Beam-Dynamics Study of the Self-Generating Field With Crab Crossing Scheme in the Future Electron-Ion Collider

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Project description

- We aim on boosting the understanding of the self-field nonlinear beam dynamics (referred as Beam-Beam and space charge effect)in the future Electron-Ion Collider (EIC), especially with the crab-crossing scheme.
- Current Status: We focus on the beam-beam effect in the crab-crossing scheme in the first year. **The progress meets the planned milestones.**
- This project is tightly aligned with the R&D task row #1 (sub-priority A), #24, #30, #32, #48.

Budget summary

	FY 2016 (K$) BNL + LBNL	FY2017 (K$) BNL + LBNL
Funds Allocated	75 + 120	68.5 + 111.2
Actual Cost	6.5 + 8.8	68.5 + 106.6

Deliverables and Schedule

Deliverables	Status
Linac-ring EIC crab crossing study (BNL/LBNL)	Preliminary results, Paused.
Enable the crab cavity with harmonic cavity in BeamBeam3D (LBNL)	✓Done, benchmarked
Determine if possible coherent instability in Ring-Ring EIC (BNL)	✓Done
Determine the beam dynamics in crab crossing in Ring-Ring EIC, frequency choice of crab cavity (BNL)	✓Done
Study the optics requirement (dispersion and phase advance) to place the CC in the colliding ring (BNL)	✓Done
Enable arbitrary optics at the location of CC in BeamBeam3D (LBNL)	✓Done, benchmarked
Noise studies of CC amplitude and phase (BNL)	✓Done, for white noise
Preparation of including other nonlinear elements in BeamBeam3D (LBNL)	✓Done
Enable the electron from non-equilibrium state capability in BeamBeam3D (LBNL)	✓Done

Questions to answer?

- Current EIC combines the highest beam-beam parameter from lepton colliders (~0.1) and the hadron collider (~0.015). Is this valid?

- Crab crossing has been only demonstrated at KEKB (lepton colliders) with damping on both beams. What are the potential problems that adapting crab crossing in EIC?

Outlines

- Simulation tool – BeamBeam3D and Simtrack
- Coherent Beam-Beam effect in ring-ring EIC
- Crab-crossing scheme in ring-ring EIC, frequency choice.
- Integration of crab cavity in the ring.
  - Dispersive effect
  - Non-ideal phase advance from IP
- Noise of amplitude and phase of crab cavity

Luminosity and Beam-Beam effect

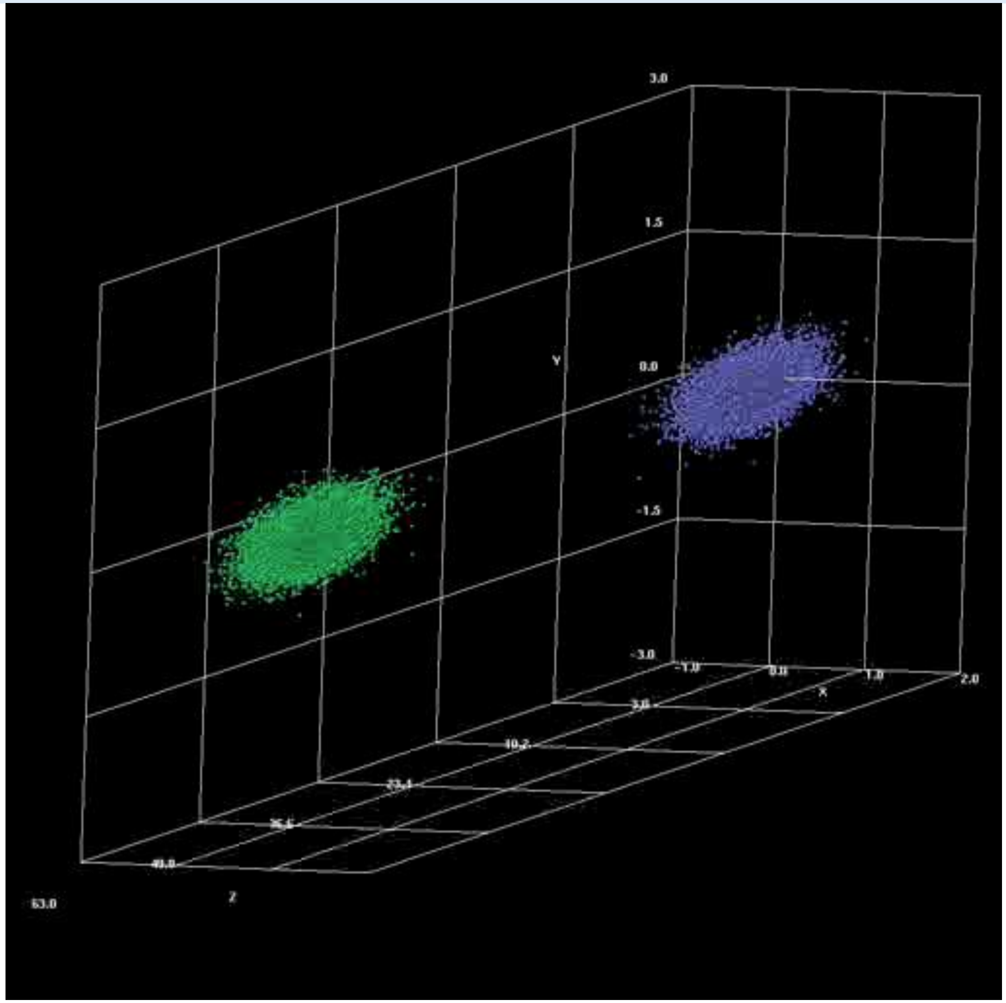
- The probability of event is proportional to the luminosity of colliding beams.
- Luminosity depends on:

$$L = f_b \left(\frac{4\pi\gamma_p\gamma_e}{r_p r_e} \right) (\xi_p \xi_e)(\sigma'_p \sigma'_e) \frac{e^{-\frac{d_x^2}{4\sigma_x^2}}}{\sqrt{1+\zeta^2}}$$

$$\xi_p = \frac{r_p \beta^*_p}{4\pi\gamma_p} \frac{N_e}{\sigma_e^2} \qquad \xi_e = \frac{r_e \beta^*_e}{4\pi\gamma_e} \frac{N_p}{\sigma_p^2} \qquad \zeta = \frac{\phi}{2}\frac{\sigma_s}{\sigma_x}$$

- Larger luminosity wants higher repetition rate, larger beam-beam parameters, smaller crossing angle and beam separation.
- However, beam-beam effects limit these factors and eventually luminosity.

An Illustration of ElectroMagnetic Interaction/Beam-Beam Interaction between Two Colliding Beams

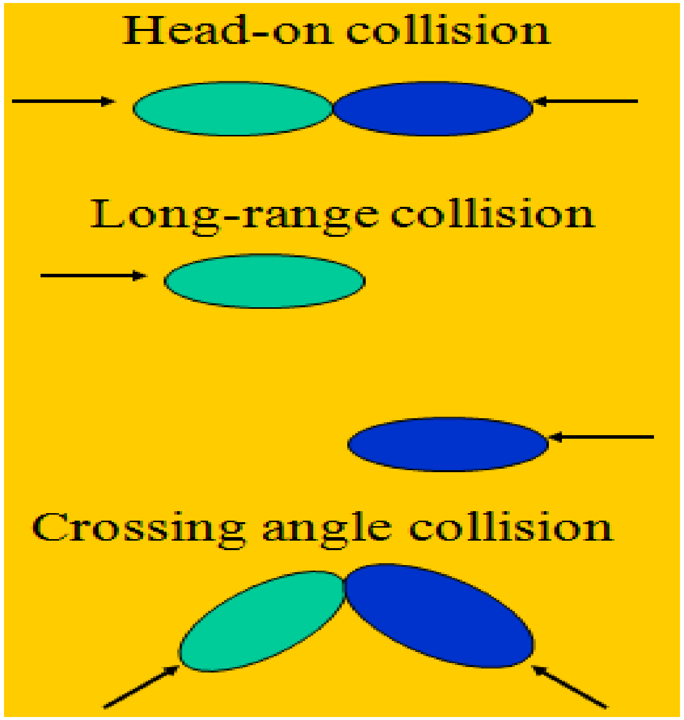


Simulation Tool

- BeamBeam3D, a strong-strong code, self-consistent simulation method. Simulate dynamics of two colliding beams at the price of slower, and more numerical noise
- Simtrack, a weak-strong code, only simulate dynamics of one beam, the other one serve as a 'beam-beam' lens. Faster and less noisy.

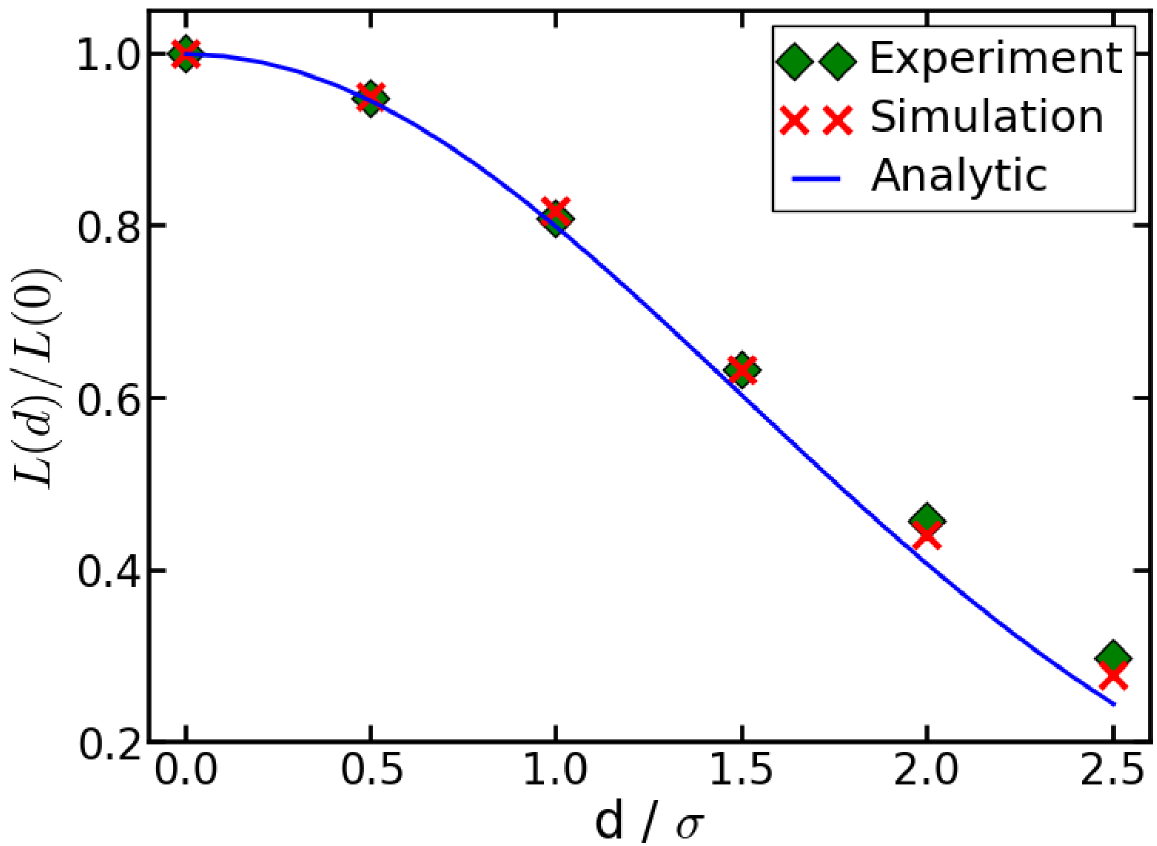
- Need modification to fit EIC needs. This proposal enables timely improvement of both codes to fit the special beam dynamics needs of EIC.

