Overview of Beam-Beam Simulation Studies for the Electron-Ion Collider

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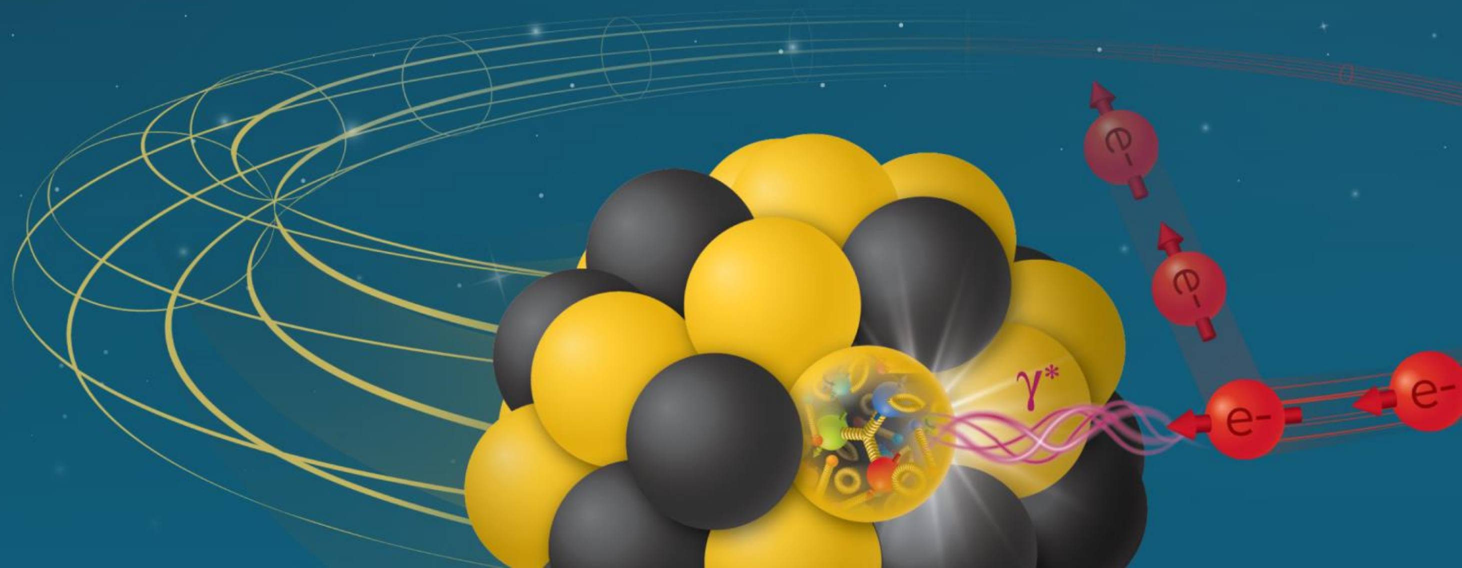
Electron-Ion Collider



