Development and Test of Simulation Tools for EIC Beam-beam Interaction

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EIC Design Goal

As stated in 2015 DOE/NSF Long Range Plan for Nuclear Science, the next generation of electron-ion collider will meet the following requirements:

1) Polarized (~70%) electrons, protons, and light nuclei,

2) Ion beams from deuterons to the heaviest stable nuclei, variable center of mass energies ~20-100 GeV, upgradable to ~140 GeV,

3) High collision luminosity ~10^{33}-10^{34} $cm^{-2}sec^{-1}$, and

4) Possibly have more than one interaction region.

Requirements 2), 3), and 4) are all related to beam-beam interaction.

Challenges in BB Interaction in EIC

- **High beam-beam parameters**

  Proton ring BB parameter~ 0.015, Electron BB parameter~0.1

  Combination not demonstrated in early electron-ion colliders

- **Large crossing angle**

  Full crossing angle is 25mrad

- **Collision with crab cavities**

  Crab cavities had been used in KEK-B

  Not used in any hadron collider

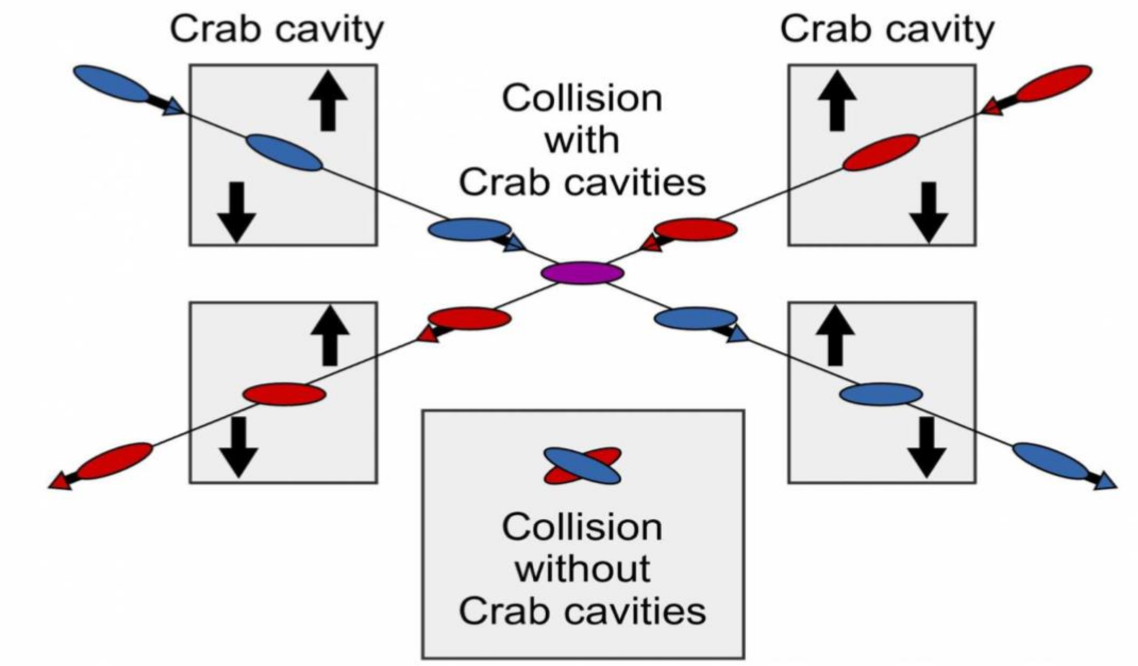
- **Other challenges**

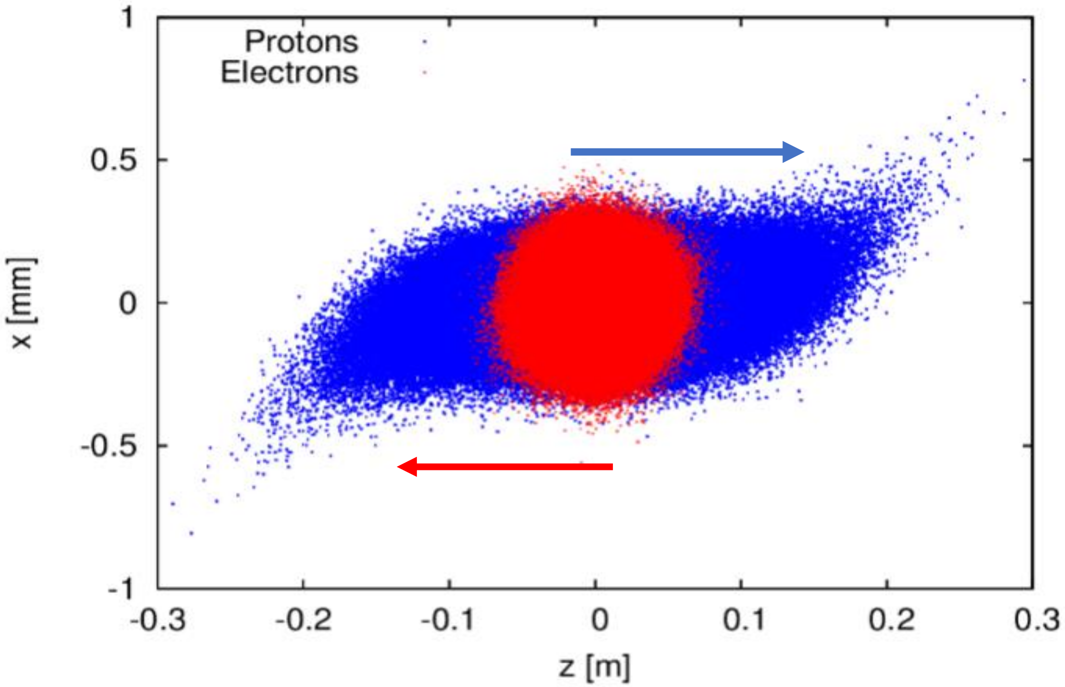
  No SR damping in hadron ring, Flat beam at IP,

  Near-integer electron tunes, Dynamic-beta effect (pinch effect),

  and so on.

Collision with crab cavities





Crab cavities are needed in both rings. Due to long proton bunch length and finite wave length of crab cavities, crabbed collision causes offset beam-beam interaction, synchro-betatron resonance, and leads to poor beam lifetime.

4 Challenging Items to Be Addressed

Beam-beam interaction have been identified as one of the most important challenges needed to be addressed to reduce the overall design risk in the 2017 NP Community EIC Accelerator R&D panel report.

4 challenging items have been selected for this project:

1) **beam dynamics** study and **numerical simulation** of collision **with crab cavities**,
2) quantitative understanding of **damping decrement** to the beam-beam performance ,
3) impacts on protons with **electron bunch swap-out** in **eRHIC** ring-ring design, and
4) impacts on beam dynamics with **gear-changing beam-beam interaction** in **JLEIC**.

Items 1 and 2 are common to both eRHIC and JLEIC. Item 3 is for eRHIC. Item 4 is for JLEIC.

Who We Are

- In the project, we join expertise from 4 institutions
  Dr. Yun Luo : Lead-PI, Brookhaven National Laboratory
  Dr. Yves Roblin: Co-PI, Thomas Jefferson National Laboratory
  Dr. Ji Qiang: Co-PI, Lawrence Berkeley Nation Laboratory
  Prof. Yue Hao: Co-PI, Michigan State University
- We also include the following experts
  Dr. He Zhang: Thomas Jefferson National Laboratory
  Dr. He Huang: Thomas Jefferson National Laboratory
  Dr. Derong Xu: postdoc, Michigan State University
- **This collaboration team with strong backgrounds in:** weak-strong beam-beam simulation, strong-strong beam-beam simulation, particle tracking in accelerators, nonlinear beam dynamics, and so on.

Achieved Deliverables in Year 1

Year 1				Year 2			
Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4
Task 1.1, 1.2, 1.3 (BNL, MSU, JLab)							
Task 1.4 (LBNL, MSU)				Task 3.1 (LBNL) Task 3.2, 3.3 (BNL)			
Task 2.1, 2.2, 2.3 (LBNL, BNL) Task 2.4 (BNL, JLab)				Task 4.1 (LBNL), Task 4.2, 4.3, 4.4 (JLab)			

Status	Task	Description
✓	Task 1.1	Code modifications to BeamBeam3D to reduce numeric noises
✓	Task 1.2	Further study of the beam-beam induced synchro-betatron resonance
✓	Task 2.1	Replace the linear ring map by a nonlinear map to up to a certain order
✓	Task 2.2	Implement high order non-linear field errors in IRs in BB3D
✓	Task 2.3	Implement real RF cavities for additional damping control in BB3D
✓	Task 2.4	Integrate and test all nonlinear tracking implementations inBB3D

