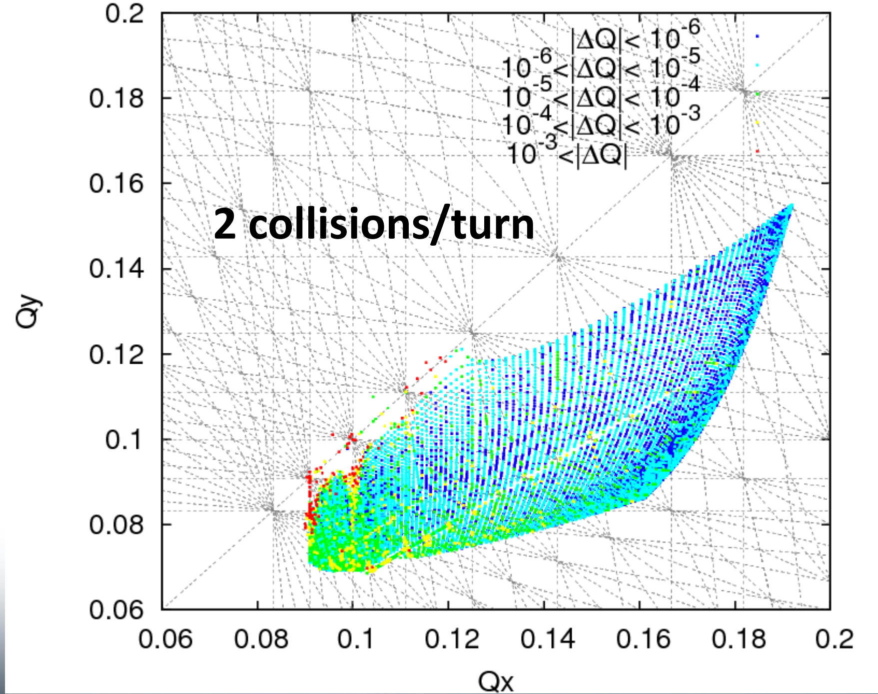
Two Collisions Per Turn

Y. Luo

- Previous BB studies focused on 1 collision per turn for each bunch.
- If we want to **delivery collisions to two experiments** and both beams have the same filling pattern, each bunch will have 2 collisions per turn.
- If we keep bunch intensities and beta* as the design, the beam-beam parameters and beam-beam tune spread will be doubled.