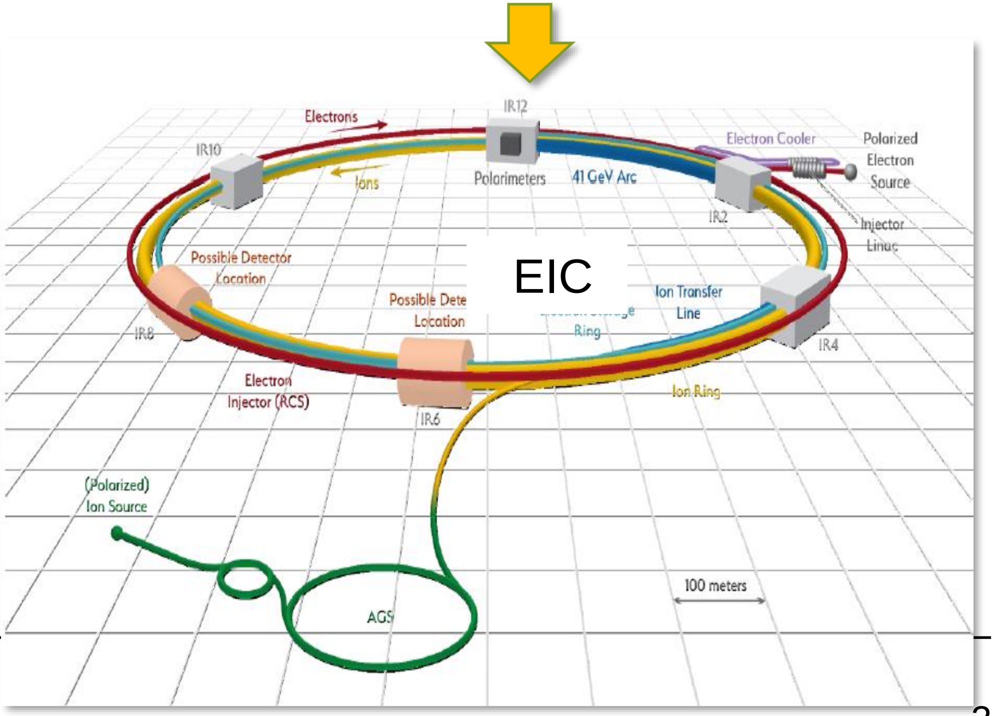
Outline

- Introduction to EIC Beam-Beam Interaction
- Scope of EIC BB Simulation Studies
- Design Parameter Optimization
- Optics and Magnetic Imperfections
- Machine Noises
- Additional Studies
- Summary

EIC Design Parameters

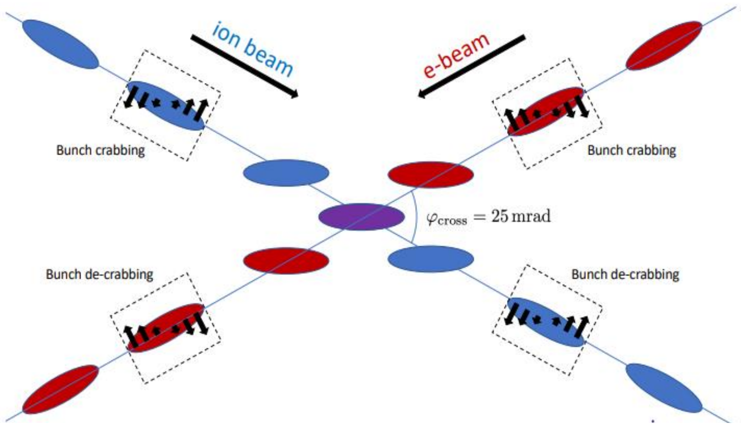
The highest luminosity mode

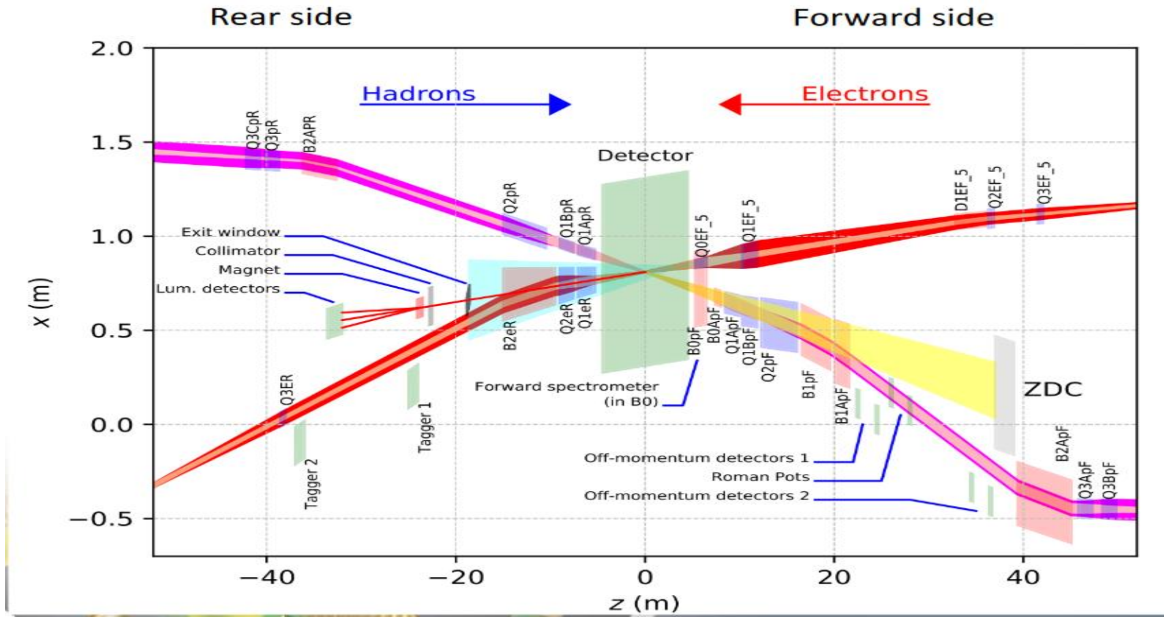
Parameter	proton	electron
Ring circumference [m]	3833.8451	
Particle energy [GeV]	275	10
Lorentz energy factor γ	293.1	19569.5
Bunch population [10^{11}]	0.688	1.72
RMS emittance (H,V) [nm]	(11.3, 1.0)	(20.0, 1.3)
β^* at IP (H, V) [cm]	(80, 7.2)	(45, 5.6)
RMS bunch size σ^* at IP (H, V) [μm]	(95, 8.5)	
RMS bunch length σ_l at IP [cm]	6	0.7
Beam-beam parameters (H, V)	(0.012, 0.012)	(0.072, 0.1)
RMS energy spread [10^{-4}]	6.8	5.8
Transverse tunes (H,V)	(29.228, 30.210)	(51.08, 48.14)
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	