A Parallel Colliding Beam Simulation Code, **BeamBeam3D**, Was Developed to Model the Beam-Beam Interaction Self-Consistently

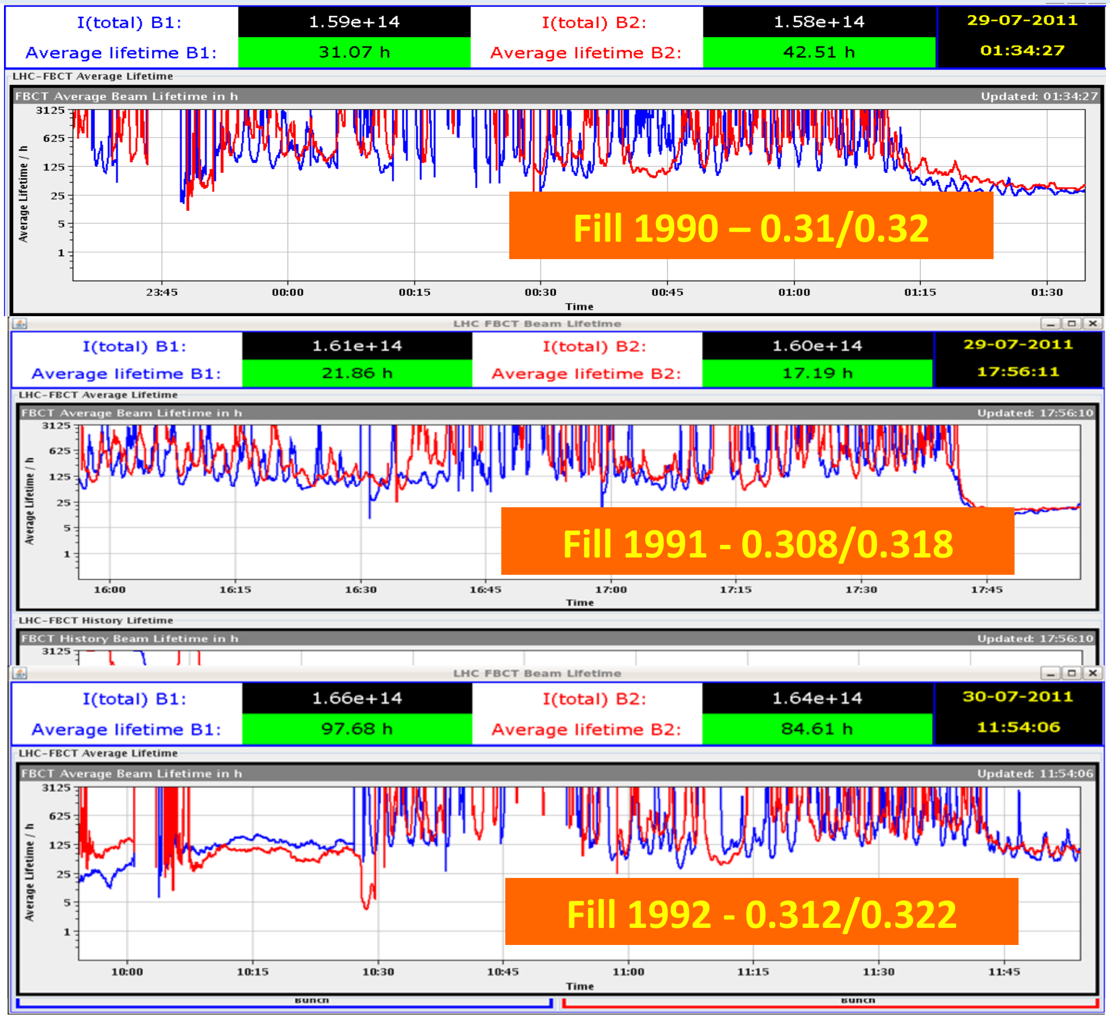


- Multiple-slice model for finite bunch length
- New algorithm -- shifted Green function -- efficiently models long-range collisions
- Parallel particle-field based decomposition to achieve perfect load balance
- Lorentz boost to handle crossing angle
- Arbitrary closed-orbit separation
- Multiple bunches, multiple collision points
- Linear transfer matrix + one turn chromaticity
- Conducting wire, crab cavity, e-lens compensation model
- Feedback model
- Impedance model

Benchmarked with experiments, I

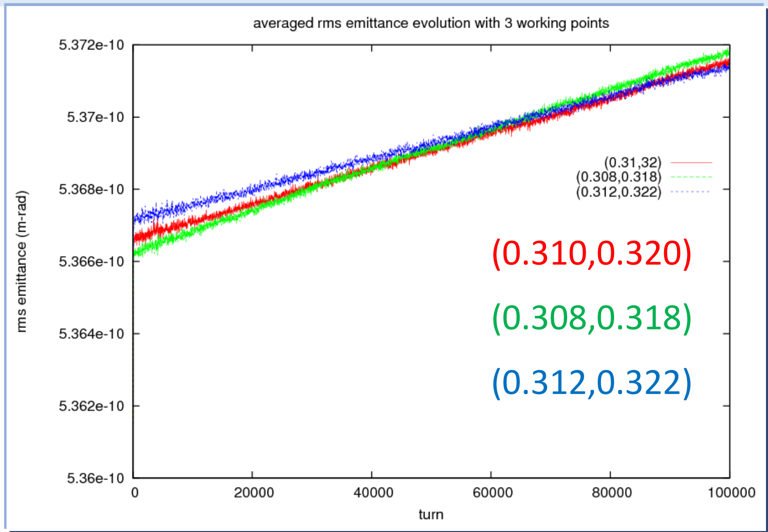


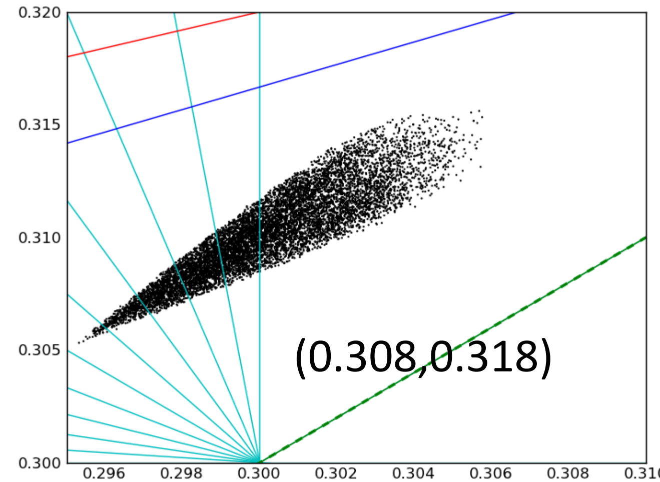
Benchmarked with experiments, II

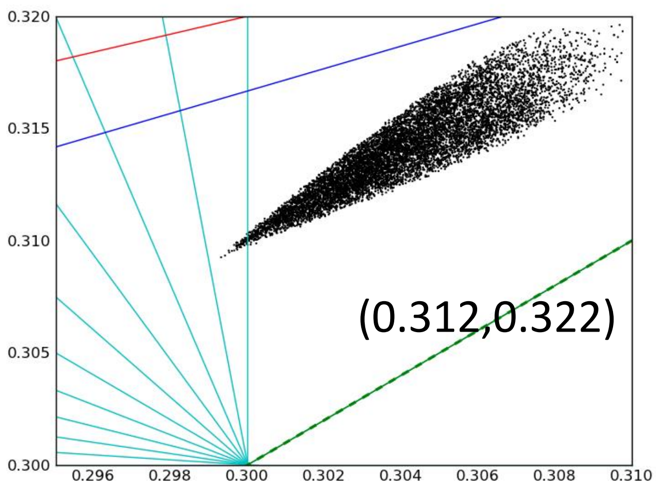


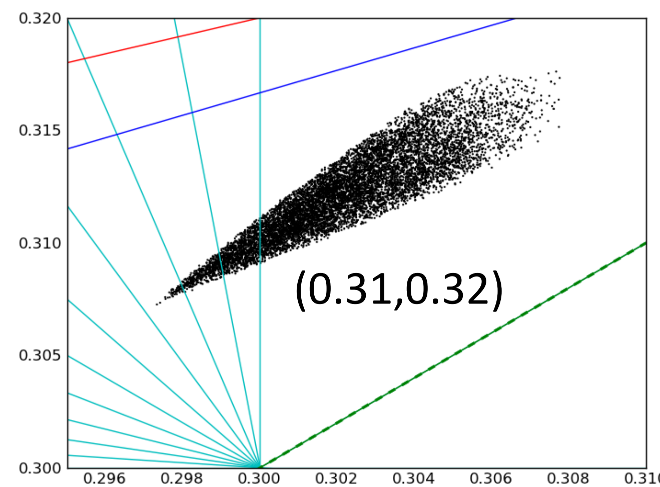
Courtesy of G. Arduini, J. Wenninger

Benchmarked with experiments, III



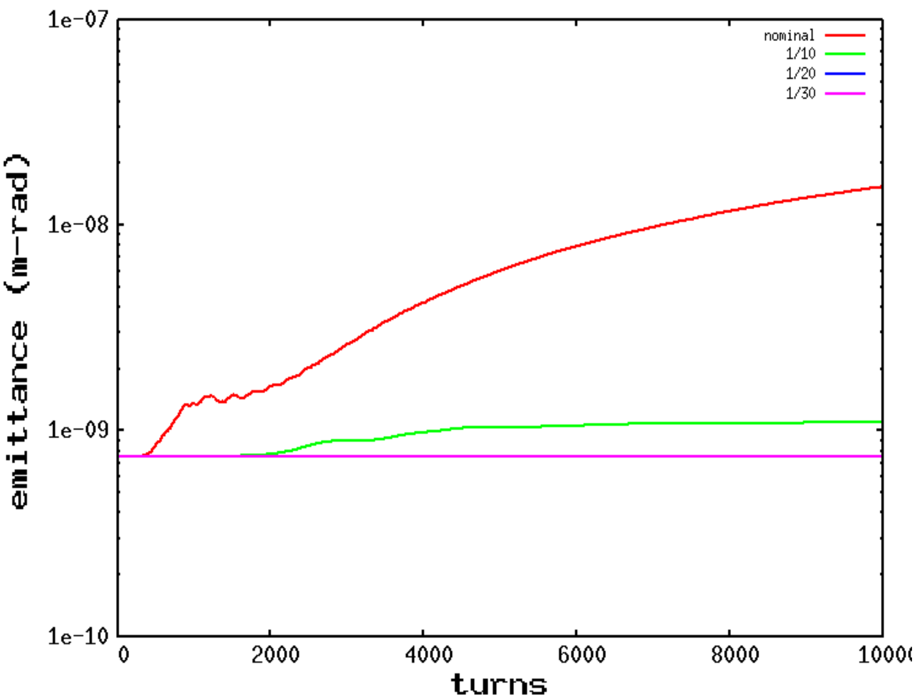




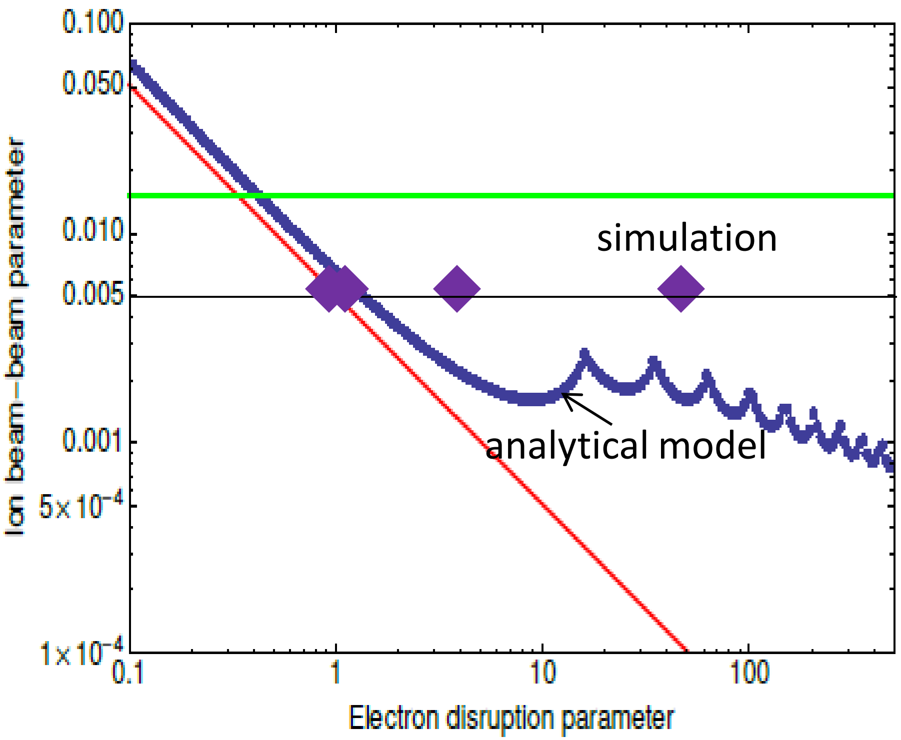


Linac-Ring EIC studies--Instabilities

Emittance growth vs. ion intensity

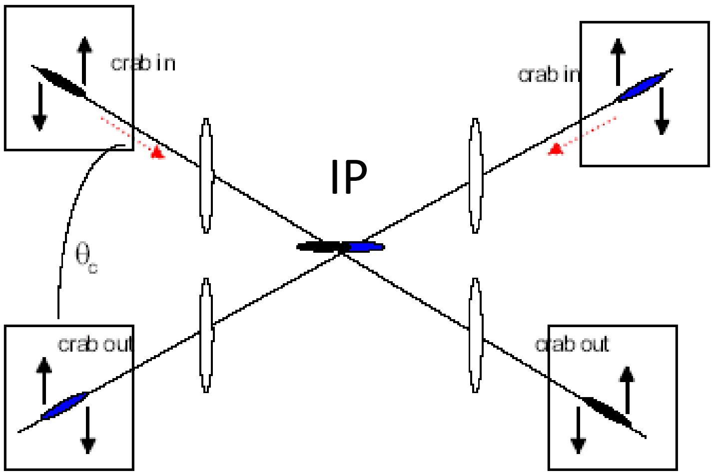


Analytical Model for Instability Threshold



- Nominal working point will be unstable
- Reducing proton intensity moves the beam into stable regime

