Beam-Beam Interaction with Crab Cavity for future Electron Ion Collider

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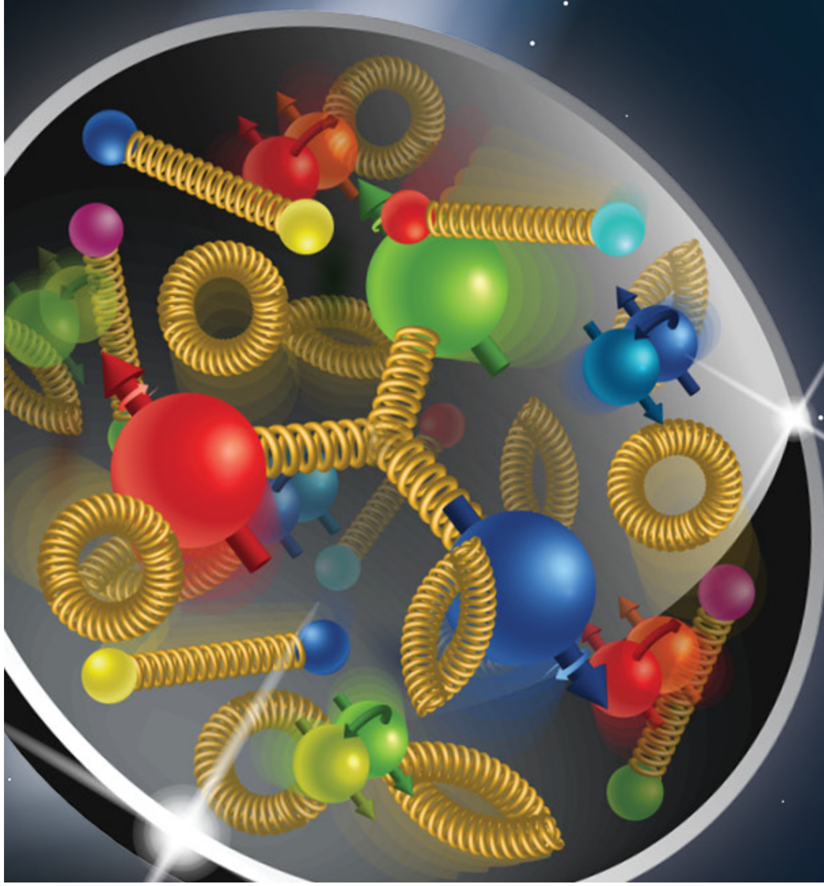

Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

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Outlines

- ❑ Studies for eRHIC crab crossing
  - ❑ Potential coupling due to crab crossing scheme.
  - ❑ Effects with crab-crossing with non-ideal parameters
- ❑ Summary
- ❑ Outlooks

Colliders with crab crossing scheme

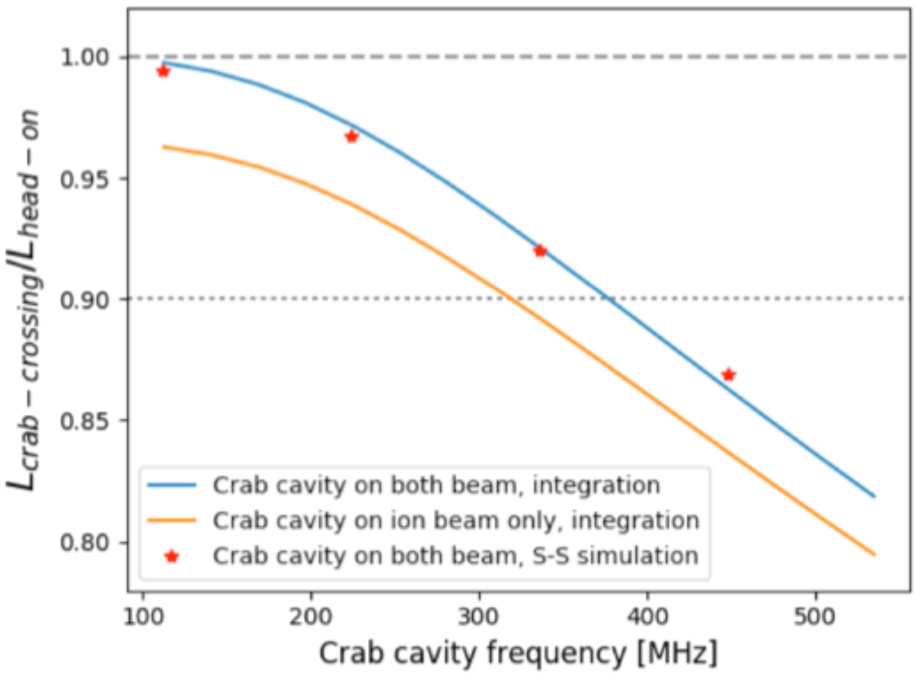
	KEK-B	LHC-HiLumi	EIC
Crossing angle (mrad)	22	0.59	22 (eRHIC) /50 (JLEIC)
Cavity frequency (MHz)	509	400	336 (eRHIC) / 952 (JLEIC)
Beam-Beam tune shift	~0.1	~0.02	Electron 0.1/ Ion 0.015
Radiation damping	Yes	No	Only Electron ring