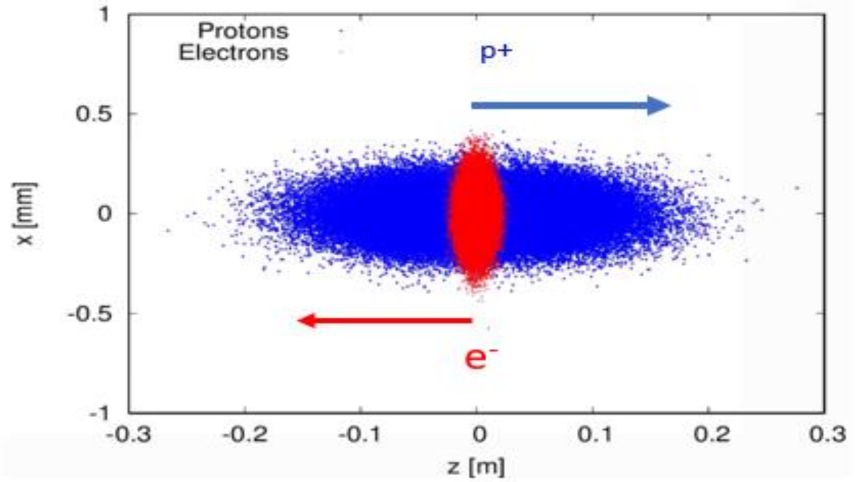
Large Crossing Angle Collision with Crab Cavities

- **Full crossing angle 25mrad**. Crab cavities are needed in both rings to compensate geometric luminosity loss. Local closed crabbing scheme is adopted.
- **List of crab cavities**: four 197 MHz and two 394 MHz crab cavities on each side of IR6 in the HSR, and two 394MHz crab cavities on each side of IR6 in the ERS.





In head-on coordinate frame



Challenges in EIC BB Interaction

- **High beam-beam parameters**
  Proton BB parameter ~ 0.015, Electron BB parameter ~ 0.1
  combination not demonstrated in early electron-proton collider
- **Large crossing angle**
  full crossing angle is 25 mrad in IR6
- **Crab cavities used in both rings**
  crab cavities had been used in KEK-B, not used in hadron collider yet
  crab dispersion leakage, interference between detector solenoid and crab cavities
  crab cavity multipoles, voltage and phase noises of crab cavities
- **Flat beam at IP and large transverse emittance ratio**
  need very strict coupling control, vulnerable vertical emittance growth with BB
- **Other concerns**
  near-integer electron tunes ➔ pinch effect ➔ larger proton BB parameter
  synchro-betatron resonances with large crossing angle and large synchrotron tunes

Scope of EIC Beam-Beam Simulation Studies

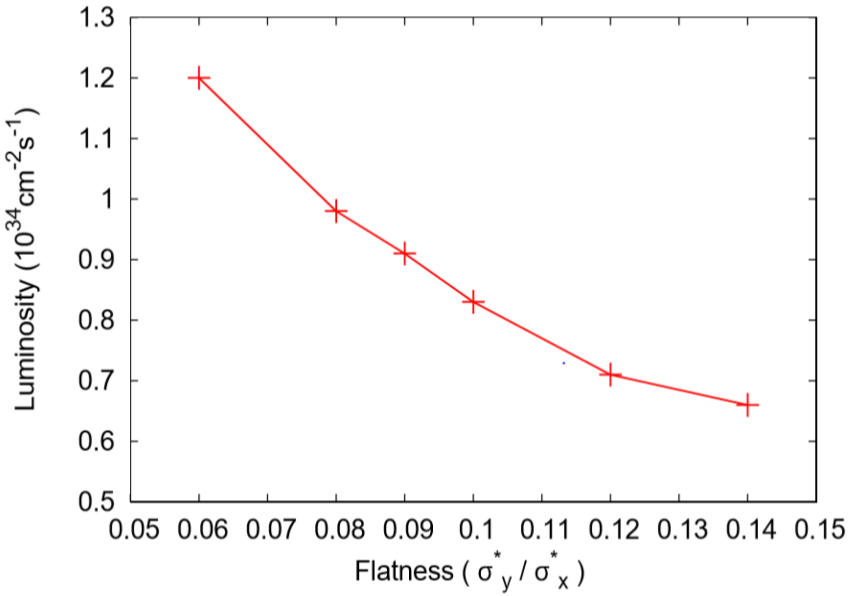
- Beam-Beam Design Parameter Optimization
- Optics and Magnetic Field Imperfections
- Effects of Machine Noises