Linac-Ring studies II—multi harmonic CC



$$x^{n+1} = x^n$$

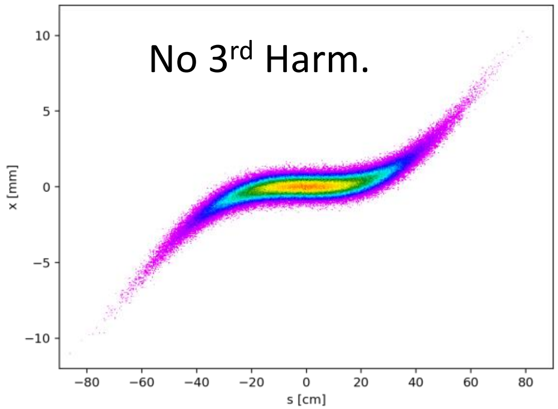
$$Px^{n+1} = Px^n + \frac{qV(1-\alpha)}{E_s}\sin(\omega z^n / c) + \frac{qV\alpha}{E_s n}\sin(n\omega z^n / c)$$

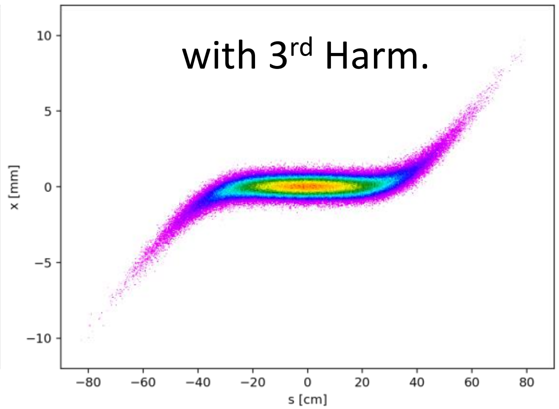
$$z^{n+1} = z^n$$

$$\delta E^{n+1} = \delta E^n + [\frac{qV(1-\alpha)\omega}{E_s}\cos(\omega z^n / c) + \frac{qV\alpha\omega}{E_s}\cos(n\omega z^n / c)]x^n$$

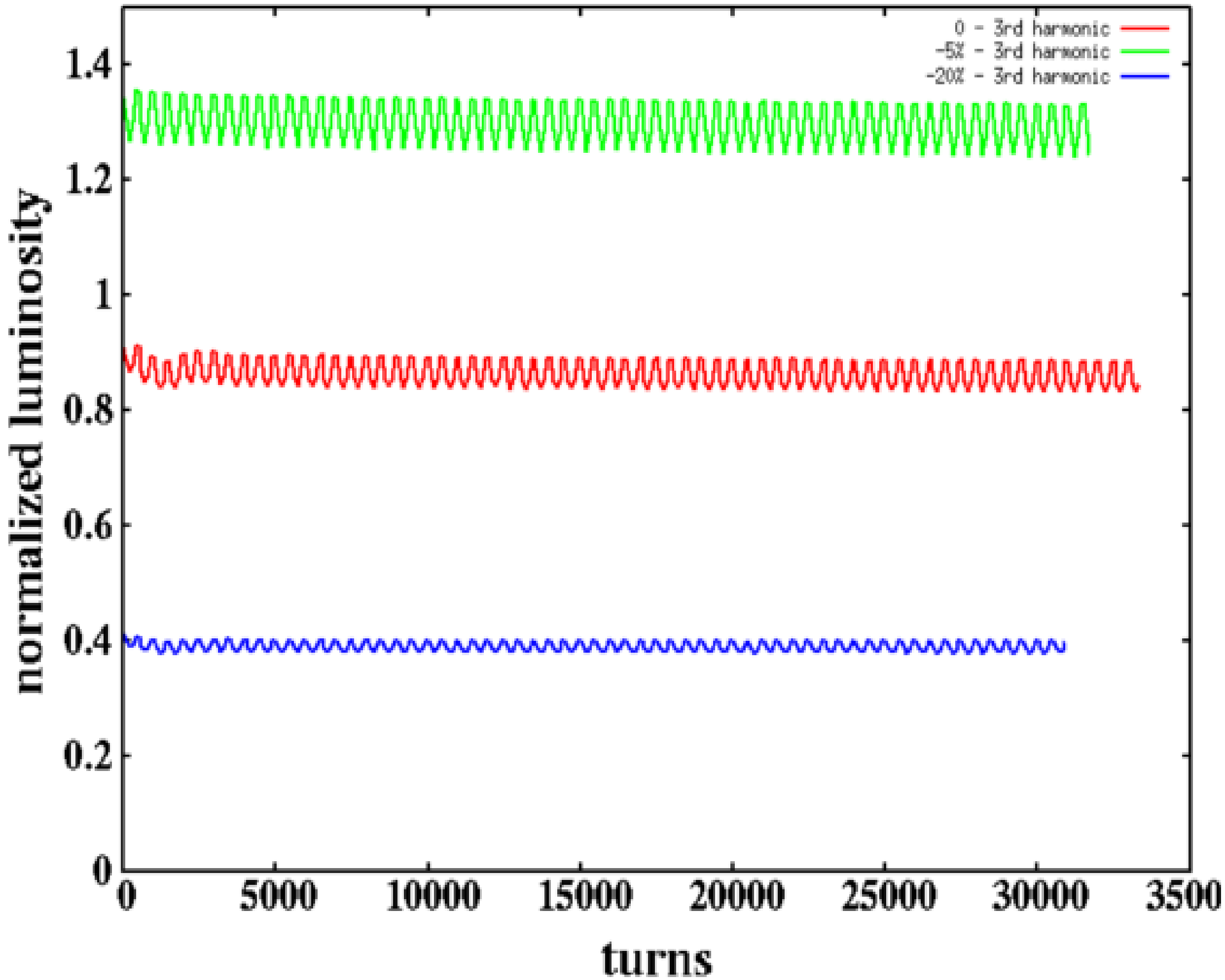
$$crabcavity\, RF\, voltage:$$

$$V = \frac{cE_s \tan(\frac{\theta_c}{2})}{\omega\sqrt{\beta_{x,crab}\beta_x^*}}$$





Linac-Ring studies III—multi harmonic CC

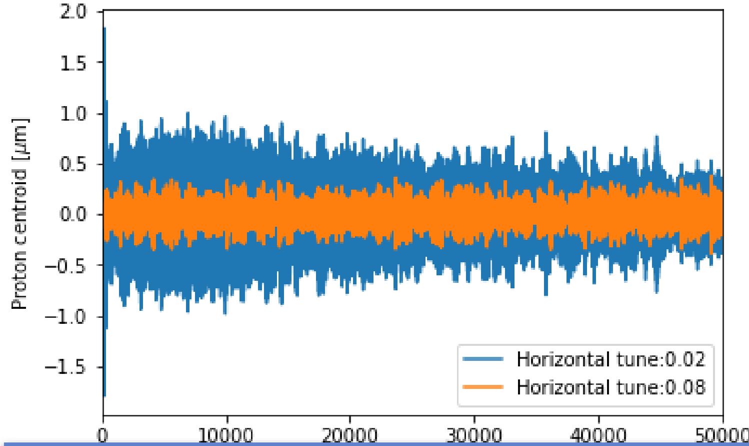


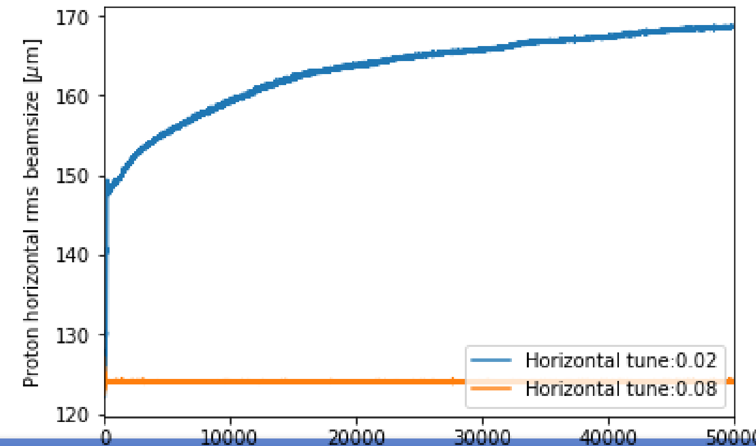
0 3rd Harm.

