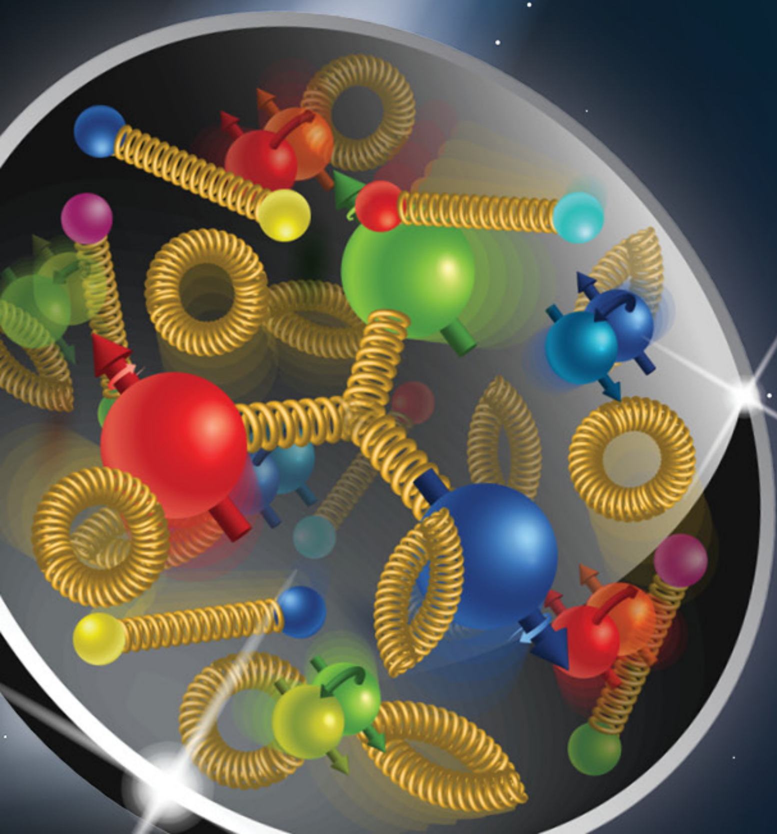
Simulation Challenges for eRHIC beam-beam Study



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Electron Ion Collider – eRHIC

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U.S. DEPARTMENT OF ENERGY | Office of Science

Electron-Ion Collider

- The 2015 Nuclear Science Advisory Committee Long Rang Plan identified the need for an electron-ion collider (EIC) facility as a gluon microscope with capabilities beyond those of any existing accelerator complex.

- The key EIC machine parameters outlined in this plan are:
  - Polarized (~70%) electrons, protons, and light nuclei,
  - Ion beams from deuterons to the heaviest stable nuclei,
  - Variable center of mass energies ~20-100 GeV, upgradable to ~140 GeV,
  - High collision luminosity ~10^{33}-10^{34} cm^{-2}sec^{-1}, and
  - Possibly have more than one interaction region.

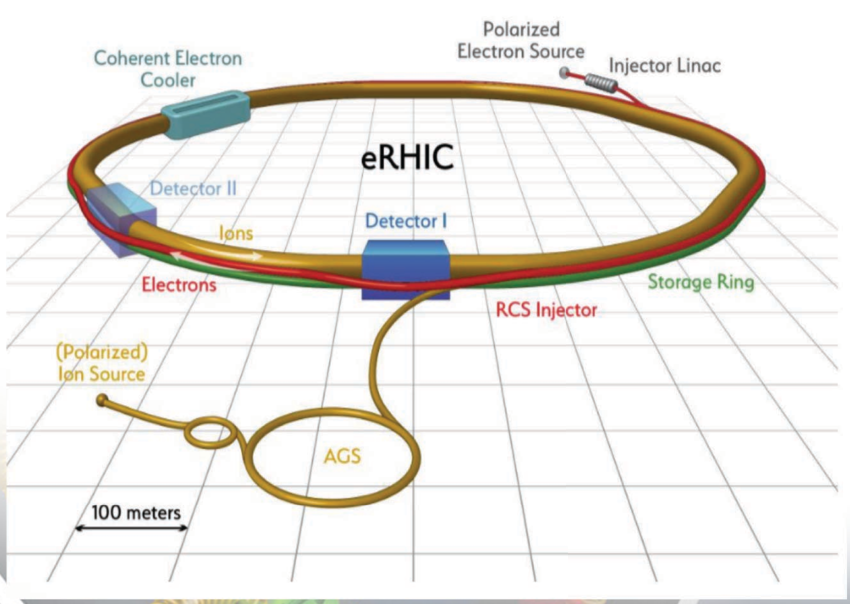
- There are two main EIC designs:

  eRHIC: based on RHIC at Brookhaven National Laboratory (BNL)