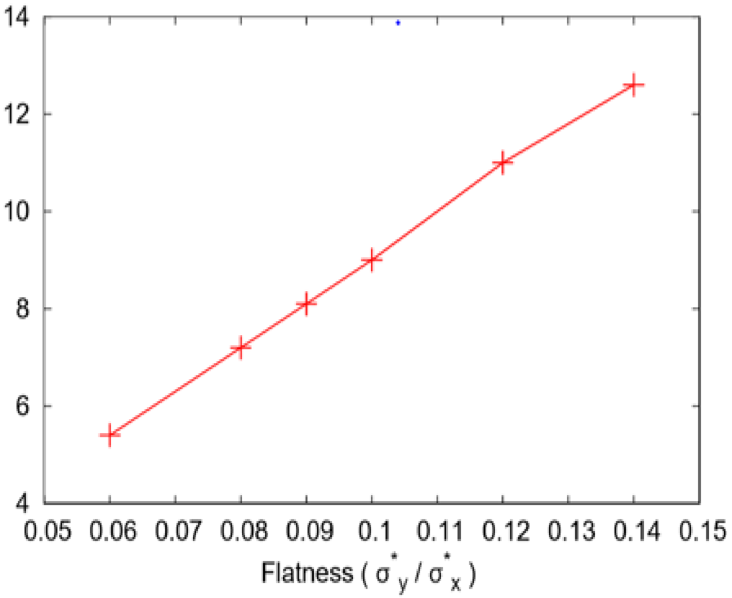
  (*Please check D. Xu's talk on Wednesday*)
- Interplay between Beam-Beam and Other Fields
- Simulation Code Development and Numerical Noise Studies

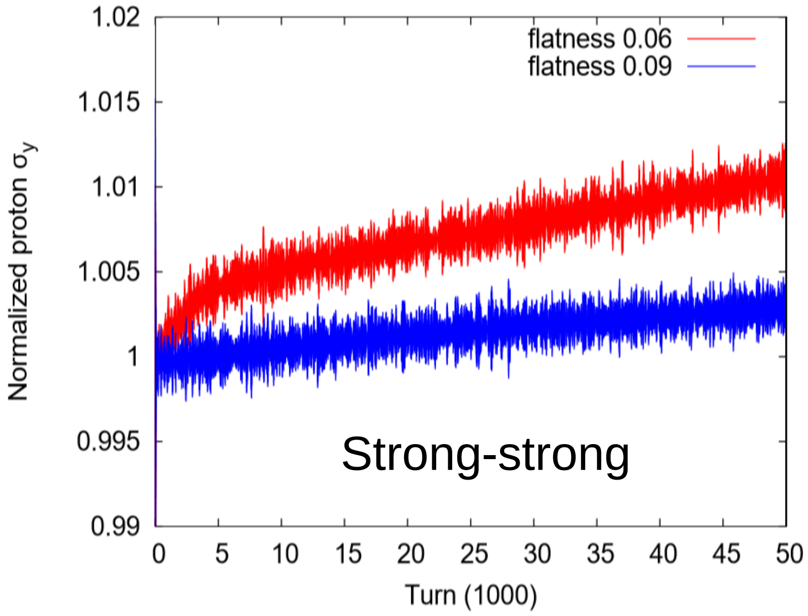
  (*Please check D. Xu's on Tuesday and Y. Luo's talk on Wednesday*)
- Commissioning Strategies and Solutions

Design Parameter Optimization – Flatness at IP

- Flatness is defined as σ^*_y / σ^*_x at IP. Flatter beams at IP deliver a higher luminosity but require a lower β_y^* in lattices. Flatter beams at IP will cause higher proton emittance growth rates and a smaller dynamic aperture.