-15%

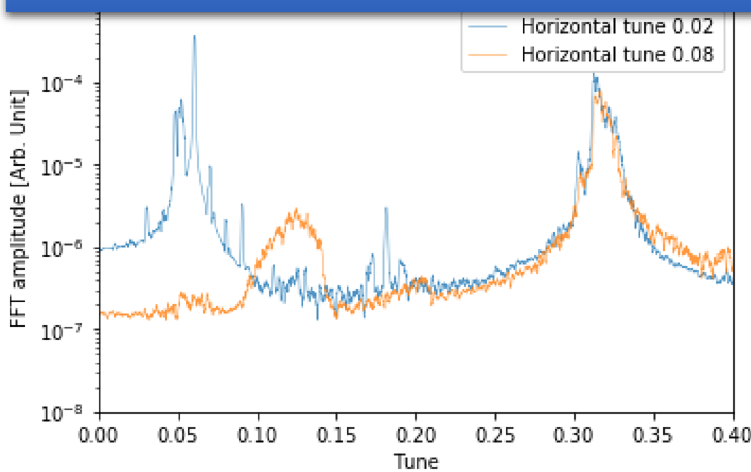
-60%

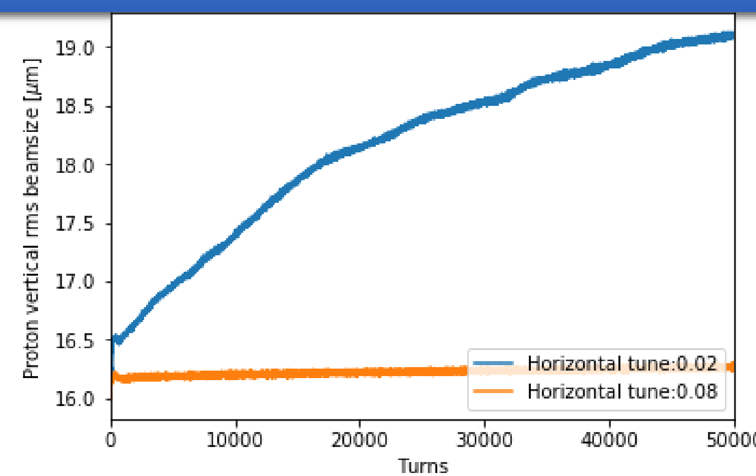
Ring-Ring EIC: Coherent Instability



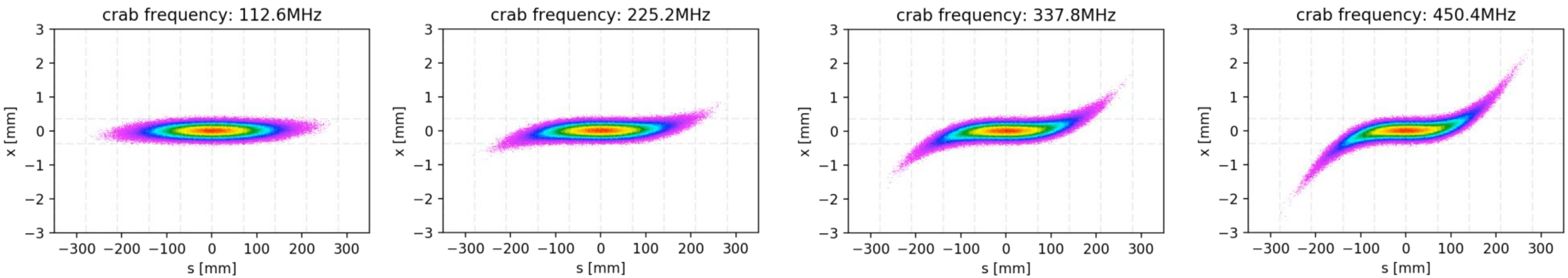


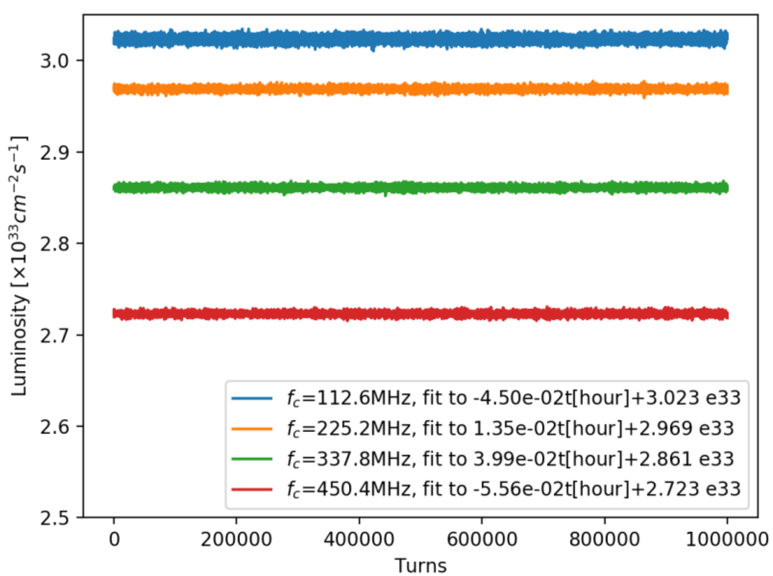
Dipole Instability, when electron tune is very close to integer.

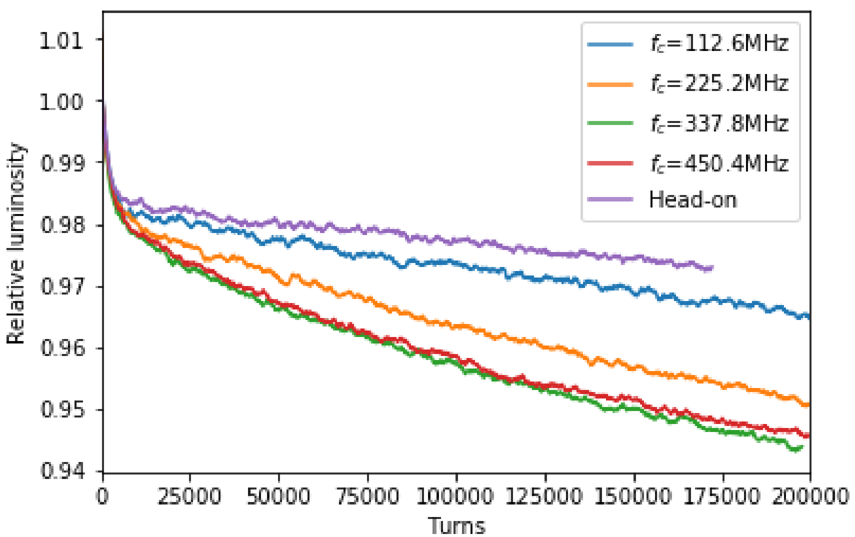




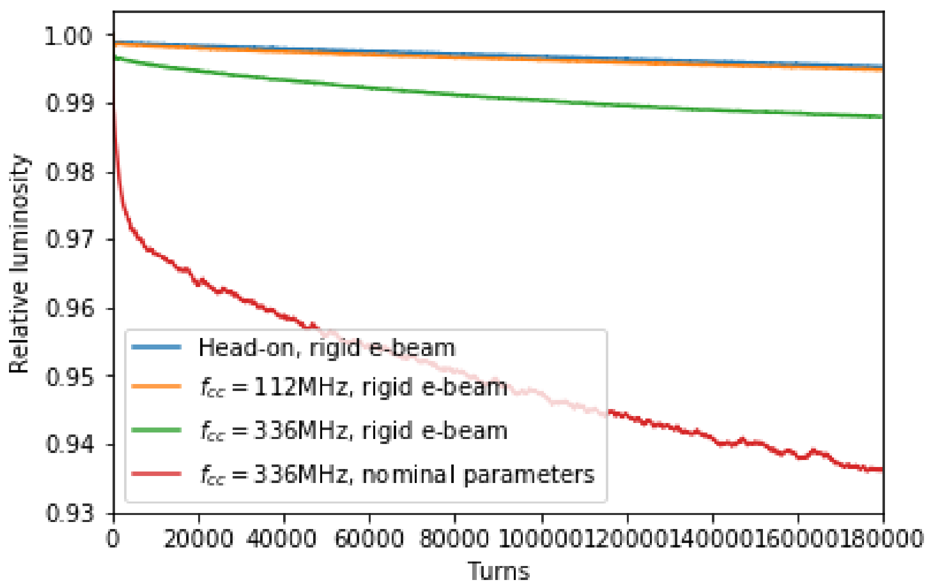
Ring-Ring EIC: Crab Crossing -- Resonance I