  JLEIC: based on CEBAF at Thomas Jefferson National Accelerator Facility (JLAB)

eRHIC Design Parameters

- To reach such a high luminosity, both eRHIC and JLEIC ring-ring designs are aimed to increasing the bunch intensities, reducing the beam sizes at IPs, increasing the collision frequency, and adopting novel cooling techniques.



- For eRHIC design

• 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

eRHIC Machine and Beam Parameters

V2.1

	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**	

Beam-beam Simulation Challenges

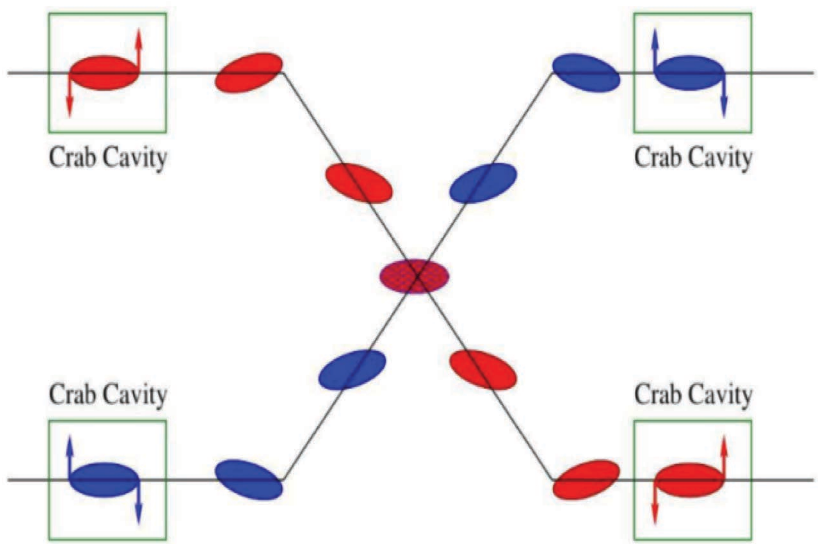
- Beam-beam study was one of the high priority R&D items to reduce the overall design risk listed in the 2016 NP Community EIC Accelerator R&D Panel Report.

- Four beam-beam related R&D items have to be addressed related to these two EIC designs :

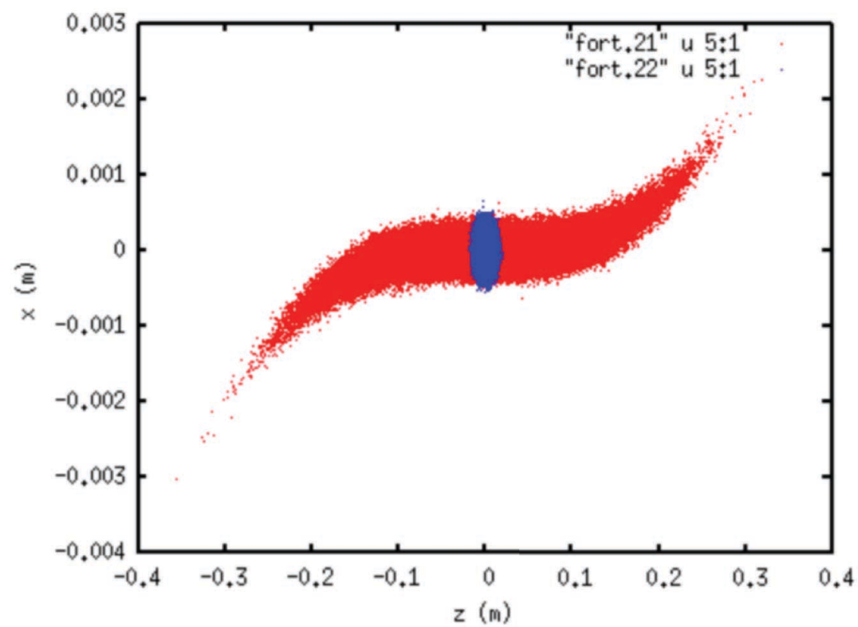
  - study and numerical simulation of crabbed collision with crab cavities,
  - quantitative understanding of the damping decrement to the beam-beam performance,
  - impacts on protons with electron bunch swap-out in eRHIC ring-ring design, and
  - impacts on beam dynamics with gear-changing beam-beam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