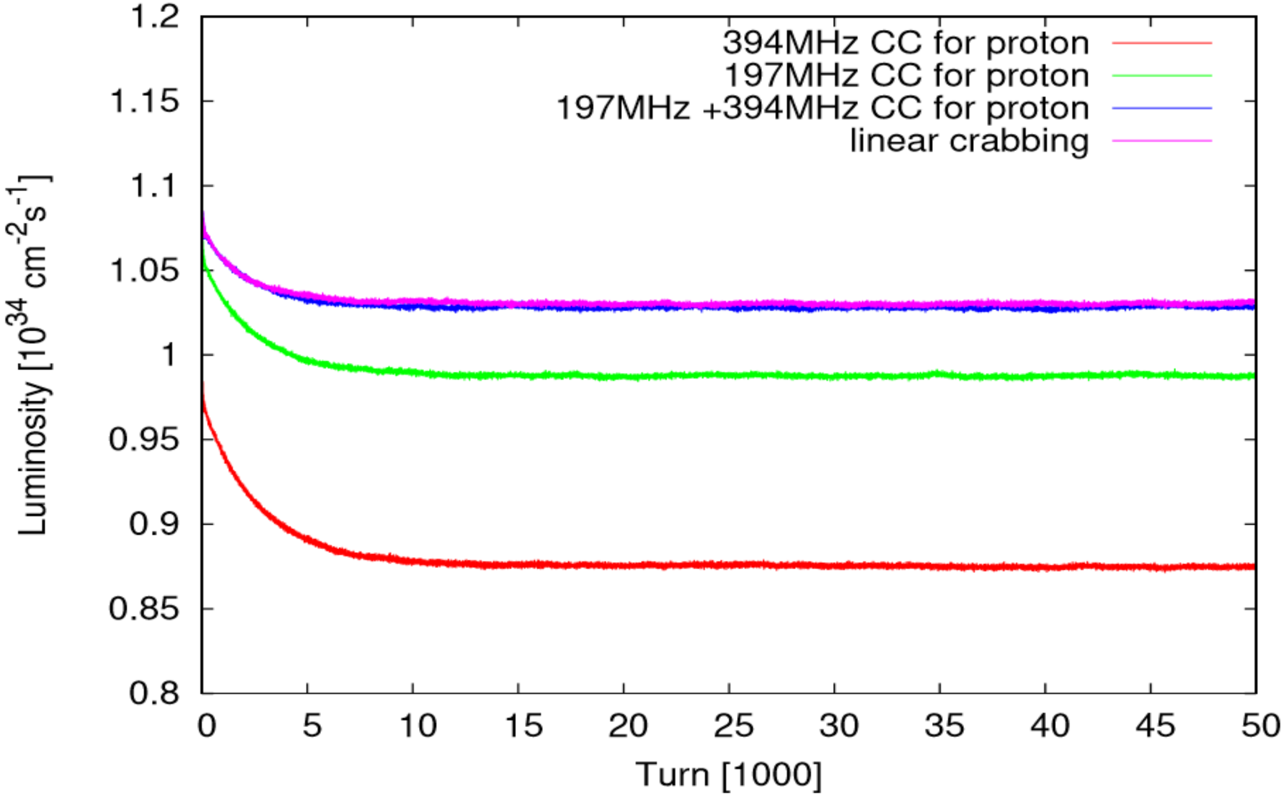
EIC Beam-beam Study Task Force in 2020

- ➢ To complete conceptual design report (CDR) writing, various study task forced were formed in April, with efforts from both BNL and JLAB personals.
- ➢ Within 6 months, the beam-beam task force will answer two fundamental questions regarding EIC design:
    1) **Study feasibility of crab crossing in steady state.**
    2) **Study electron injection / accumulation process.**
- ➢ The deliverables from beam-beam task force largely overlapped with the deliverables from FOA'18 beam-beam study team. Also, the members of beam-beam task force includes us from FOA'18 team members.

Design Parameters for e-p 10GeV * 275GeV collision

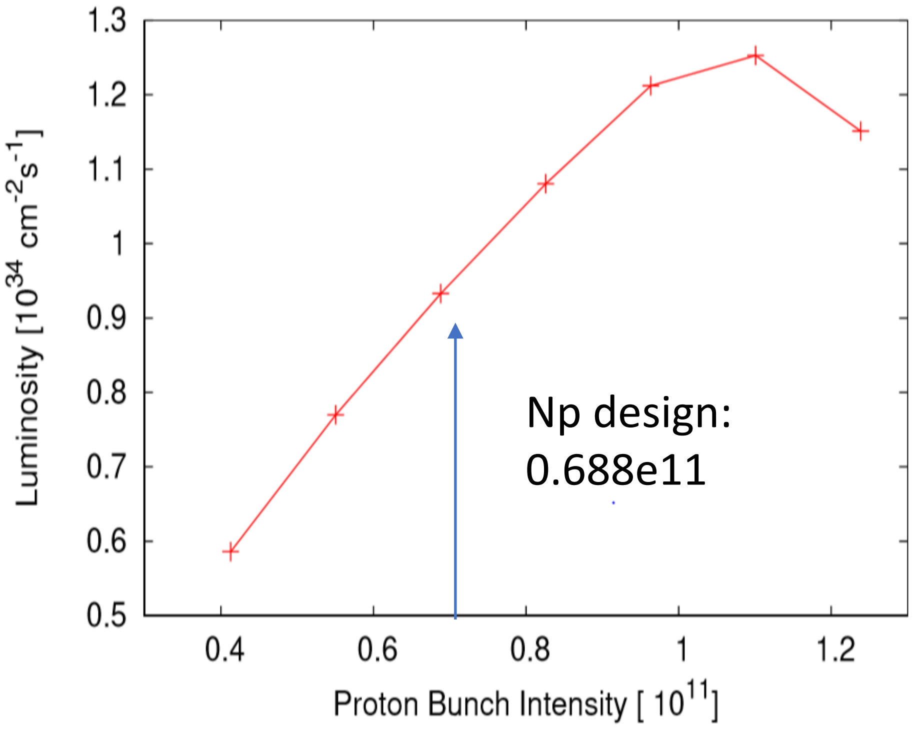
Parameter	proton	electron
Ring circumference [m]	3833.8451	
Particle energy [GeV]	275	10
Lorentz energy factor γ	293.1	19569.5
Bunch population [10^{11}]	0.688	1.72
RMS emittance (H,V) [nm]	(11.3, 1.0)	(20.0, 1.3)
β^* at IP (H, V) [cm]	(80, 7.2)	(45, 5.6)
RMS bunch size σ^* at IP (H, V) [μm]	(95, 8.5)	
RMS bunch length σ_l at IP [cm]	6	2.0
Beam-beam parameters (H, V)	(0.012, 0.012)	(0.072, 0.1)
RMS energy spread [10^{-4}]	6.6	5.5
Transverse tunes (H,V)	(29.228, 30.210)	(51.08, 48.06)
Synchrotron tune	0.01	0.069
Longitudinal radiation damping time [turn]	-	2000
Transverse radiation damping time [turn]	-	4000
Luminosity [10^{34}cm^{-2}s^{-1}]	1.0	

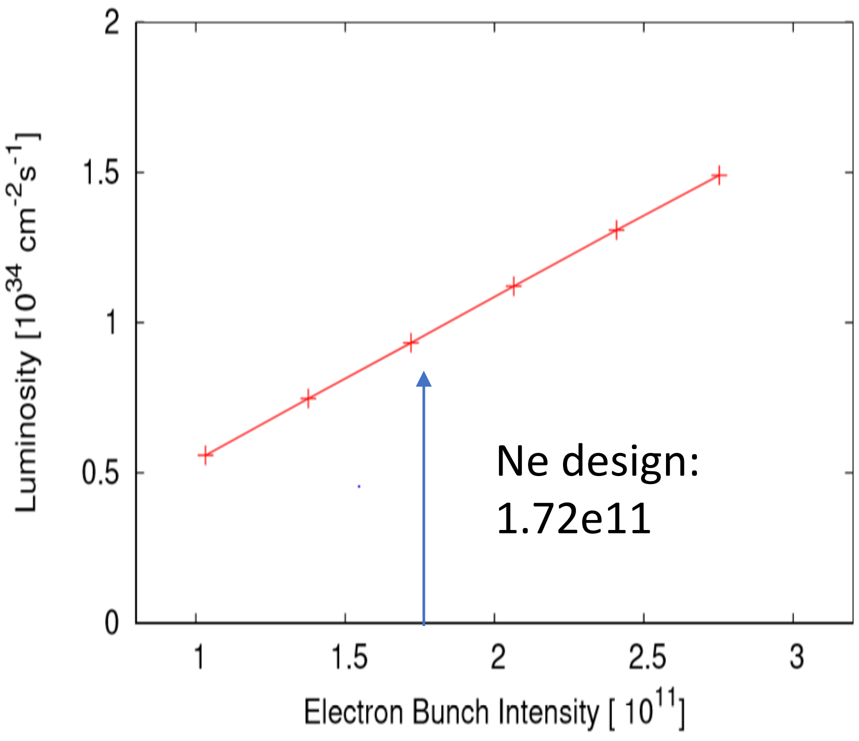
Luminosity Evolution



The design frequencies of crab cavities for the proton and electron rings are 197MHz and 394MHz. Second harmonic crab cavities 394MHz for protons are under consideration, which improves proton lifetime.

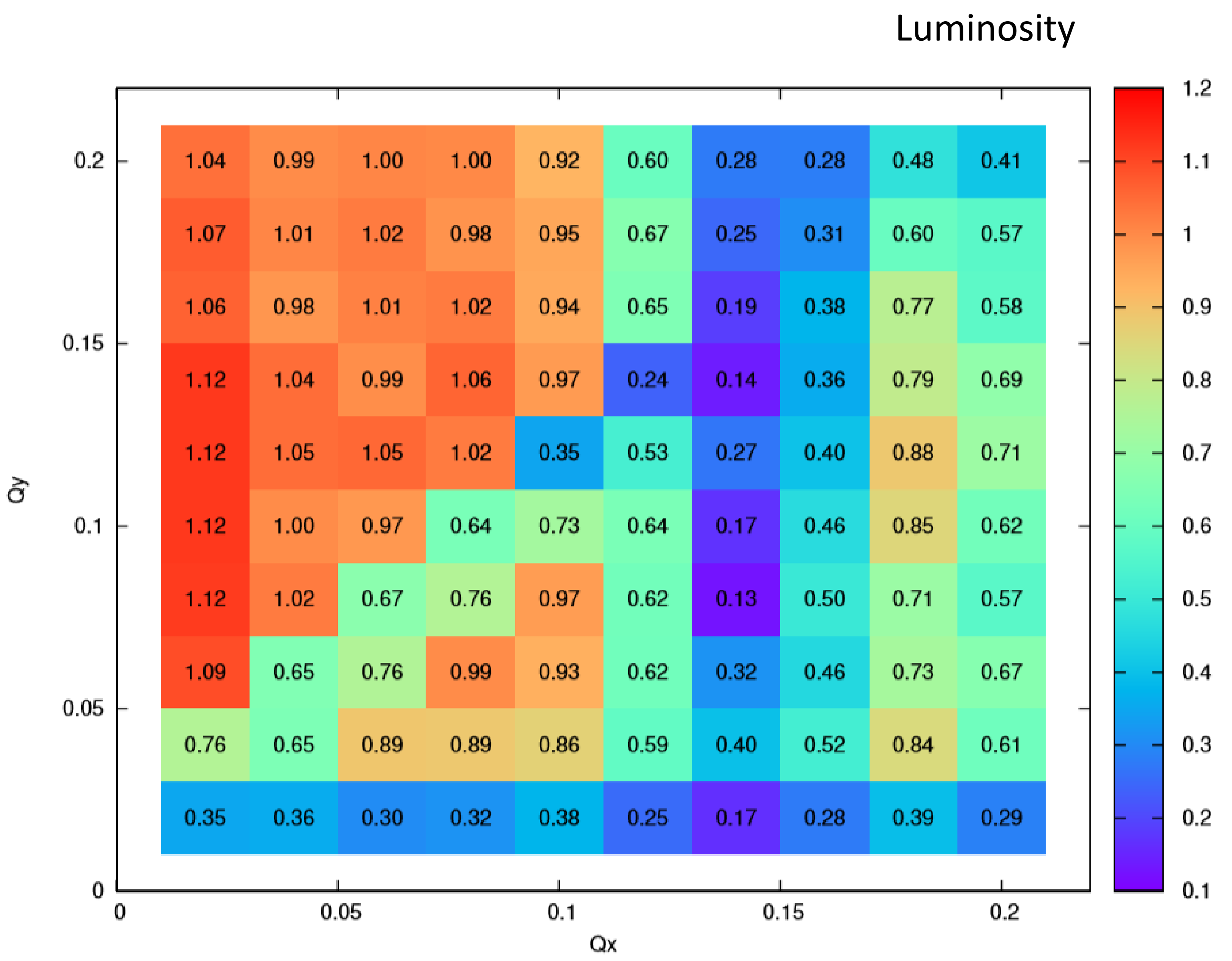
Bunch Intensity Scan





The design beam-beam parameters for proton and electron beams are 0.012 and 0.1. Increasing bunch intensity will increase beam-beam parameter for the opposite beam. Current design bunch intensities are in a reasonable range.