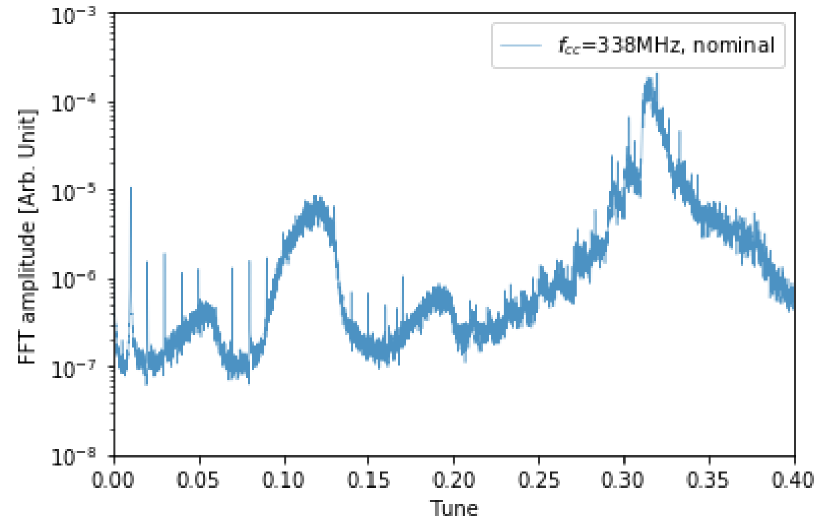


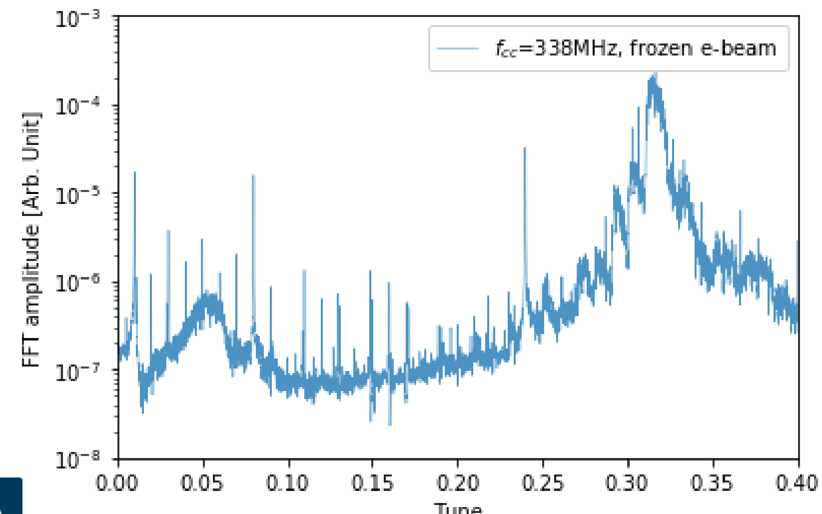




Ring-Ring EIC: Crab Crossing -- Resonance II

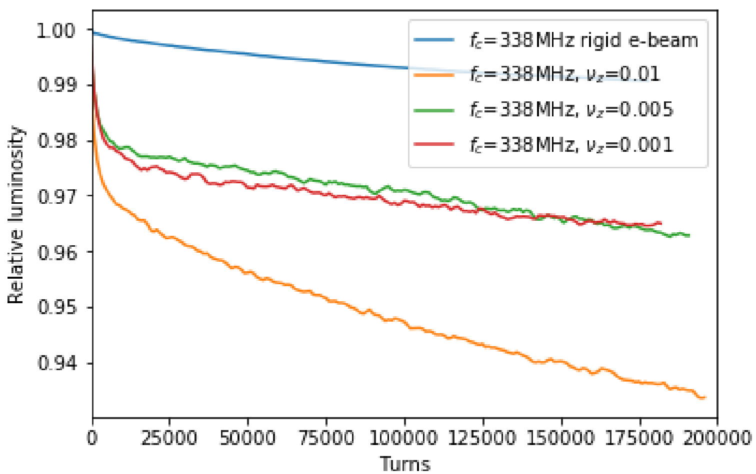


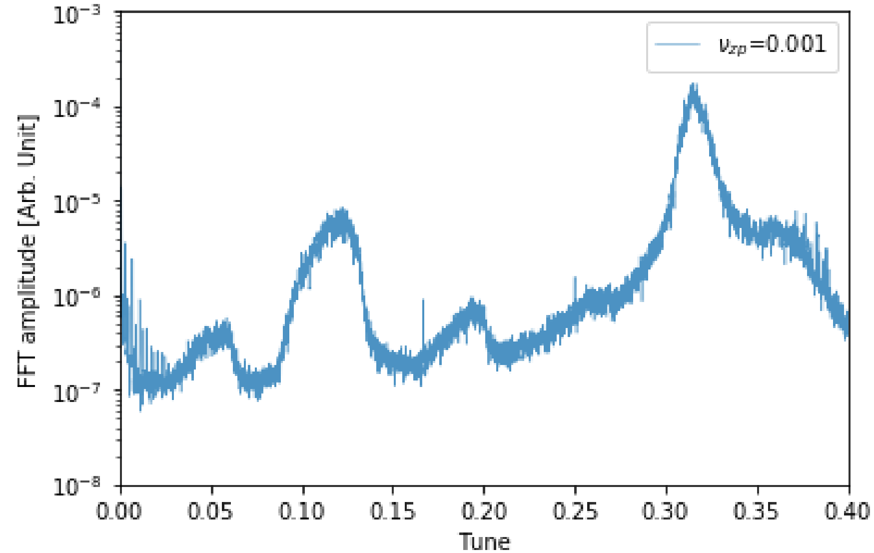


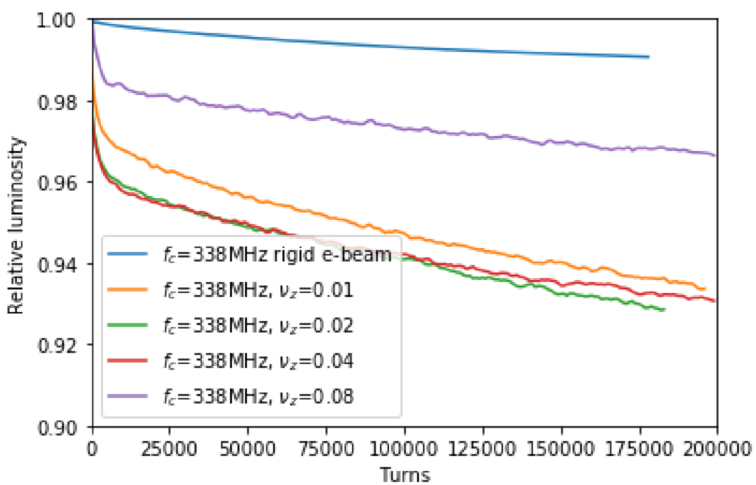


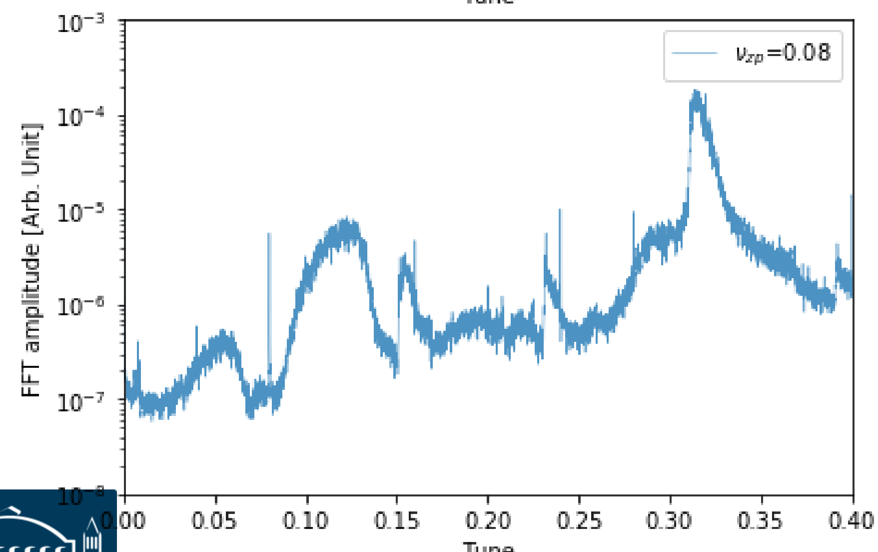
By comparing with the ‘frozen’ electron case, we believe there is physics reason that cause the lumi-degradation.

Ring-Ring EIC: Crab Crossing -- Resonance III









Ring-Ring EIC: Crab Crossing – Dispersion @ crab cavity I (linear theory)

Effective CC matrix @IP

$$M_{cc} = M_{IRC}^{-1} K_{cc} M_{IRC}$$

$$K_{CC} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & \frac{\theta_c}{\sqrt{\beta_c}\sqrt{\beta_s}|\sin(\psi)|} & 0 \\ 0 & 0 & 1 & 0 \\ \frac{\theta_c}{\sqrt{\beta_c}\sqrt{\beta_s}|\sin(\psi)|} & 0 & 0 & 1 \end{bmatrix}$$

Total IP matrix

$$M_{IR} = M_{cc2} M_{LT}^{-1} K_{bb} M_{LT} M_{cc1}$$

Effect of Dispersion at one crab cavity:

- Tune shift
- Dispersion and crab dispersion

$$M_{LT} M_{cc} = \begin{bmatrix} \epsilon^2\theta_c^2 + \epsilon\theta_c + 1 & \beta_s\eta\theta_c(\epsilon\theta_c + 2) & \epsilon\theta_c^2 & -\beta_s\epsilon\eta\theta_c \\ 0 & -\epsilon\theta_c + 1 & 0 & \epsilon^2\theta_c \\ -\epsilon^2\theta_c & -\beta_s\epsilon\eta\theta_c & -\epsilon\theta_c + 1 & 0 \\ 0 & -\epsilon\theta_c^2 & 0 & \epsilon^2\theta_c^2 + \epsilon\theta_c + 1 \end{bmatrix}$$

$$\epsilon = d_x / \sqrt{\beta_c\beta_s} \qquad \eta = (\alpha_c d_x + \beta_c d'_x) / \sqrt{\beta_c\beta_s}$$

Recent params	$\sqrt{\beta_c\beta_s}$	$\sqrt{\beta_c/\beta_s}$
eRHIC	~35	~33
JLEIC	~6	~60

Ring-Ring EIC: Crab Crossing – Dispersion @ crab cavity II

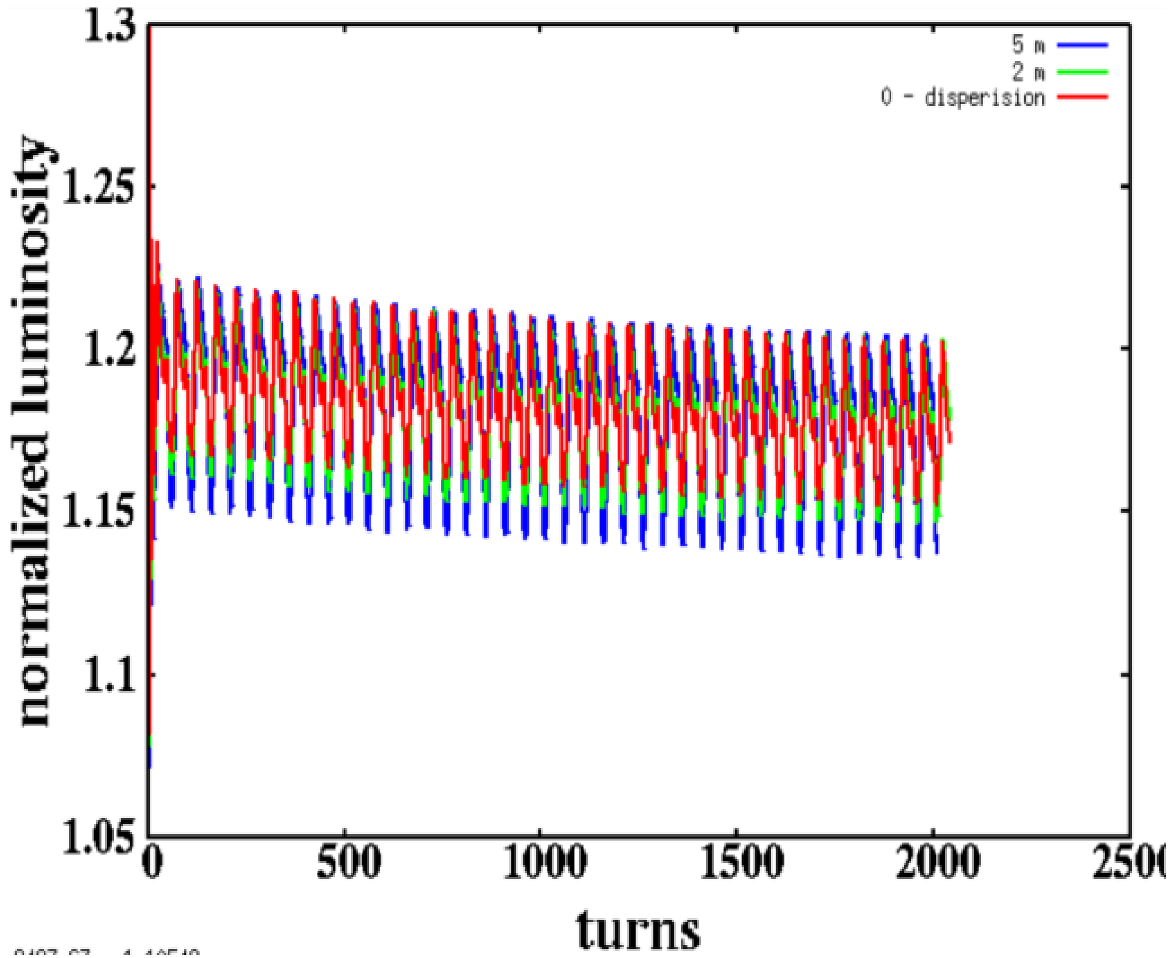
- The matrix model is implemented in Beam-Beam3D.

$$M = Ma\ M1\ Mb\ M1^{-1}\ M\ M2^{-1}\ Mc\ M2$$

  - Ma: transfer map from head-on crossing angle beam-beam collision
  - Mb,c: transfer maps from crab cavity deflection
  - M1-2: transfer maps between crab cavity and collision point
  - M: one turn transfer map of machine

- Cross checked with linear theory, Match exactly.

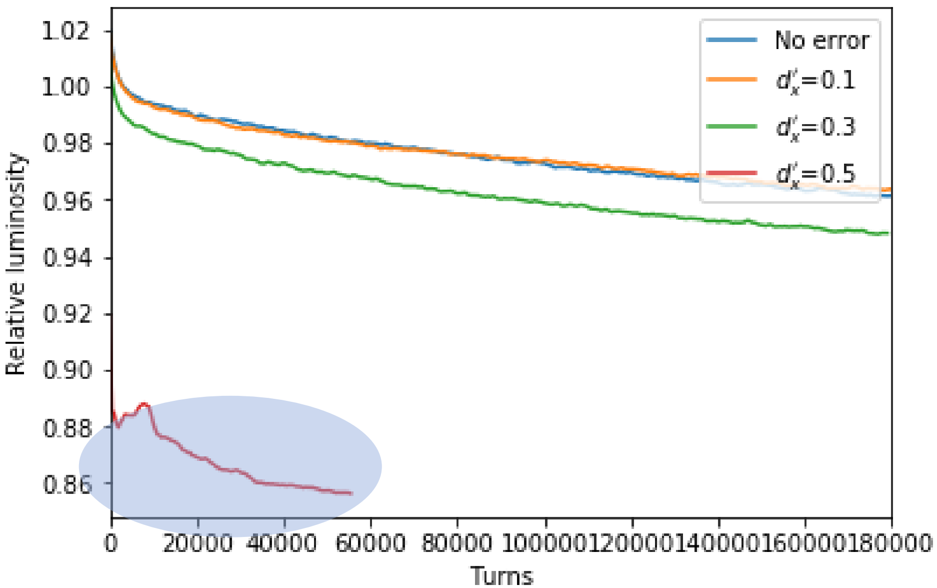
Ring-Ring EIC: Crab Crossing – Dispersion @ crab cavity II

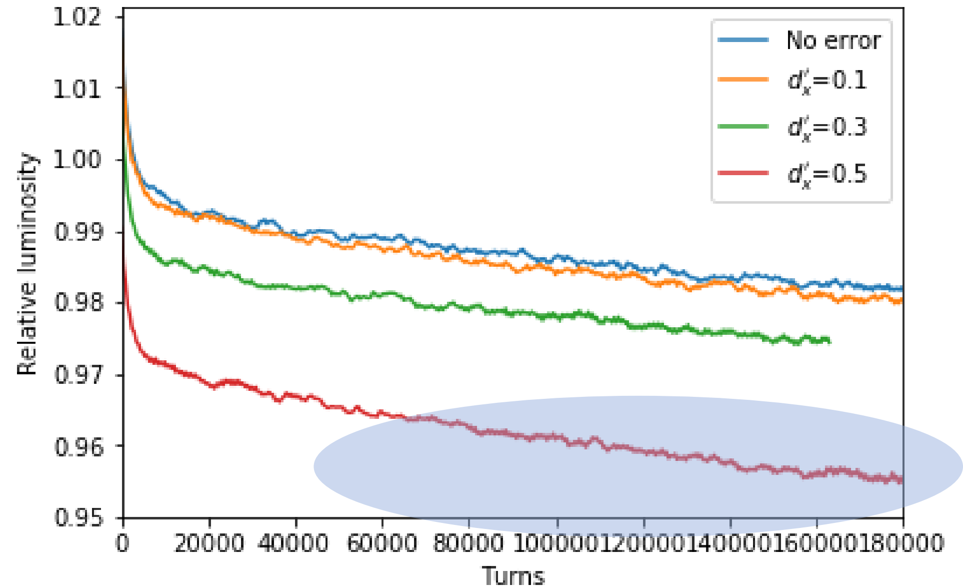


First test:

Confirm the effect of dispersion function at CC is strongly suppressed.

Dispersion tolerance, with nonlinear B-B





With synchro-betatron resonances

Resonance is suppressed
Luminosity degradation enhanced by 50% (slope).