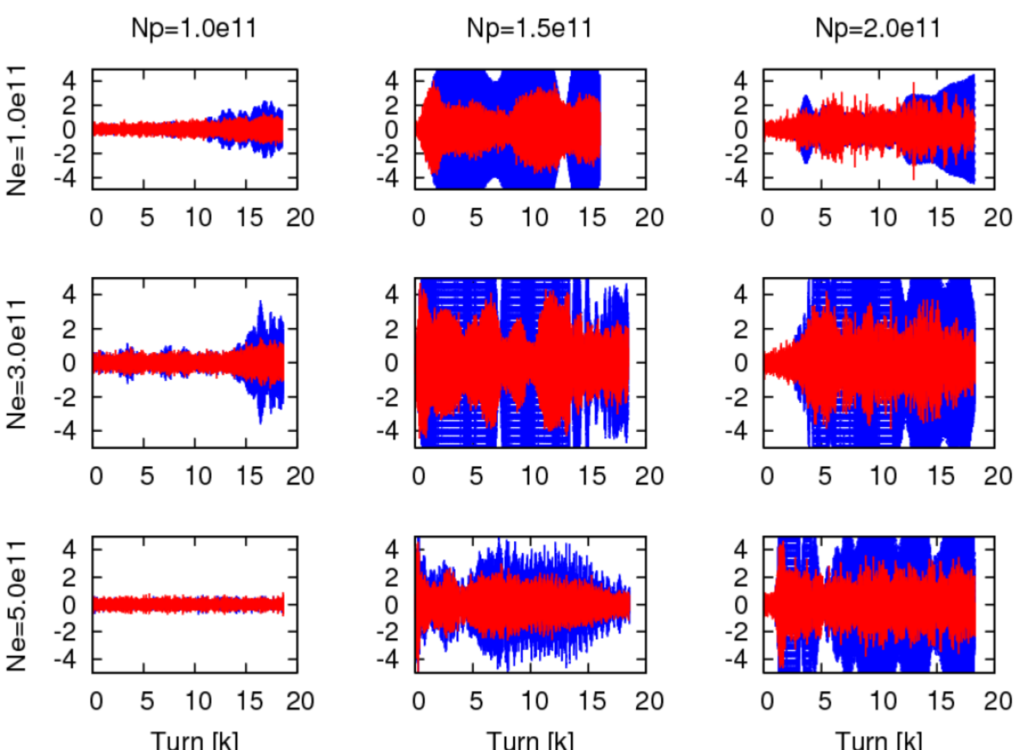




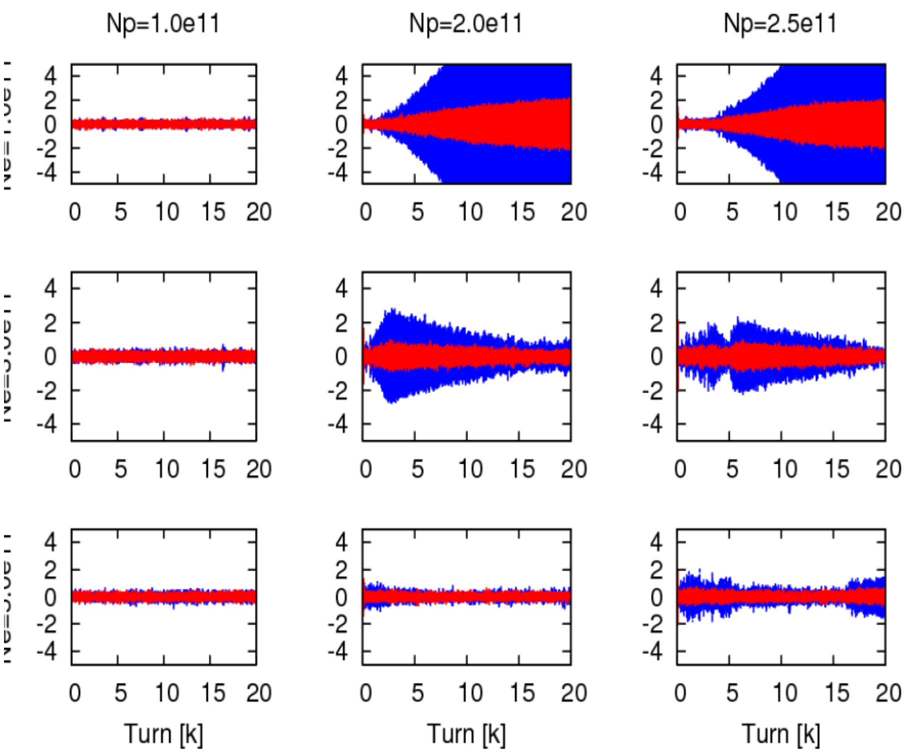
Simulation Results (I)

- 2 collisions per turn: at IP6 & IP8 , or at IP6 & IP12.
- Both weak-strong and strong-strong BB Simulations were performed .
- In the **strong-strong beam-beam simulation**, we did a 2-d bunch intensity scan.

