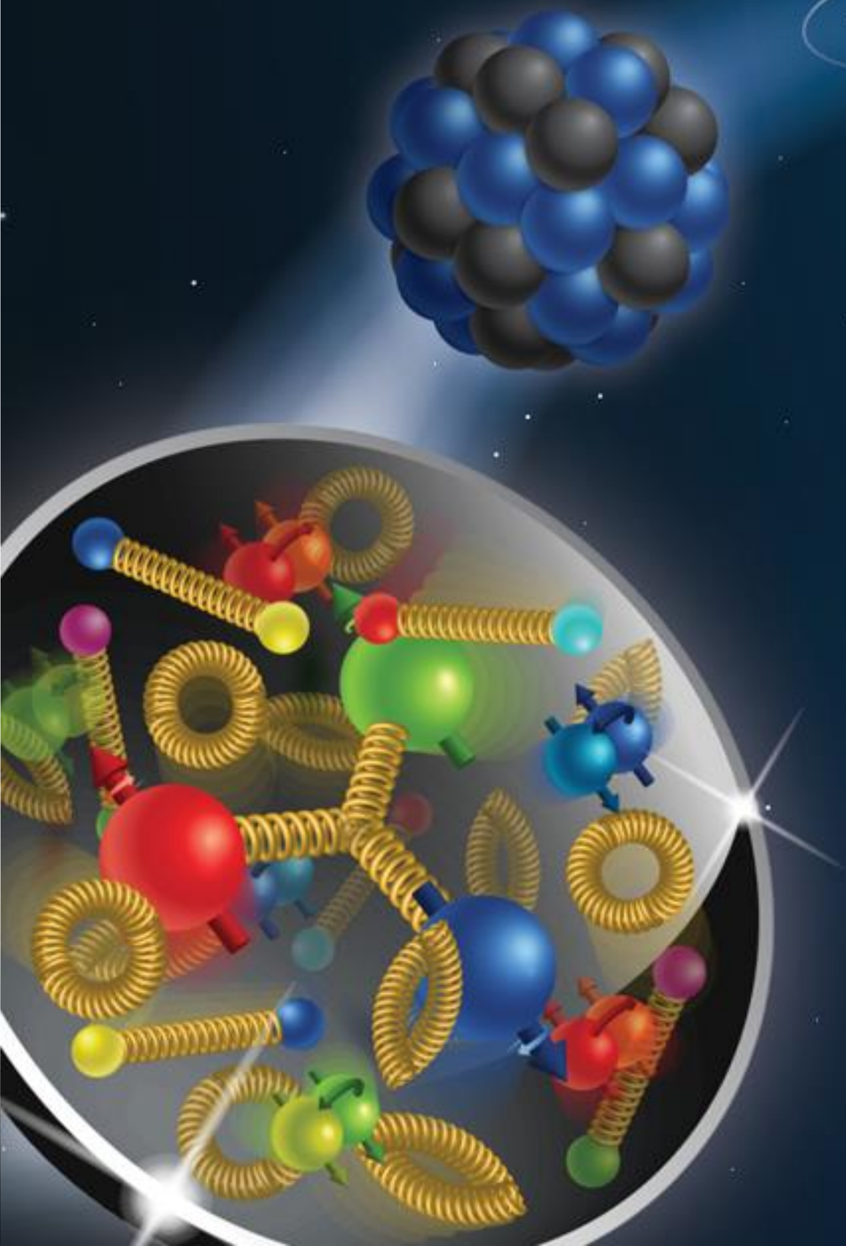


EIC Beam-beam Effects

Yun Luo

EIC Accelerator Collaboration
Workshop
October 7-9, 2020

Electron-Ion Collider

Outline

- Introduction
- Beam-beam Challenges for EIC
- Simulation for e-p 10GeV * 275GeV collision
- Important parameters to BB performance
- Simulation for electron bunch replacement
- Summary

Acknowledgement

Backup slides

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.

Luminosity and Beam-beam

Luminosity is given by:

$$L = \frac{N_p N_e f_c}{2\pi\sqrt{\sigma_{p,x}^2+\sigma_{e,x}^2}\sqrt{\sigma_{p,y}^2+\sigma_{e,y}^2}} H$$

To achieve such a high luminosity in EIC, we need to

1) **increase bunch intensities**
2) **reduce transverse beam sizes at IP**
3) **increase collision frequency.**

However, methods 1) and 2) are limited by beam-beam interaction which is measured with beam-beam parameter:

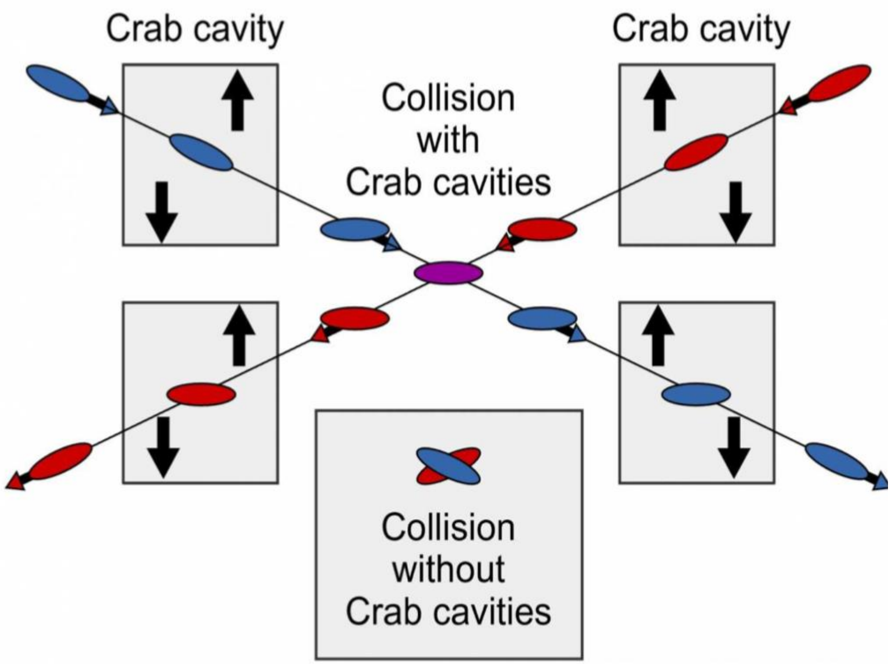
$$\xi_{e,p,z} = \frac{N_{p,e} r_{e,p}}{\gamma_{e,p}} \frac{\beta^*_{e,p,z}}{2\pi\sigma^*_{p,e,z}(\sigma^*_{p,e,x}+\sigma^*_{p,e,y})}$$

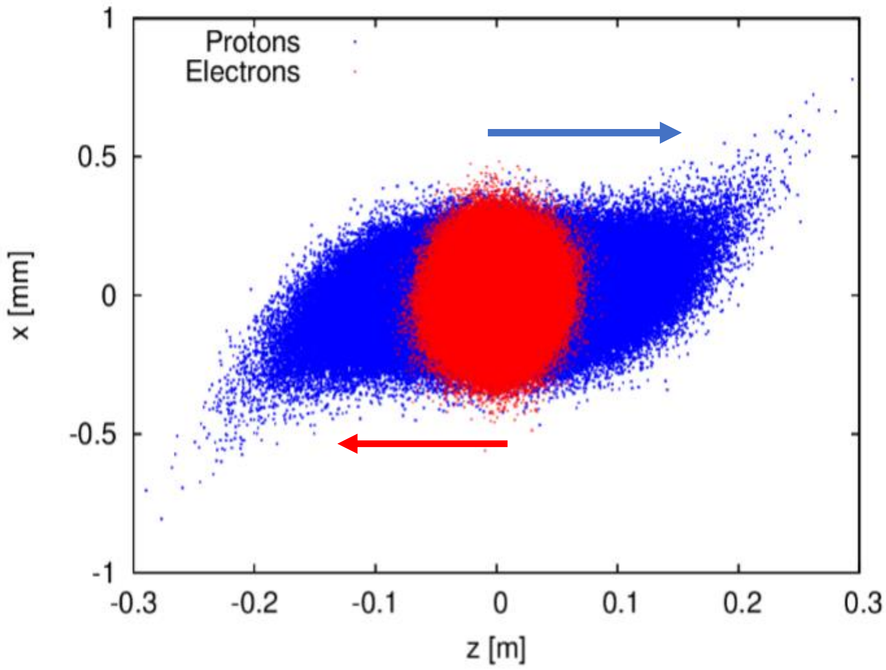
Method 3) requires crossing collision which involves crab cavities.

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.

Simulation tools and methods

Both strong-strong and weak-strong simulation methods have been used for EIC BB studies. Strong-strong simulations are mostly used for equilibrium beam sizes and luminosity calculation, coherent beam-beam studies. Weak-strong simulations are mostly used for long-term stability and dynamic aperture calculation.