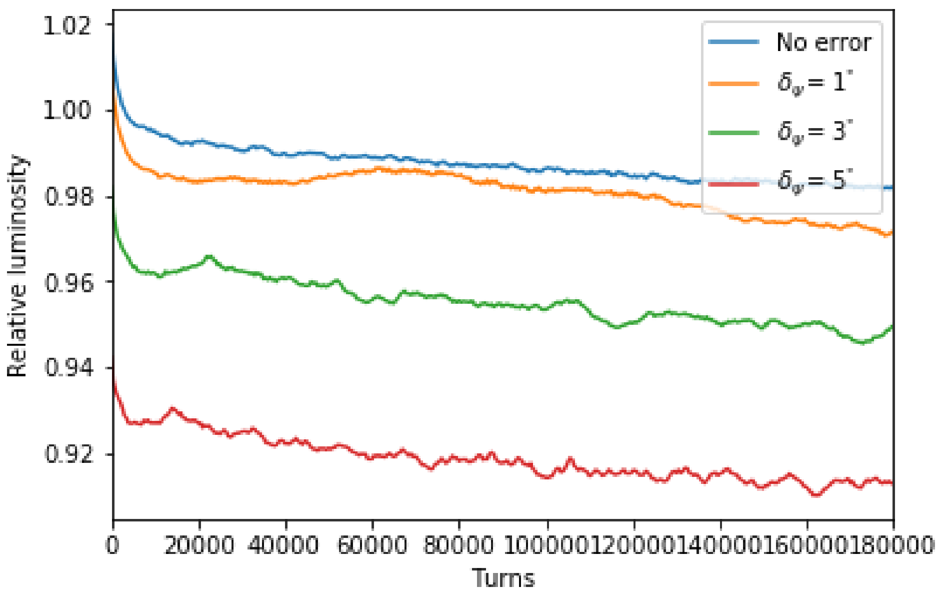
Non-pi/2 phase advance, linear B-B

$$M_{IR} = M_{cc2} M_{LT}^{-1} K_{bb} M_{LT} M_{cc1}$$

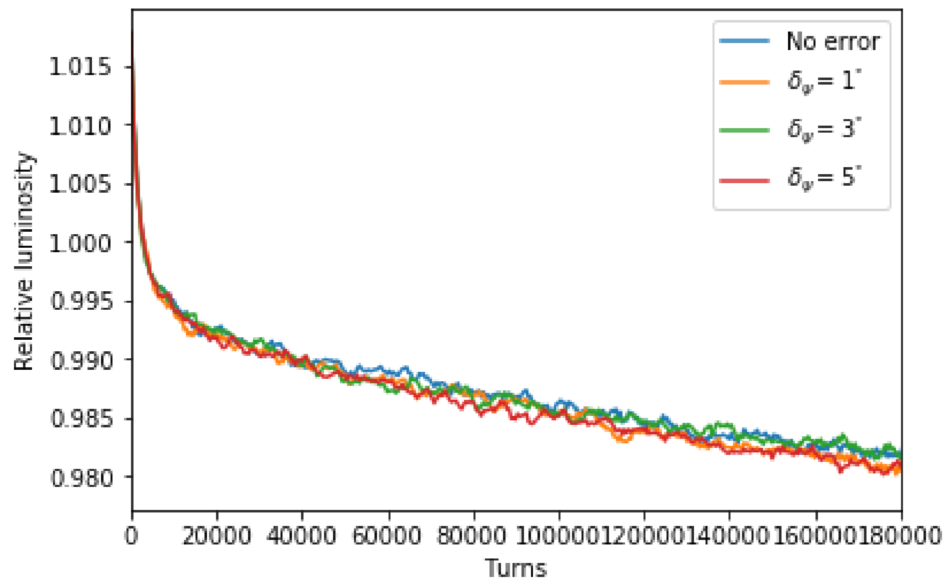
$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ k & 1 & \frac{\theta_c \sum_i \tan(\delta_{\psi i})}{\beta_s} & 0 \\ 0 & 0 & 1 & 0 \\ \frac{\theta_c \sum_i \tan(\delta_{\psi i})}{\beta_s} & 0 & \frac{\theta_c^2 \sum_i \tan(\delta_{\psi i})}{\beta_s} & 1 \end{bmatrix}$$

Linearly, the phase advance on two side of IP can add up, regardless of the optics at crab cavity if dispersion free. The R23 and R41 can be easily compensated by 3rd CC.

Non-Pi/2 phase advance, Nonlinear B-B



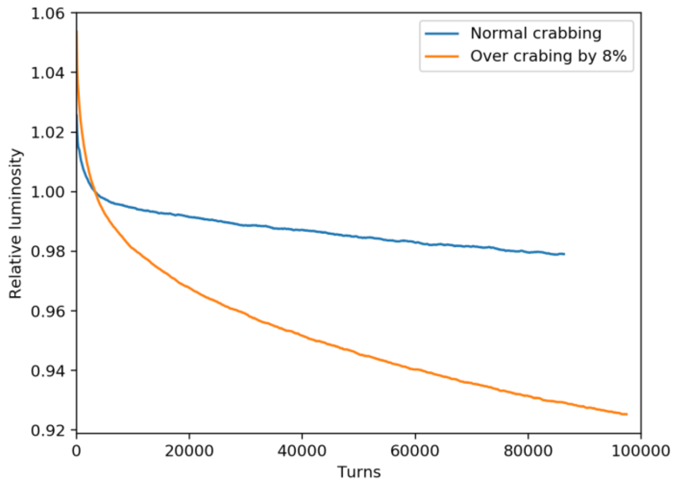
Two side phases have the same sign.

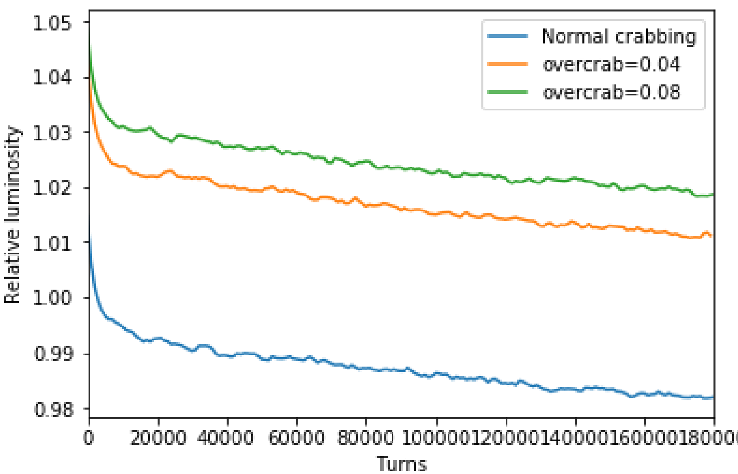


Two side phases have the opposite sign.

Over crabbing?

- For eRHIC parameter, increase the crabbing voltage by 8% will have 3% bonus luminosity.
- Will lead to fast-lumi degradation due to the inter-beam synchro-beta resonance.

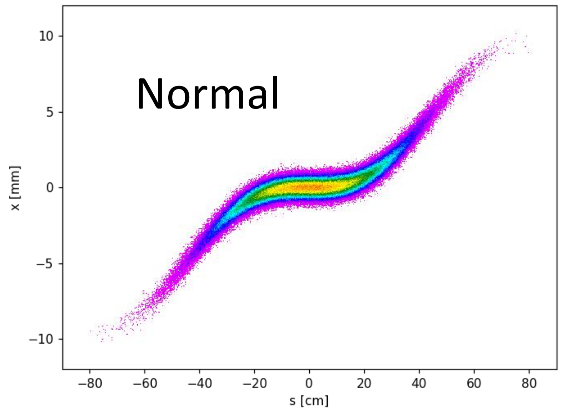


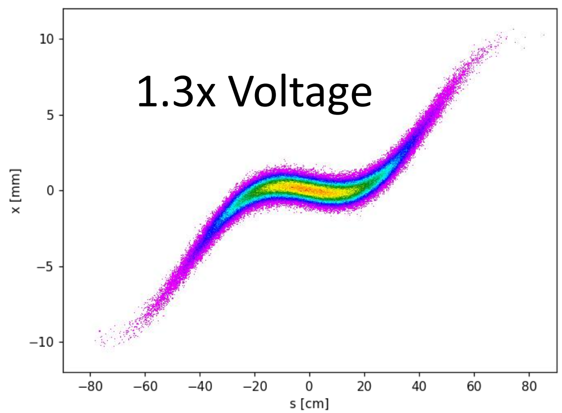


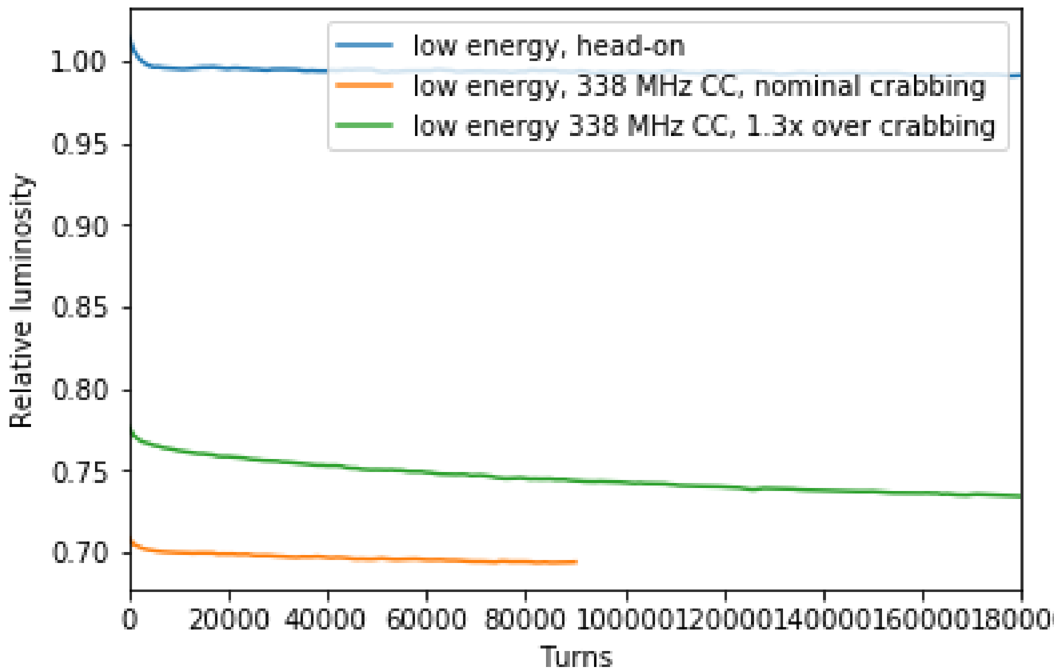
the synchro-beta resonances prohibit over crabbing

After reducing the synchro-beta resonances by reducing the synchrotron tune of ion beam to 0.001