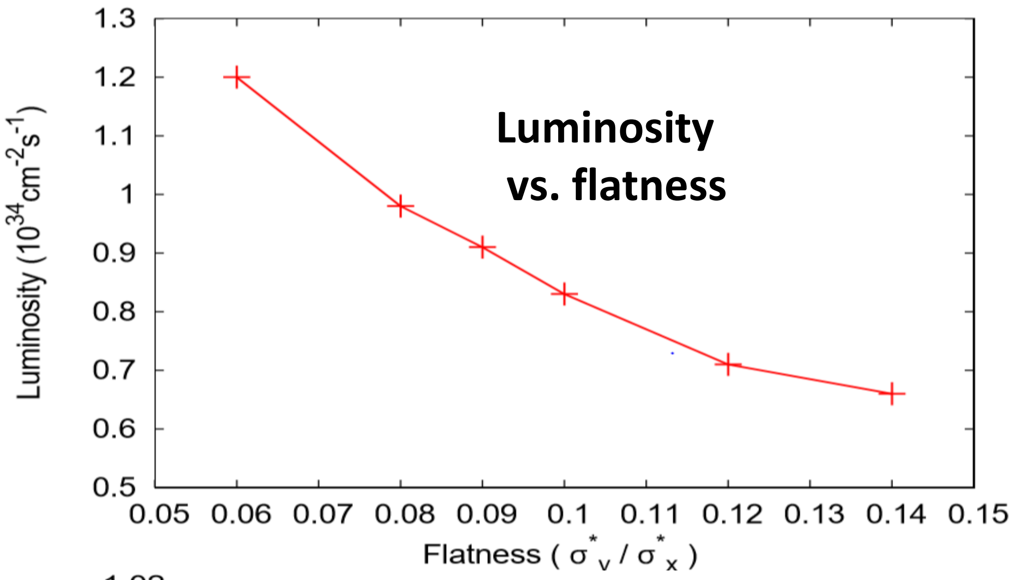
Electron Tune Scan: strong-strong

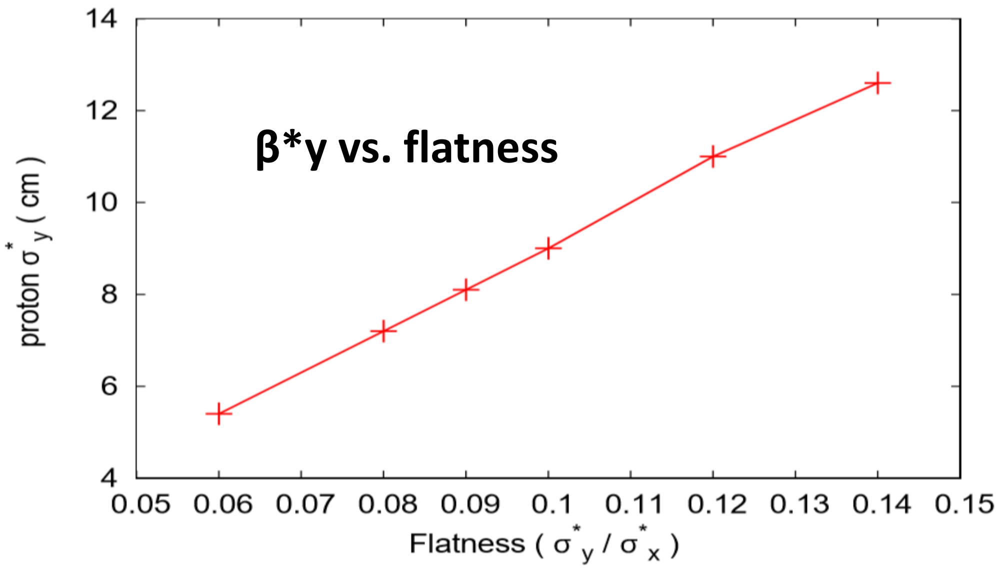


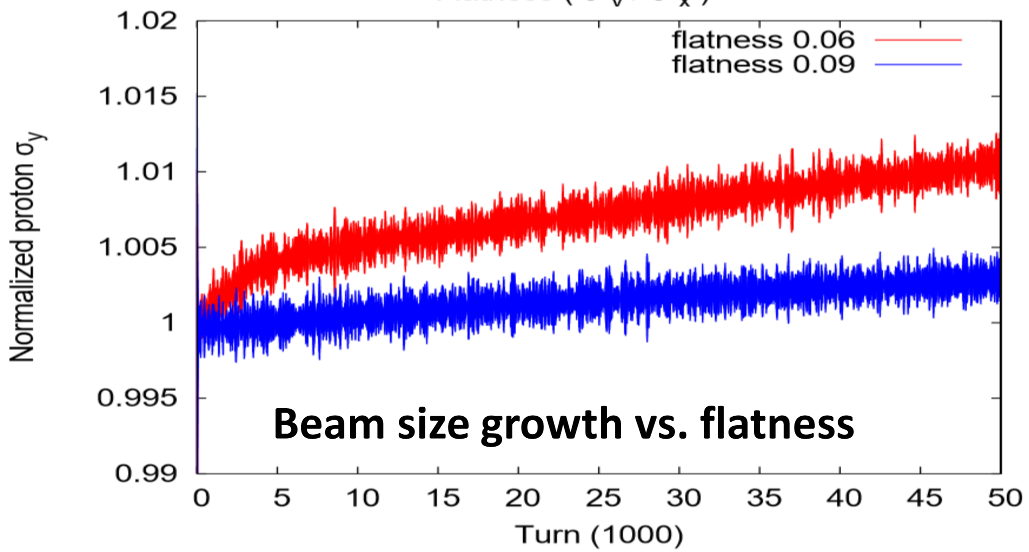
Higher luminosity can be obtained with lower horizontal tunes and higher vertical tunes. However, higher vertical tunes give relatively fast proton vertical emittance growth.

Currently we focus on two choices for electron tunes: (0.08, 0.06) and (0.10, 0.12). Proton lifetime prefers lower electron vertical tune while polarization prefers higher electron vertical tune.

Flatness and BB performance

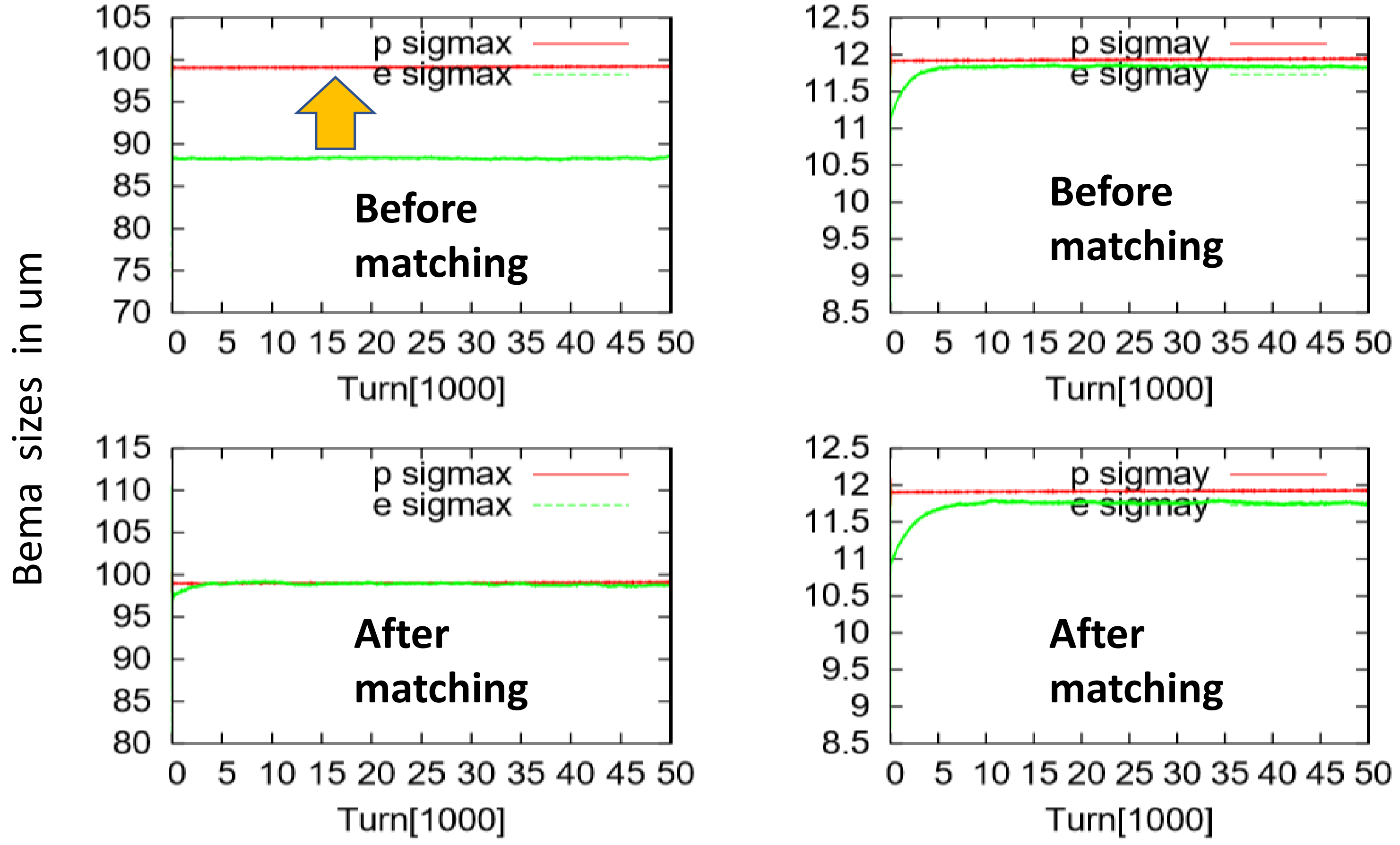






Flatness is defined as σ*y/ σ*x at IP. Lower flatness needs lower betay* in lattices. Lower flatness or flatter beams yields a higher luminosity. However, through beam-beam simulation, we noticed that flatter beams cause faster proton vertical beam size growth.