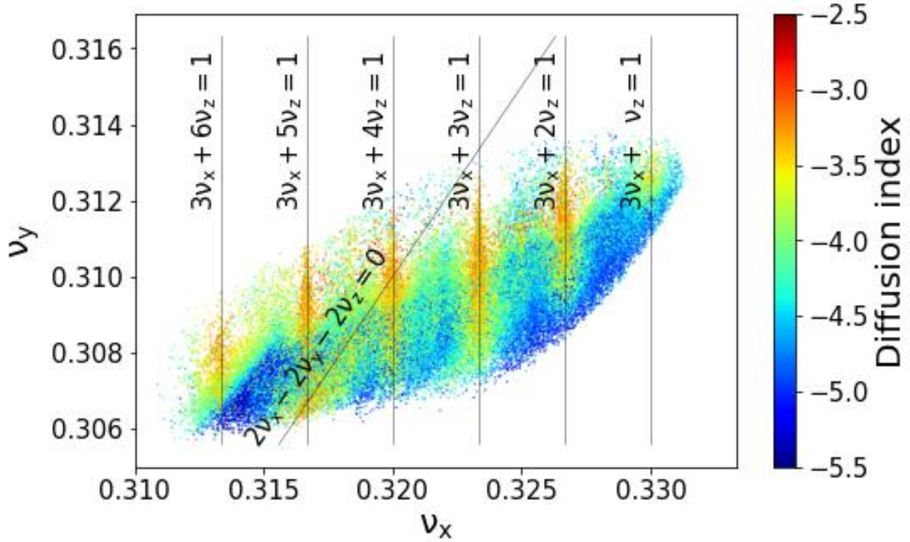


- Flatness 0.09 (that is, σ^*_y/σ^*_x ~ 1:11) was chosen for the EIC e-p collision to achieve the maximum design peak luminosity and to maintain a relatively low proton emittance growth rate.

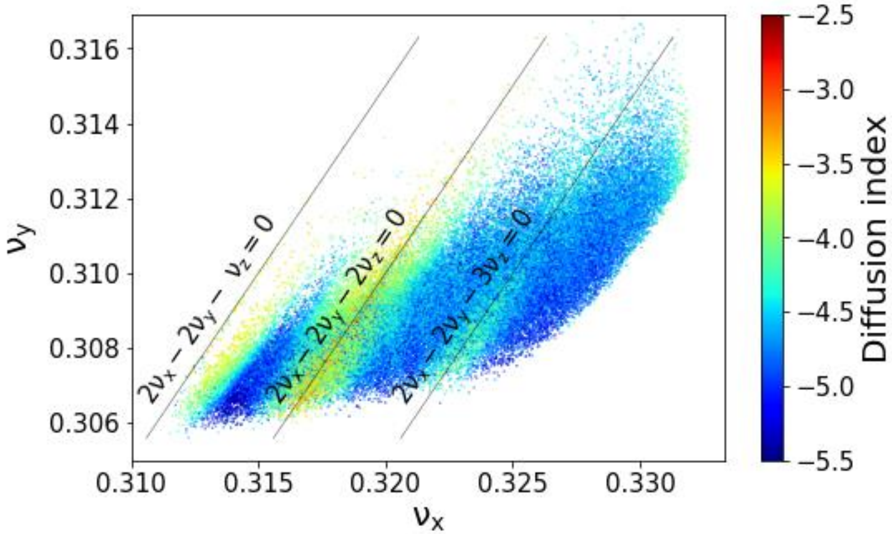
Synchro-Betatron Resonances in HSR

Frequency map analysis (FMA) with working point (0.310, 0.305)