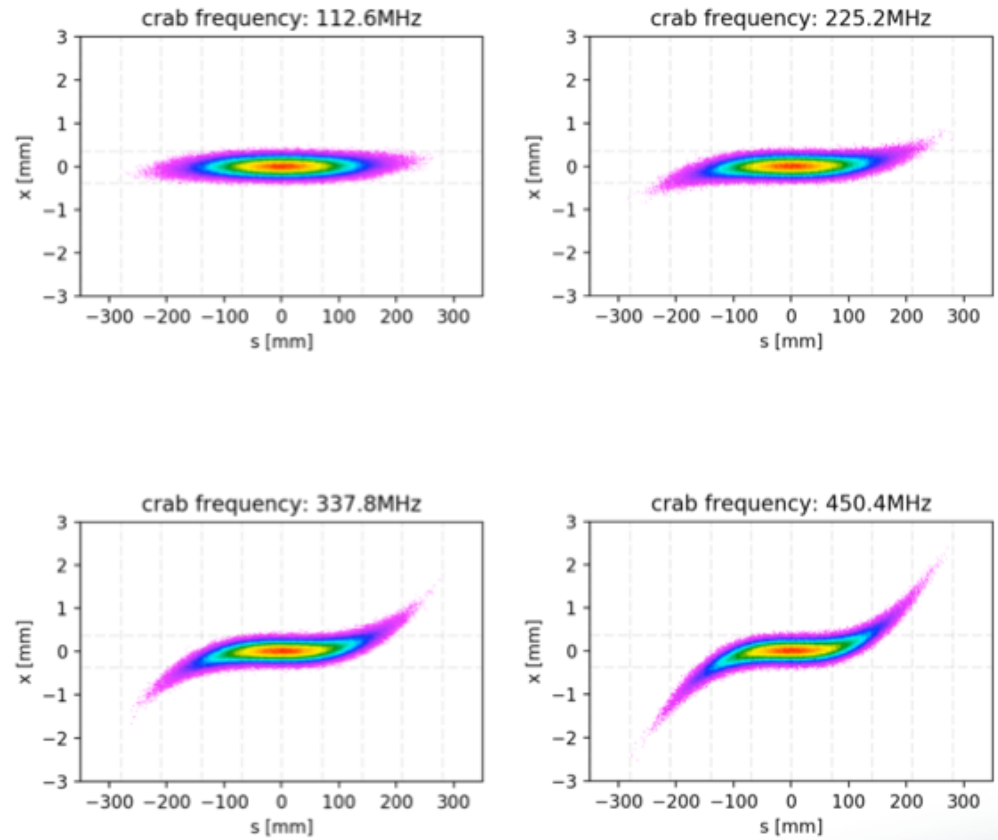
Parameters of Crab Crossing

	eRHIC	JLEIC
Full Crossing angle (mrad)	22	50
Horizontal beam size (μm)	123	18.12
Bunch length (mm)	70	10
β^* (m)	0.94	0.1
β_{cc} (m)	1200	363
Piwinski angle	6.26	13.8
Crab cavity frequency (MHz)	337.8	952.6

eRHIC parameter is very close to the 'eRHIC parameters, v3; No Cooling-High Divergence'.
JLEIC 's parameter (highest luminosity) always assumes cooling.