Dynamics study and numerical simulation of crabbing collision with crab cavities

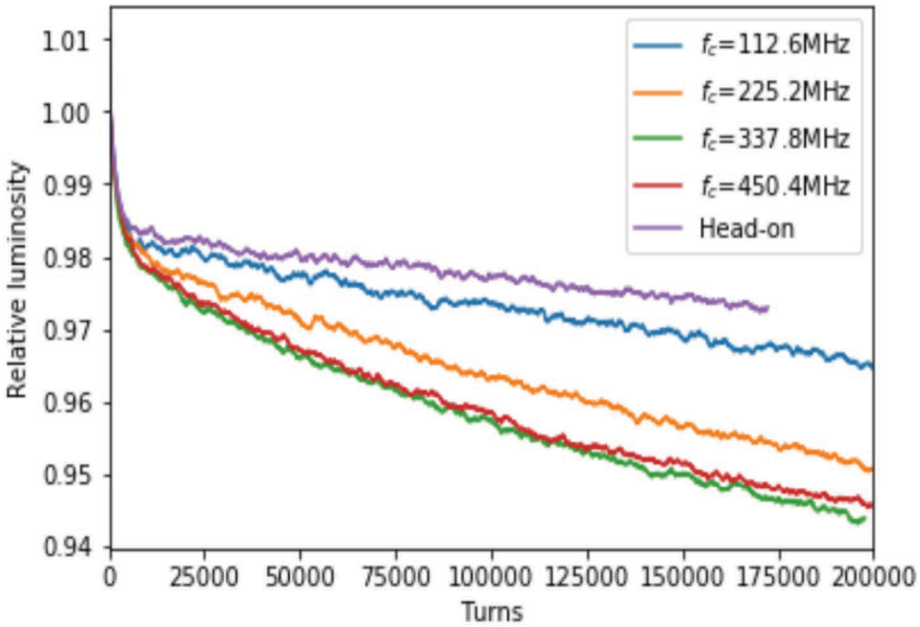
- To compensate the geometric luminosity loss, crab cavities are needed to tilt both beams in the x-z plane to make them head-on collide at IP.
- However, due to the wave length of the carb cavities, the particles in the bunch head and tail will not be perfectly crabbed. The beam-beam interaction may introduce synchro-betatron resonance and head-tail instability.

