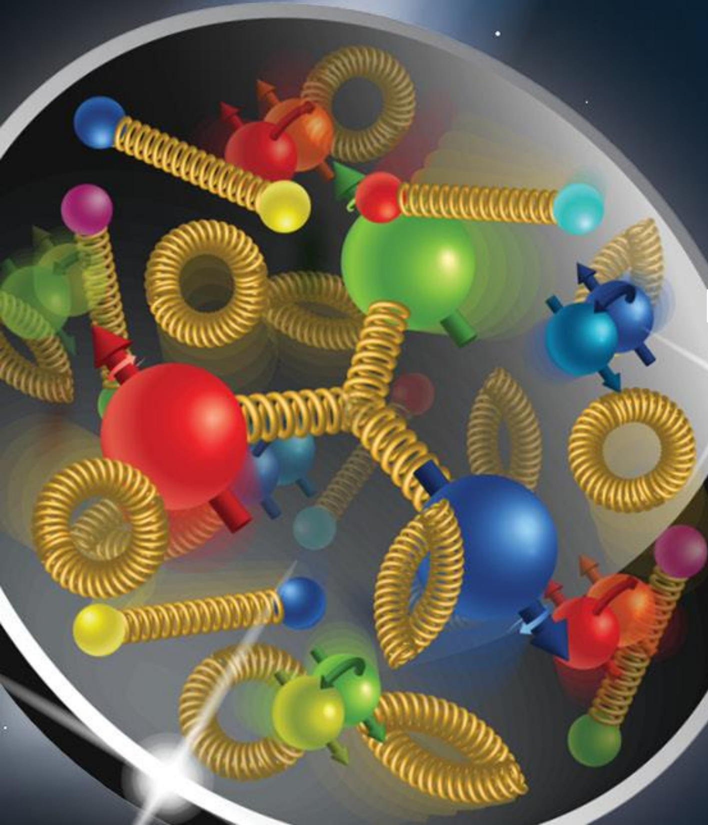
Beam-beam Studies, Tool Development and Tests



EIC Collaboration Meeting, Jlab, Oct. 29-Nov. 1, 2018

Yun Luo for eRHIC beam-beam study team

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

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Beam-beam Studies for eRHIC

- Main beam-beam study activities in the past year
  - FOA Lab-1848 proposal
  - eRHIC pre-CDR writing and finalization
  - eRHIC pre-CDR review in April
  - Dr. Ohmi visited BNL for two weeks in Sept.-Oct.

- New eRHIC beam-beam studies
  - Repeated all simulations for Pre-CDR with v5.1 parameters
  - Extensive / fine tune scans for both rings
  - Parameter dependences of numeric noises
  - Parameter dependences of luminosity degradation
  - Effects of artificial random/oscillating noises
  - Modified weak-strong BB simulations
  - Revisited head-on BB simulations
  - Currently focusing on ‘slow’ emittance growth

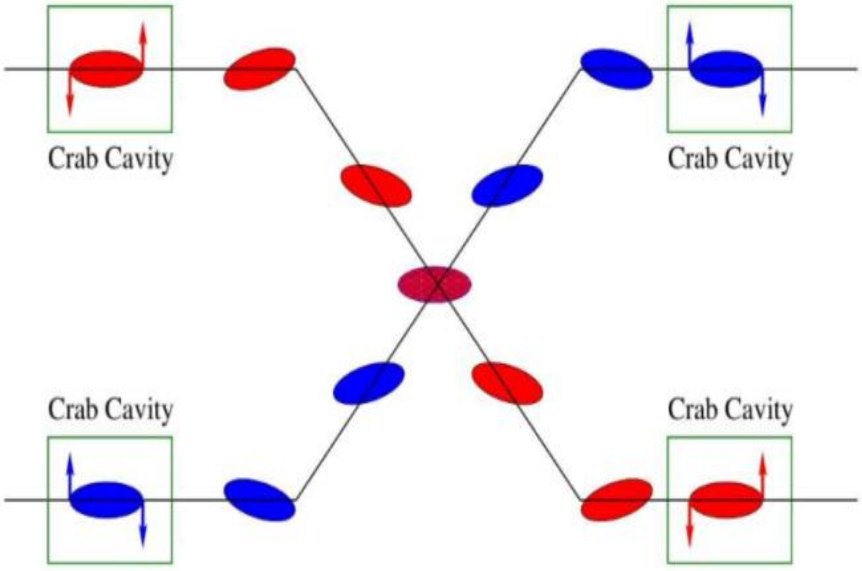
Beam-beam Related Machine & Beam Parameters（v5.1）

Table 4.9: Machine and beam parameters for the beam-beam interaction study.