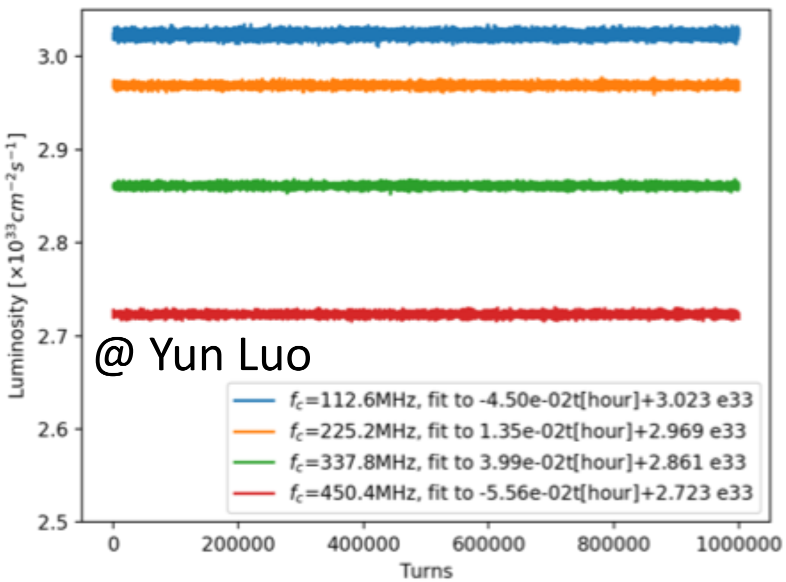
Luminosity consideration

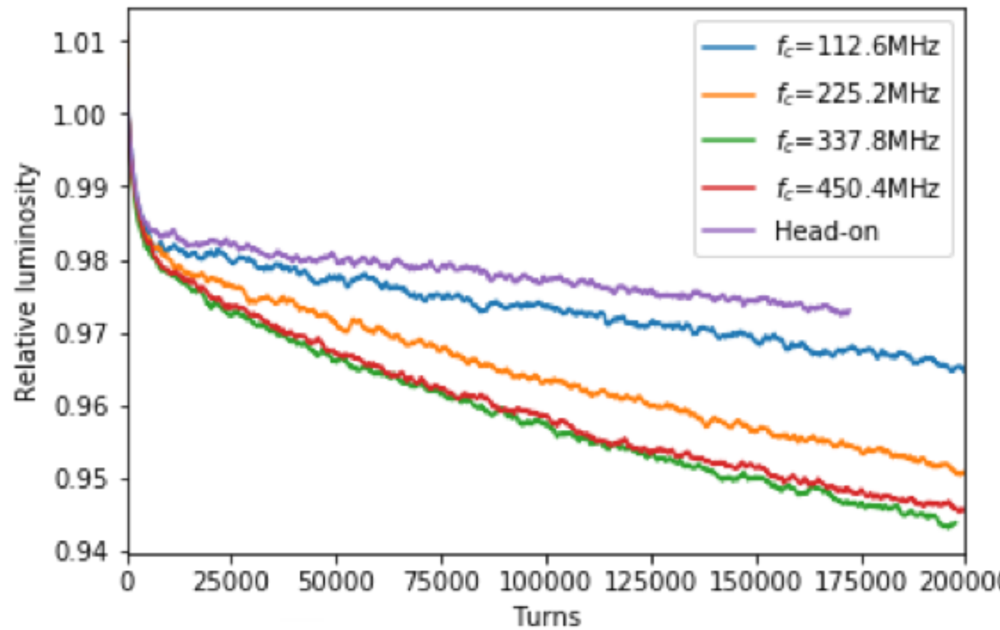




$$H_L = \frac{L_{crab-crossing}}{L_{head-on}}$$

Beam dynamics impact of crab crossing scheme



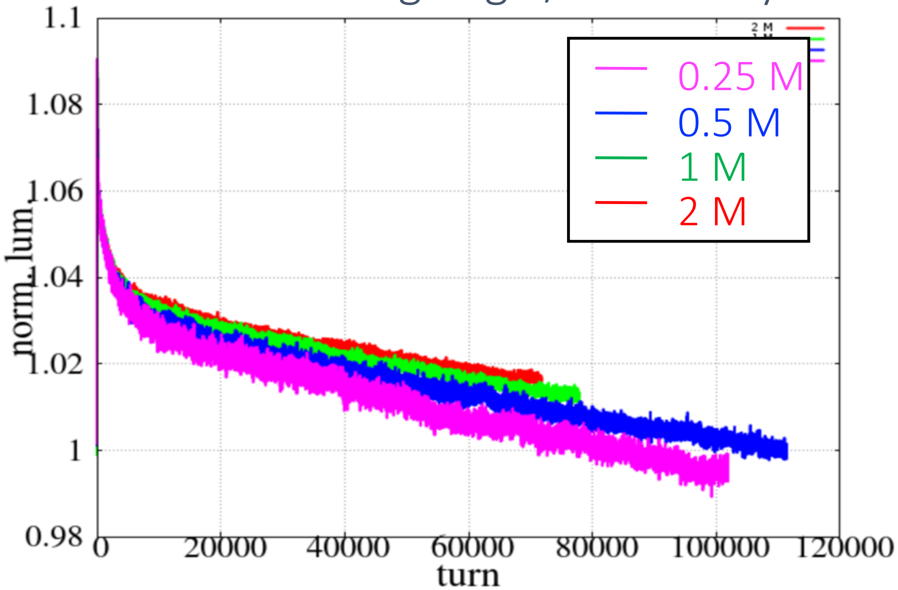


Weak (ion)-Strong (e) model

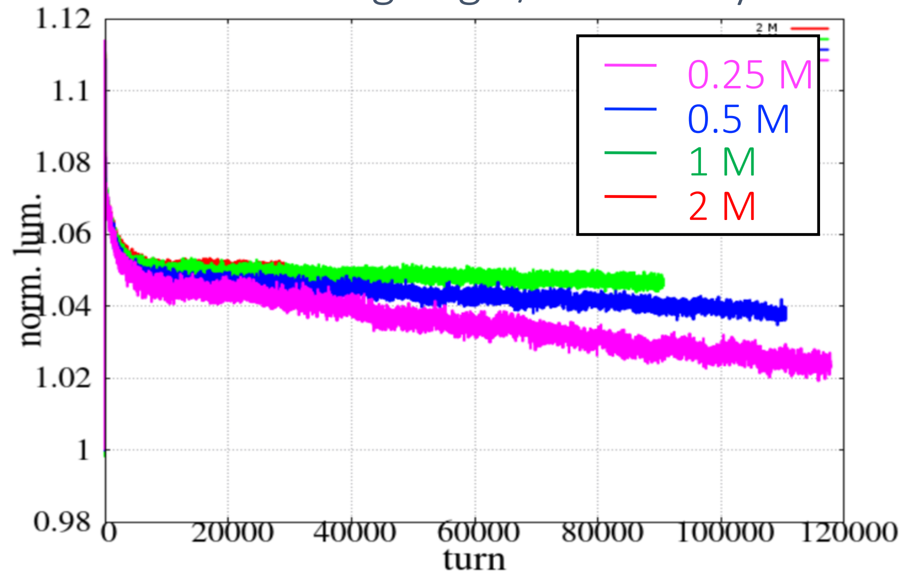
Strong - Strong model

Noise Trend in S-S Simulation

with crossing angle/crab cavity

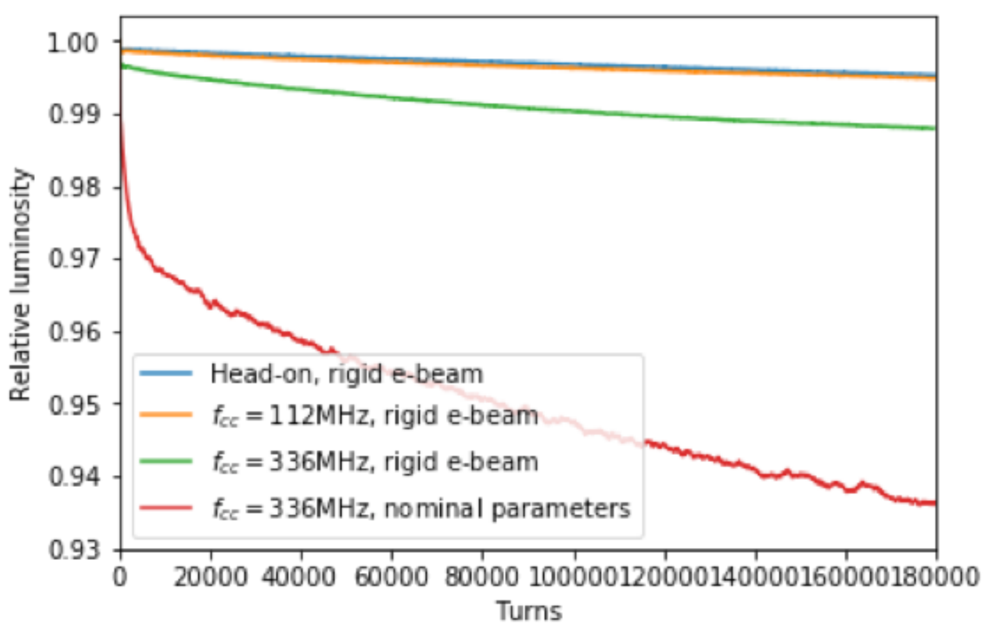


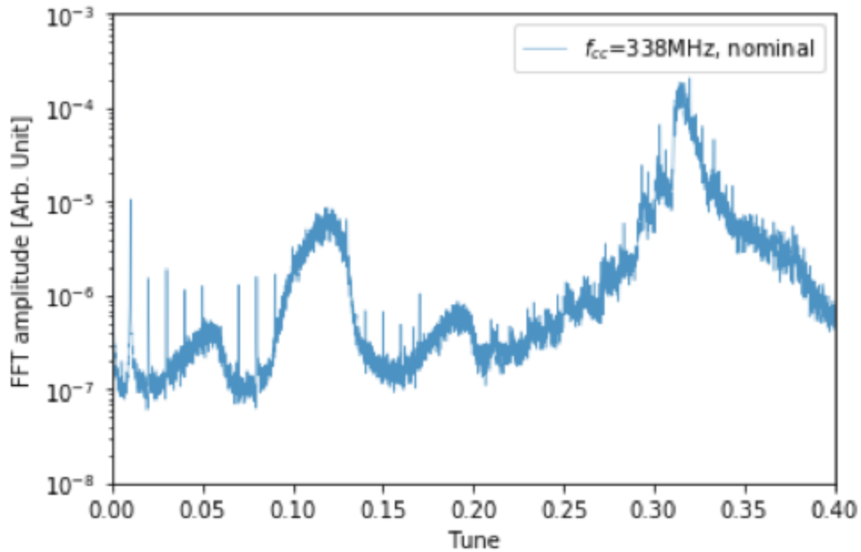
0 crossing angle/crab cavity



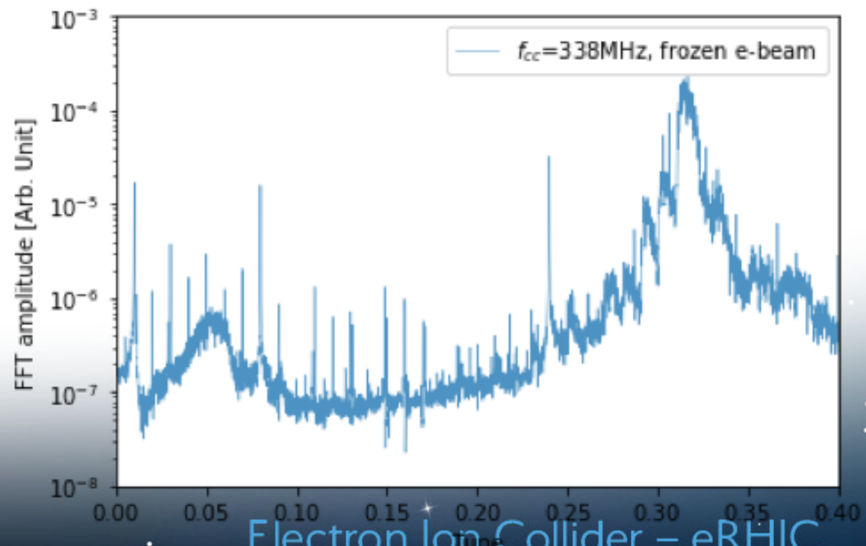
@ Ji Qiang

Real Degradation in Strong-Strong Simulation?