center motion <x> : blue-proton, red->electron



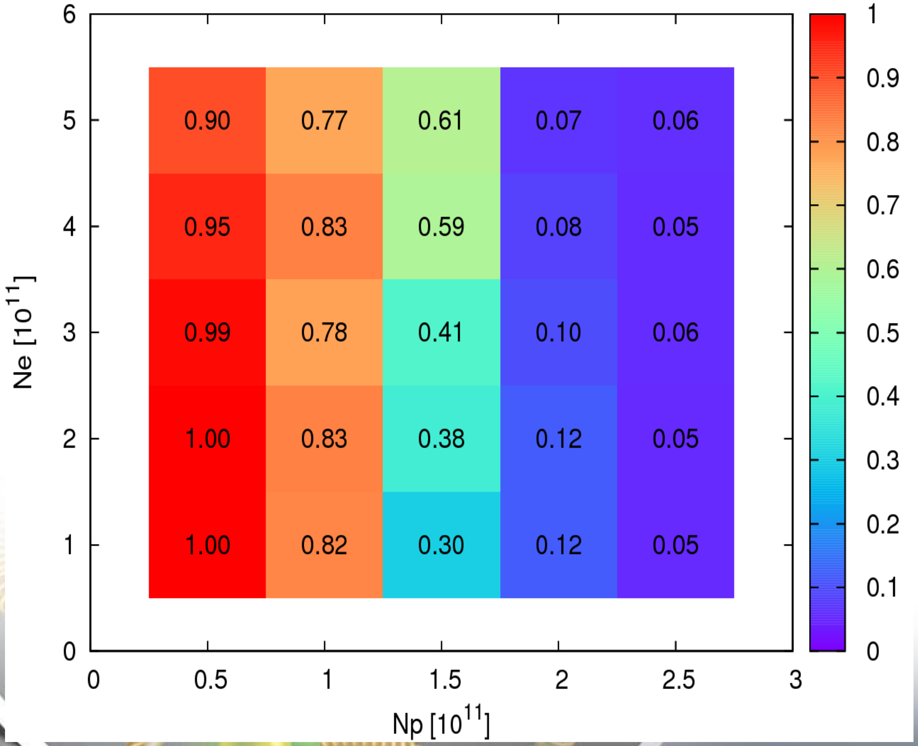
2 collisions/turn : IP6 & IP8



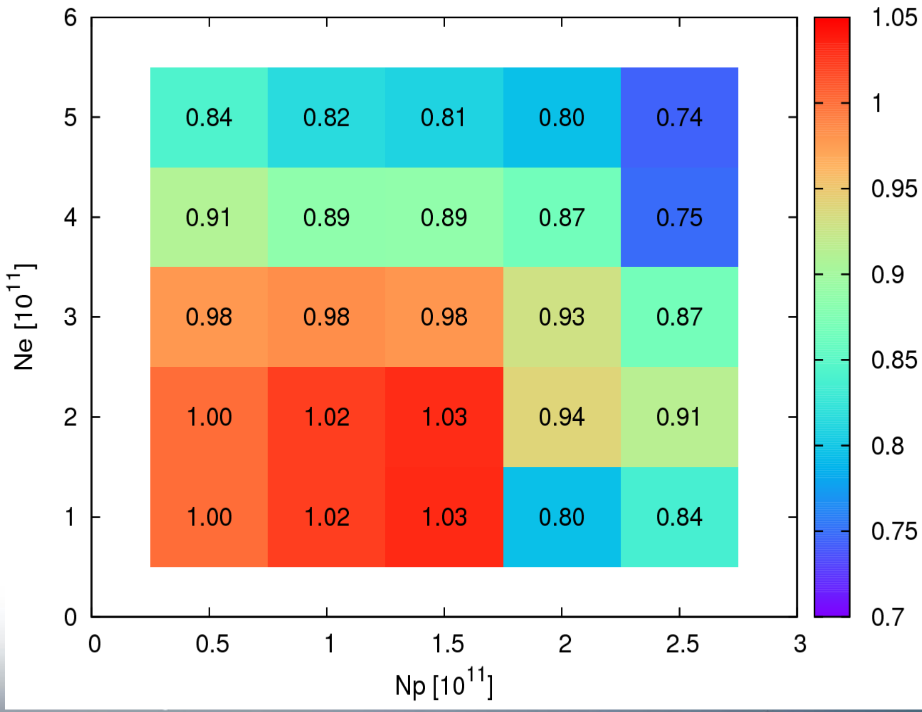
2 collisions/turn : IP6 & IP12

Simulation Results (II)

- Define $\kappa = \frac{L(N_p, N_e)}{L(N_{p0}, N_{e0})} \frac{N_{p0}}{N_p} \frac{N_{e0}}{N_e}$
- **Simulation results show that each bunch can not collide twice per turn with present design beam and optics parameters.**



2 collisions/turn : IP6 & IP8



2 collisions/turn : IP6 & IP12

Bunch Filling Scheme

Y. Luo

- To delivery collisions to two experiments simultaneously without reducing the bunch intensities, one solution is to adopt **bunch shift scheme** (M. Blaskiewicz etc.) to avoid 2 collisions per turn for any bunch.