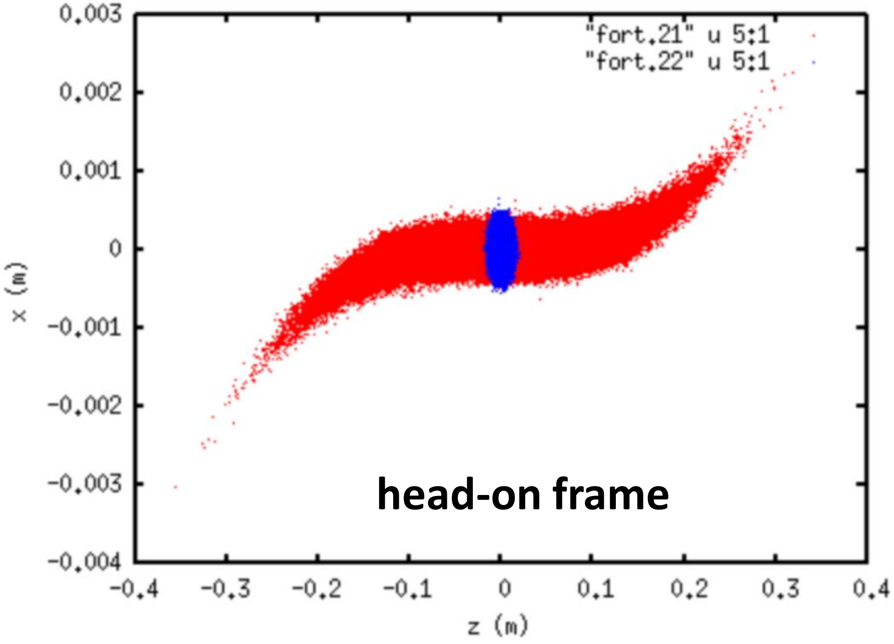
Parameter	proton	electron
Ring circumference [m]	3833.8451	
Particle energy [GeV]	275	10
Lorentz energy factor γ	293.1	19569.5
Bunch population [10^{11}]	1.05	3.0
rms emittance (H,V) [nm]	(13.9, 8.5)	(20.0, 4.9)
β^* at IP (H, V) [cm]	(90, 5.9)	(63, 10.4)
rms bunch size σ^* at IP (H, V) [μm]	(112, 22.5)	
rms bunch length σ_l at IP [cm]	7	1.9
rms energy spread [10^{-4}]	6.6	5.5
Transverse tunes (H,V)	(29.310, 30.305)	(51.08, 48.06)
Synchrotron tune	0.01	0.069
Longitudinal radiation damping time [turn]	-	2000
Transverse radiation damping time [turn]	-	4000
No. of bunches	660	660
Luminosity [$cm^{-2}s^{-1}$]	(4.39)	

Crabbed Collision

- To compensate geometric luminosity loss, crab cavities are used to tilt both beams in the x-z plane to recover head-on collision at IP.
- However, due to finite wave length of crab cavities, protons in the bunch head and tail are not perfectly crabbed. Beam-beam interaction may generate synchro-betatron resonance and head-tail instability.