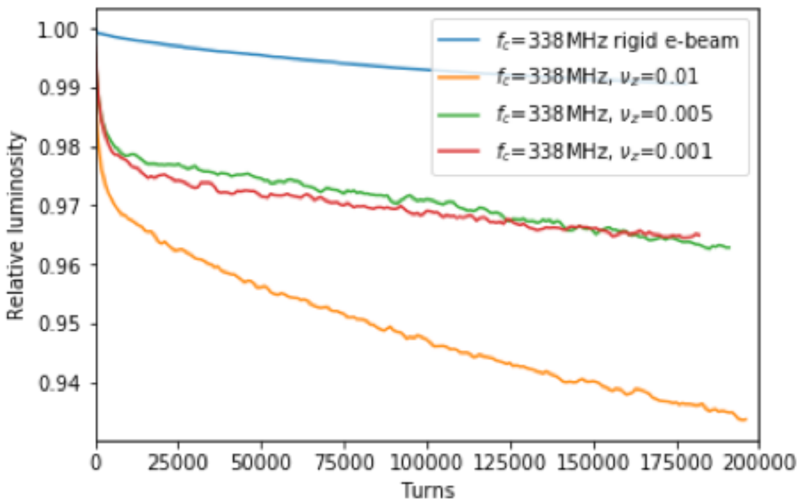


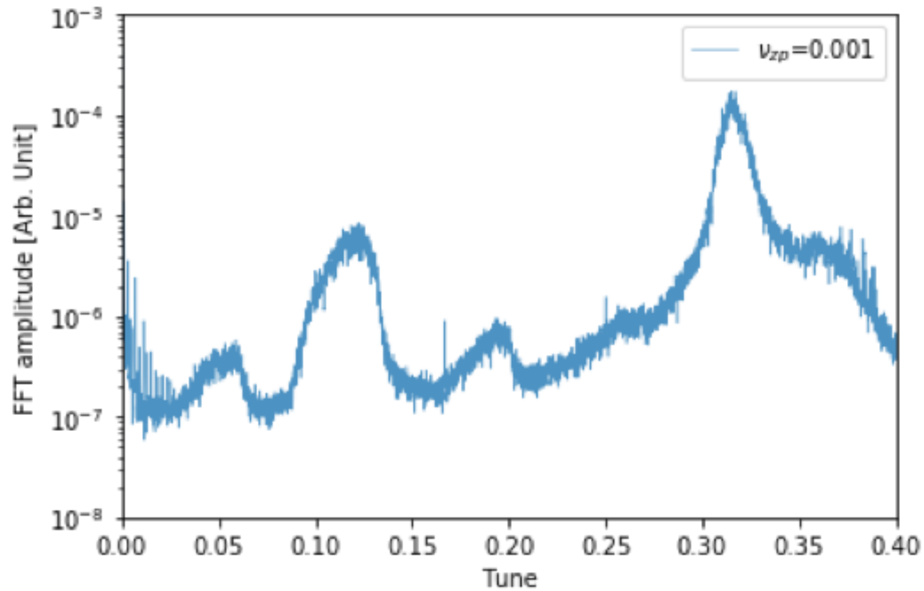


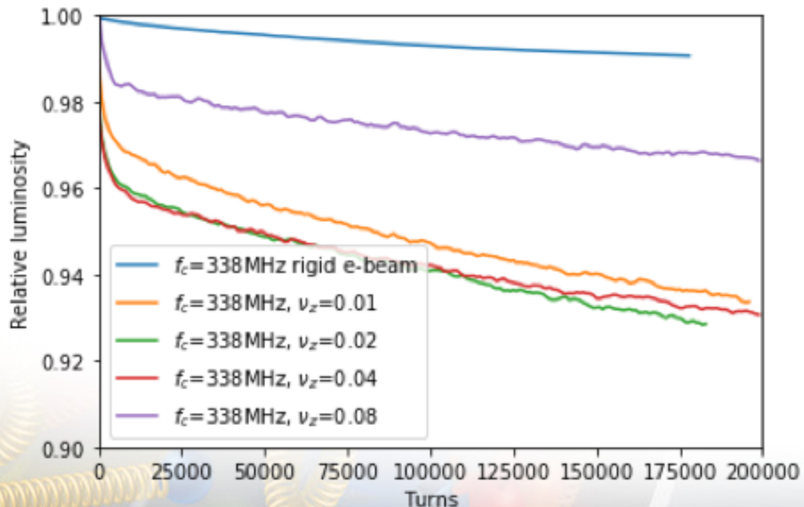
By comparing with the 'frozen' electron case, we believe there is physics reason that cause the lumi-degradation.