➢ **RF System**:

proton ring: 112MHz, 1440 buckets, bucket width 2.66m

electron ring: 560MHz, 7200 buckets, bucket width 0.53m

➢ **Filling Patterns**:

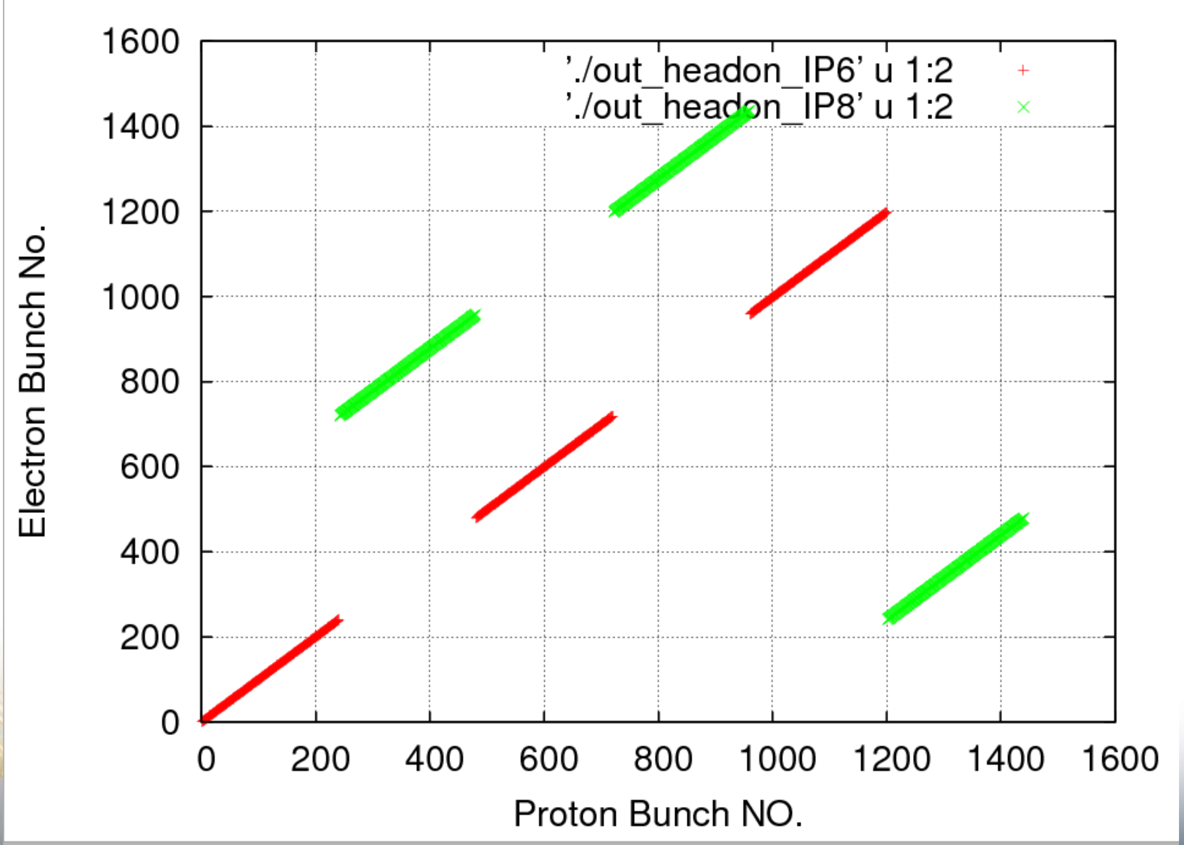
proton: 1 bunch / bucket, 1440 bunches

electron: 3*(240*5 + 3 + 239*5 + 2) = 7200 buckets, 1437 bunches

➢ **PHENIX experiment moved south** by 0.53m (1 electron bucket width)

With the bunch shift scheme

1) Each bunch only collides once per turn at IP6 or IP8 .
2) There are 720 collisions at IP6 (STAR) each turn, 717 collisions at IP8 (PHENIX).
3) Integrated luminosity per experiment is half of that with only 1 experiment.



- Assumption:
  1) Proton bunches go counter-clockwise, electron bunches clockwise.
  2) Proton bunch 1 and electron bunch 1 collide at IP6.