Beam Size Matching at IP



Example: with flatness 0.12

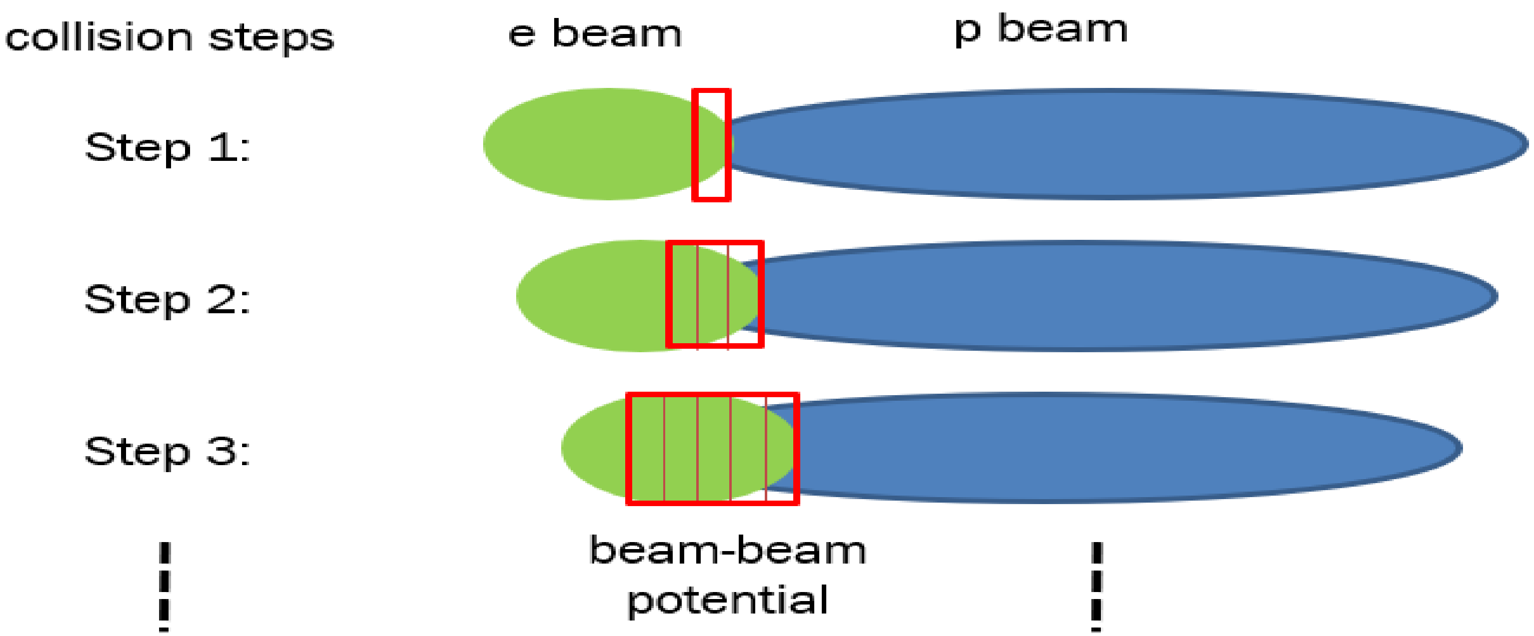
Due to SR effect in electron ring and BB interaction , electron and proton beam sizes are not matched at IP in most cases.

We noticed that mismatched beam sizes will hurt beam lifetime, especially when electron beam sizes are smaller than proton's sizes.

To match electron and proton's beam sizes, we normally adjust electron's $\beta^*_{x,y}$ and /or emittances at IP.

A Strong-Strong and Strong-Weak Model for EIC Long Term Beam-Beam Simulation to Improve the Computational Speed

- Run fully strong-strong beam-beam simulation for a number of turns
- Store the beam-beam interaction potentials during the electron and proton collision
- Switch to strong-weak simulation using the stored beam-beam potentials



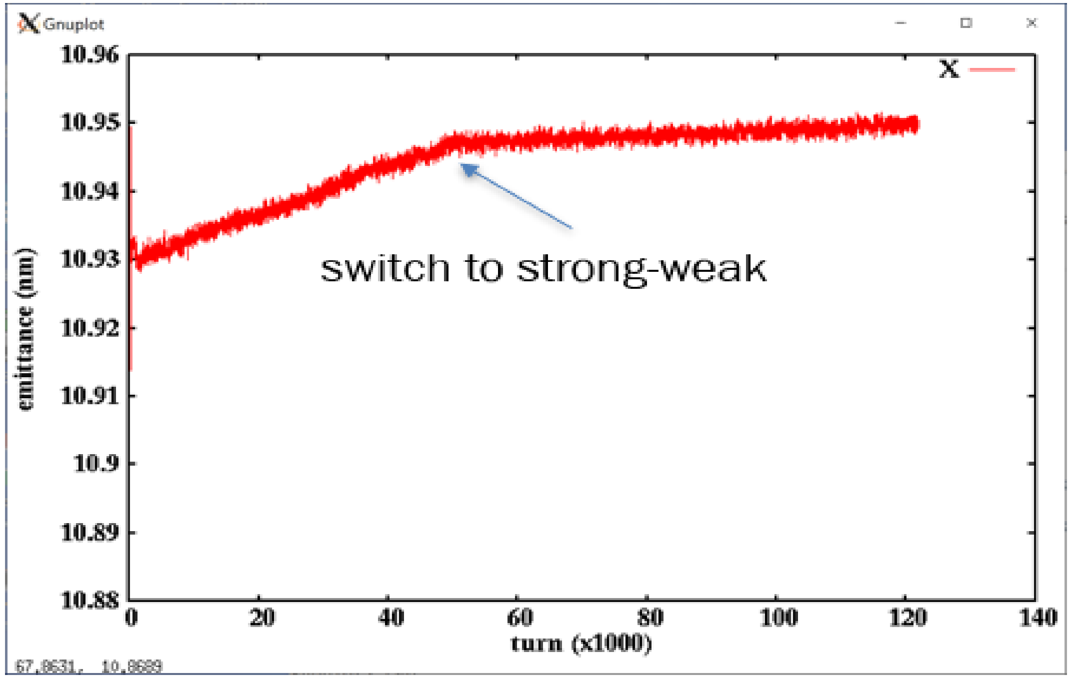
Task 1.4

Dr. Ji Qiang

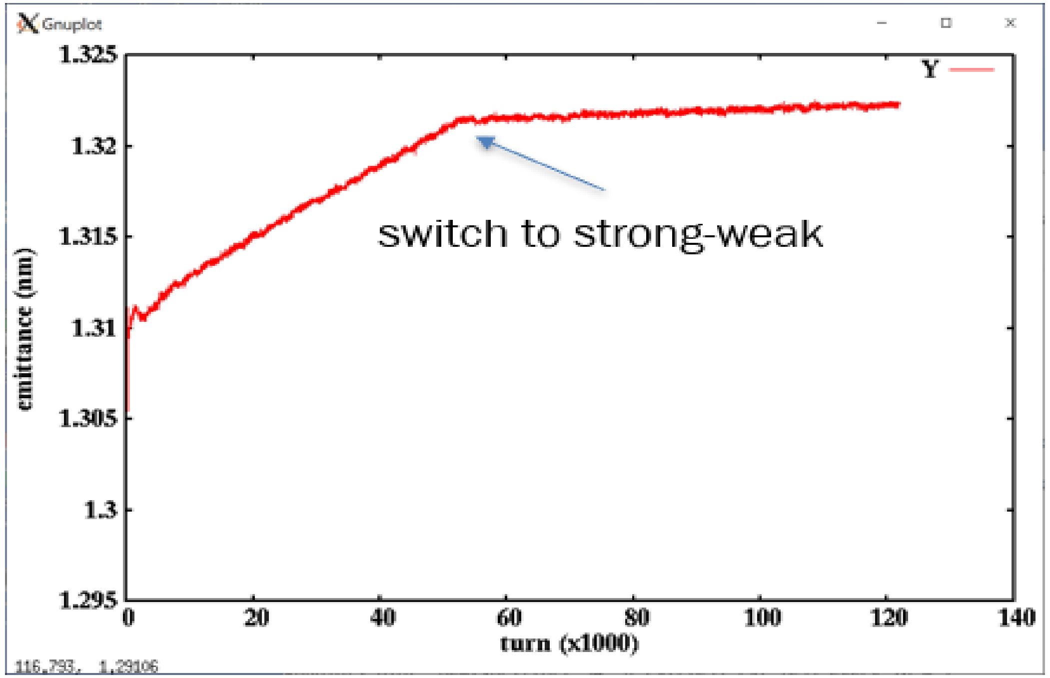
Less Numerical Emittance Growth in Proton Beam with the Faster Strong-Strong and Strong-Weak Simulation