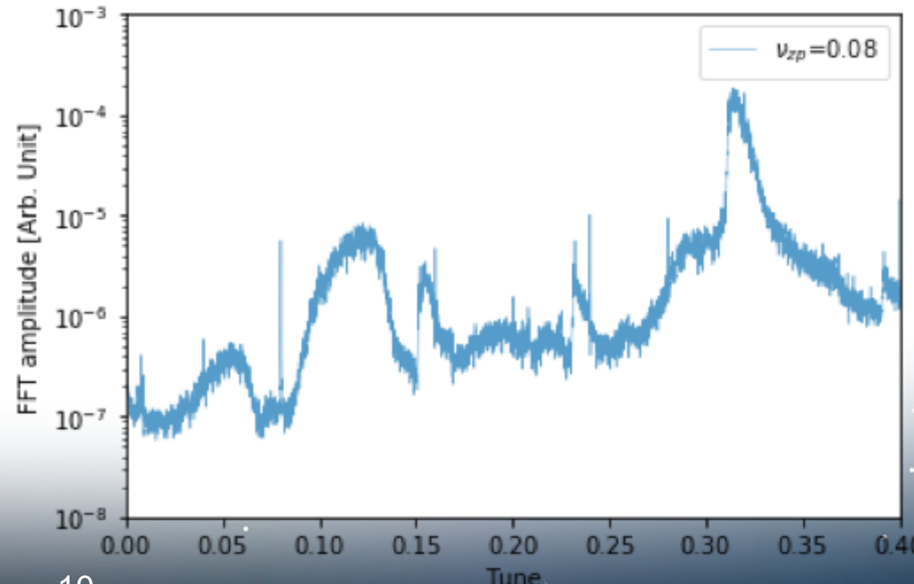


A Special Synchro-beta Coupling

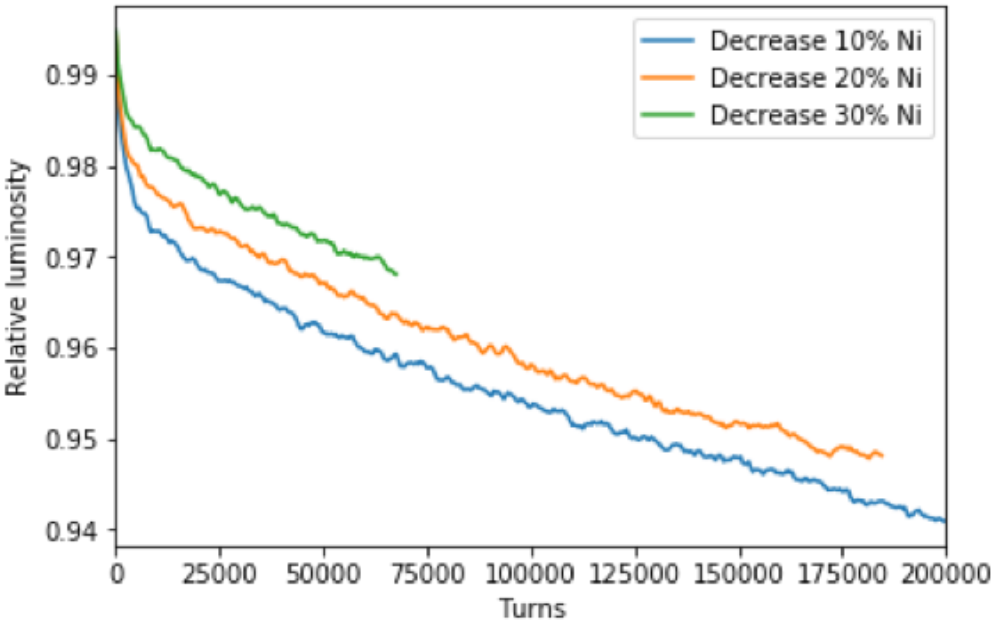


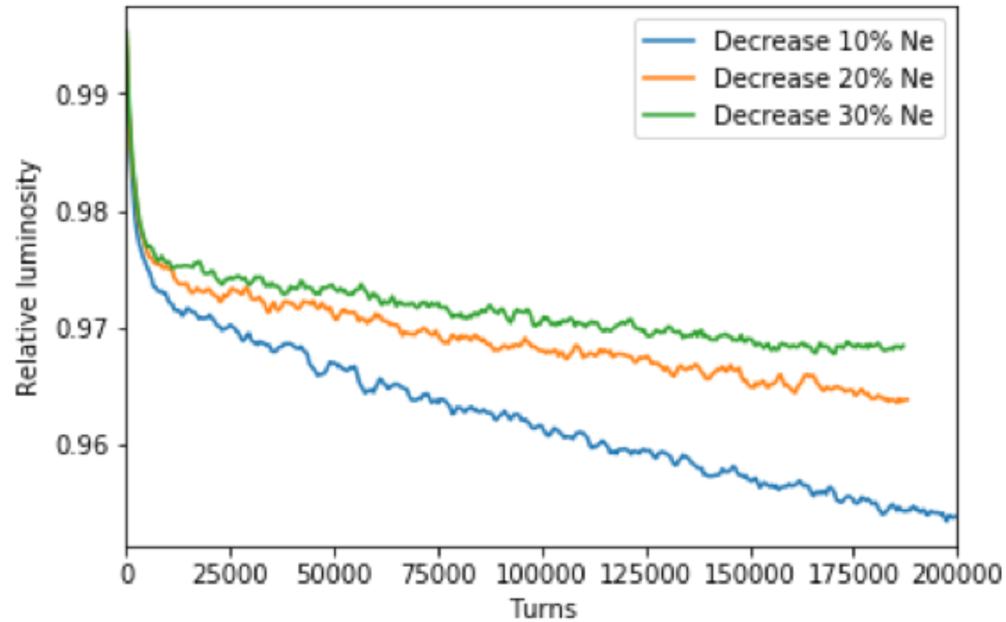






Scaling with Tune Shift





Scale down the electron beam-beam tune shift

Scale down the ion beam-beam tune shift

Summary I

- The imperfect crab-crossing will induce a special synchro-beta resonance between the proton longitudinal motion and the electron ‘s transverse motion.
- Strong-Strong simulation is necessary due to the quite different behavior of two beams.
- Possible solutions
  - ~~Decrease the synchrotron tune~~
  - ~~Increase the synchrotron tune so that the footprint can fit in between synchrotron lines.~~
  - ~~Move away the electron tune away from near-integer? Need more check.~~
  - Use harmonic cavity to linearize the voltage.
  - Decrease the beam-beam parameter of the ion beam.

Dispersion Effects, Linear B-B

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

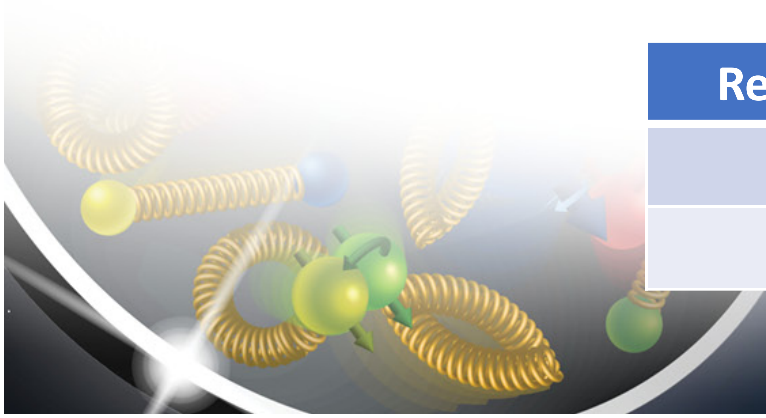
$$M_{IR} = M_{cc2} M_{LT}^{-1} K_{bb} M_{LT} M_{cc1}$$

Effect of Dispersion at one crab cavity:
- Tune shift
- Dispersion and crab dispersion