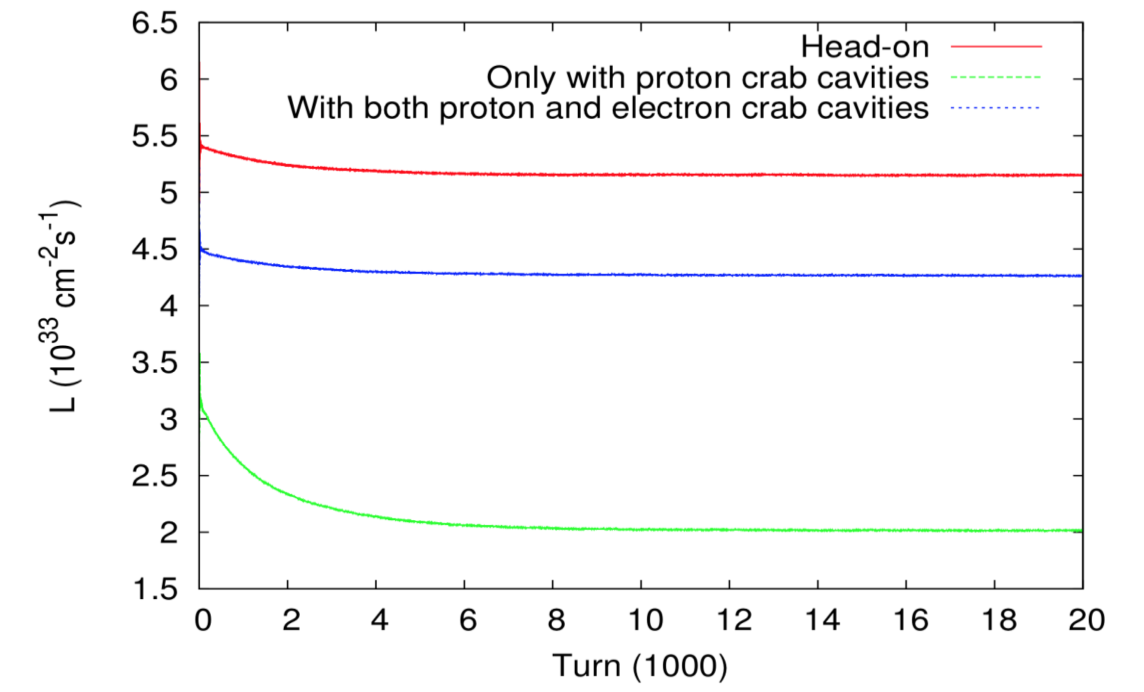


local crabbing scheme



Luminosity w/o Crab cavities

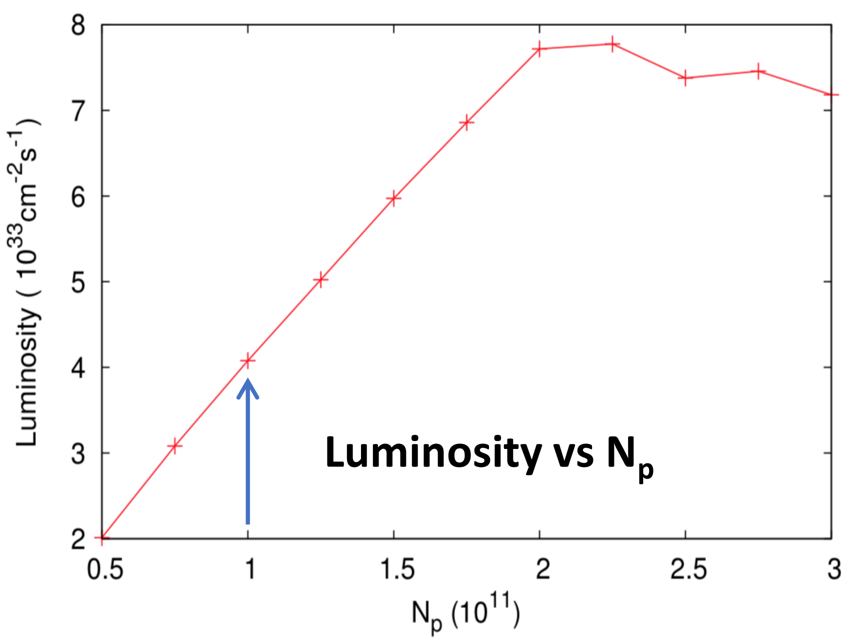
- For current eRHIC design, crab cavities are needed for both proton and electron rings to obtain a high luminosity.
- Following plot shows luminosities w/o crab cavities. Here we assumed 338MHz for both proton and electron beams.

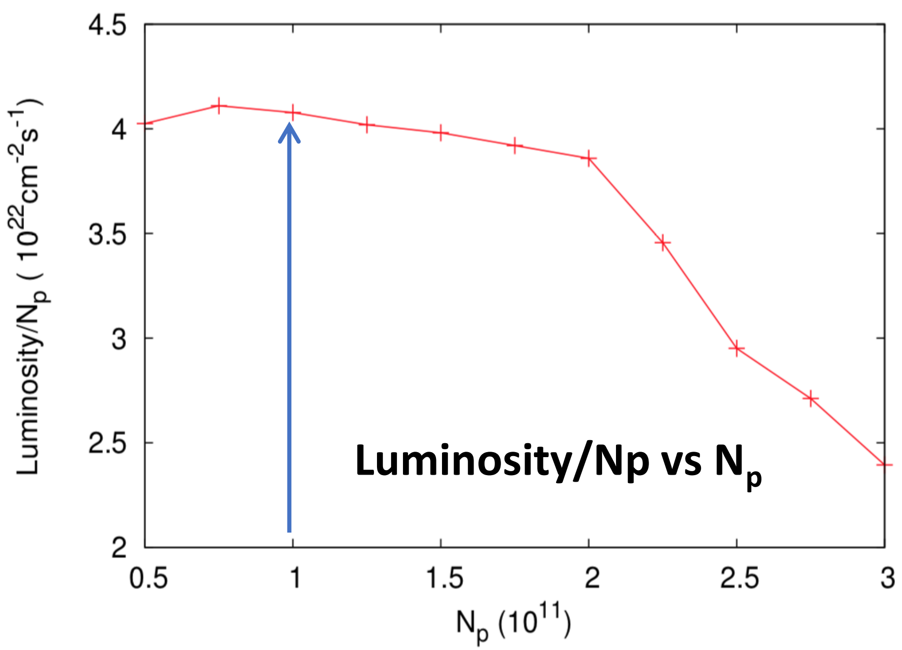


- With C.C. in both rings, luminosity is **83%** of that with head-on collision.
- Only C.C. in proton ring, luminosity is **47%** of that with C.C. in both rings.