Horizontal and Vertical RMS Emittance Evolution

horizontal

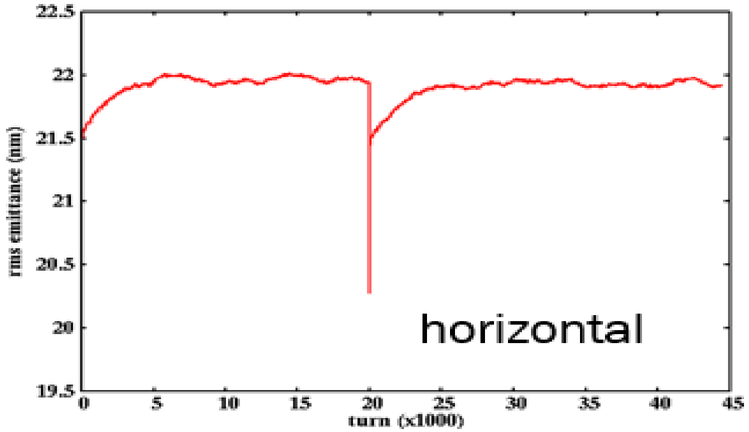


vertical

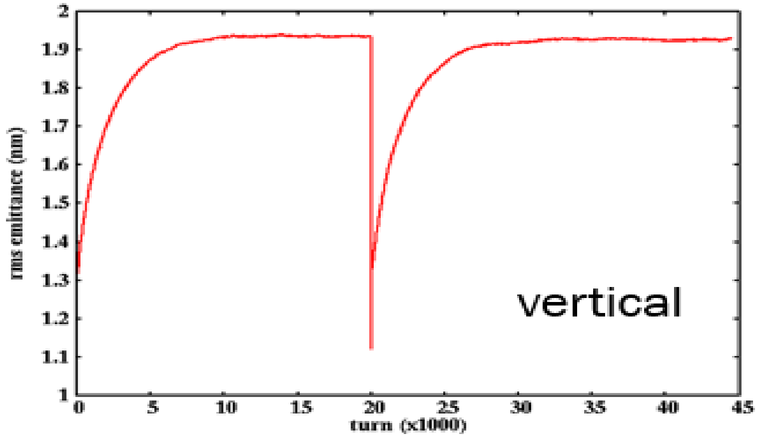


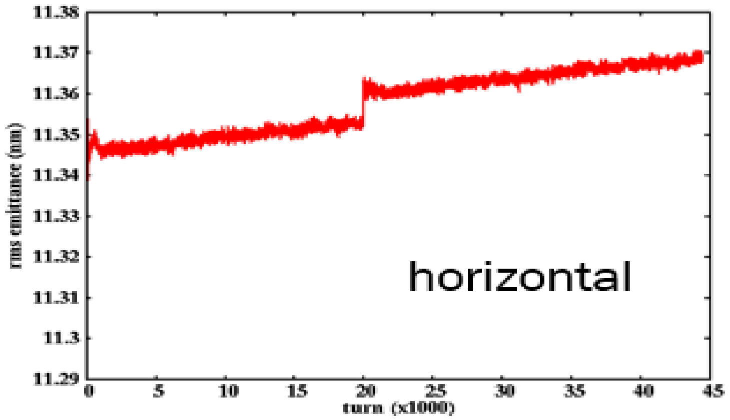
Electron Replacement Results in Small Proton Beam Emittance Growth

Horizontal and Vertical RMS Emittance Evolution with Nominal Electron Injection Replacement

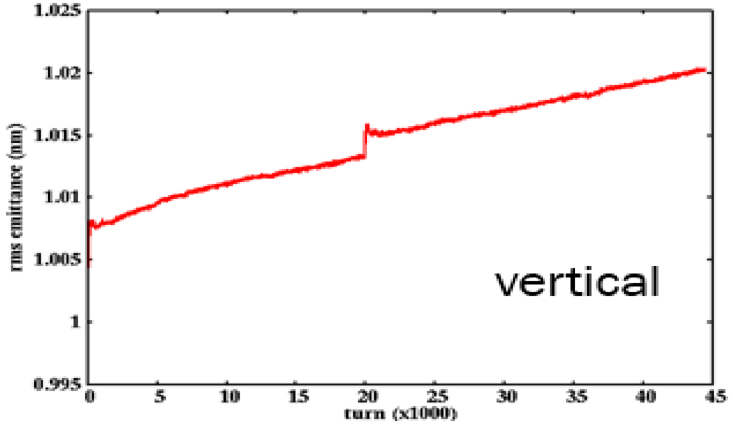


electron beam





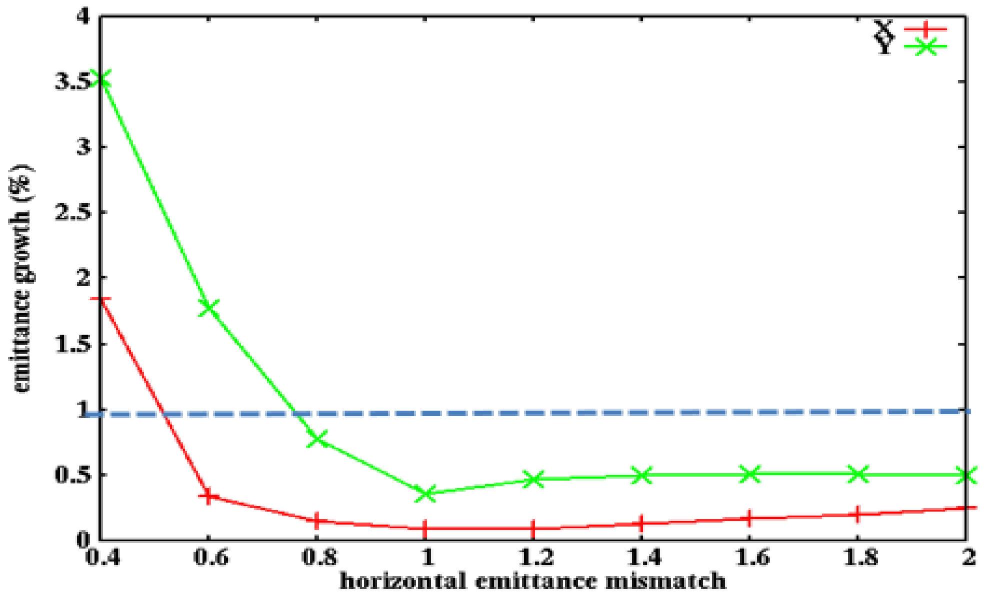
proton beam



Task 3
Dr. J. Qiang

Electron Beam Emittance Mismatch Needs to Be Controlled to Avoid Significant Proton Emittance Growth

Proton Beam Horizontal and Vertical Emittance Growth with Horizontal Emittance Mismatch Electron Injection Replacement

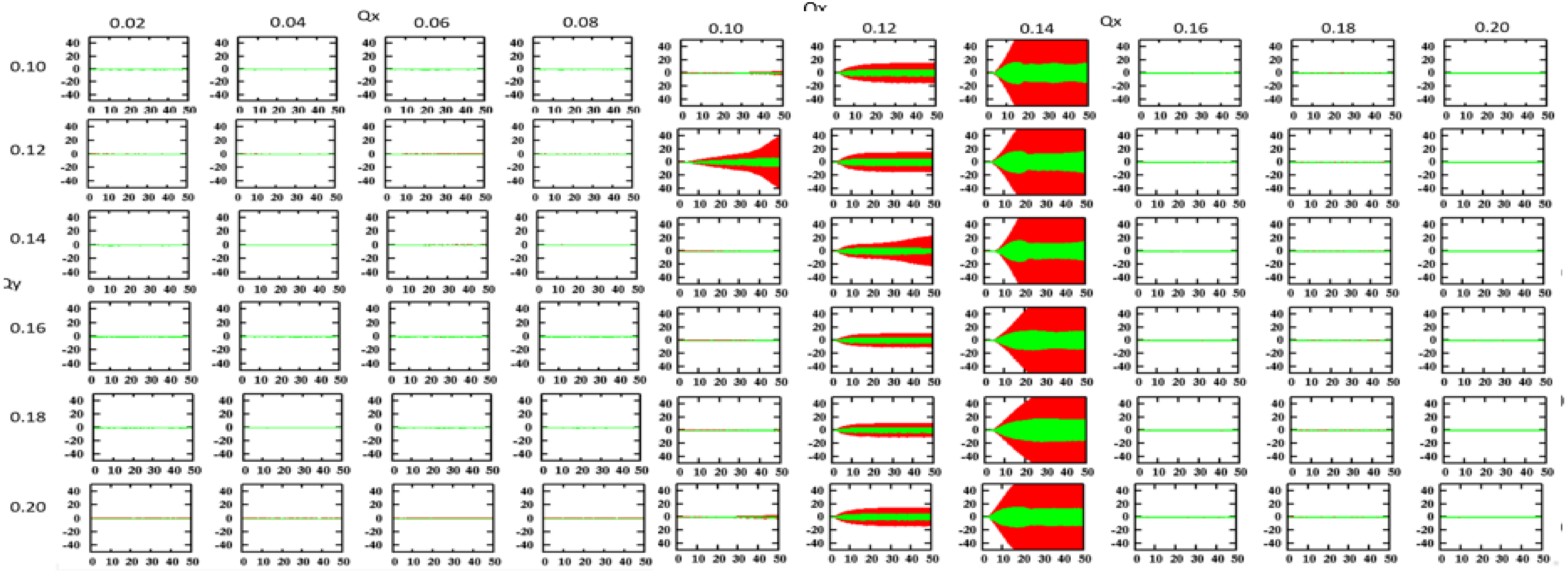


- Proton beam emittance growth is small for emittance mismatch over 0.8
- Smaller emittance mismatch factor results in large emittance growth
- Proton beam emittance growth saturates not sensitive to large emittance mismatch

Electron Beam Tune Scan Shows Instability Stopband

Proton Beam (red) and Electron Beam (green) Horizontal Centroid Evolution vs. Electron Beam Horizontal (Qx) and Vertical (Qy) Tunes

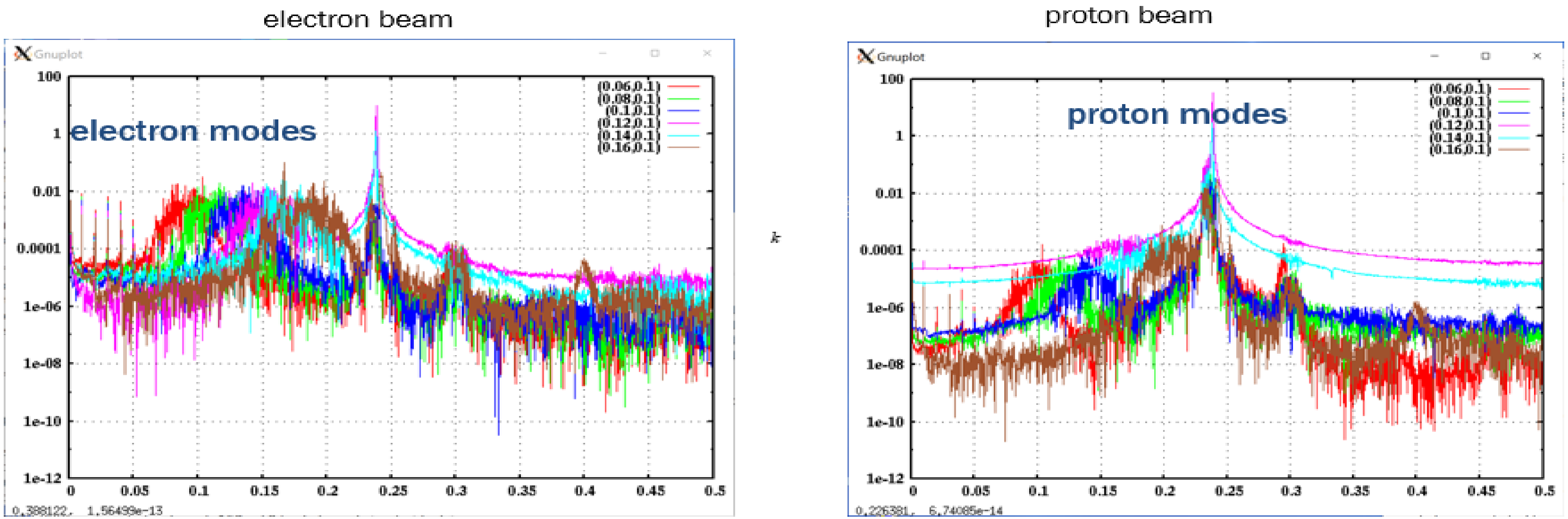
Dr. Ji Qiang



- Nominal beam-beam parameters: Electron beam (0.088,0.1) Proton beam (0.01,0.012)
- Horizontal centroids become unstable with electron beam horizontal tune between 0.1 and 0.14