LR BB Effect

Y. Luo

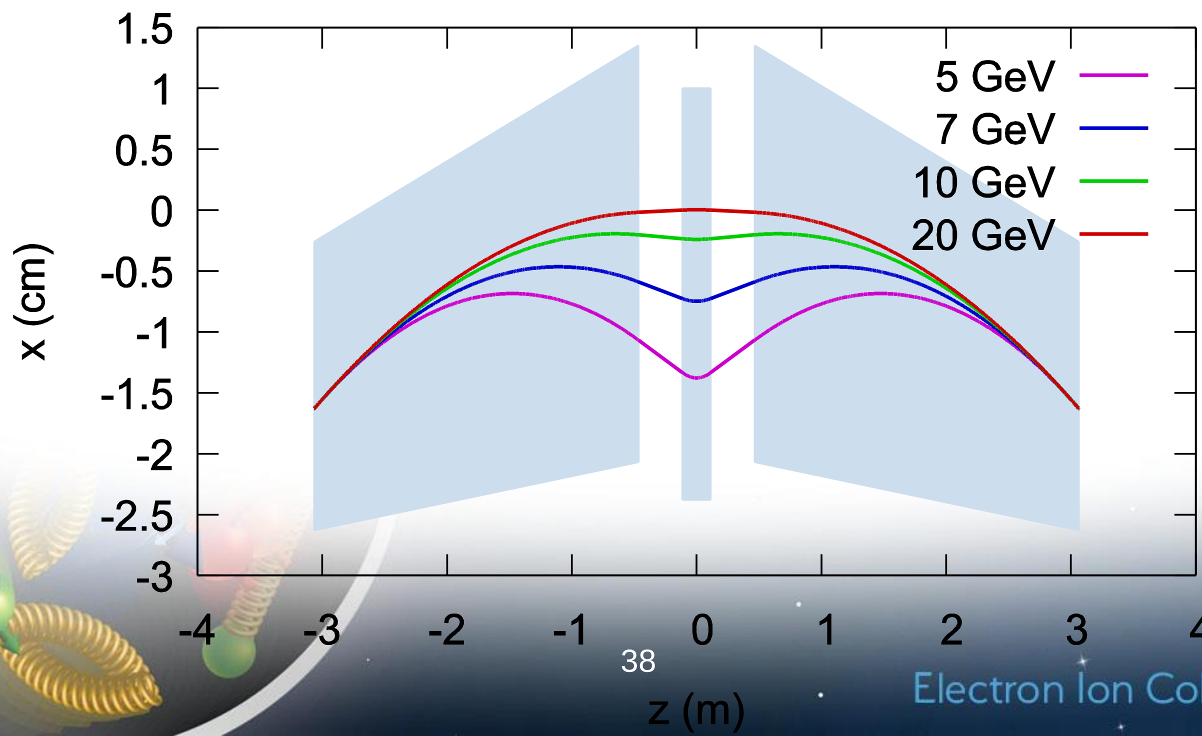
- The common beam pipe at the experiment IRs is +/-4.5m.
- LR BB effect with 2 experiments has to be evaluated.
- From the following table, the minimum separation with 2 experiments are $82\sigma_p$ and $71\sigma_e$.
- Therefore, **the LR BB effect is negligible for eRHIC design.**

	1 experiment	2 experiments
Number of LR BB	**6**	**12**
Nearest distance to IP [m]	**1.33**	**0.53**
Horizontal separation d [mm]	29.26	11.66
Local beam sizes (σ_p, σ_e) [mm]	(0.212, 0.291)	(0.142, 0.165)
Separation in beam size ($\frac{d}{\sigma p}$,$\frac{d}{\sigma e}$)	(138 , 101)	**(82 , 71)**

Radiation Damping Decrement

Y. Luo

- To reach the beam-beam parameter 0.1 for the electron ring, based on KEKB experience, it requires radiation damping decrement 1/4000, or the radiation damping time 4000 turns in transverse plane.
- To achieve the same radiation damping decrement at all beam energies, **superbends** are being considered for lattice design.