Beam-beam Limit

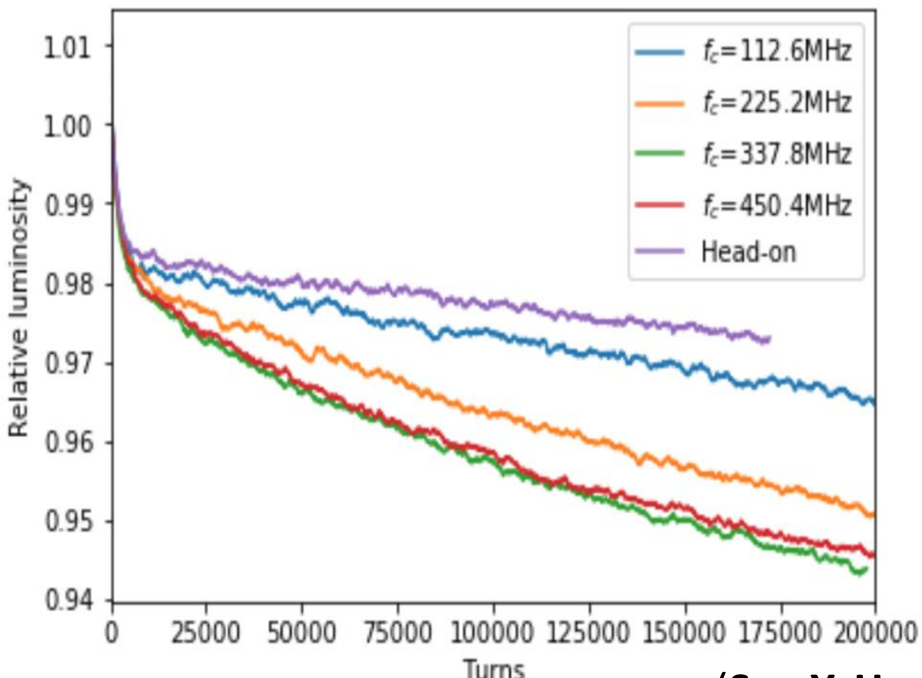
- When the beam-beam limit is reached, due to the coherent motion and/or emittance blowup, the luminosity will not linearly increase with the bunch intensity.
- For current eRHIC design, based on strong-strong simulation, the design beam-beam parameter is at about half the beam-beam limit.

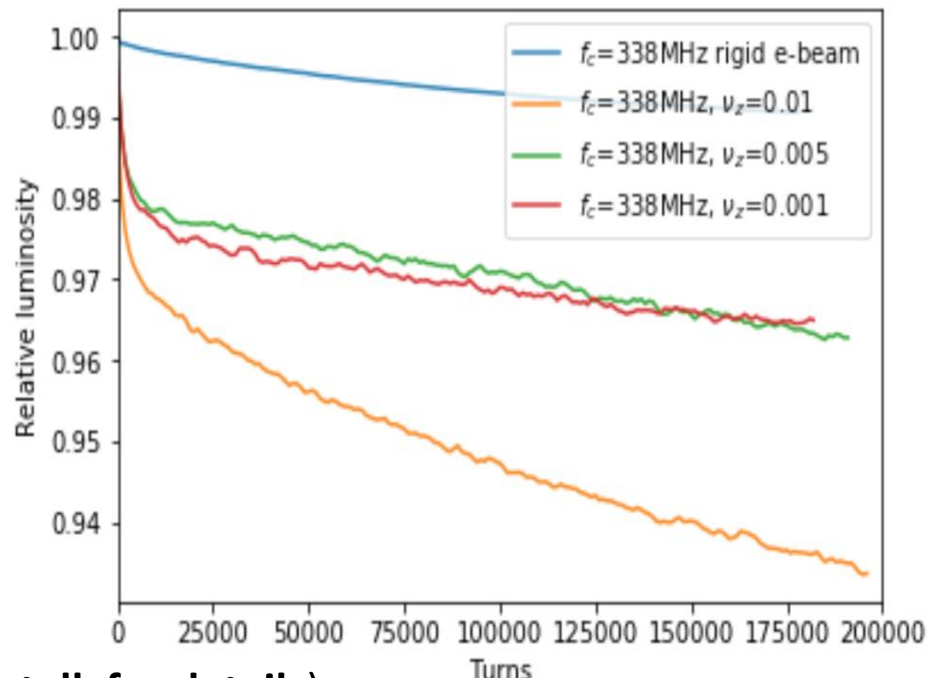




Parameter Dependence of Luminosity Degradation with Crabbed Collison

- With self-consistent strong-strong simulation, we found that the luminosity degradation rate depends on proton crab cavity frequency, proton synchrotron tune, proton bunch length, and so on.
- Following plots show the luminosity dependence on the crab cavity frequency (Left) and the synchrotron tune of the proton ring (Right).





(See Y. Hao's talk for details)