Strong-strong codes:

BeamBeam3D by J. Qiang, BBSS by K. Ohmi

SimTrack by Y. Luo, EPIC by Y. Hao (Soft-Gaussian)

Weak-strong codes:

SimTrack by Y. Luo (symplectic, element-by-element)

BeamBeam3D by J. Qiang (LBNL) (frozen electron distribution in S-S)

Checks and indicators for beam stabilities:

emittance growth, luminosity degradation (related to numeric errors)

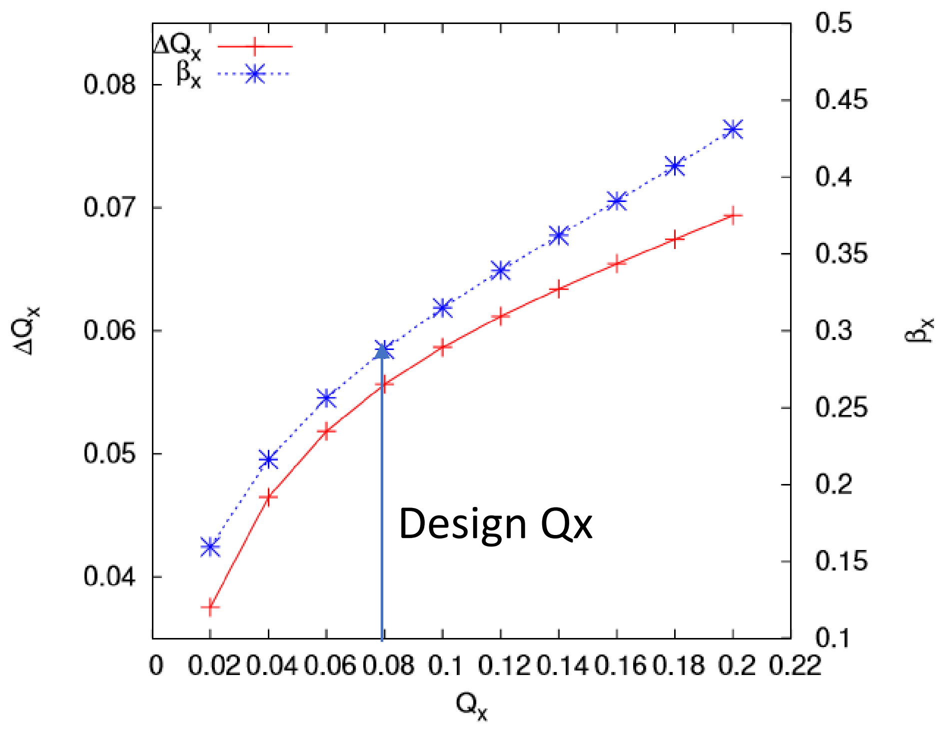
FMA, action diffusion, RDTs (how to link to real beam lifetime)

dynamic aperture (weak-strong, a robust measure).

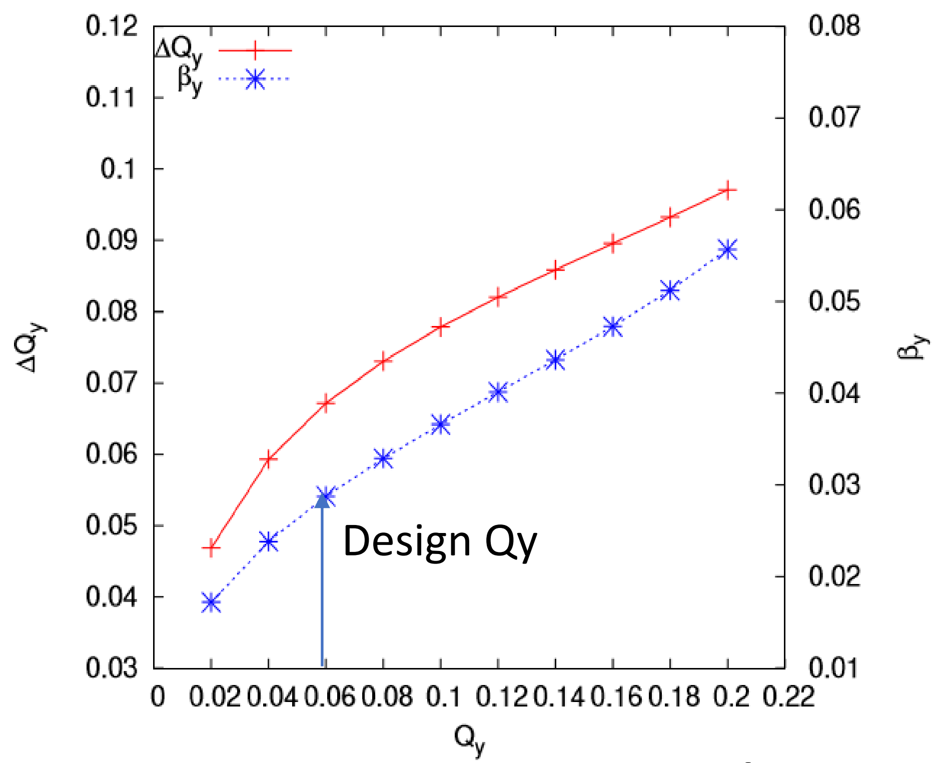
Design Parameters for e-p 10GeV * 275GeV collision

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	

Dynamic-beta effect: electron



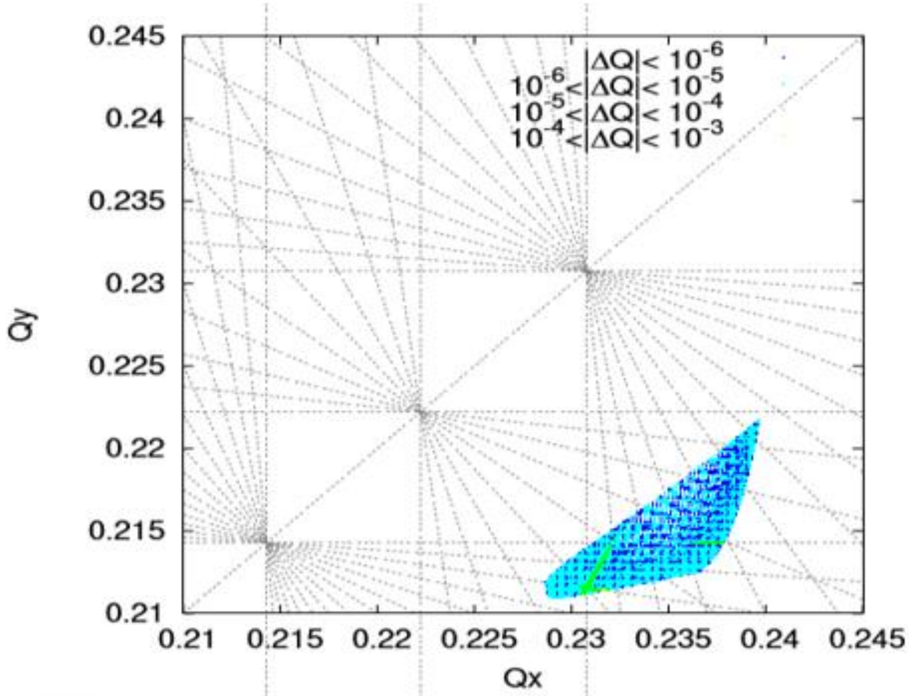
Horizontal



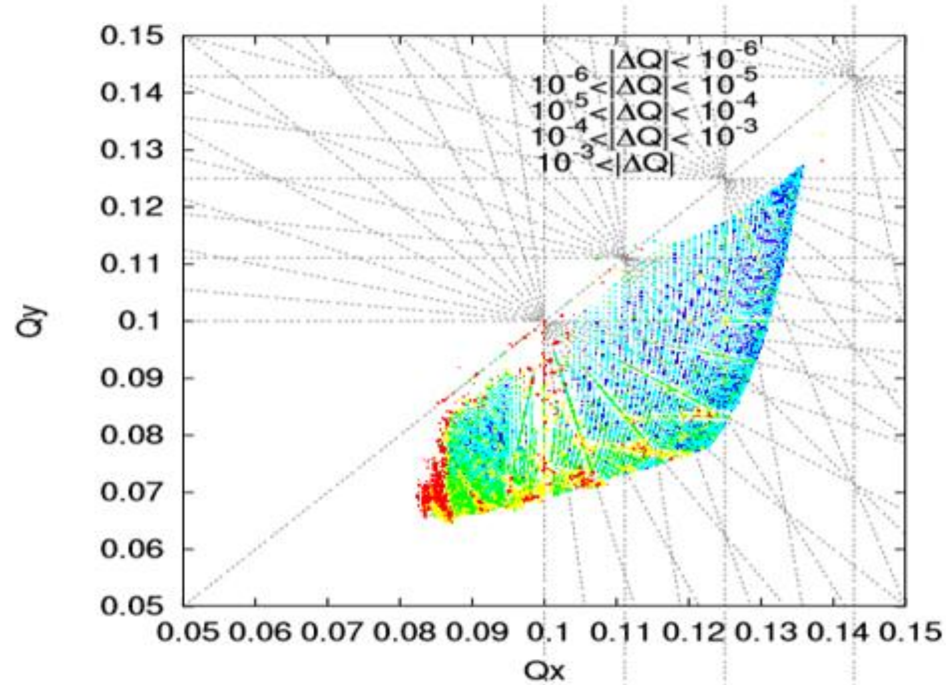
Vertical

Dynamic-beta reduces beta-functions at IP and generates even smaller beam sizes at IP, which enhances luminosity BUT increases proton's beam-beam parameter.