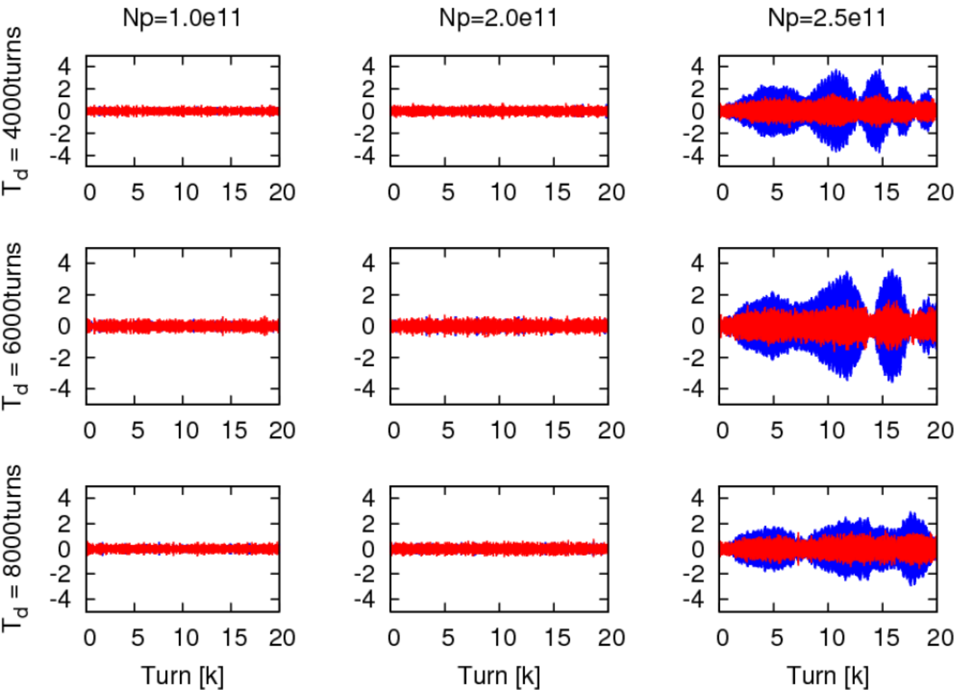


Schematic Superbend

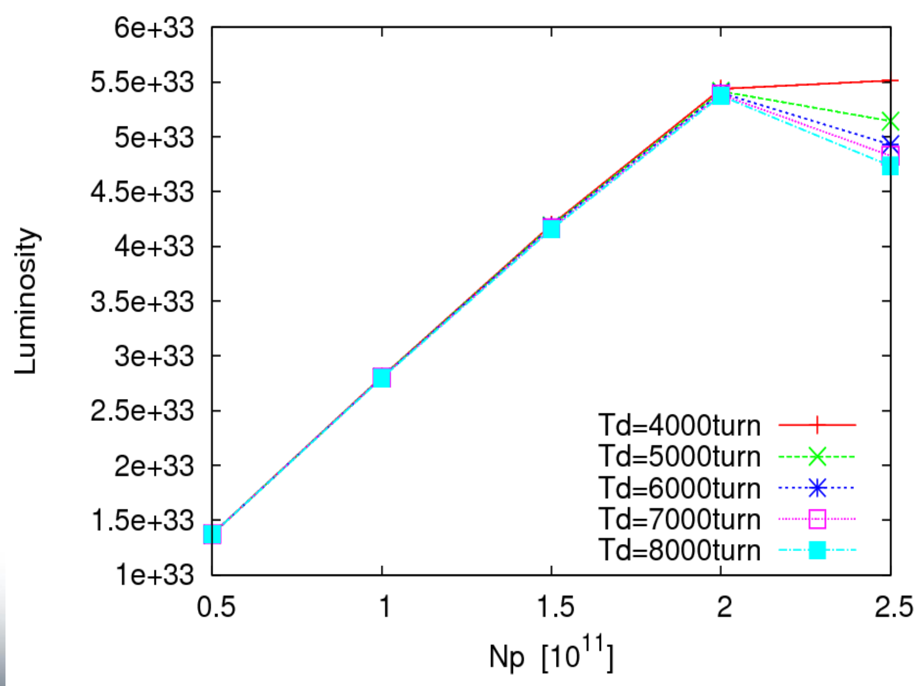
Simulation Results (I)

- Here we study the effects of damping decrement to beam-beam interaction.
- **Strong-strong BB simulation** was performed with different damping time **from 4000 turns to 8000 turns**. Electron energy is 10 GeV for this study.