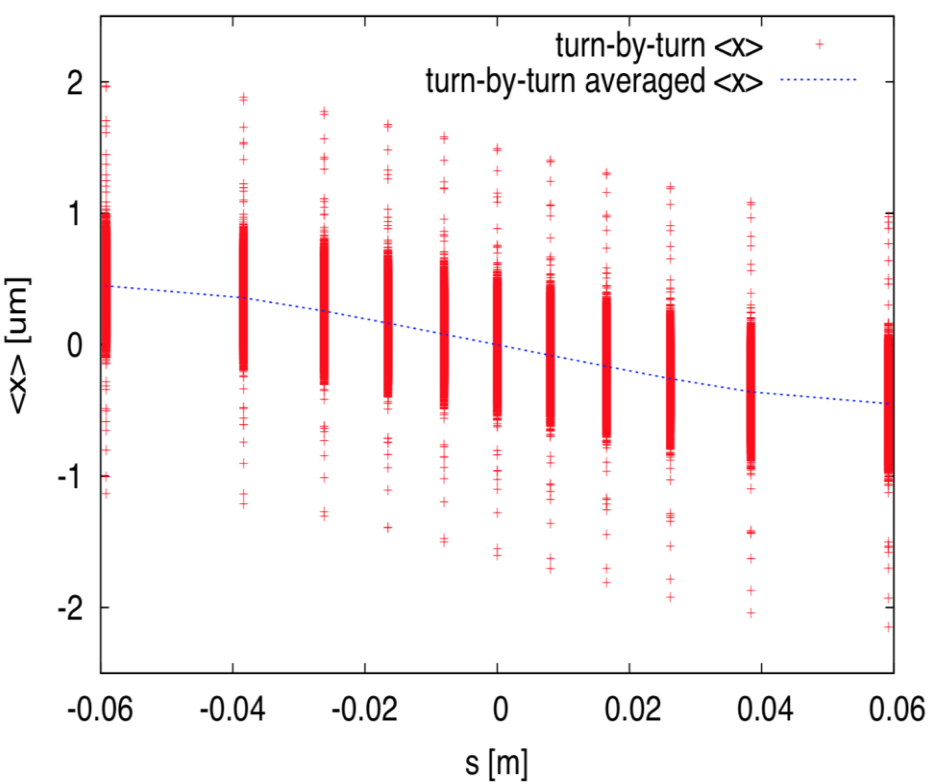
Modified Weak-strong BB Simulation

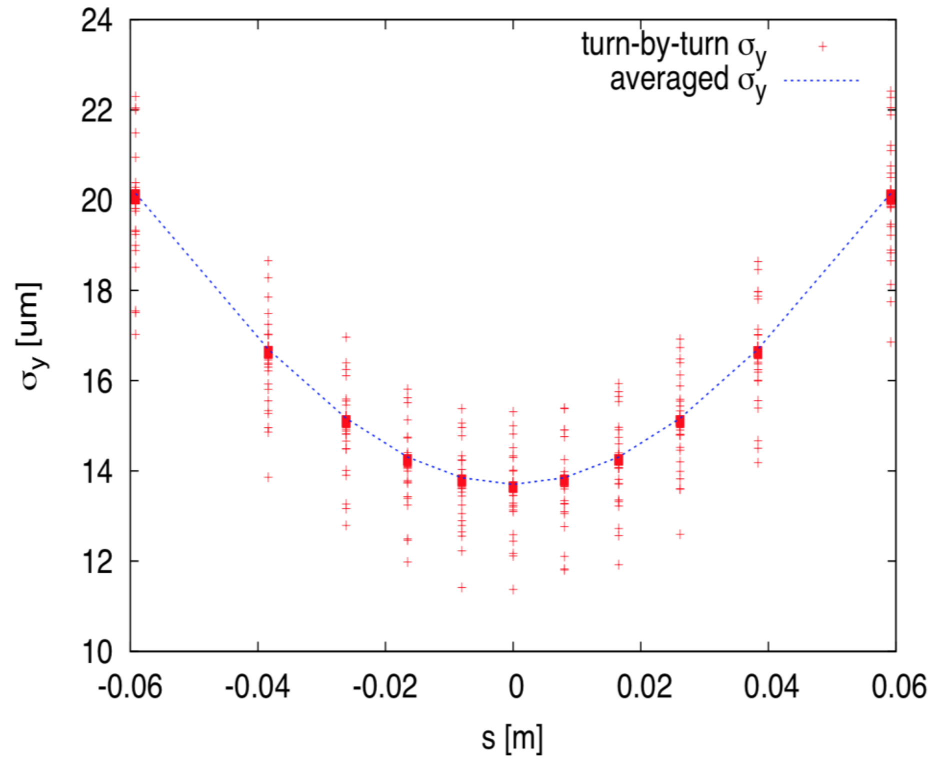
- To understand the sources of emittance growth and luminosity degradation and to determine their realistic growth/degradation rates, we carried out a modified weak-strong simulation.
- Modified weak-strong will answer that incoherent or coherent motion or both cause the emittance growth.

- The procedure as following:

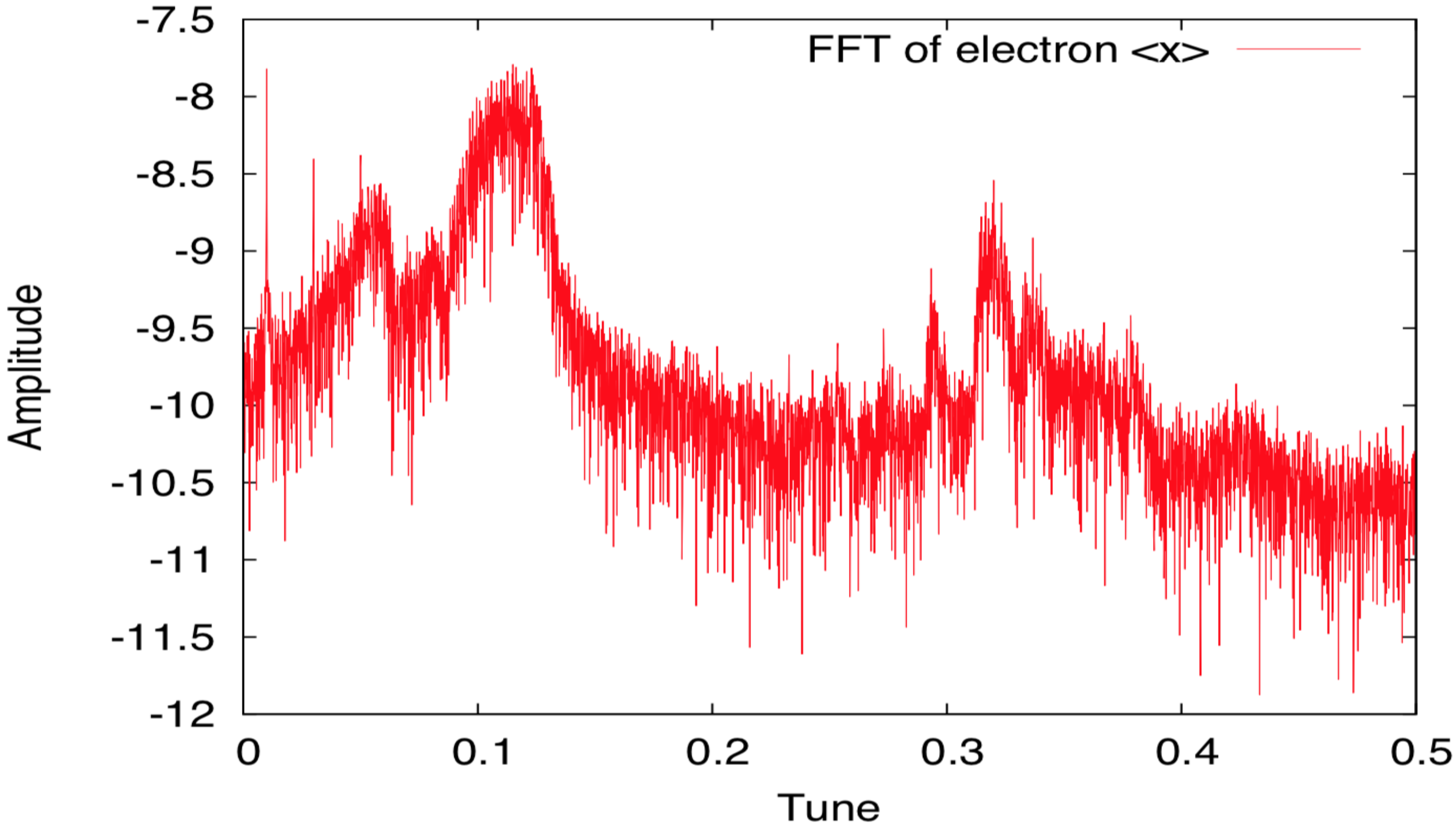
- First perform strong-strong simulation to extract 'equilibrium' positions and beam sizes of the electron bunch.
- Secondly perform a weak-strong simulation with above electron bunch information to calculate proton emittance growth.

This work is on-going. Here we show some preliminary results.





Electron bunch information from the strong-strong beam-beam simulation
Left: electron bunch centroid <x>. Right: electron vertical bunch size.
The horizontal axis is s coordinate with respect to IP.



Spectrum of the horizontal centroid of the electron bunch. Multiples of proton synchrotron tunes are visible. The proton synchrotron tune is 0.01.

Simulation Tool Development & Tests

- Beam-beam interaction was identified as one of the high priority R&D items to reduce the overall design risk in the 2016 NP Community EIC Accelerator R&D Panel Report.

- In our FOA Lab-1848 proposal, 4 beam-beam related R&D items are selected for further studies:

  - Beam dynamics study and numerical simulation of crabbed collision with crab cavities (for both eRHIC and JLEIC)
  - Quantitative understanding of the damping decrement to the beam-beam performance (for both eRHIC and JLEIC)
  - Impacts on protons with electron bunch swap-out in eRHIC ring-ring design, (for eRHIC only)
  - Impacts on beam dynamics with gear-changing beam-beam interaction in JLEIC design (for JLEIC only).