Spectral Analysis Shows the Coupling between Electron and Proton Beam Modes

Electron and Proton Beam Horizontal Spectrum vs. Electron Horizontal Tune



- The coupled mode from the proton beam becomes unstable

$$lQ_x^e \pm mQ_x^p = n$$

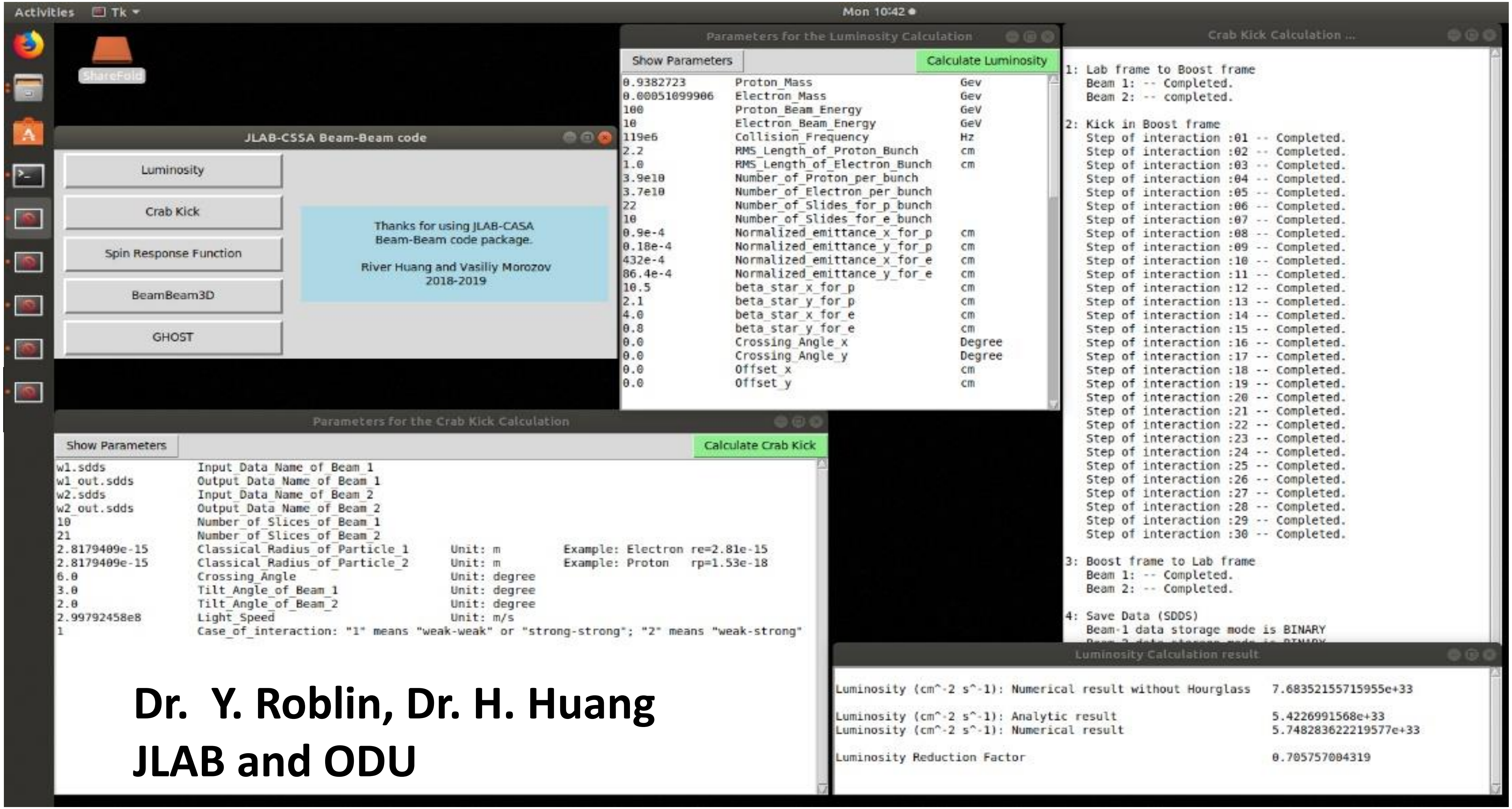
Jlab Team Efforts

Dr. Y. Roblin
Task 4 redefined

- Since EIC design will be based on BNL ring-ring design, where **gear-changing beam-beam interaction is avoided** by using radially shifted orbit in hadron ring to match the revolution frequencies and bunch gaps between electron and hadron rings.
- Therefore, **Jlab team re-defined their beam-beam study scope**. They developed a beam-beam package on top of ELEGANT:
  1) to implement beam-beam effects based on a Basetti-Erksine model.
  2) to simulate errors in crab cavities, optical elements, mis-powering, …
  3) This package also allows for spin tracking like Zgoubi.
- This has been benchmarked successfully and could be used for EIC studies.

GUI of CASA Beam-Beam

Jefferson Lab



Dr. Y. Roblin, Dr. H. Huang

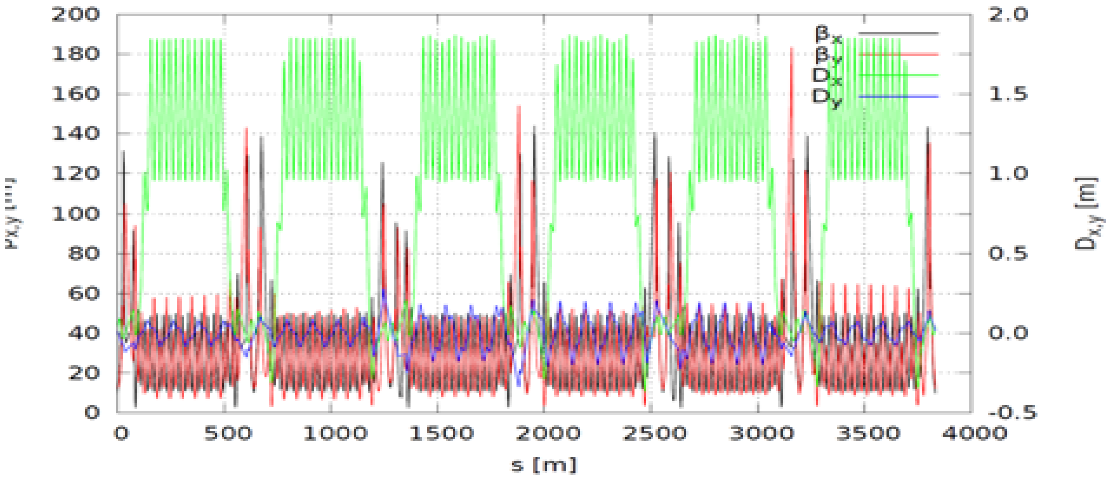
JLAB and ODU

Example of Crab Kick Calculation

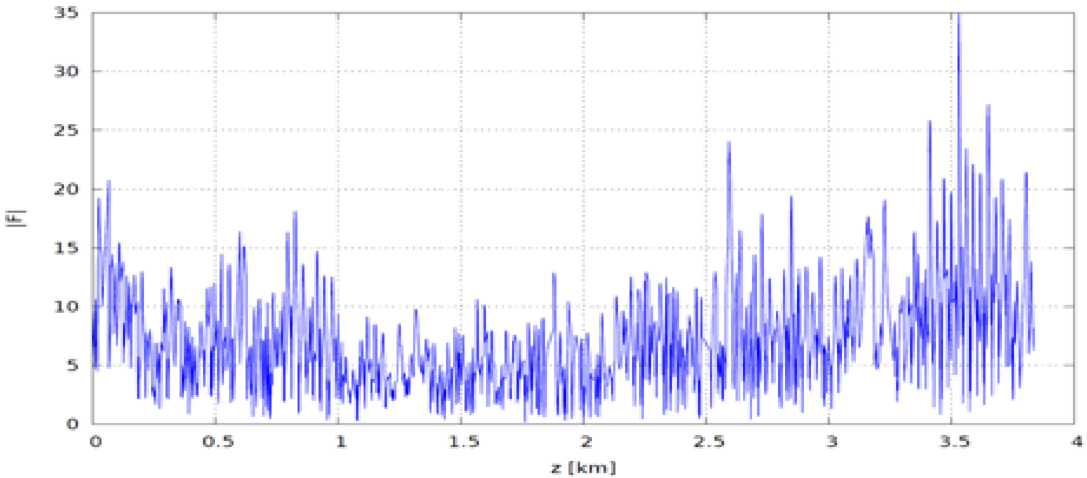
- Crab dynamics simulations are in progress using Elegant without Beam-Beam effect
- Based on Bassetti-Erskine analytic solution, we developed an adequate beam-beam model .
- Our code in Python can be used for simulating beam-beam effect along with crab kicks.
- Errors on trajectory, powering, etc.. can be introduced
- Spin can be tracked alongside

Example: CASA beam-beam application for Spin Response

For race-track, the spin response with two identical Siberian snakes at opposite locations can be calculated by CASA Beam-Beam.

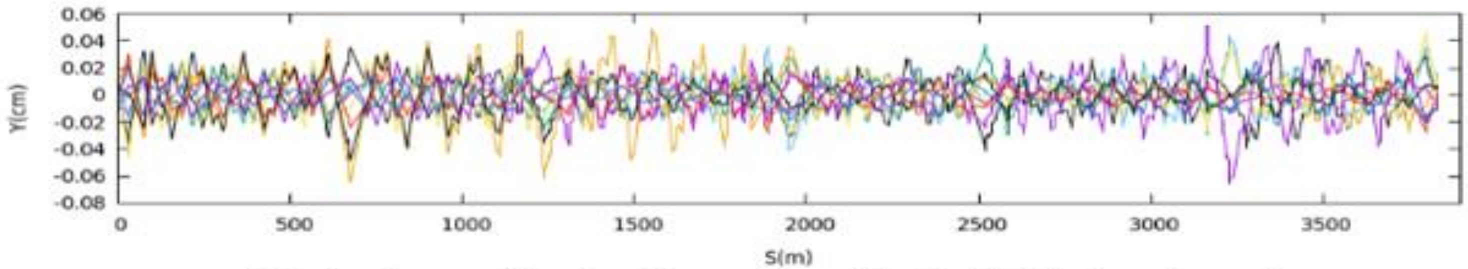


Optics of RHIC's blue ring at injection (24 GeV) calculated using Zgoubi.