Centroid motion <x> [um]

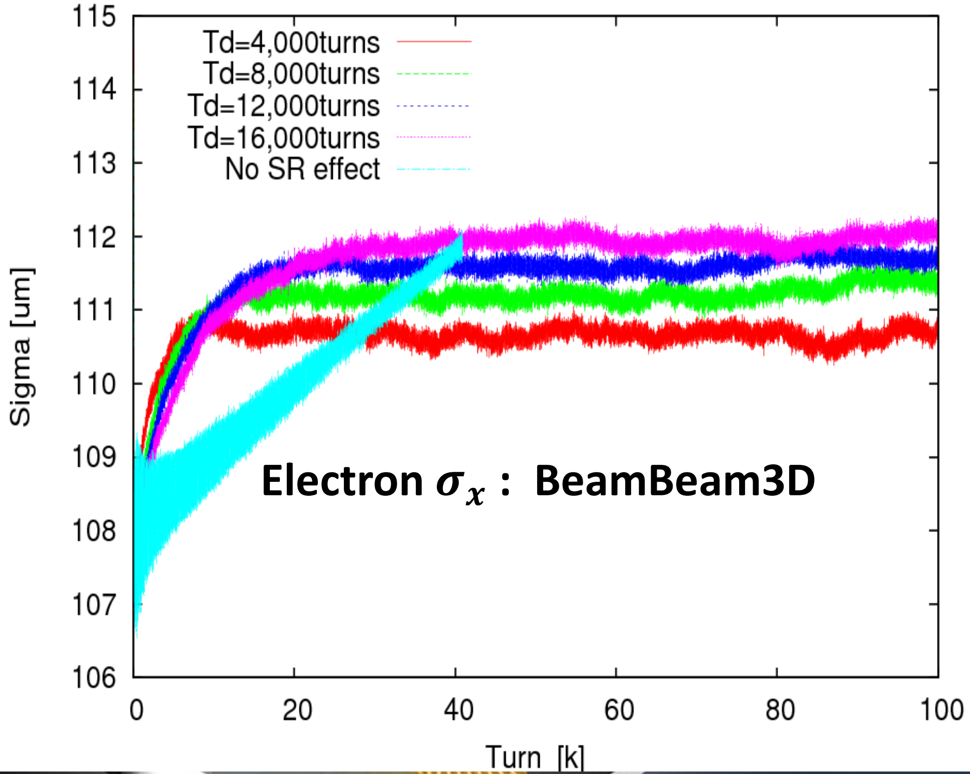


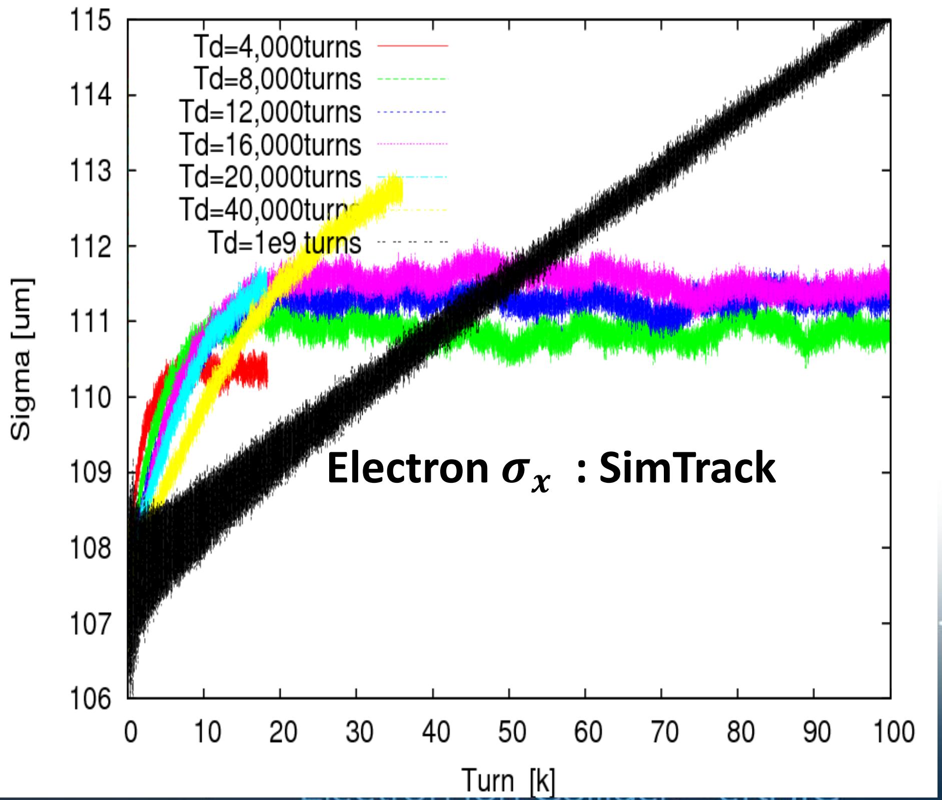
Luminosity



Simulation Results (II)

- We continue increasing the radiation damping time beyond 8000 turns.
- With a longer SR damping time, it takes a longer time to reach equilibrium.
- The difference in equilibrium beam sizes is small if radiation time is less than 16,000 turns.
- **BB simulation shows that we may have damping time longer than 4000 turns**.