Tune Footprint (Weak-strong)



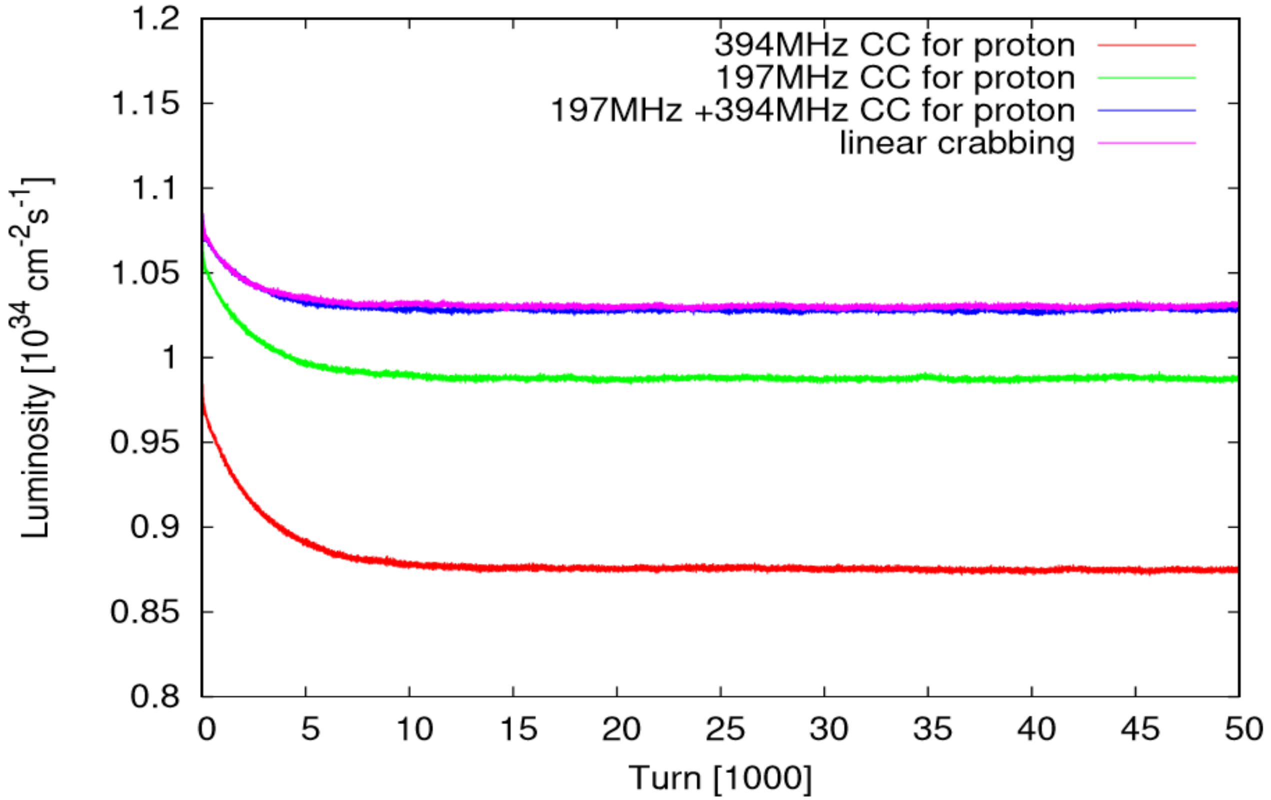
Proton



Electron

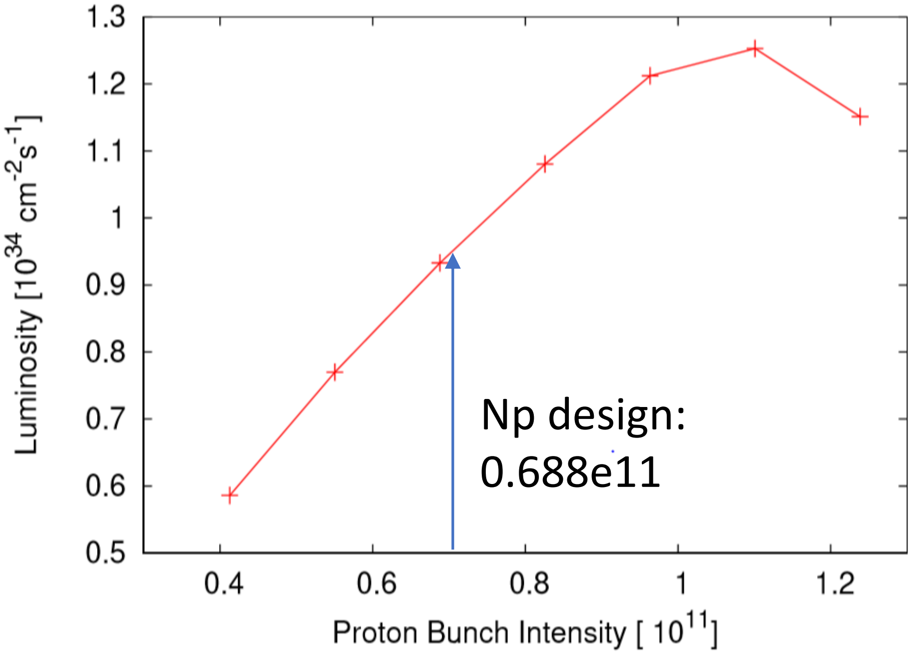
Beam-beam generates amplitude dependent tune shift. Proton tune footprint crosses 9th order resonances. Electron tune footprint crosses 10th order resonances. Difficult colors represent different order of magnitudes of tune diffusion in above plots.

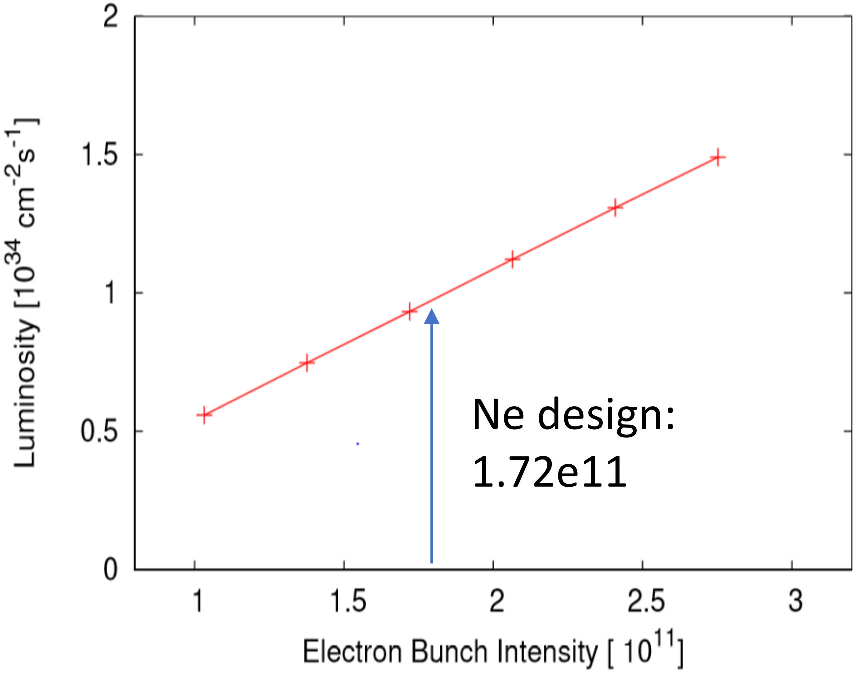
Luminosity Evolution



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.

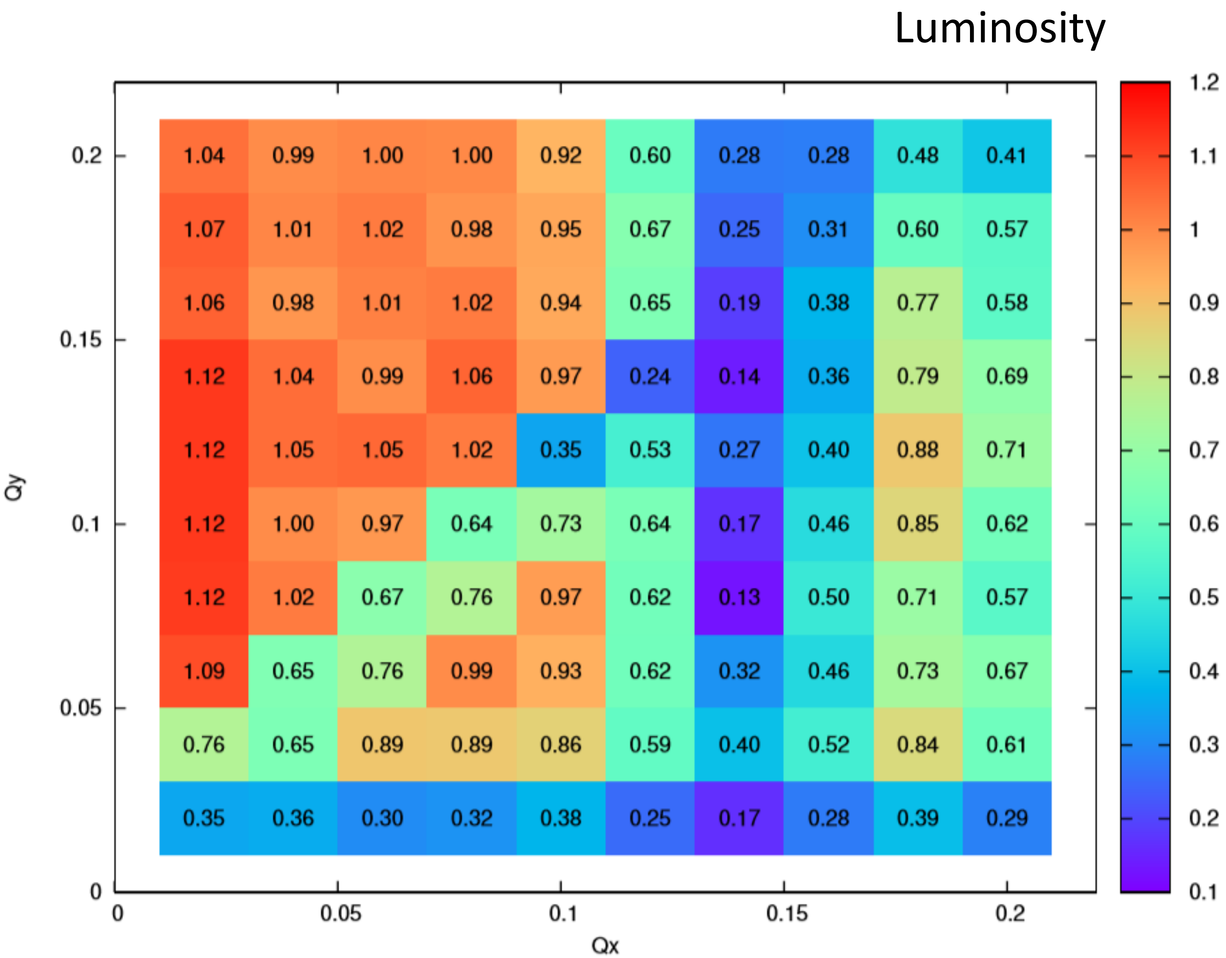
Bunch Intensity Scan





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.