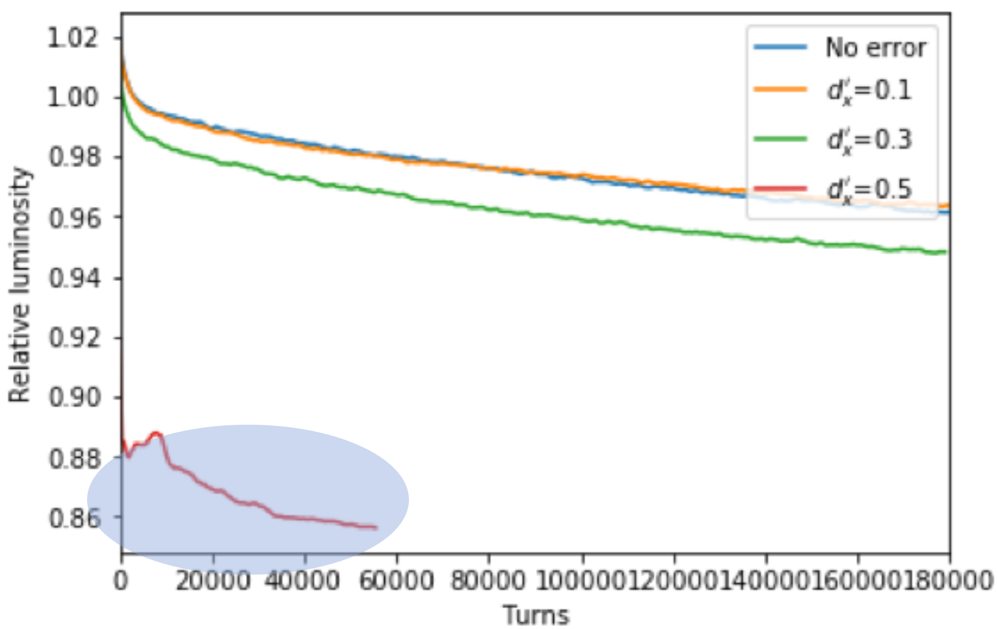
$$M_{LT} M_{cc} = \begin{bmatrix} \epsilon^2\theta_c^2 + \epsilon\theta_c + 1 & \beta_s\eta\theta_c\left(\epsilon\theta_c + 2\right) & \epsilon\theta_c^2 & -\beta_s\epsilon\eta\theta_c \\ 0 & -\epsilon\theta_c + 1 & 0 & \epsilon^2\theta_c \\ -\epsilon^2\theta_c & -\beta_s\epsilon\eta\theta_c & -\epsilon\theta_c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

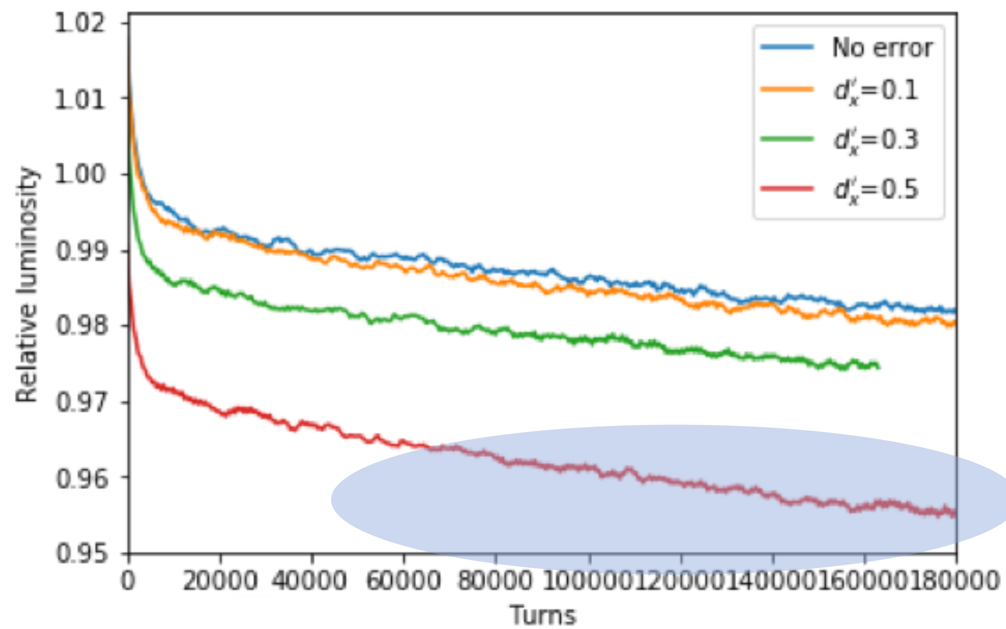
$$\epsilon = d_x / \sqrt{\beta_c \beta_s} \qquad \eta = \left(\alpha_c d_x + \beta_c d_x'\right) / \sqrt{\beta_c \beta_s}$$