Low energy case

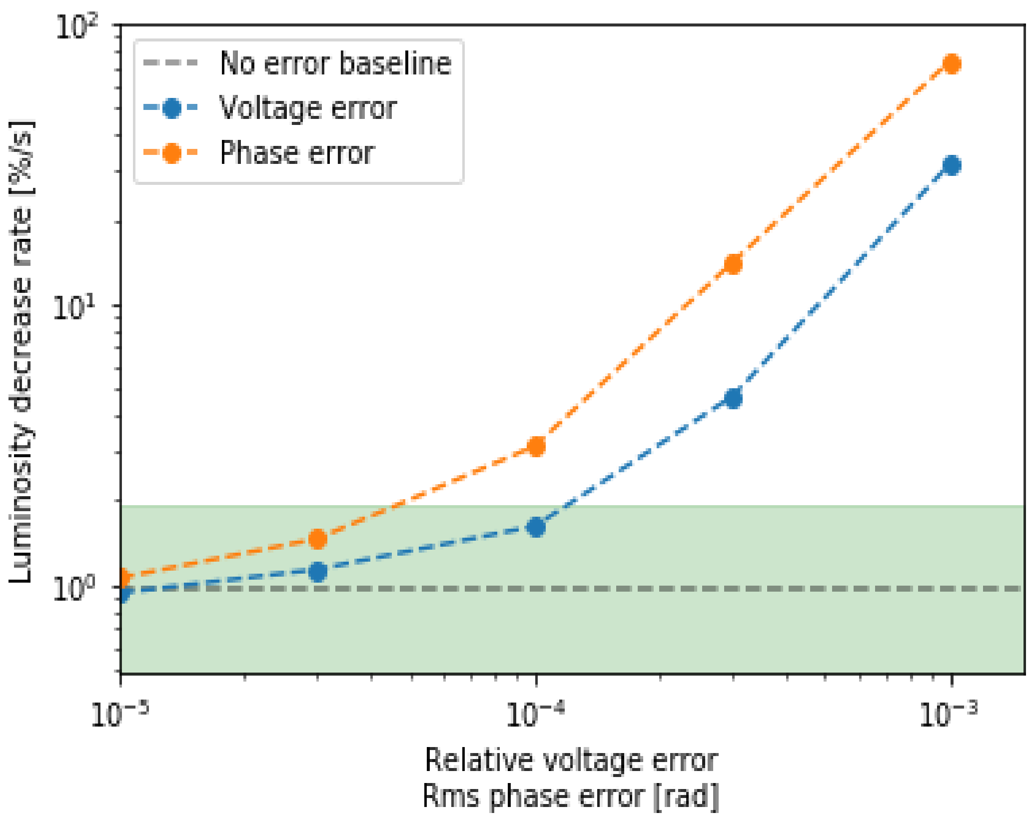


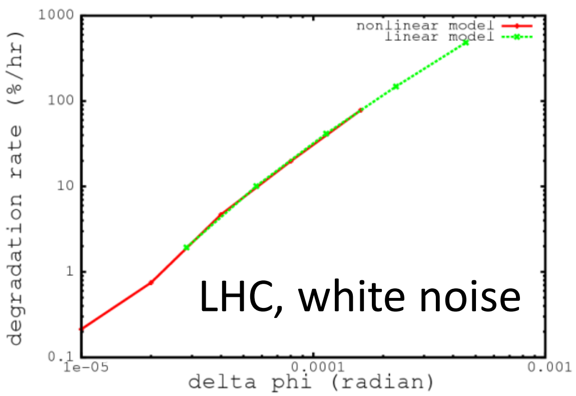


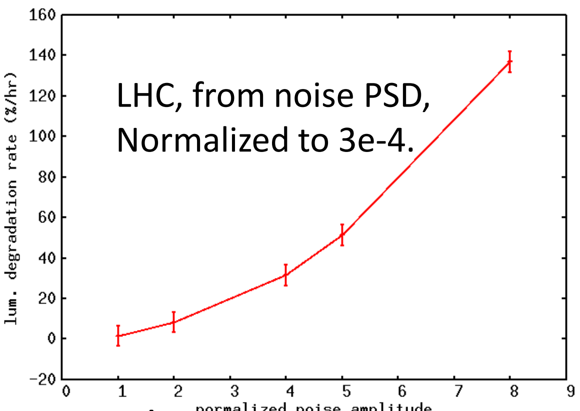


Lower energy has longer ion bunch length, smaller synchrotron tune and beam-beam parameter. Degradation is minimum for normal crabbing. More studies required for 1.3x over crabbing to explain the enhance luminosity degradation.

Noise of the amplitude and phase

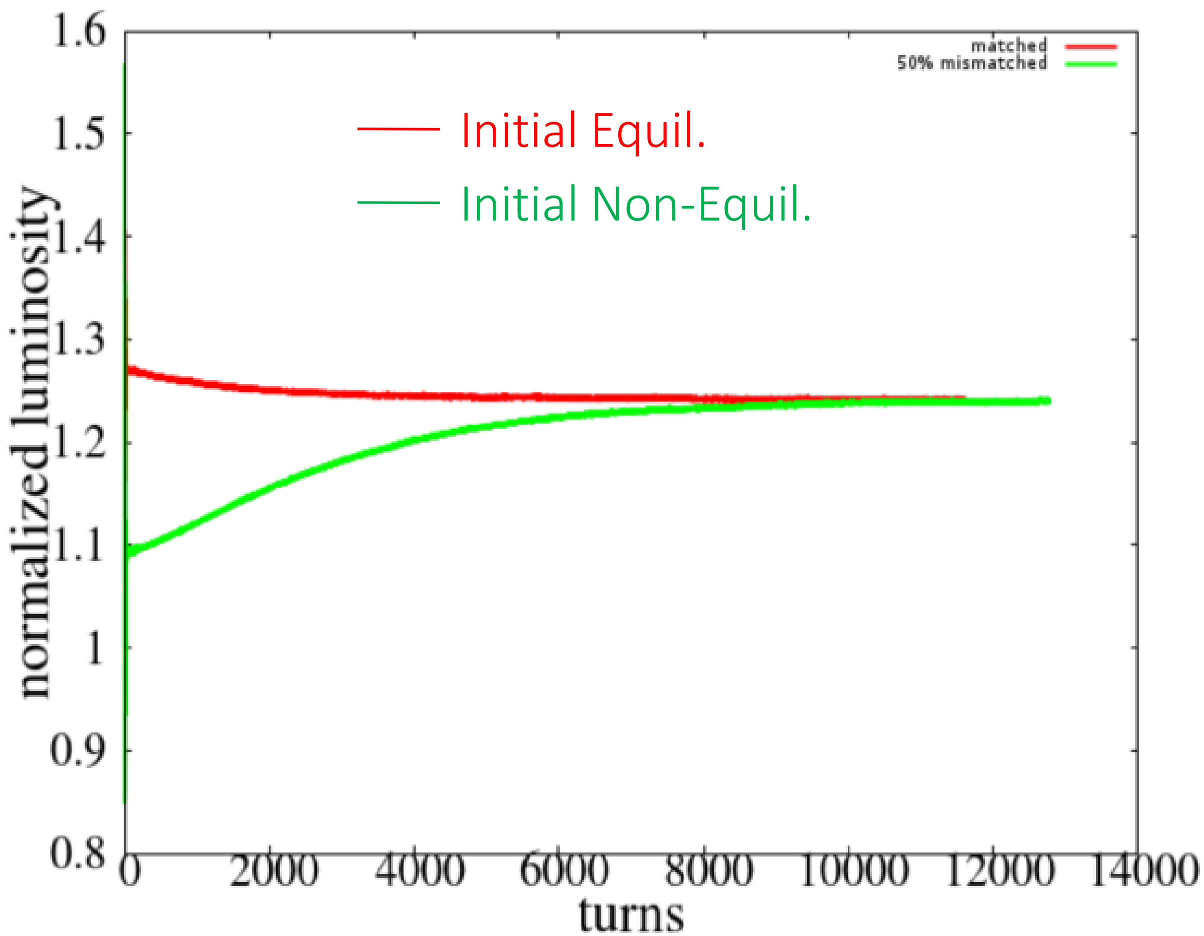






From studies of LHC Hi-lumi , the PSD of the noise of LLRF control is very important to achieve reasonable results. Need to understand the most driving frequencies for EIC.

New demand, non-equilibrium electron beam



Luminosity recovers after a few electron damping time.

Summary of the results

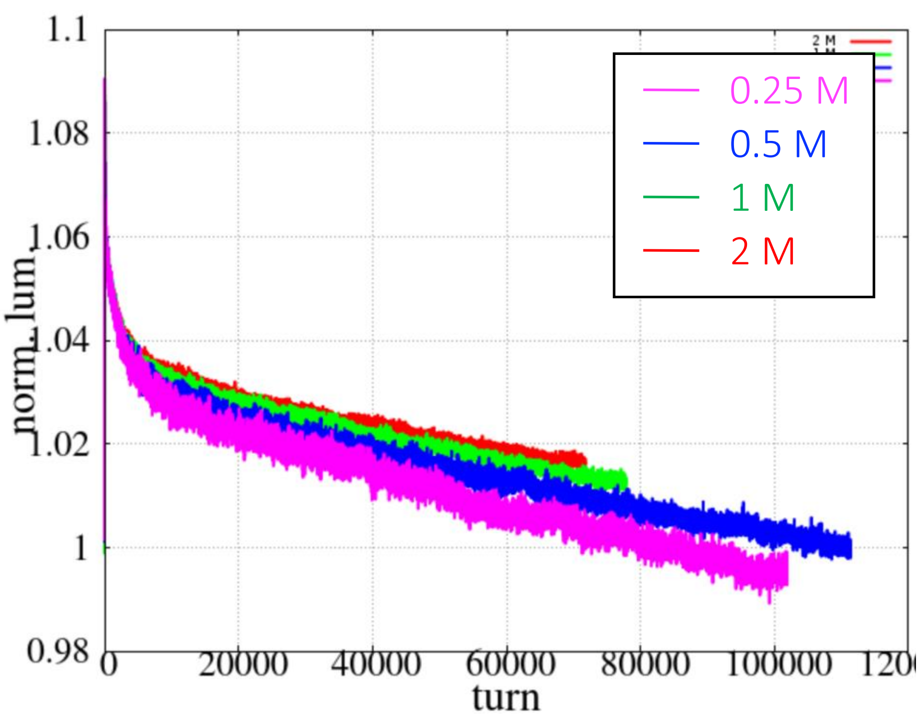
- The outcome of this proposal has two important components
  - For the first time, we explore the dynamics of the beam-beam interaction in crab crossing scheme of EIC, with large beam-beam parameters.
  - We evolved the powerful simulation codes to fit the special need of simulating EIC.
- The discoveries indicate that we do not have enough understandings of the beam-beam dynamics for the future EIC, not mentioning the cross talk among the beam-beam, space charge effects and the machine nonlinearity.
- **We would like to continue the studies and explore the unknowns.**

What we would like to do next—Noise Reduction I

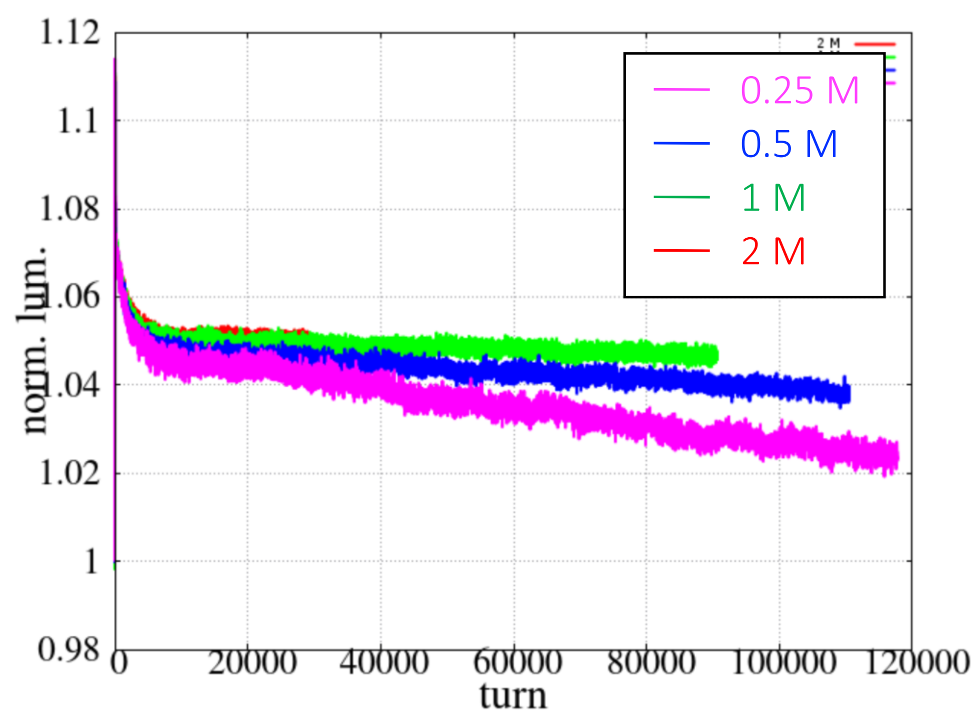
Normalized Luminosity Evolution with Number of Macroparticles:

numerical noise ➔ large number of macroparticles is needed to converge: possible with parallel code.