Crossing angle collision



Head-on collision

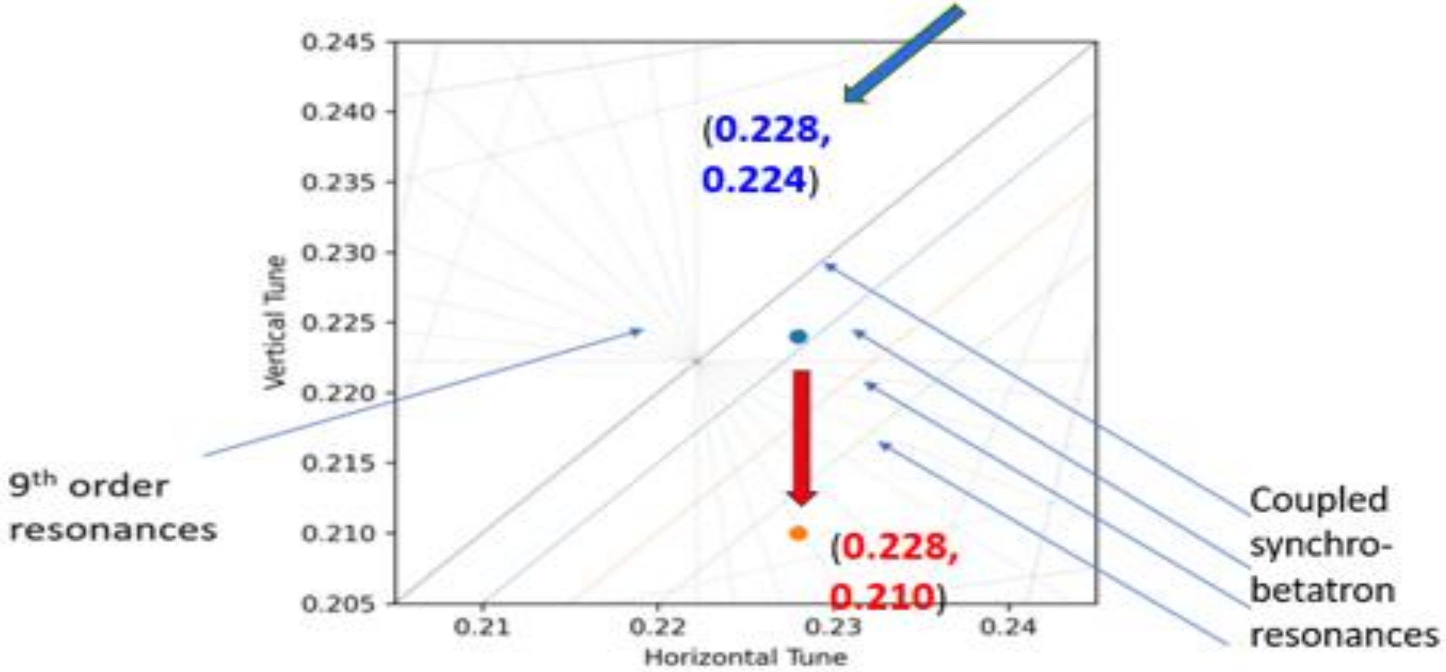


- Synchro-betatron resonances have been observed in many EIC BB simulation studies.
- Two kinds of synchro-betatron resonances identified in FMA:

  m*Qx+ p*Qs and 2*Qx-2*Qy +p*Qs

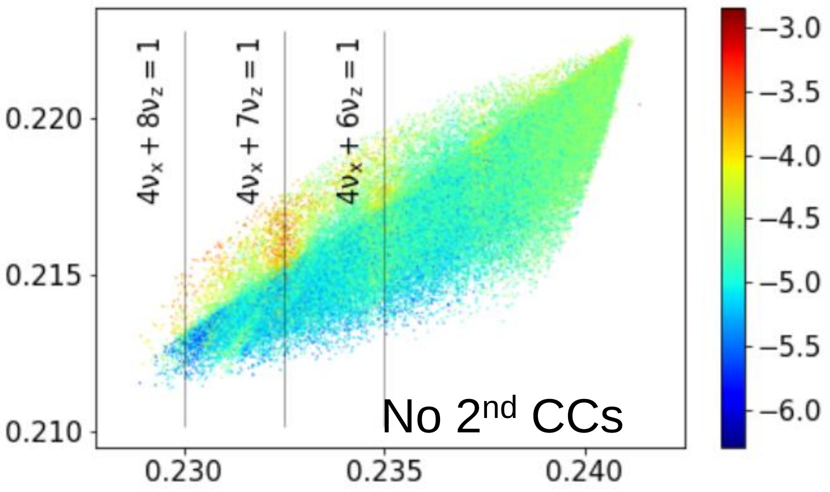
- Mitigation measures: 1) working point optimization, 2) second harmonic crab cavities.