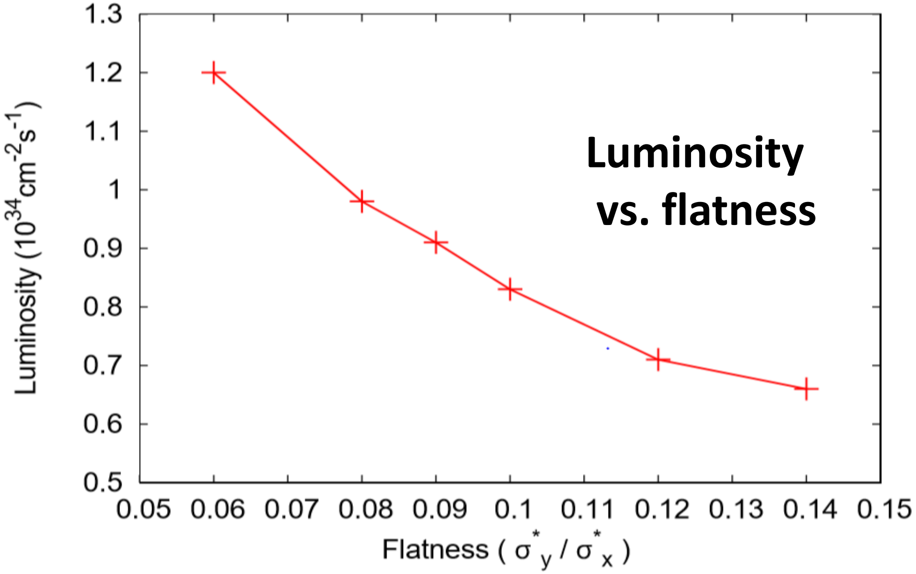
Electron Tune Scan: strong-strong

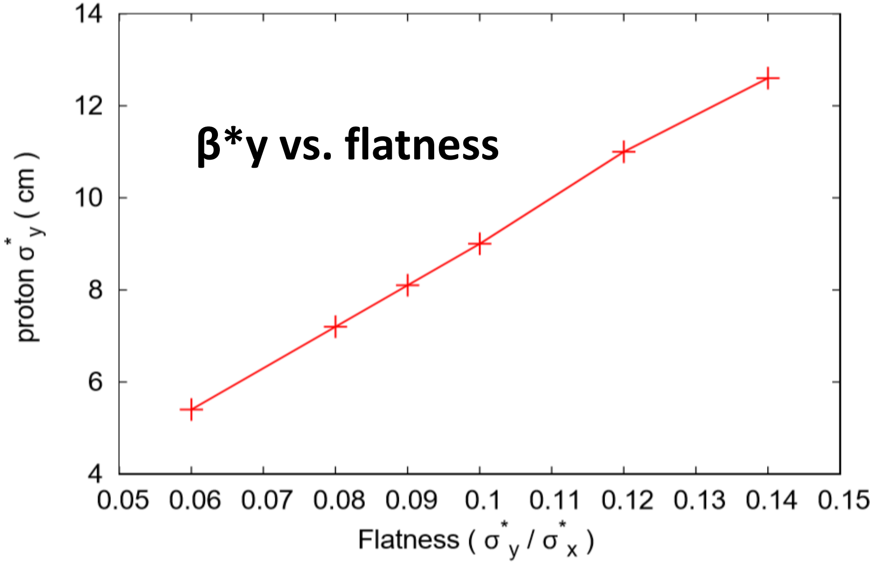


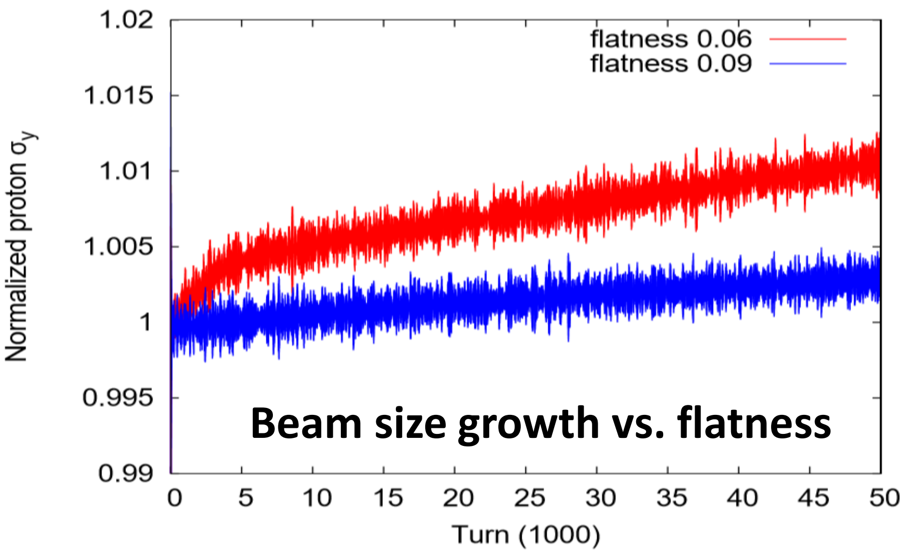
Higher luminosity can be obtained with lower horizontal tunes and higher vertical tunes. However, higher vertical tunes give relatively fast proton vertical emittance growth.

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



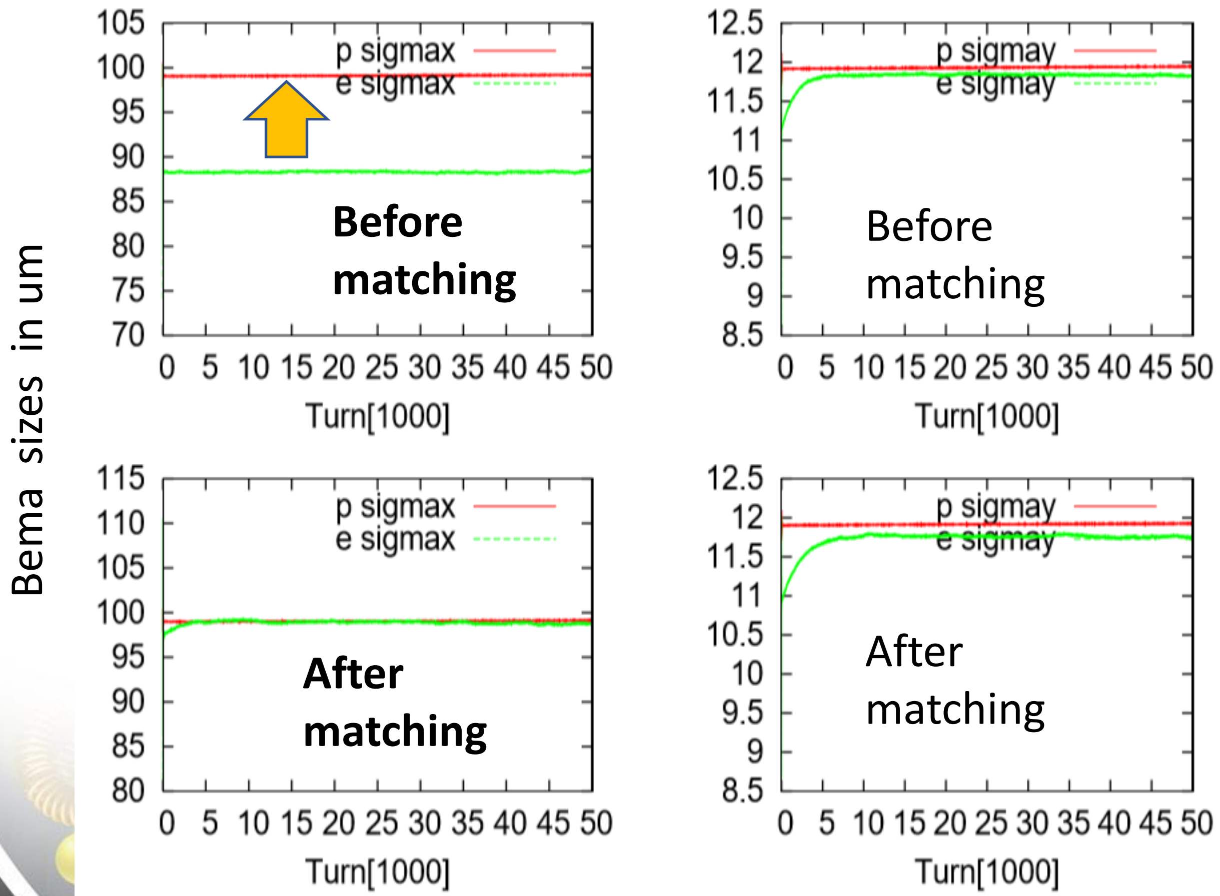




Flatness is defined as σ*y/ σ*x at IP. Lower flatness needs lower betay* in lattices. Lower flatness or flatter beams yields a higher luminosity. However, through beam-beam simulation, we noticed that flatter beams cause faster proton vertical beam size growth.