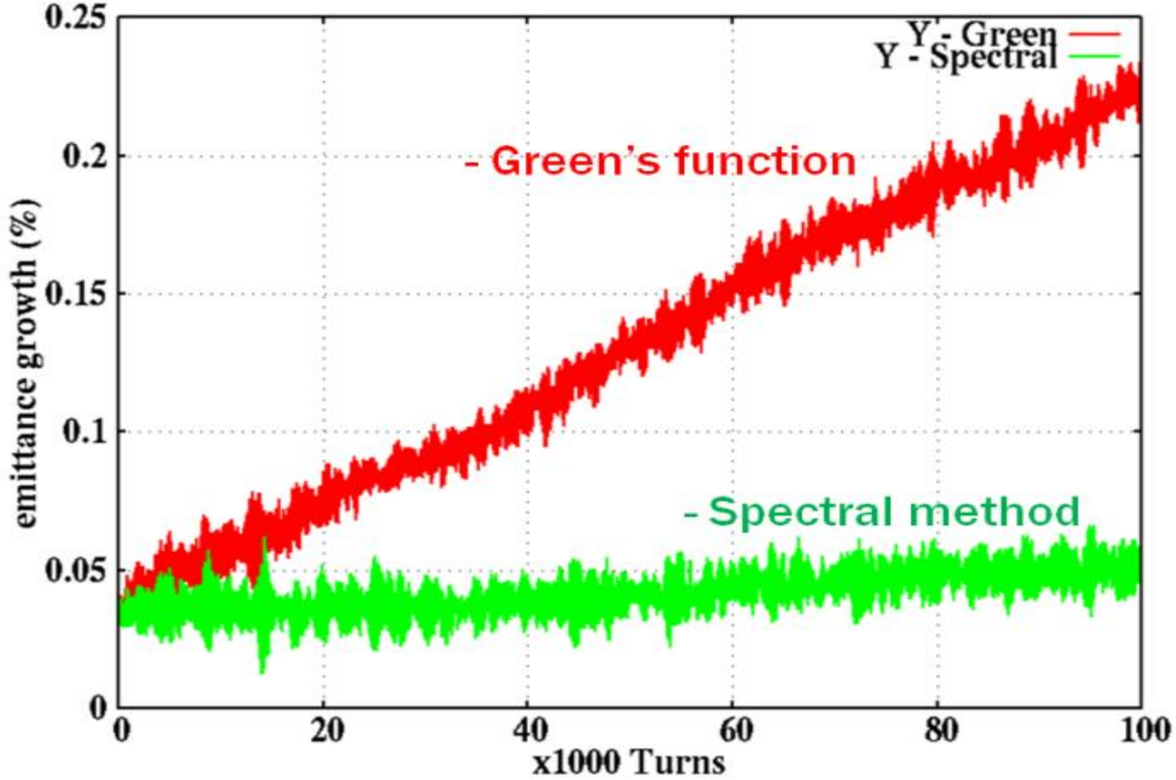
- FOA 18 beam-beam proposal involves expertise from BNL, Jlab, LBNL, and MSU, and will last two years.

Dynamics study and numerical simulation of crabbing collision with crab cavities

- For eRHIC strong-strong beam-beam simulations, we used following 2 codes: **BeamBeam3D** by J. Qiang (LBNL), **BBSS** by K. Ohmi (KEK) .
- In both codes particle-in-cell (**PIC**) method with **FFT** is used to solve 2-d Poisson equation to obtain the beam-beam force.

- Besides a deeper understanding of the involved physics, **we have to greatly reduce the numeric noise in the strong-strong beam-beam simulation.**
- There are other methods for space charge force calculation:
  1) Spectral Method, 2) Fast Multipole Method (FMM), 3) Adaptive Mess Size, and so on.

In our FOA 18 proposal, we planned to implement **spectral method** to solve the Poisson equation. In this method, the particle charge distribution will be approximated with a finite number of global basis functions.



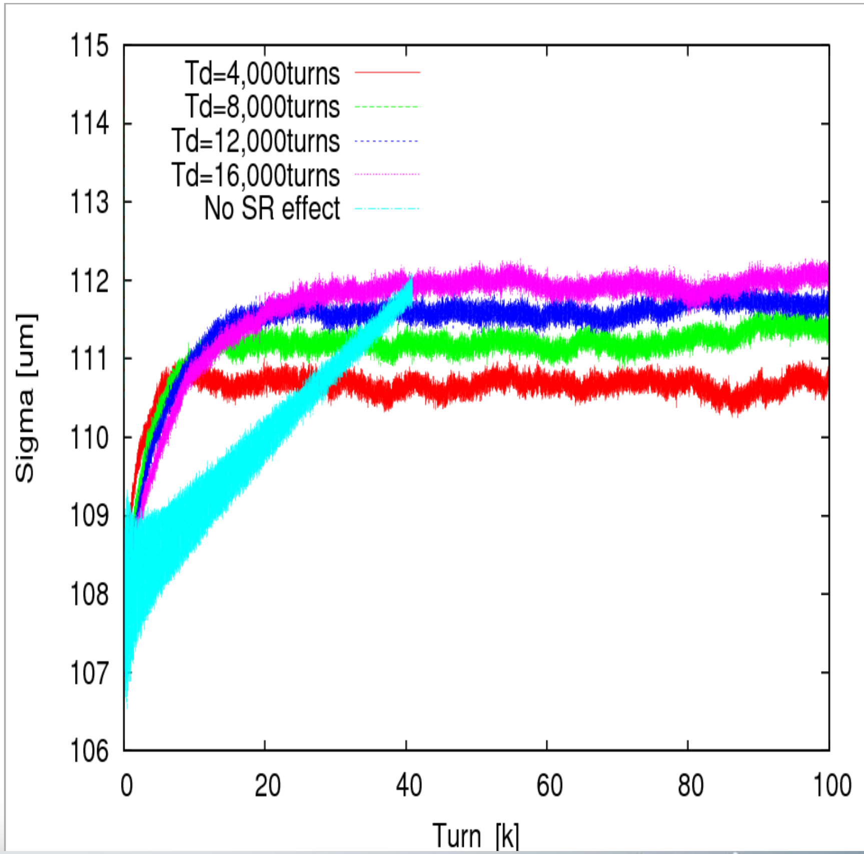
(J. Qiang)

An example of 2 slice interaction is shown above with LHC parameter.
In this case, the actual beam-beam caused emittance growth is negligible.