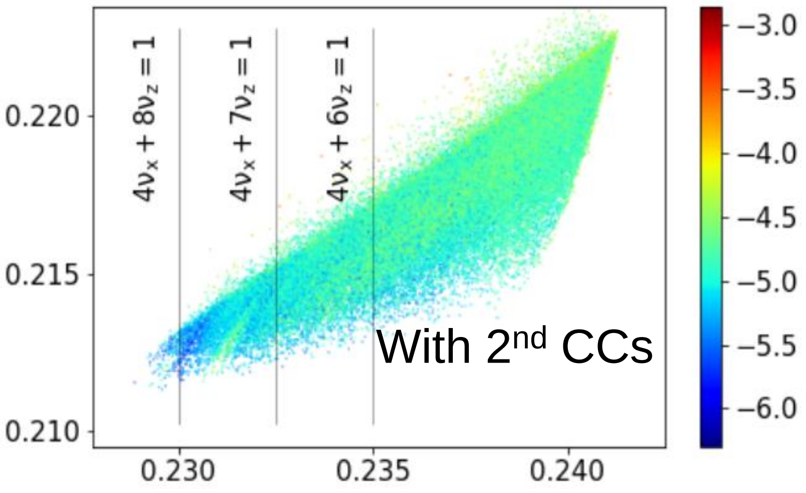
Proton Working Point Optimization



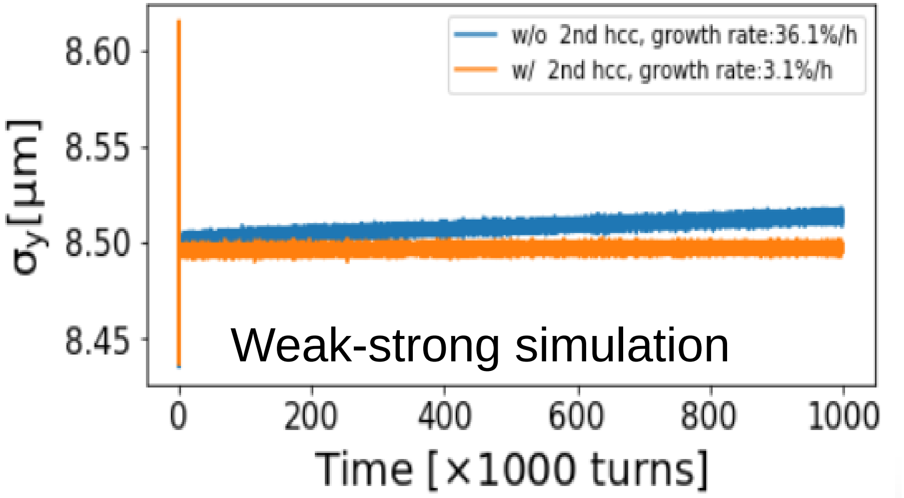
- Moving original (0.310, 0.305) down to (0.228, 0.224): 1st kind of resonances are changed from 3*Qx + p*Qs to 4*Qx + p*Qs.
- Increasing tune split from (0.228, 0.224) to (0.228, 0.210): 2nd kind of resonances 2*Qx −2*Qy + p*Qs are excited with a higher order p.