Beam Size Matching at IP

Example: flatness 0.12

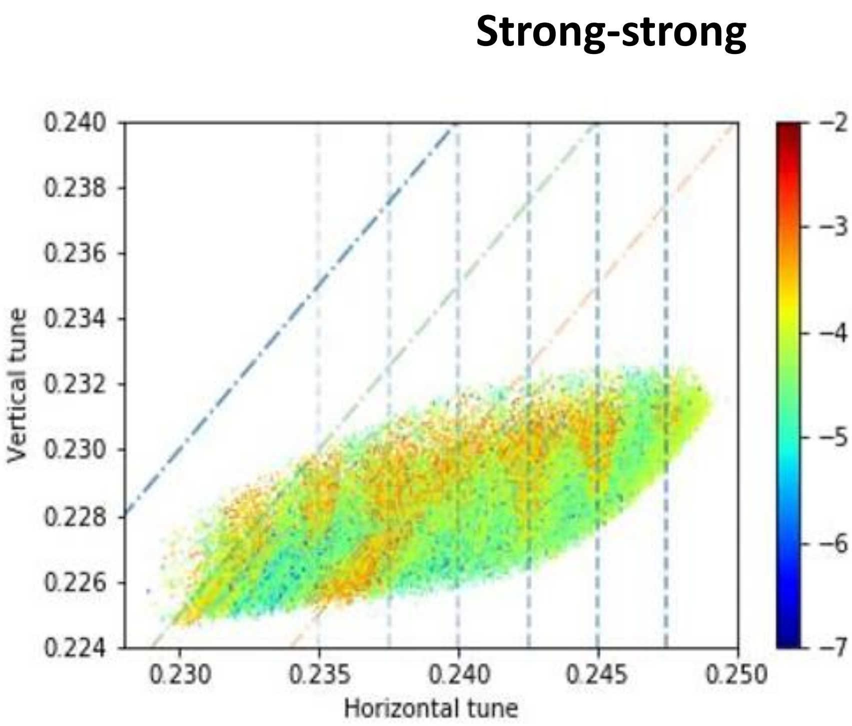


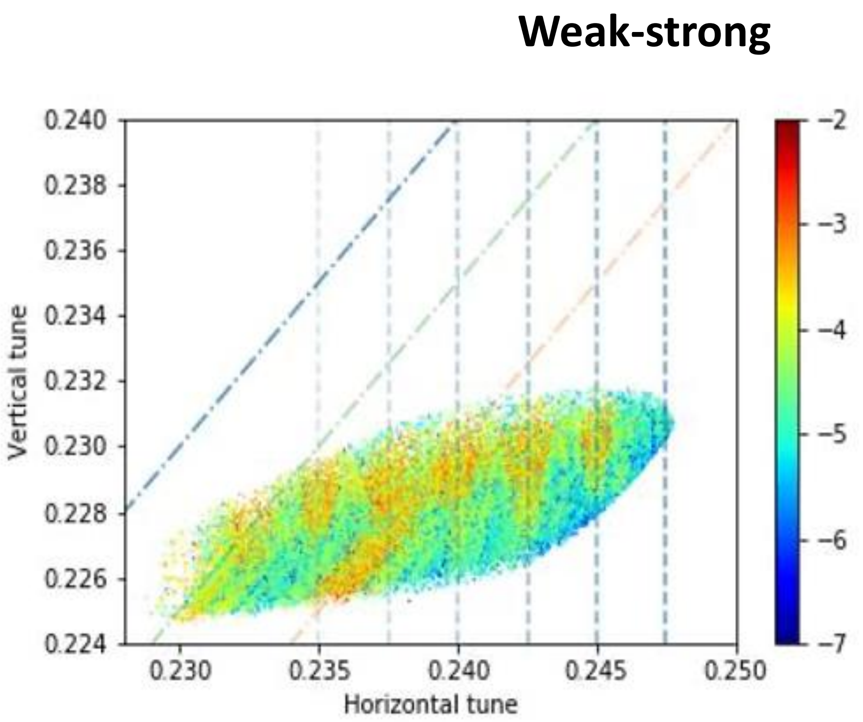
Due to SR effect in electron ring and BB interaction , electron and proton beam sizes are not matched at IP in most cases.

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 β*x,y and /or emittances at IP.

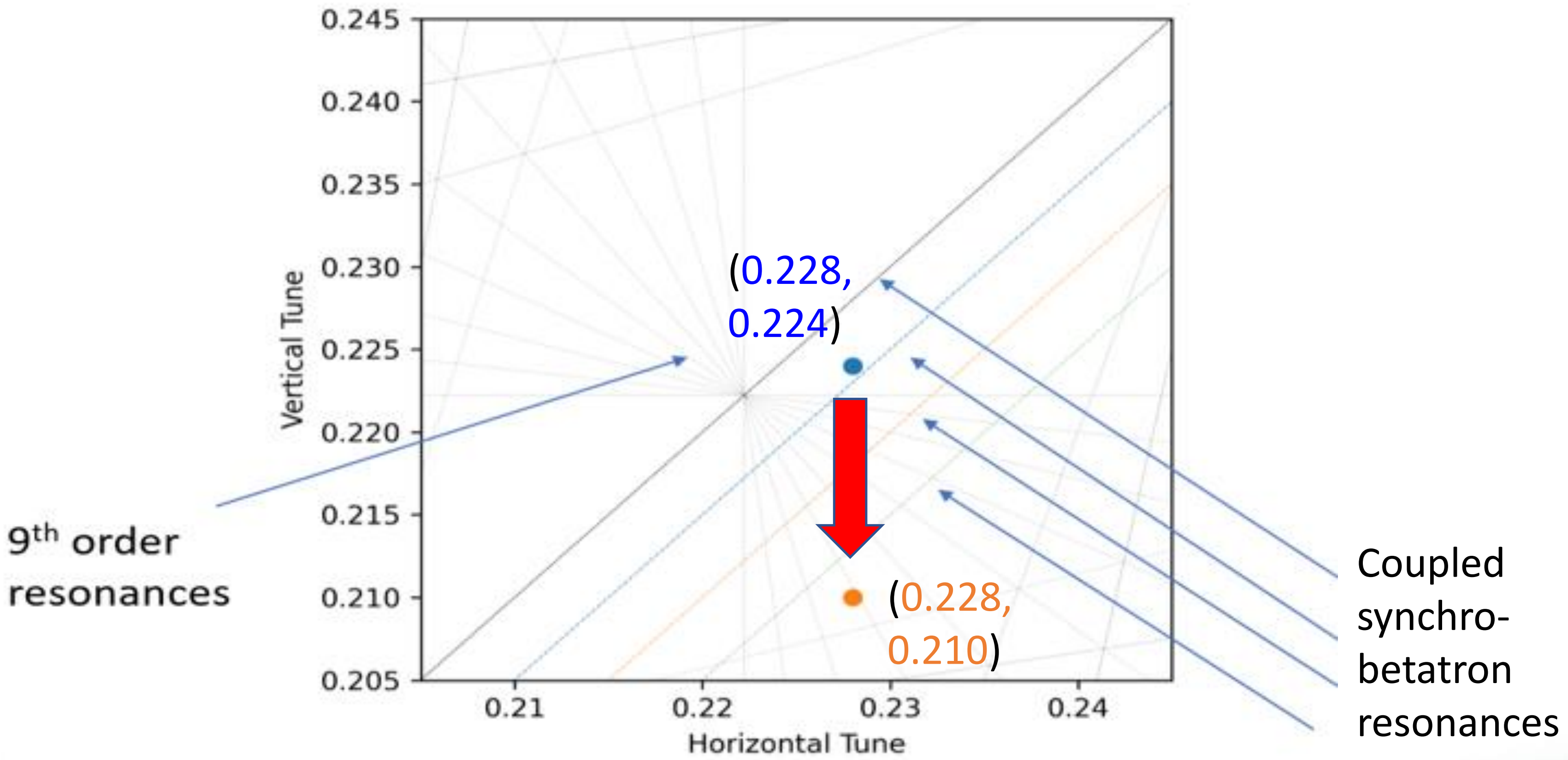
Synchro-Betatron Resonance





Resonances mQx+pQs and 2Qx-2Qy+pQs for protons are revealed from FMA in both strong-strong and weak-strong simulations. Those resonances are related to crossing collision. Second harmonic crab cavities help minimizing synchro-betatron resonances.

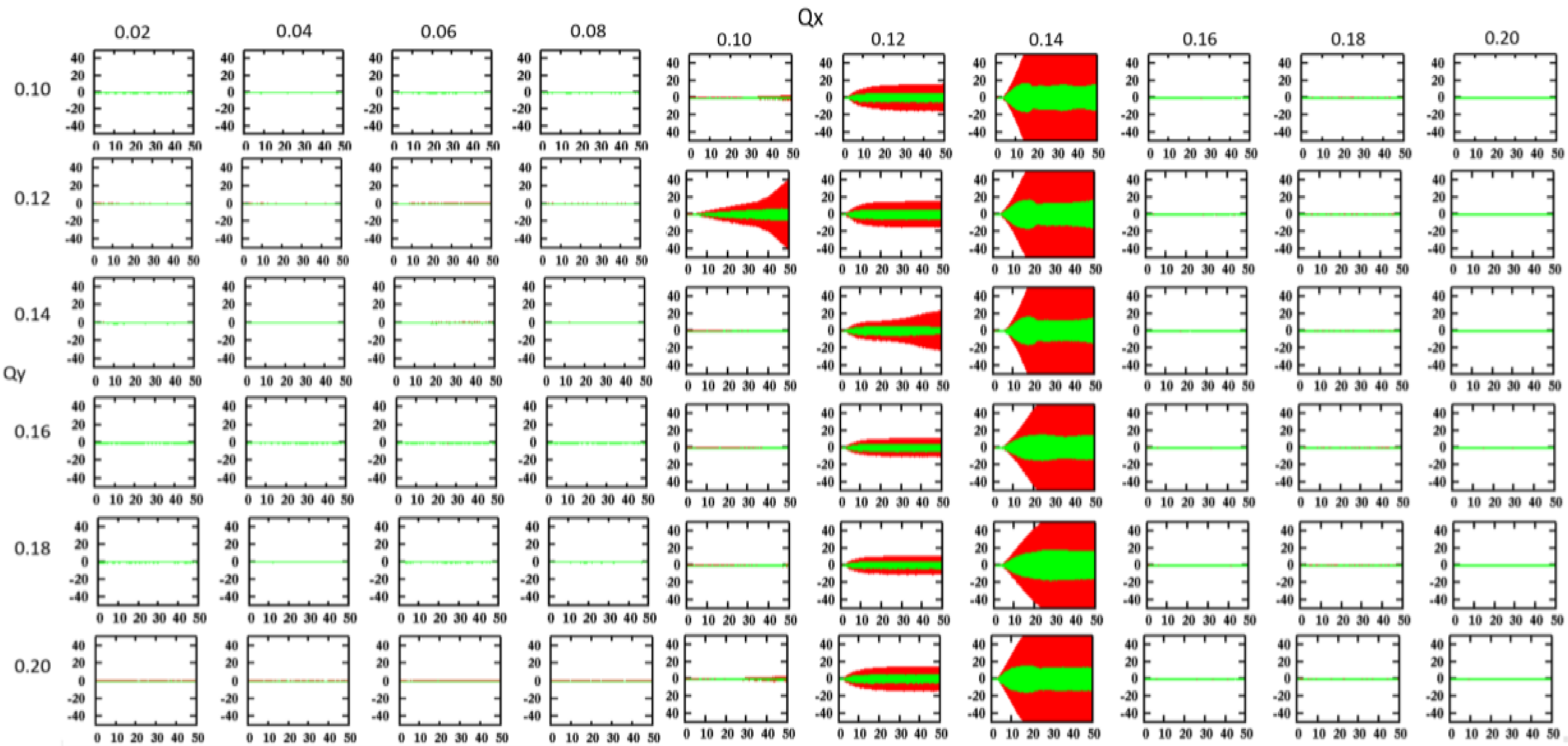
Proton Working Point



Moving proton tunes from (0.310,0.305) down to (0.228, 0.224) helps minimizing mQx+pQs resonance effect. Further lowering vertical tune from diagonal helps minimizing 2Qx-2Qy+pQs resonance effect.