with crossing angle/crab cavity



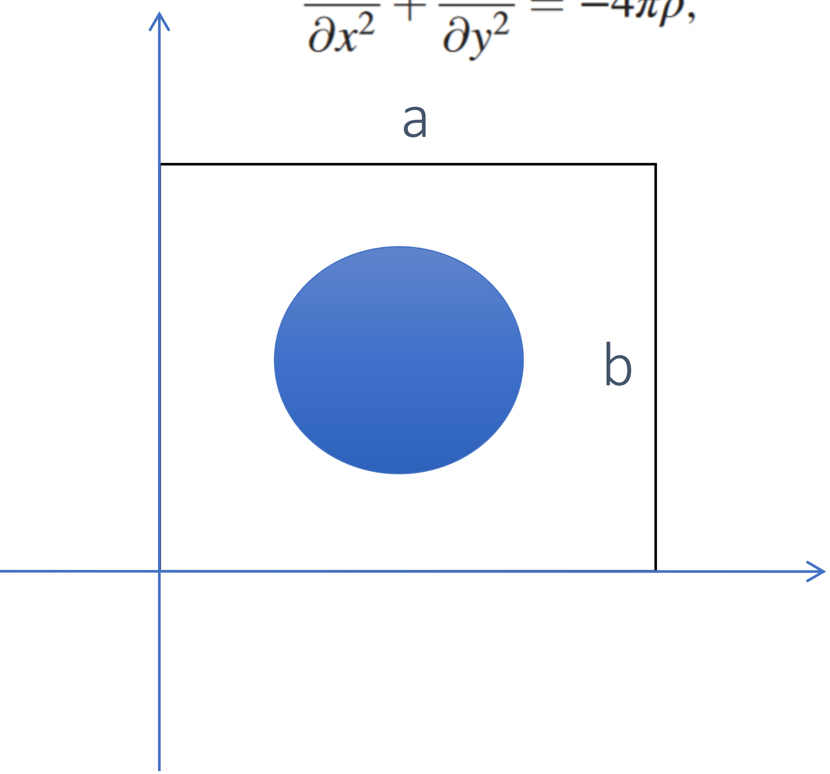
0 crossing angle/crab cavity



What we would like to do next—Noise Reduction II

New Spectral method

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = -4\pi\rho,$$



$$\rho(x,y) = \sum_{l=1}^{N_l} \sum_{m=1}^{N_m} \rho^{lm} \sin(\alpha_l x) \sin(\beta_m y)$$

$$\phi(x,y) = \sum_{l=1}^{N_l} \sum_{m=1}^{N_m} \phi^{lm} \sin(\alpha_l x) \sin(\beta_m y),$$

$$\rho^{lm} = \frac{4}{ab} \int_0^a \int_0^b \rho(x,y) \sin(\alpha_l x) \sin(\beta_m y) dx dy$$

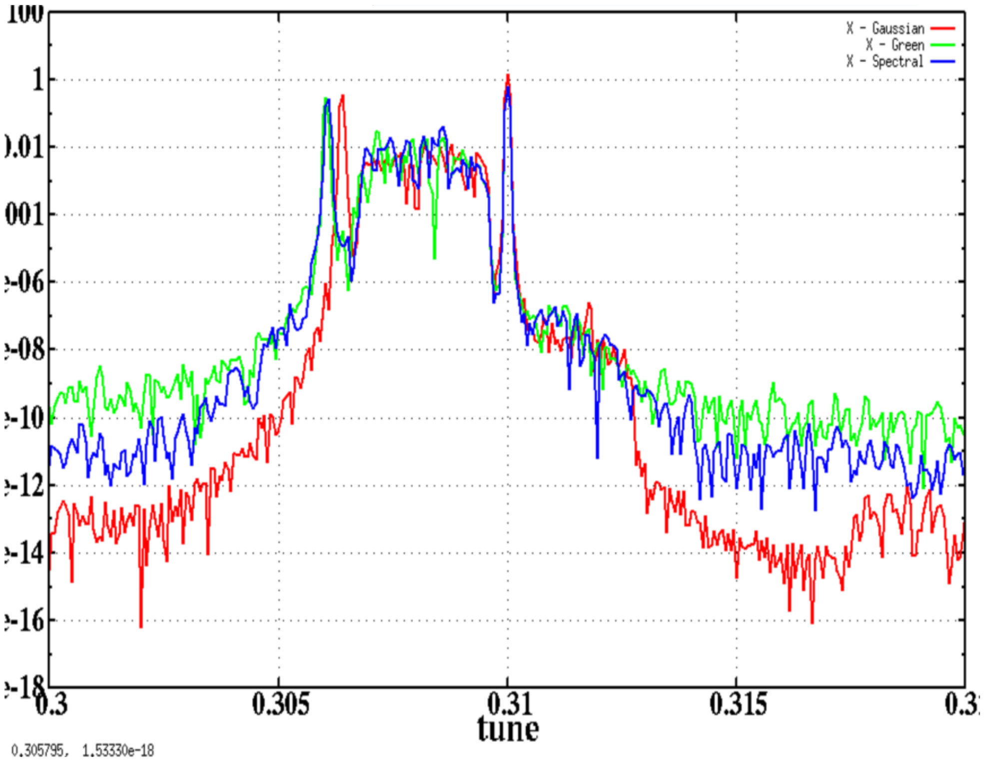
$$\phi^{lm} = \frac{4}{ab} \int_0^a \int_0^b \phi(x,y) \sin(\alpha_l x) \sin(\beta_m y) dx dy,$$

where $\alpha_l = l\pi/a$ and $\beta_m = m\pi/b$.

$$\phi^{lm} = \frac{4\pi\rho^{lm}}{\gamma_{lm}^2}$$

where $\gamma_{lm}^2 = \alpha_l^2 + \beta_m^2$.

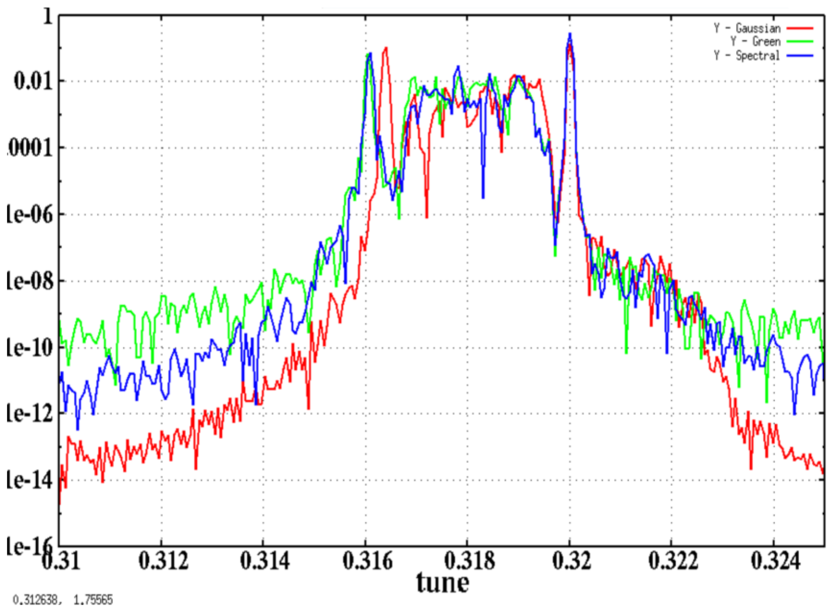
What we would like to do next— Noise Reduction III



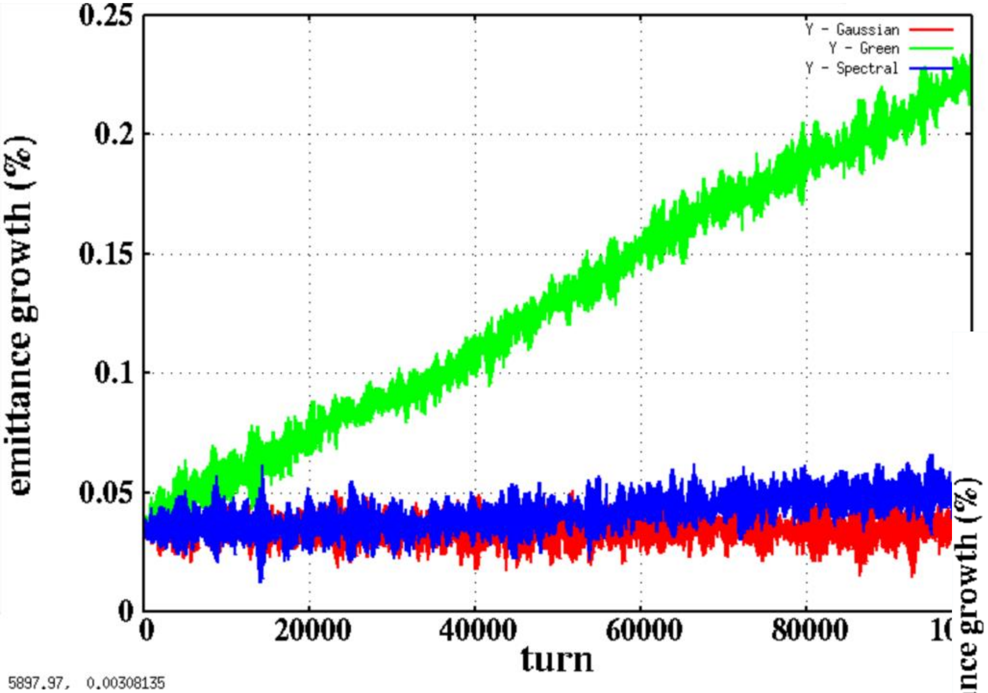
-- Soft Gaussian model

-- Green's function method (128x128)

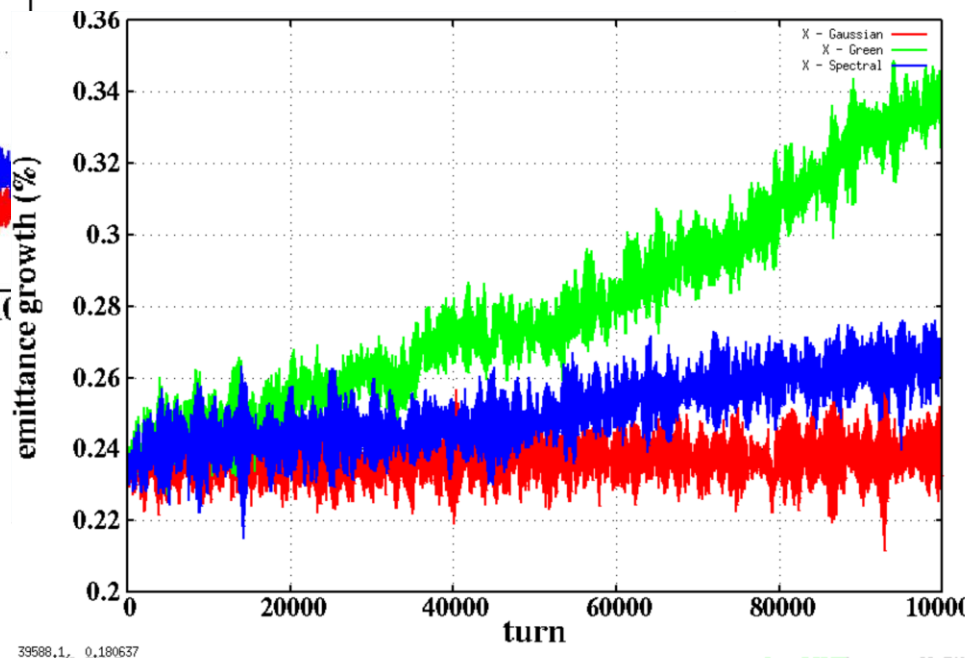
-- Spectral method (32x32)



What we would like to do next— Noise Reduction IV



-- Soft Gaussian model
-- Green's function method (128x128)
-- Spectral method (32x32)



New Spectral method requires fewer particles to obtain similar noise level

What we would like to do next—
Beam-Beam and Space charge effects

Machine and Beam energy	Space charge tune shift
eRHIC (linac-ring), 250/100 GeV proton	0.01 - 0.06
eRHIC (Ring-ring), 250/100 GeV Proton	0.004 - 0.06
JLEIC, 100/30 GeV Proton	0.06
RHIC, 23.5 GeV Proton	0.03 (Found luminosity deterioration)

In the past RHIC operation, a significant beam lifetime reduction was observed due to the beam-beam tune shift (0.01) in conjunction with a larger space charge tune shift (0.03) *. In the future EIC, the beam-beam tune shifts have negative sign of the space charge tune shift, while they have same sign in RHIC. The interplay of the beam-beam interaction and the space-charge effect has not been numerically studied.

* A.V. Fedotov, et.al, 'Interplay of Space-Charge and Beam-Beam Effects in a Collider', in the proceedings of HB2010, Morschach, Switzerland

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