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



Dispersion tolerance, with nonlinear B-B





With synchro-betatron resonances

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

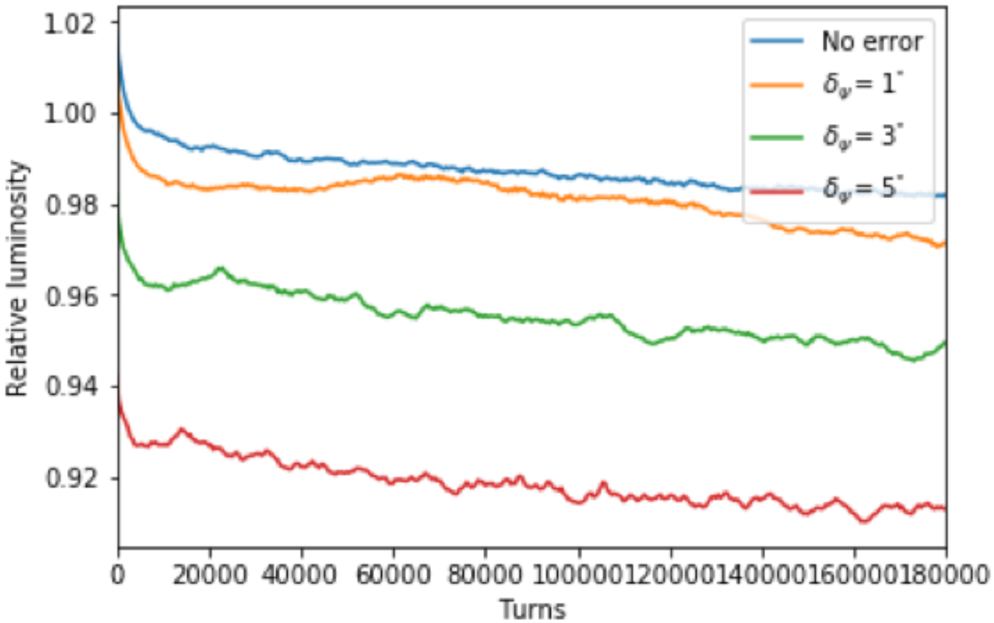
Non-pi/2 phase advance, linear B-B

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

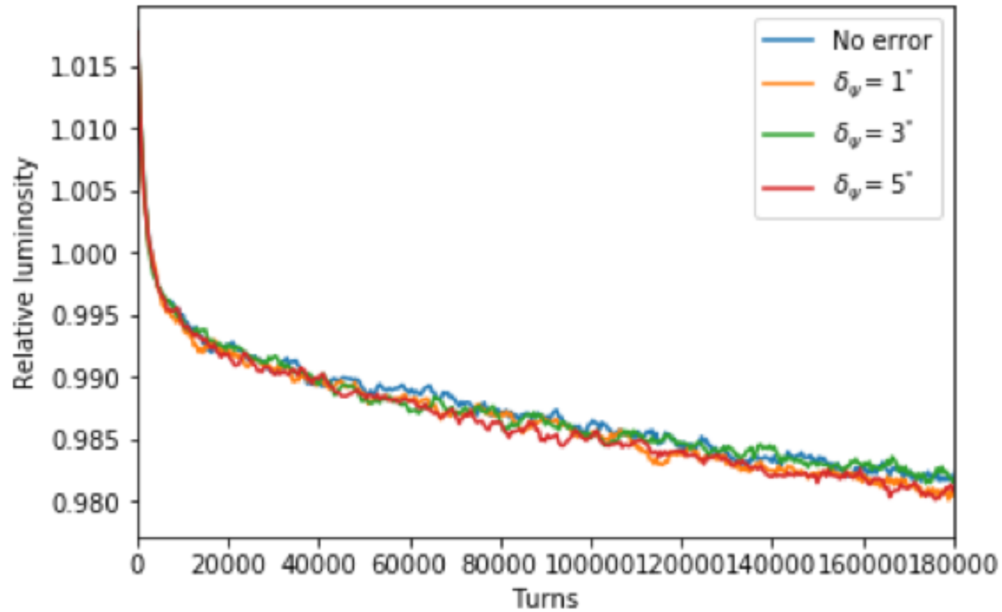
$$= \begin{bmatrix} 1 & 0 & 0 & 0 \\ k & 1 & \frac{\theta_c \sum_i \tan(\delta_{\psi i})}{\beta_s} & 0 \\ 0 & 0 & 1 & 0 \\ \frac{\theta_c \sum_i \tan(\delta_{\psi i})}{\beta_s} & 0 & \frac{\theta_c^2 \sum_i \tan(\delta_{\psi i})}{\beta_s} & 1 \end{bmatrix}$$

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



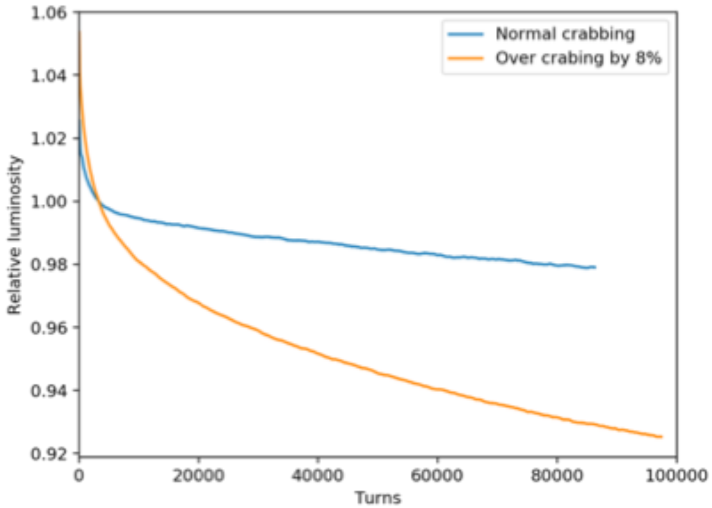
Two side phases have the same sign.

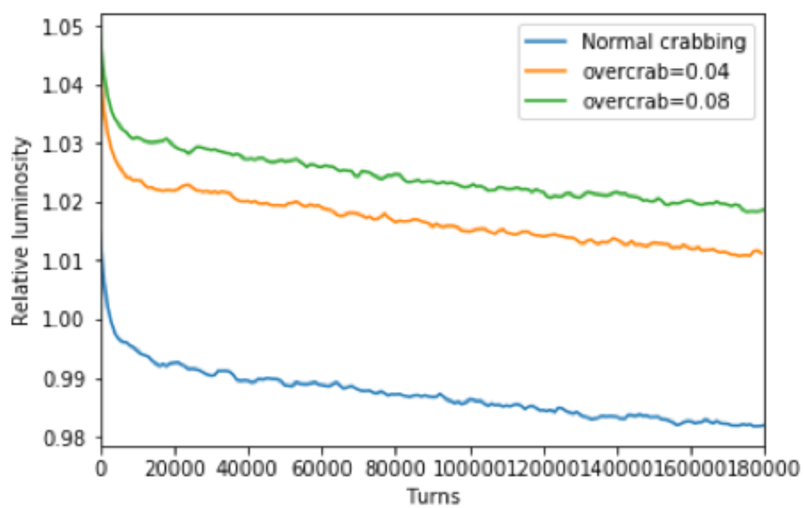


Two side phases have the opposite sign.

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.