Coherent Beam-beam Instability

<Xp> and <Xe> in electron tune scan

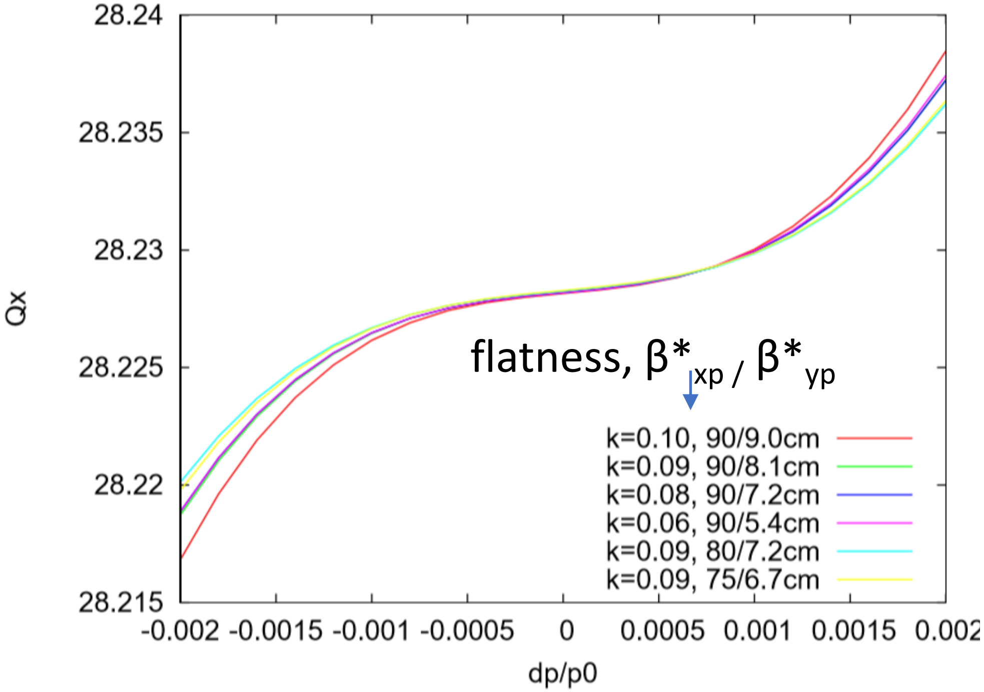


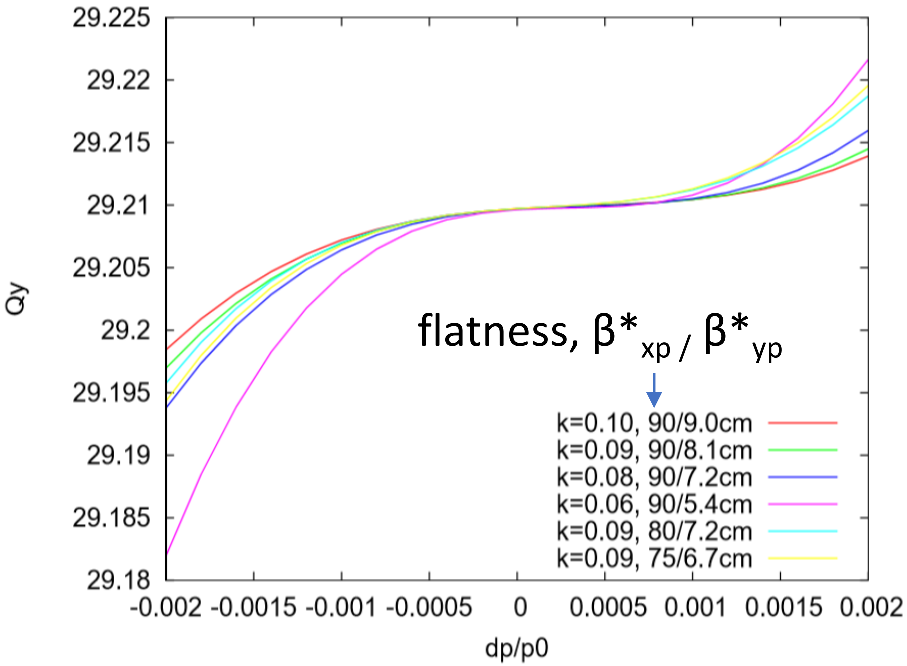
Coherent BB instability was observed with the electron horizontal tune are between 0.1 and 0.14. More studies show these instabilities were caused by coherent coupling resonance between horizontal proton tune and horizontal electron tune.

Proton Lattice Design

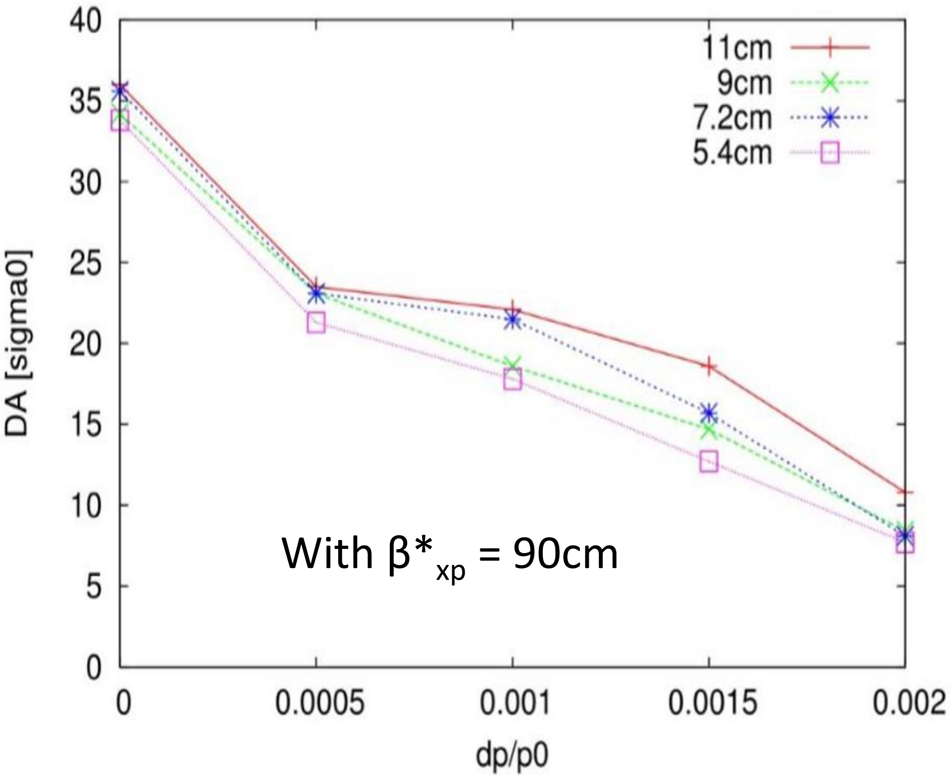
Hadron ring lattice design went side by side with strong-strong beam-beam simulation studies. Lattices with different design parameters are created and tracked.

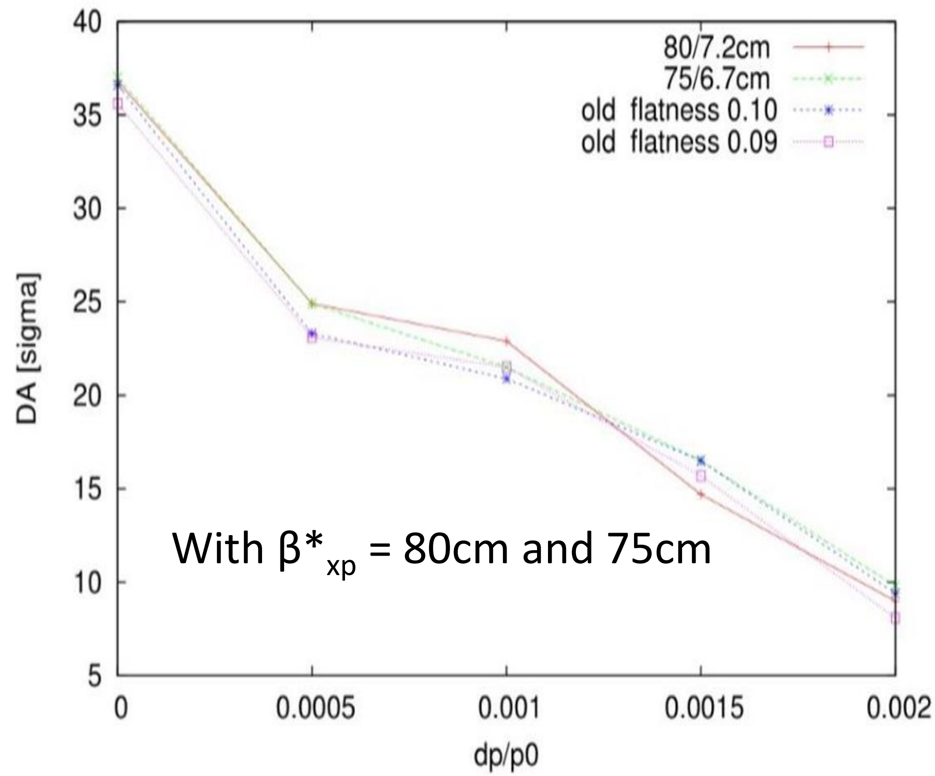
Off-momentum tunes, $(dp/p0)_{rms}$=6.6e-4.