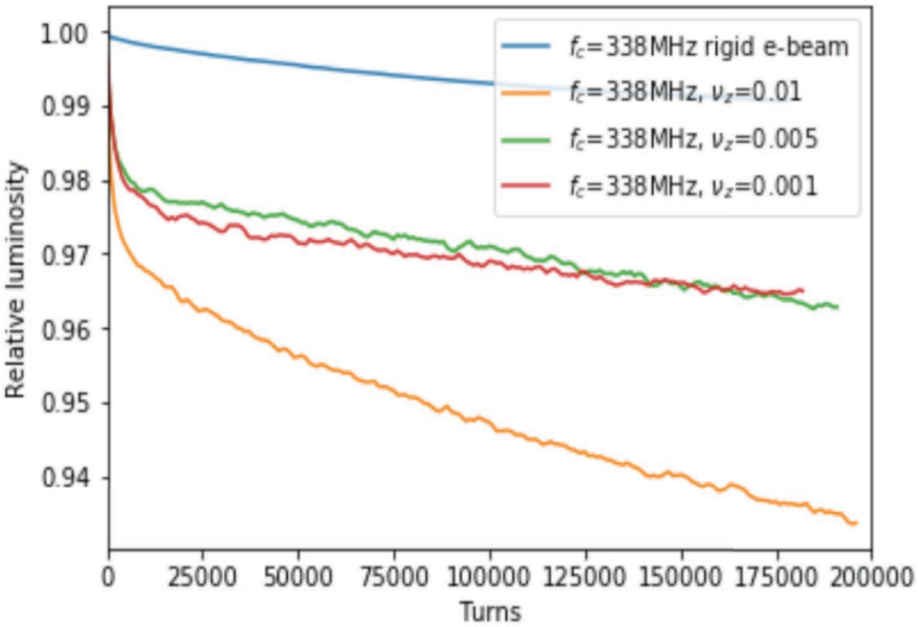


plot @CERN

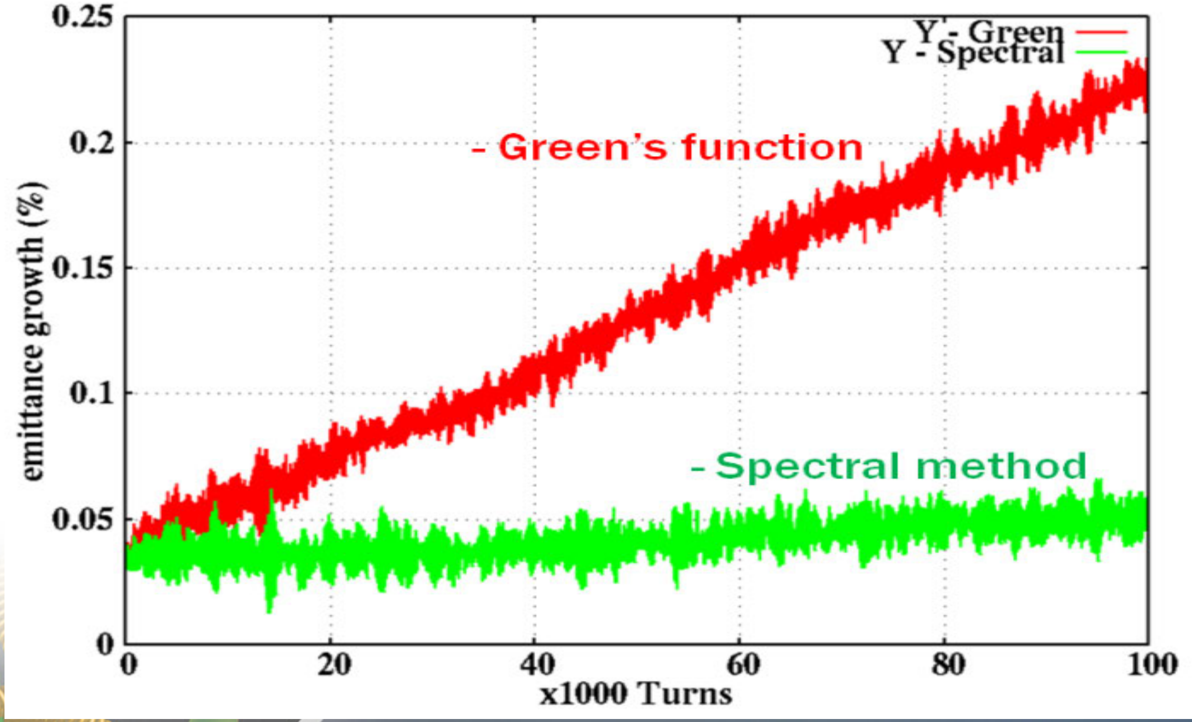


- Earlier simulation for the current eRHIC design show different emittance growth and luminosity degradation rates. They depend on the crab cavity frequency, proton synchrotron tune, proton bunch length, and so on.
- Due to the numeric noise in the strong-strong beam-beam simulation, it is difficult for us to distinguish and separate the emittance growth from different sources.
- Besides a deeper understanding of the involved physics, we have to greatly reduce the numeric noise in the strong-strong beam-beam simulation.