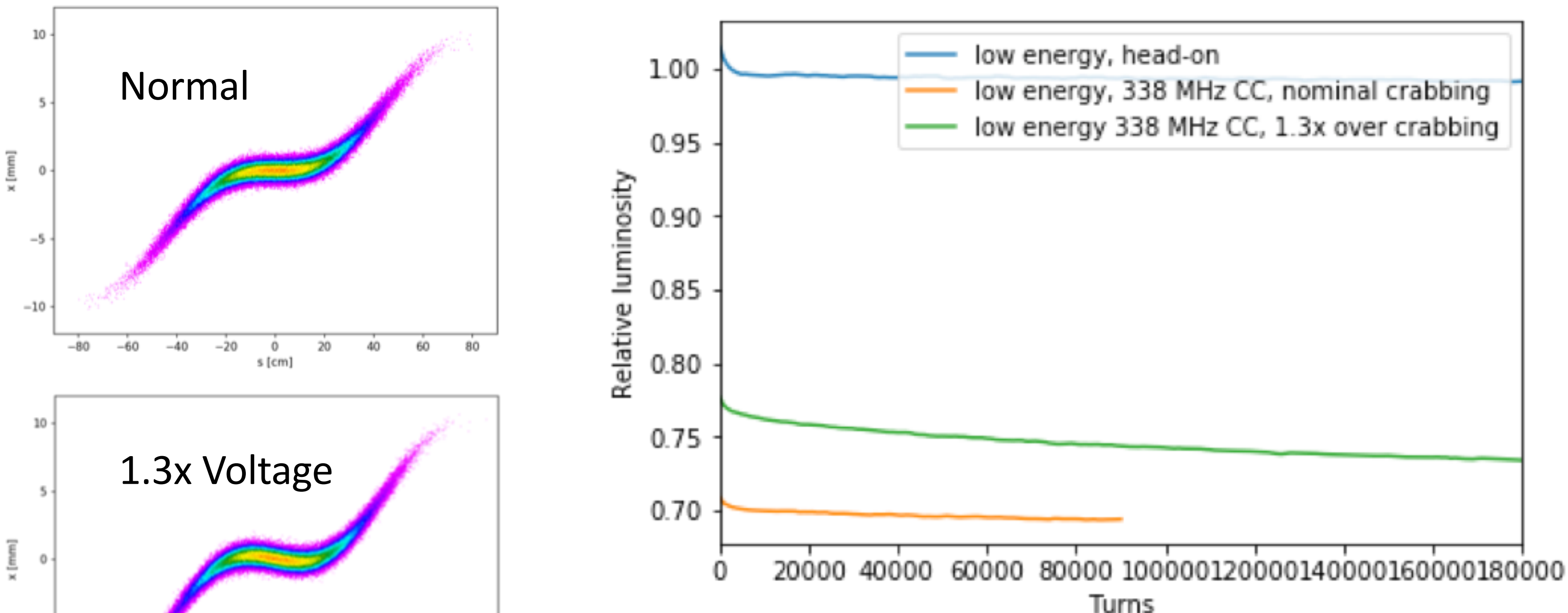




the synchro-beta resonances prohibit over crabbing

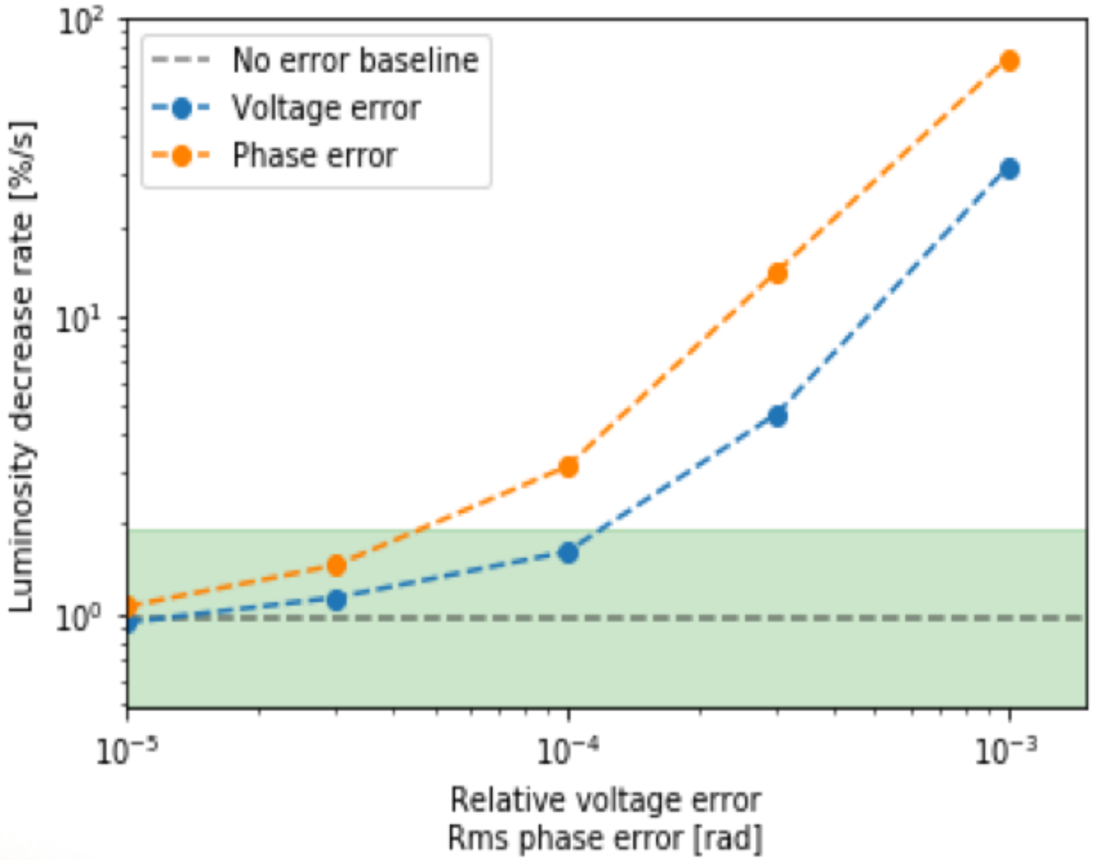
After reducing the synchro-beta resonances by reducing the synchrotron tune of ion beam to 0.001

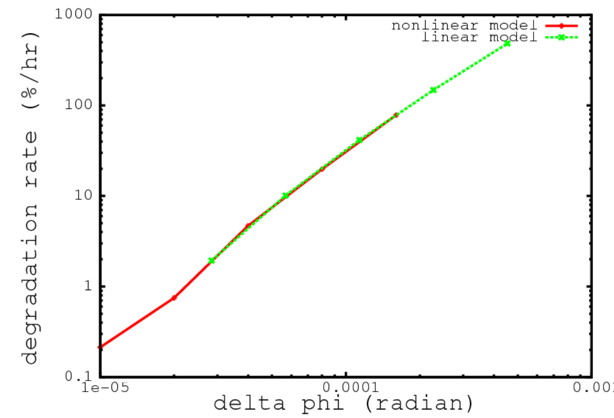
Low energy case

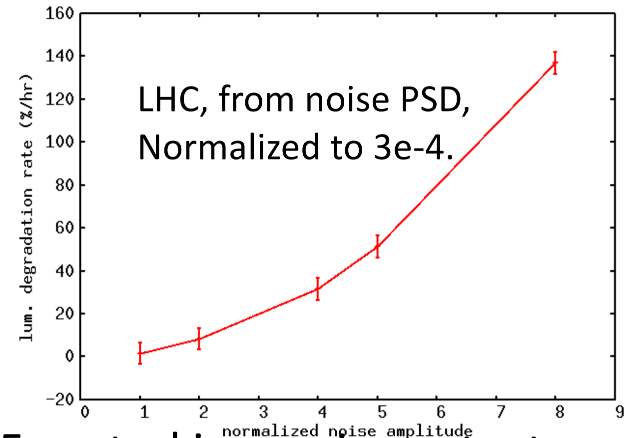


Lower energy has longer ion bunch length, smaller synchrotron tune and beam-beam parameter. Degradation is minimum for normal crabbing. More studies required for 1.3x over crabbing to explain the enhance luminosity degradation.

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.

Summary II

- The optics of CC can deviate from ideal case.
- The tolerance of the dispersion function at crab cavity and the phase advance deviation is determined by the luminosity degradation
- The over-crabbing method may be beneficial. However, more studies are needed for the low-energy long-bunch cases.
- The white noise model will largely overestimate the tolerance of the CC voltage and phase jitter. A realistic PSD of lower-level RF will be helpful for predicting the tolerance.

Outlooks

- The crab cavity dynamics studies reveals a weak coupling resonance that may degrade the luminosity
  - State-of-art simulation tool is need for further investigation.
  - Can be cured.
  - Such tools is also essential to determine the tolerance of dispersion @ crab cavity, phase advance, over-crabbing scheme and effect of cavity LLRF noise.

Thank you for your attention!