Dynamic aperture calculation



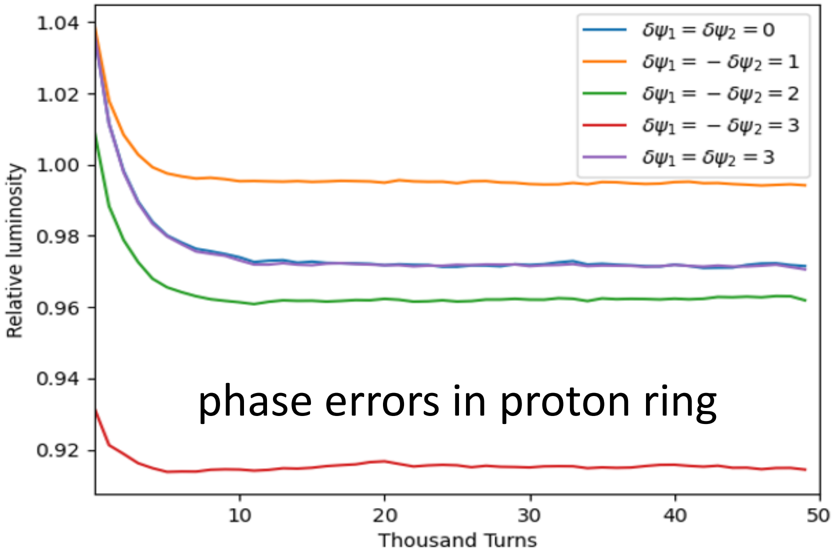


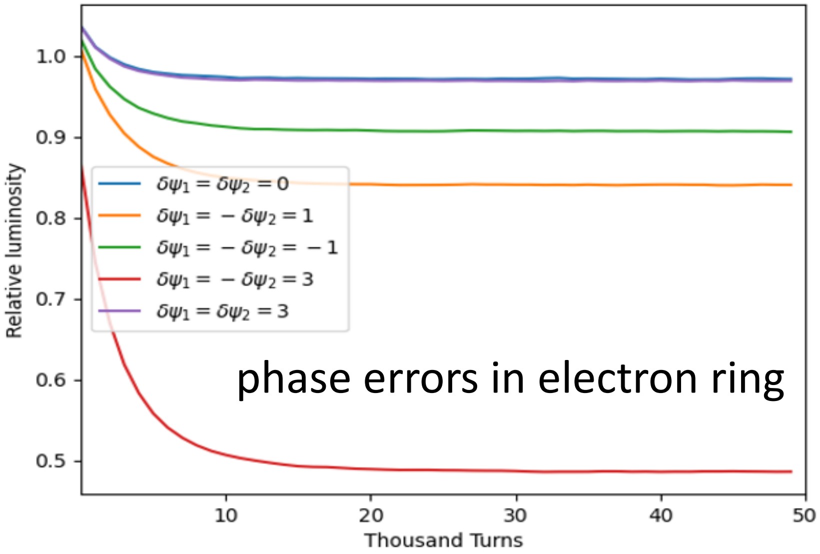
Left: Dynamic aperture as function of different β^*_{yp}. Right: Dynamic aperture with β^*_{xp} =80cm and 75 cm . To reach the design luminosity 10^{34} $cm^{-2}s^{-1}$ with flatness 0.09, we reduced horizontal β^*_{xp} slightly from 90cm to 80cm.

Electron-Ion Collider

Imperfection with Crab Cavities

Imperfections with crab cavities have been studied. Imperfections include phase errors between crab cavity and IP, dispersion and dispersion derivative at crab cavities, crab cavity voltage mis-calibration, voltage and phase noises, detector solenoid effect, and so on. Imperfection with crab cavities are is still going on.



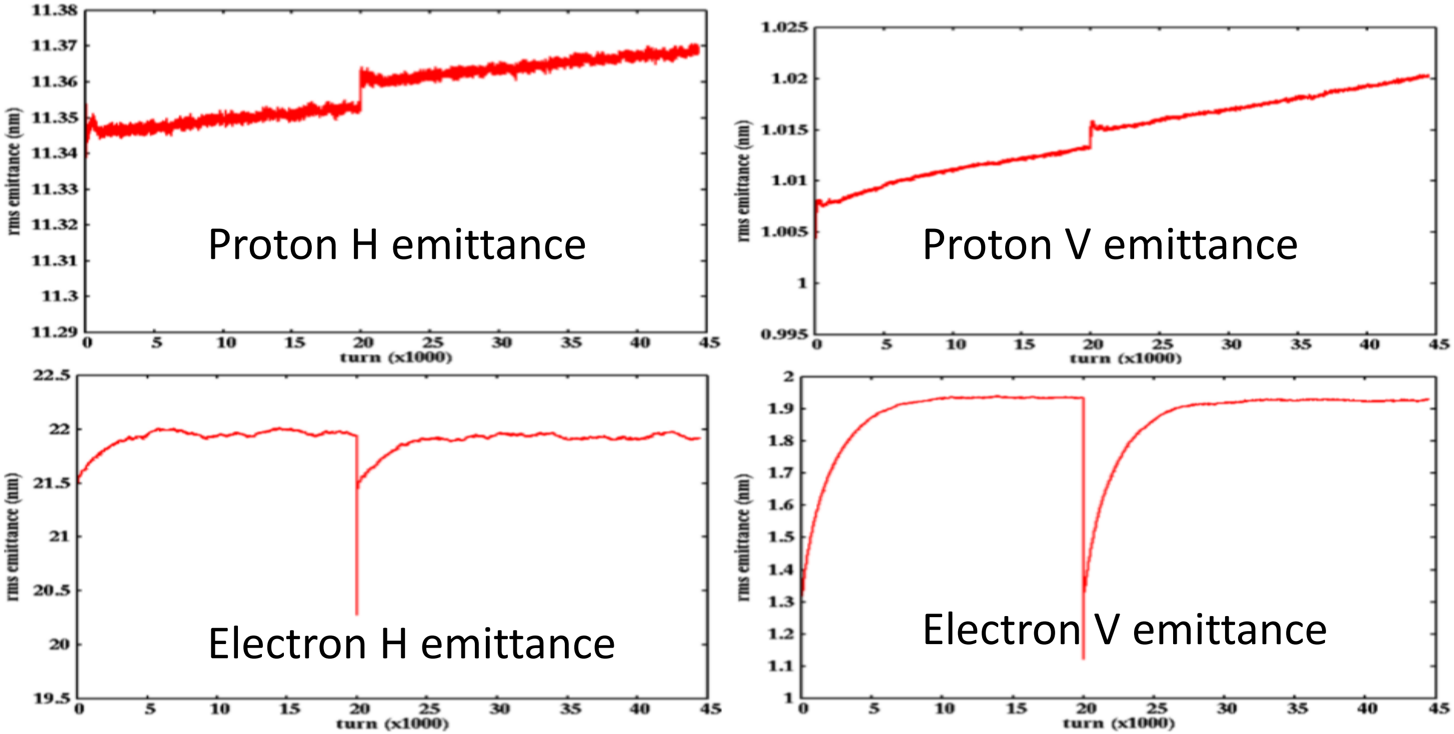


Simulations show that proton ring may tolerate 2 degrees phase error on each side of IP, if they are in opposite sign. The tolerance for electron ring is tighter, which can be reduced by choosing a higher vertical electron tune or a third crab cavity to create a closed bump.

Electron bunch replacement

Due to short electron polarization lifetime, each electron bunch will be replaced in minutes. Transient beam-beam effect during electron bunch replacement had been studied, especially for any possible proton emittance growth during this process.

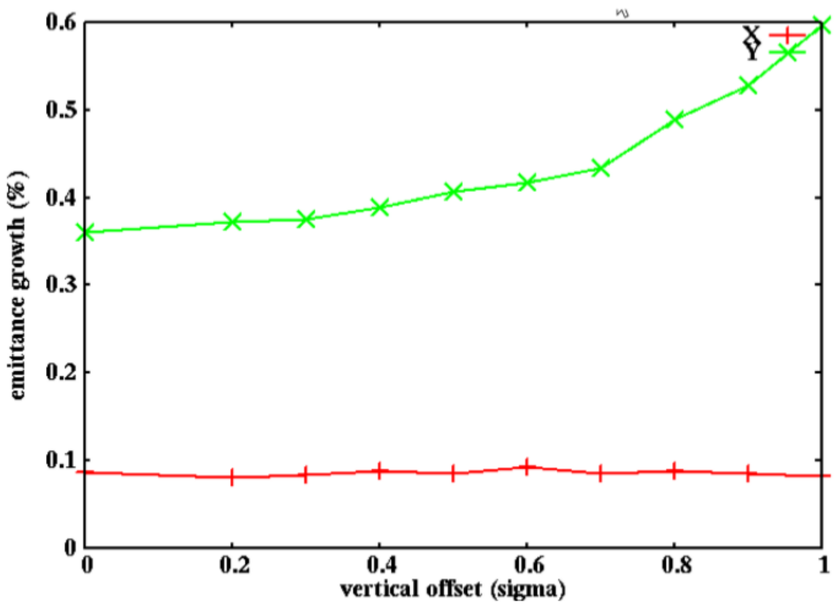
electron replacement at 20,000th turn

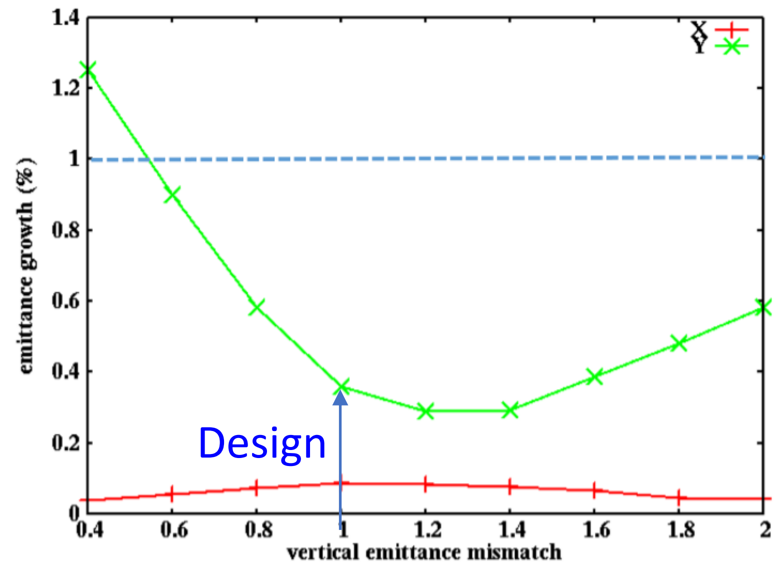


No injection error here.