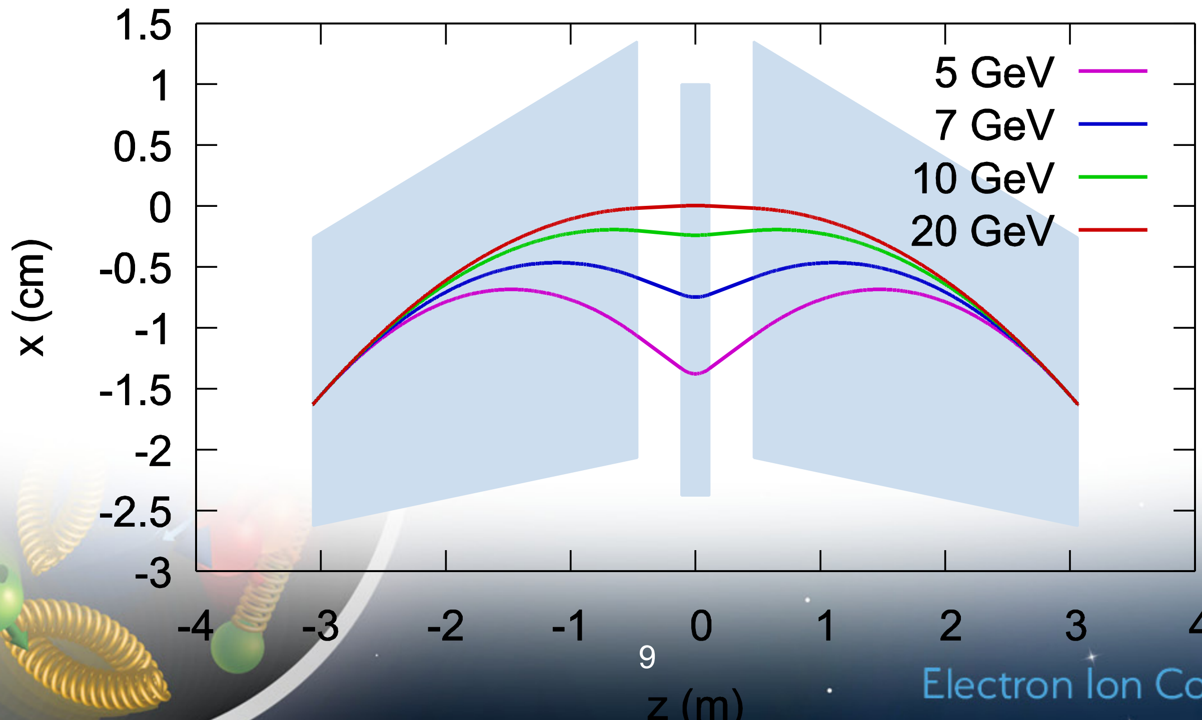


- For eRHIC strong-strong beam-beam simulations, we used following 2 codes: BeamBeam3D by J. Qiang (LBNL), BBSS by K. Ohmi (KEK) .
- In most of existing strong-strong codes, particle-in-cell (PIC) and FFT are used to solve the 2-d Poisson Equation to derive the beam-beam force.
- In our proposal, we plan to adopt a **spectral method** to solve the Poisson Equation. The charge distribution is approximated with a finite number of global basis functions. An example of 2 slice interaction is shown below.



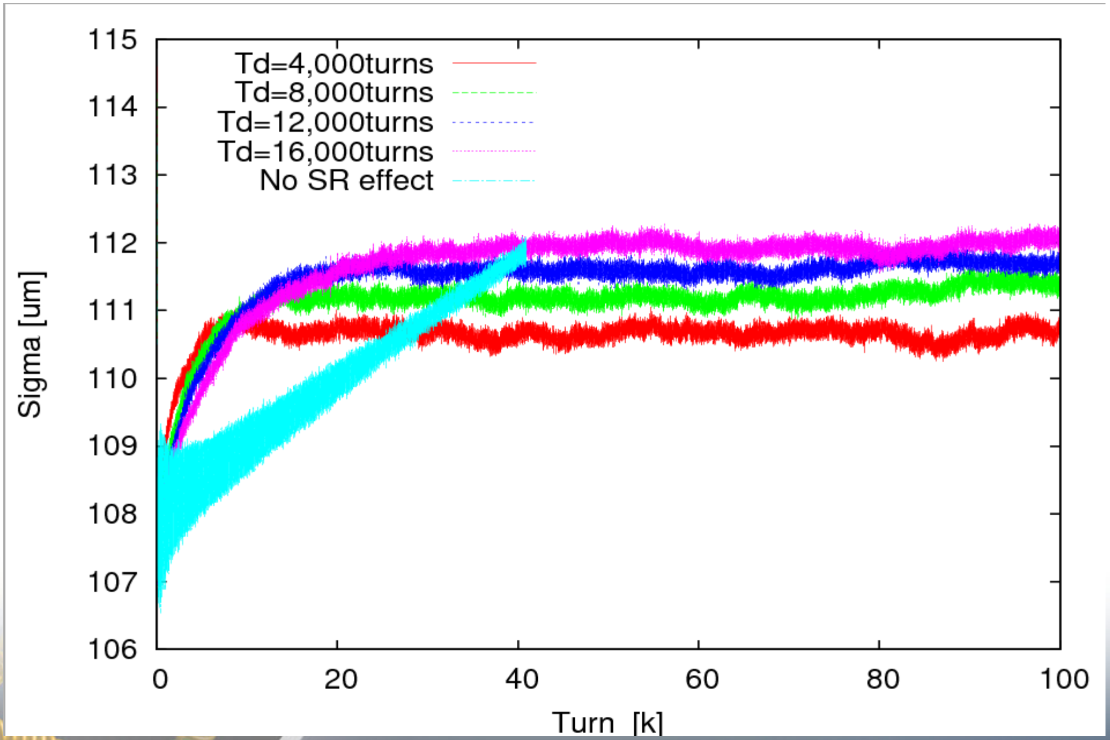
Quantitative understanding of the damping decrement to the beam-beam performance