Quantitative understanding of the damping decrement to the beam-beam performance

- 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.

- Strong-strong simulations with different codes show that there are little difference in the equilibrium beam sizes of electron beam and the final luminosity even when the damping time increased by a factor of 4 !



- As we know, both beam-beam interaction and the lattice nonlinearity generate particle amplitude diffusion. The equilibrium emittances and stability of particles are determined by both the lattice nonlinearity and beam-beam interaction.
- In most of the existing strong-strong codes, for computing speed consideration, the lattice nonlinearity is not included.

- In our FOA 18 proposal, we planned to :

- replace the linear ring matrix with a higher order symplectic map,
- include the IR multipole field errors,
- use exact RF sinuous waves in longitudinal plane.

Impacts on protons with electron bunch replacement in eRHIC design

- At physics store, to maintain a high electron polarization, each electron bunch will be replaced in 5 minutes. After an electron bunch is kicked out, 5 smaller electron bunches will be injected into the same bucket from the RCS injector.

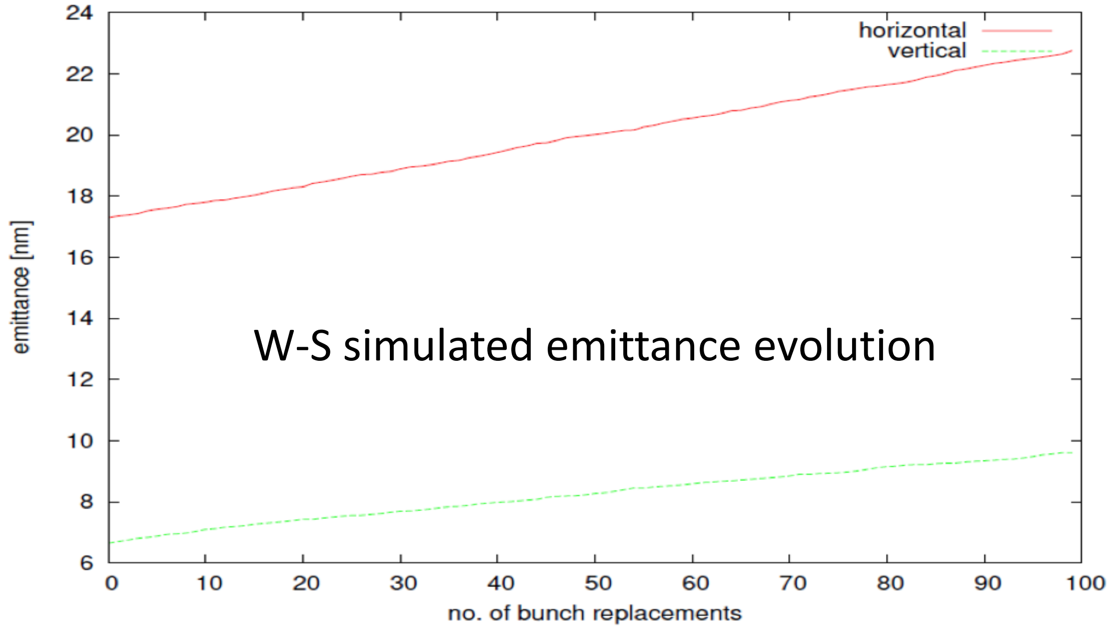
- During the electron bunch replacement, the beam-beam parameter of the corresponding proton bunch is altered, which may cause the proton bunch emittance growth.

- Analytically, the emittance growth due to beam-beam introduced lattice mis-match can be calculated according to:

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

(by *M. Blaskiewicz*)

- **Weak-strong Beam-beam simulation** was performed to evaluate the proton bunch emittance growth during the electron bunch replacement. In the simulation, proton bunch represented by macro-particles, electron bunches by rigid distribution. The simulated proton emittances are shown below.
- To fully study the effects, in our FOA 18 proposal, we planned to carry out **a 6-d strong-strong beam-beam simulation.** For this purpose, we plan to re-structure BeamBeam3D for this task.
- BTW, beam experiment using electron lenses was performed in RHIC to study this effect and for simulation code benchmarking.



(*C. Montag*)

Summary

- We repeated all the beam-beam simulations for the eRHIC pre-CDR with v5.1 machine and beam parameters.
- We carried new simulations to understand and to calibrate the emittance growth and luminosity degradation observed in the strong-strong beam-beam simulations.
- In the next 2 years, we will address 4 simulation challenges for beam-beam interaction to reduce the overall EIC design risk.

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