Simulation with injection errors

Electron injection errors include: H/V positions, H/V angles, energy and arrival time, emittance mismatching, etc.





Example 1: The proton beam emittance growth percentage after one electron beam replacement as a function of electron beam's vertical injection position error.

Example 2: The proton beam emittance growth percentage after one electron beam replacement as a function of initial electron beam vertical emittance mismatching.

Summary

- ✓ During beam-beam related design parameter optimizing, we noticed that beam flatness, beam size matching at IP, both electron and proton's working points and so on affect the proton vertical emittance growth.
- ✓ To reach the design luminosity $1\times10^{34}cm^{-2}s^{-1}$ with a relatively low proton beam size growth, we chose a set of design parameters with flatness =0.09 and proton $\beta^*_{x,y,p}$ =(80,7.2)cm as our base design set.
- ✓ Hadron ring lattice design and dynamic aperture calculation were done. Current design parameters gives dynamic aperture more than 8 σs. Realistic IR magnetic nonlinearity is to be included in DA calculation.
- ✓ Design parameter optimizing is still going on. Better understanding underlying physics is needed. Effects with realistic lattice nonlinearity and crab cavity imperfection need more studies.

Acknowledgement

EIC Beam-beam task force (April-Sept. 2020):

Members: S. Berg(BNL),), X. Gu (BNL), Y. Luo(BNL), J. Qiang (LBNL), Y. Hao (MSU), D. Xu(MSU), E. Nissen (JLAB)

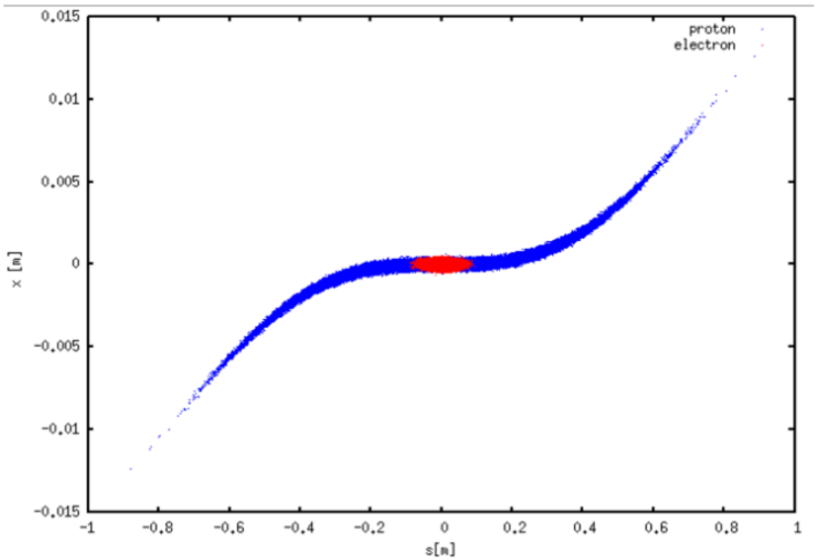
Helpers and consultants: M. Blaskiewicz, W. Fischer, H. Lovelace III, C. Montag, B. Palmer, S. Peggs, V. Ptitsyn

And many more others.

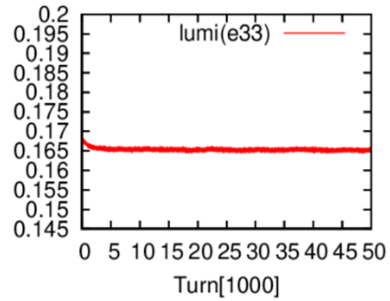
Backup slides: e-Au 10GeV*100GeV Collison

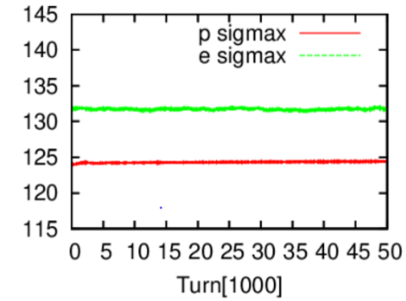
Table 3.6: EIC beam parameters for e-Au operation for different center-of-mass energies $\sqrt{s}$, with stochastic cooling.

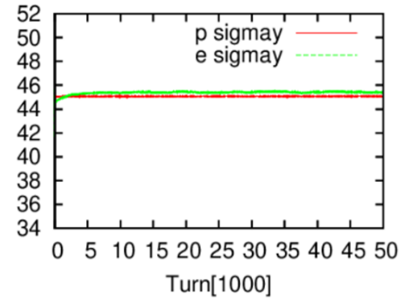
Species	Au ion	electron	Au ion	electron	Au ion	electron	Au ion	electron
Energy [GeV]	110	18	110	10	110	5	41	5
CM energy [GeV]	89.0		66.3		46.9		28.6	
Bunch intensity [10^{10}]	0.10	7.29	0.10	30	0.08	30	0.09	30
No. of bunches	290		580		580		580	
Beam current [A]	0.29	0.26	0.57	2.18	0.44	2.18	0.50	2.18
RMS norm. emit., h/v [μm]	2.0/2.0	845/60	2.0/2.0	391/102	2.0/2.0	196/63	2.0/2.0	196/113
RMS emittance, h/v [nm]	16.9/16.9	24.0/1.7	16.9/16.9	20.0/5.2	16.9/16.9	20.0/6.4	45.4/45.4	20.0/11.5
β^*, h/v [cm]]	288/12	203/116	91/12	77/39	146/12	113/31	149/50	339/196
IP RMS beam size, h/v [μm]	221/45		124/45		157/45		261/150	
K_x	0.202		0.363		0.284		0.577	
RMS $\Delta\theta$, h/v [μrad]	77/380	109/38	136/376	161/116	108/380	127/144	174/302	77/77
BB parameter, h/v [10^{-3}]	3/1	35/100	11/4	66/93	11/3	100/96	9/5	100/100
RMS long. emittance [10^{-3}, eV·sec]	64		64		64		64	
RMS bunch length [cm]	15	0.9	18	2	18	2	18	2
RMS $\Delta p/p$ [10^{-4}]	10	10.9	10	5.8	10	6.8	13	6.8
Max. space charge	0.001	neglig.	0.001	neglig.	0.001	neglig.	0.007	neglig.
Piwinski angle [rad]	8.5	0.5	18.1	2.0	14.3	1.6	8.6	1.0
Long. IBS time [h]	2.65		2.65		3.39		2.02	
Transv. IBS time [h]	1.02		0.80		1.32		0.93	
Hourglass factor H	0.54		0.54		0.54		0.65	
Luminosity [10^{33}cm^{-2}sec^{-1}]	0.14		2.06		1.27		0.31	



Au’s RMS bunch length: 18 cm !

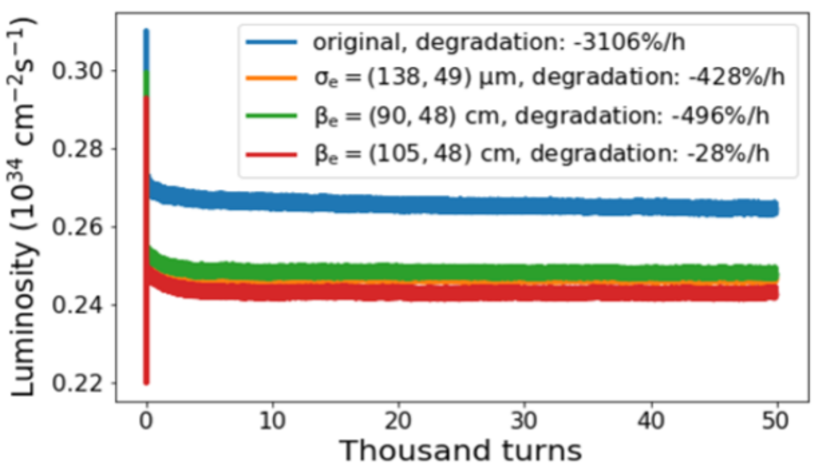






Job18:
E beam beta*s: 105/48cm

Luminosity: 2.46e33 > design luminosity 2.06e33 !



- We checked and verified the design parameters for 10GeV * 100GeV e-Au collision. To match the beam sizes at IP to improve the Au ion horizontal growth rate, we increased electron beam beta*xy = (77, 39)cm to (105, 48)cm.
- We did systematic beam-beam studies with these adjusted design parameters: intensity scans, tune scans, bunch length ‘scan’, second harmonic crab cavities, code benchmarking, and so on.
- The design parameters for 10GeV * 100GeV e-Au collision is achievable and is less challenging than the design parameters for 10*GeV*275GeV e-p collision.