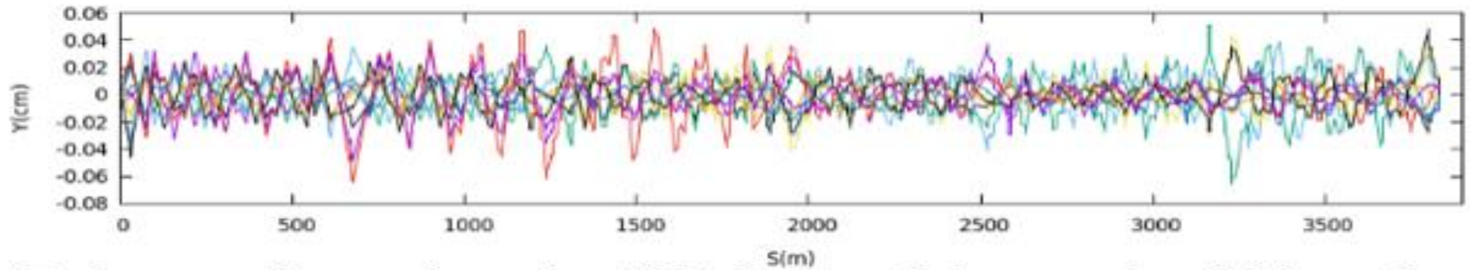


Spin response function of RHIC's blue ring for optics.

For a particle with initial spin (0, 1, 0): the RMS shift of 0.0053(mm) is introduced for both Y and Z position; for the closed orbit, the followings demonstrate the fluctuations of the trajectory caused by the random shift of Y-Z position and X-rotation. Here, both rms value of Y-shift, Z-shift is 0.00053(cm) and skew-angle-shift is 0.024(mrad).



Trajectory: fluctuation when Y-Z shift introduced.

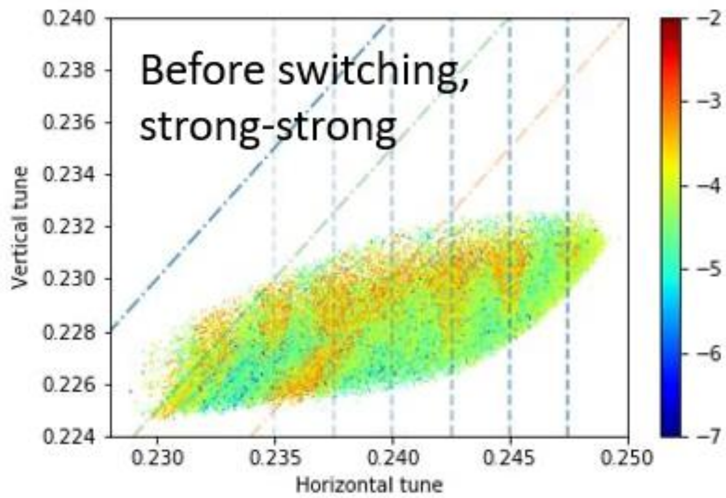


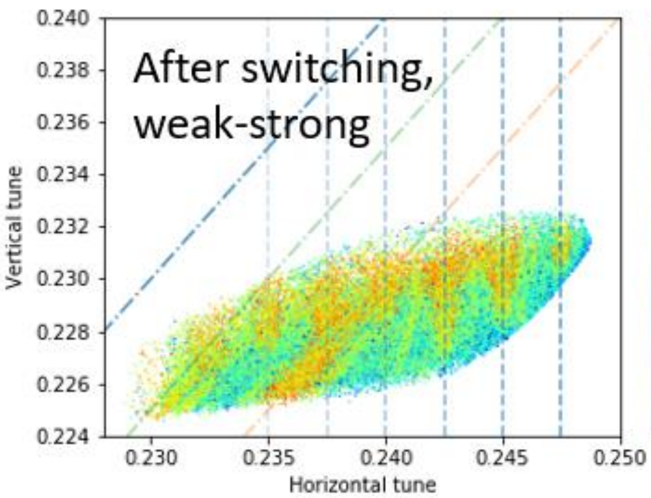
Trajectory: fluctuation when Y-Z shifts and skew-angle-shift introduced.

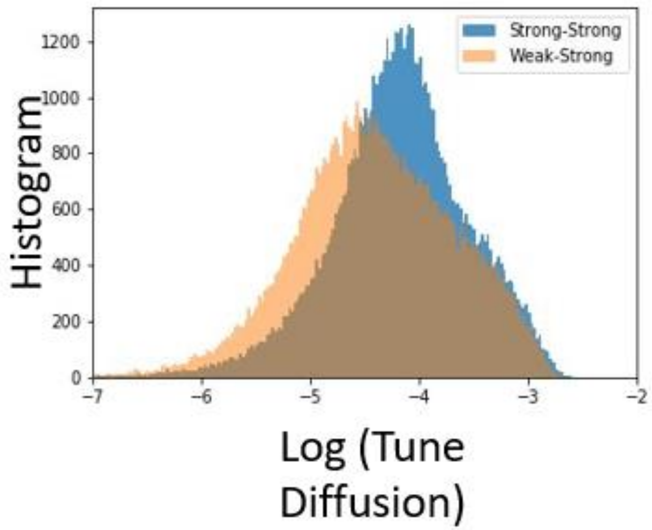
Synchro-betaron Modes in BB3D

- LBNL team provided new feature in BB3D with functionality of switching from the strong-strong and weak strong on the fly and showed less noise effect from numerical error.
- FMA study is used to confirm that the real physics feature is maintained during the switch

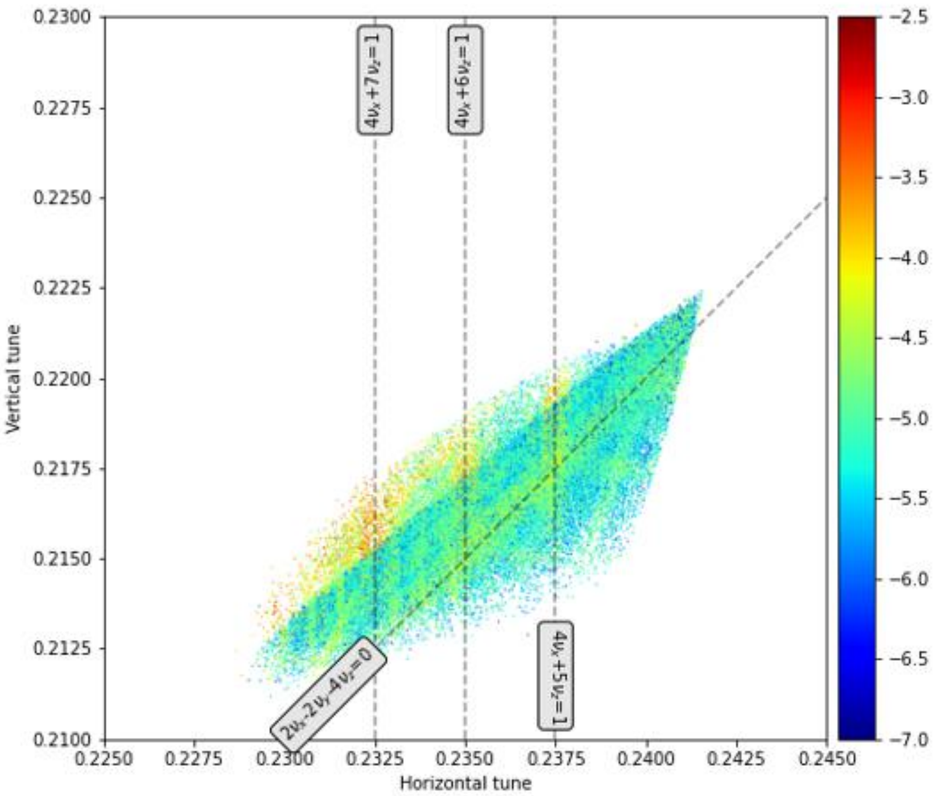
Task 1.1, Code development







Single frequency crab cavity



$$n\nu_x + p\nu_z = 1$$

Caused by

- imperfect crab crossing

$$2\nu_x - 2\nu_y + p\nu_z = 0$$

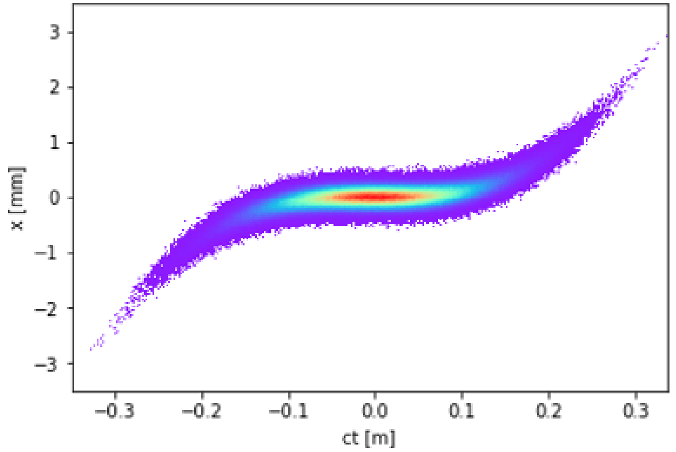
Caused by

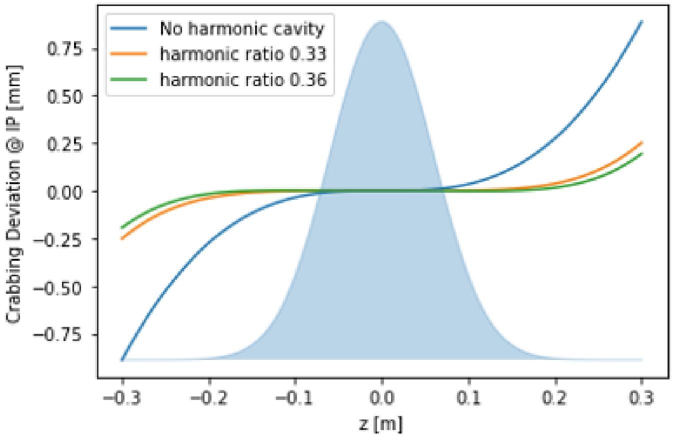
- Hourglass effect
- imperfect crab crossing