Transient BB Effect During Bunch Replacement

C. Montag

- Required electron bunch in the eRHIC storage ring up to 50nC, which exceeds the electron gun capability and also leads to instabilities in the rapid cycling synchrotron (RCS) injector.
- At physics store, to maintain acceptable electron polarization, bunch-by-bunch replacement with a frequency of 1Hz.

- **Design injection scheme:**
  - longitudinal phase space injection
  - 5 bunches of 10nC from RCS into one electron bunch of storage ring.

- **The emittance growth during to BB parameter variation**

$$\epsilon_1 = \frac{\epsilon_0}{2} \cdot \left(\frac{\beta_1}{\beta_0} + \frac{\beta_0}{\beta_1} \right) \qquad \beta_1^* = \beta_0^* \cdot \frac{\sin(2\pi Q_0)}{\sin(2\pi Q_1)}$$

(by *M. Blaskiewicz*)

Weak-strong Simulation Results

- **Weak-strong Beam-beam simulation** was performed to evaluate the proton bunch emittance growth during the electron bunch replacement.
- In simulation, proton bunch represented by macro-particles, electron bunches by rigid distribution. Electron bunches are injected with $8\sigma_p$.
  SR damping is included.

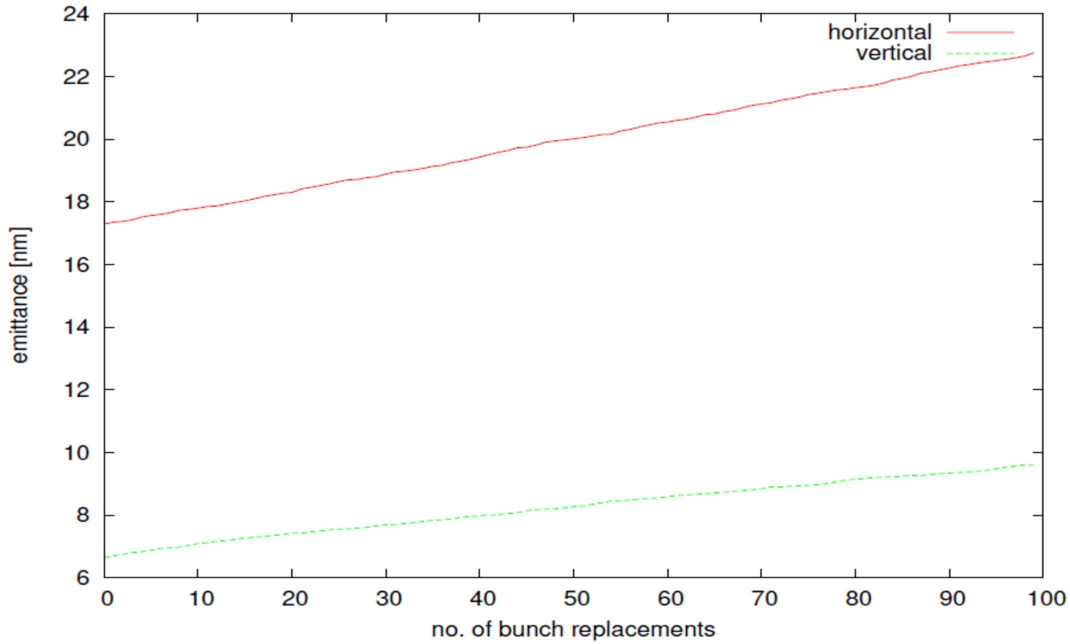


Figure 2: Proton beam emittance evolution during 100 electron bunch replacements, with electron bunches being accumulated in 5 steps each time, and injected off-energy.

(The time span of 100 bunch replacement is about 9 hours.)