- 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.
- To achieve the same radiation damping decrement at all beam energies, **super-bends** are being considered for lattice design.



Schematic Super-bend

- The connection between the damping decrement and the achieved beam-beam parameter is empirical. We would like to study the effects of damping decrement to the beam-beam performances for eRHIC.
- We carried out strong-strong beam-beam simulations with different codes. We found that there are little difference in the equilibrium beam sizes of electron beam and the final luminosity when we increased the SR damping time by a factor of 2 ,3, even 4.



- As we know, both beam-beam interaction and the lattice nonlinearity generate beam amplitude diffusion. The equilibrium emittances are decided by the ratio of these two diffusion rates.

- In most of the existing strong-strong codes, the lattice nonlinearity is not included. The lattice nonlinearity includes sextupoles in arcs, higher order field errors in interaction regions (IRs), and so on.

- In our proposal, we plan to
  - replace 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

- 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. Any electron bunch will be replaced in 5 minutes.

- **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 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. SR damping is included by simply adjusting electron bunch's center position bunch sizes.
- **To full study / understand the effects on the protons during electron bunch replacement, a 6-d strong-strong beam-beam simulation is need. For this purpose, we plan to re-structure BeamBeam3D for this task.**

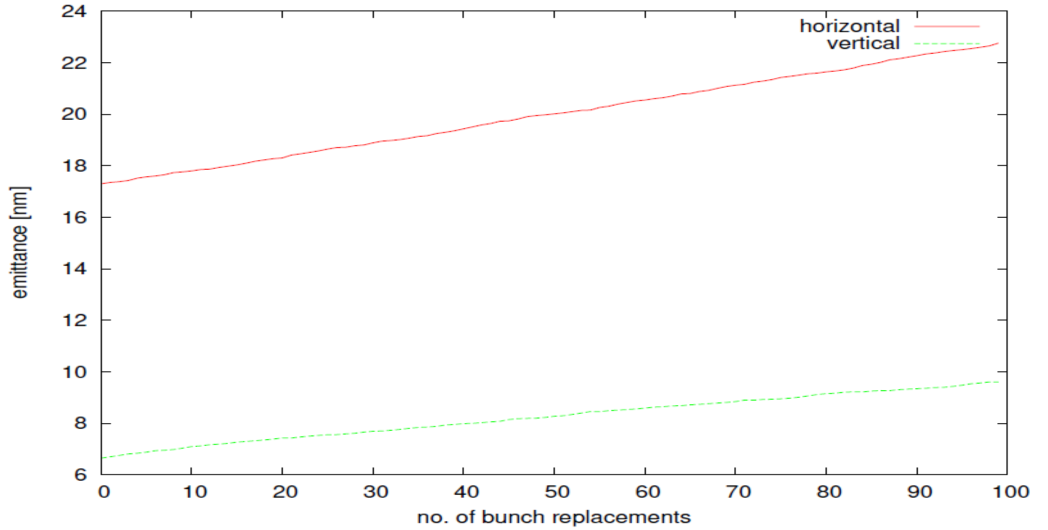


Figure 2: Proton beam emittance evolution during 100 electron bunch replacements, with electron bunches being accumulated in 5 steps each time, and injected off-energy.

Courtesy of
C. Montag

Summary

- We presented the high priority R&D items related to the beam-beam interaction for the EIC designs.
- To address these simulation challenges, we proposed new simulation algorithms and methods. Modifications to code BeamBeam3D are required for these tasks.
- At the completion of this proposal, we will have a clear understanding of the beam-beam interaction related beam lifetime reduction, emittance blowup, and luminosity degradation.