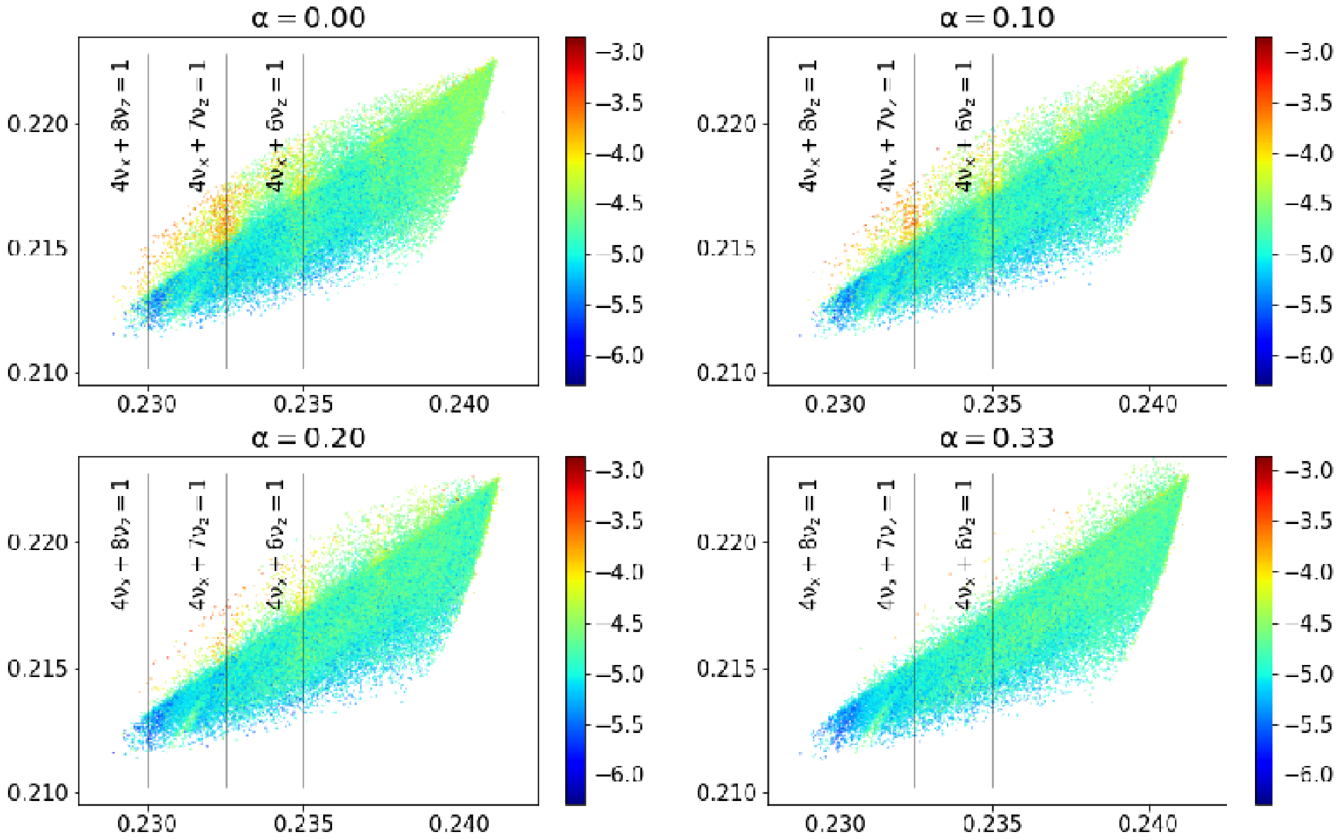
With the new code after the switching from strong-strong to weak strong.

Task 1.2, Study of synchro-beta resonance.

Crab cavity with 2nd harmonic







2^{nd} harmonic cavity largely reduces the strength of the synchro-beta resonance.

Task 1.2, Study of synchro-beta resonance.

Dispersion errors at crab cavity

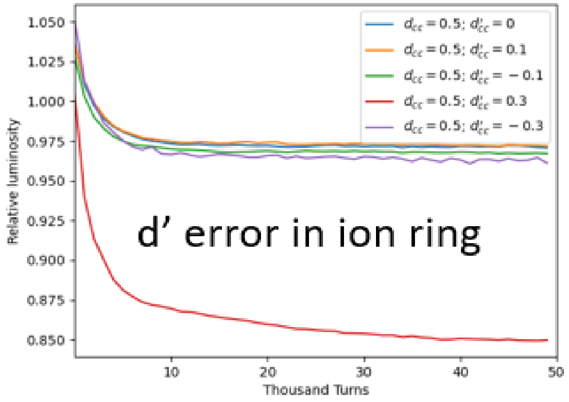
- Dispersion modifies the transfer map between IP and the crab cavity.

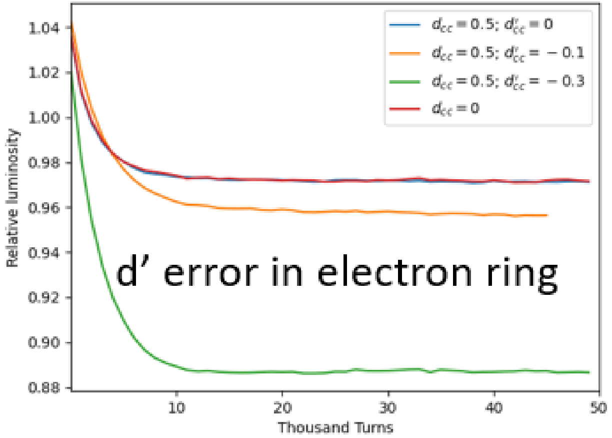
$$M = \begin{bmatrix} \eta^2\theta_c^2 + \eta\theta_c + 1 & \beta_{sx}\eta'\theta_c\left(\eta\theta_c + 2\right) & -\eta\theta_c^2 & \beta_{sx}\eta\eta'\theta_c \\ 0 & -\eta\theta_c + 1 & 0 & -\eta^2\theta_c \\ \eta^2\theta_c & \beta_{sx}\eta\eta'\theta_c & -\eta\theta_c + 1 & 0 \\ 0 & \eta\theta_c^2 & 0 & \eta^2\theta_c^2 + \eta\theta_c + 1 \end{bmatrix}$$

$$\eta_x = \frac{d_x}{\sqrt{\beta_{sx}\beta_{cx}}}$$

$$\eta_x' = \frac{\beta_{cx}d_x' + \alpha_{cx}d_x}{\sqrt{\beta_{sx}\beta_{cx}}}$$

- For the design feature, the derivative of the dispersion at crab cavity should be carefully controlled.

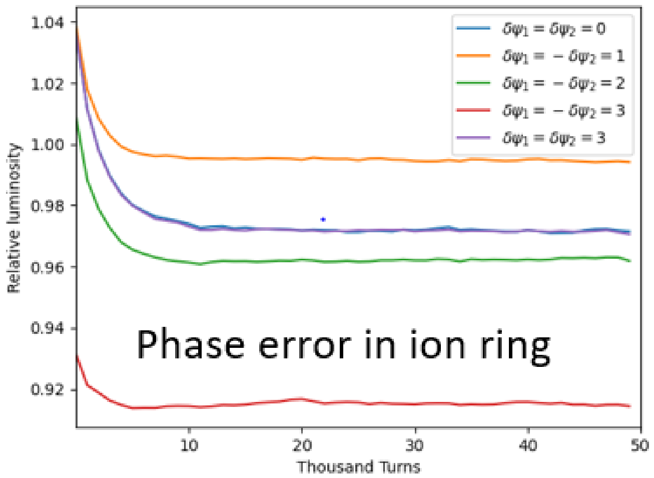


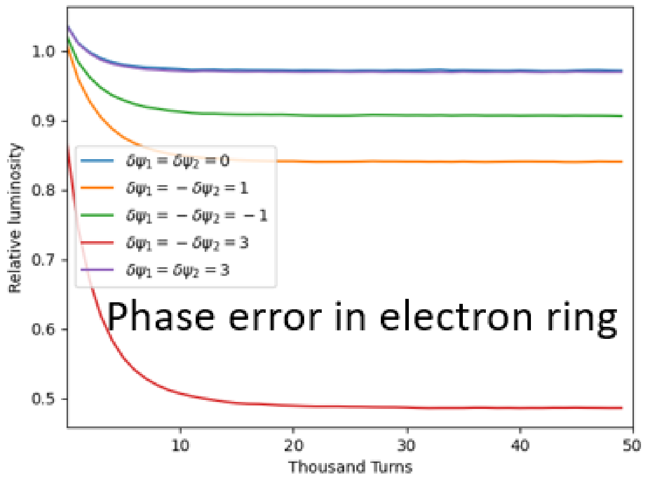


Task 1.2, Study of synchro-beta resonance.

Phase error between IP and crab cavity

- Phase error between IP can crab cavity(CC) leads to a non-cancel crab dispersion outside the CC pairs, unless the phase advance between CC is 180 degree.





- The precise evaluation of phase error requires detailed modeling outside the CC pairs. Further code development is necessary.

Task 1.2, Study of synchro-beta resonance.

Achieved Deliverables in Year 2

Year 1				Year 2			
Qtr 1	Qtr 2	Qtr 3	Qtr 4	Qtr 1	Qtr 2	Qtr 3	Qtr 4
Task 1.1, 1.2, 1.3 (BNL, MSU, JLab)							
Task 1.4 (LBNL, MSU)				Task 3.1 (LBNL) Task 3.2, 3.3 (BNL)			
Task 2.1, 2.2, 2.3 (LBNL, BNL) Task 2.4 (BNL, JLab)				Task 4.1 (LBNL), Task 4.2, 4.3, 4.4 (JLab)			

Status	Task	Description
✓	Task 1.1	Code modifications to BeamBeam3D to reduce numeric noises
✓	Task 1.2	Further study of the beam-beam induced synchro-betatron resonance
✓	Task 1.3	Studies of imperfection with crab cavities
✓	Task 3.1	Code development for electron bunch replacement with beam-beam
✓	Task 3.2-3.3	Simulation studies for electron bunch replacement
✓	Task 4.1-4.4	Redefined. Wrote a beam-beam package on top of ELEGANT.
		Study errors in crab cavities, optical elements, mis-powering, and so on.

Summary

- We joined expertise from BNL, JLAB, LBNL and MSU to address four challenging items related to beam-beam interaction in next generation EIC. **In past two years, we achieved all our goals on schedule.**
- **We developed and tested new beam-beam simulation algorithms and methods in BeamBeam3D, Elegant**, such as, spectral method, frequency map analysis, weak-strong with frozen electron distribution, and so on.
- **We carried out detailed physics studies for the beam-beam interaction in EIC.** We verified and optimized the EIC beam-beam related design parameters and examined the effects of imperfections with crab cavities. All those studies are crucial to the CDR writing.