Second Harmonic Crab Cavities in HSR



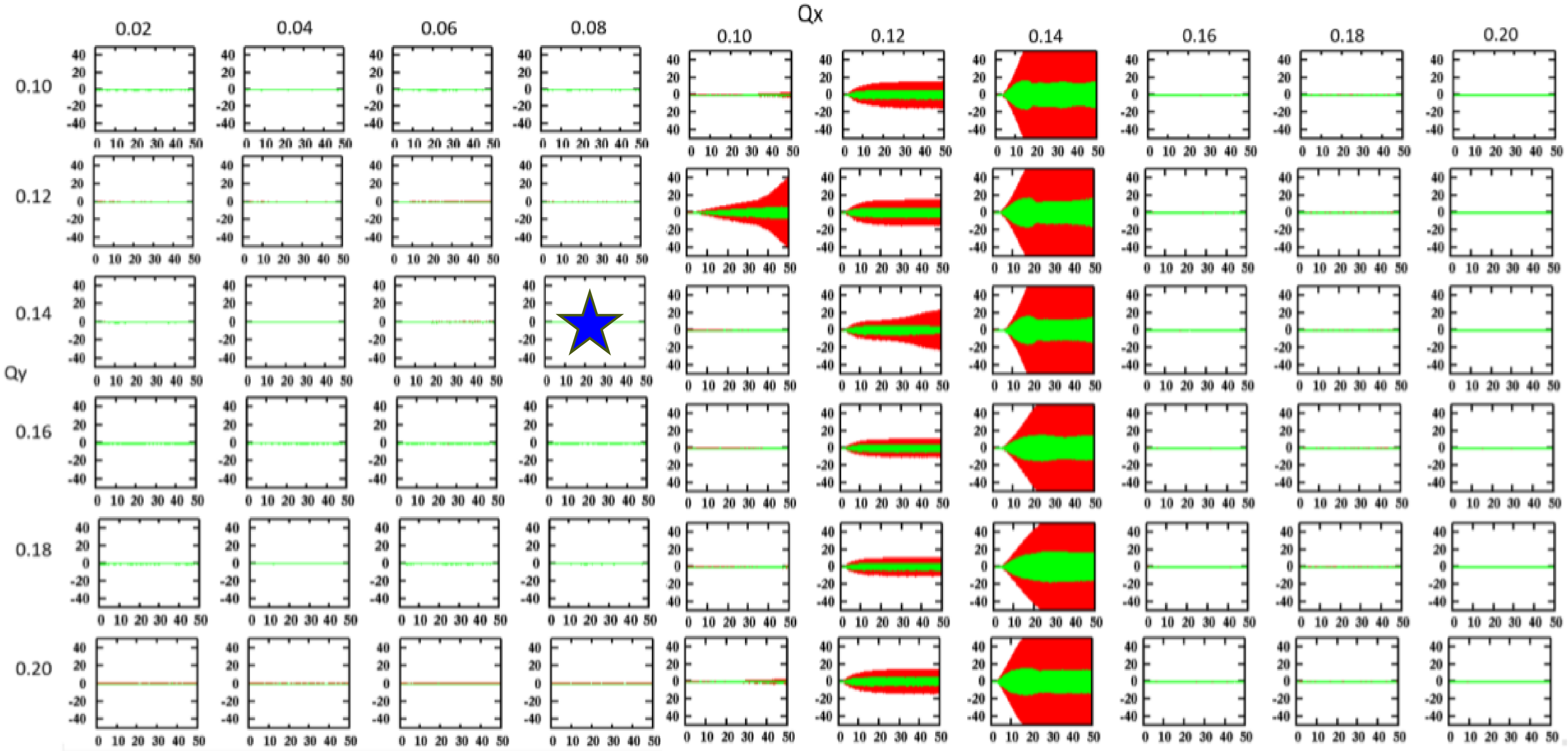


- BB simulations show that second harmonic crab cavities improve proton vertical emittance growth and dynamic aperture.
- Second harmonic crab cavities are included in the baseline HSR design.



No Coherent BB Instability for Design Parameters

- Coherent BB instability was only observed during electron tune scan when electron beam's horizontal tune is between 0.1 and 0.14, which is caused by coupling resonance m*Qx,p + n*Qx,e .
- ESR design tunes are (0.08, 0.14), the blue star shown in the plot.



<Xp> and <Xe> in electron tune scan

Optics and Magnetic Imperfections

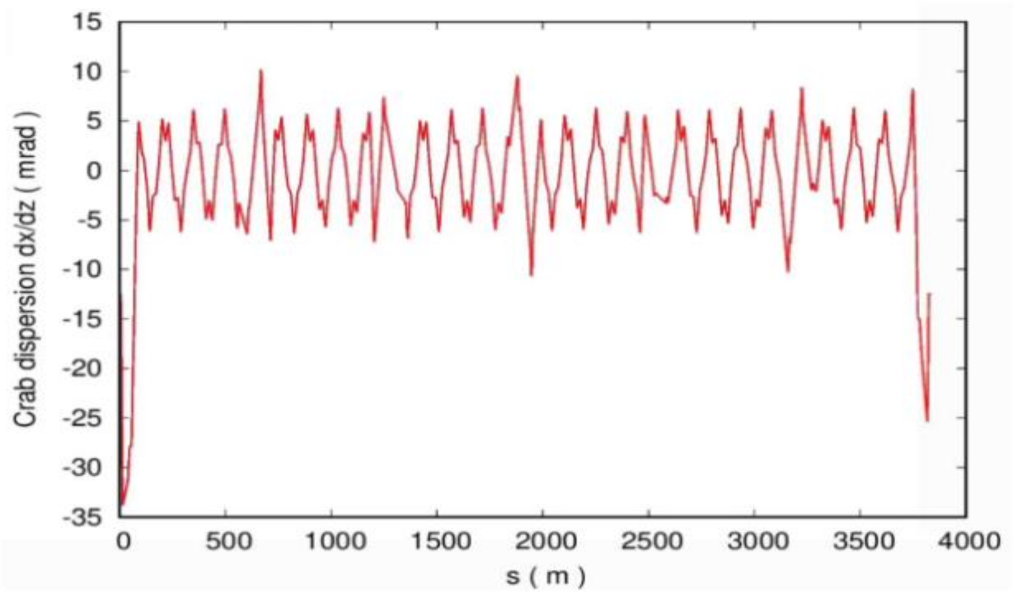
To achieve the peak design luminosity and sufficient beam-beam lifetime, we need to have a very good control of optics and machine imperfections and keep them below tolerances.

- **Optics Imperfections**: Twiss parameters at IP and crab cavities, phase advances between IP and crab cavities, crabbing bump closure, detector solenoid effect, vertical crab dispersion at IP, crab dispersion leakage, etc.
- **Machine Imperfections**: misalignment and roll errors of magnets, magnetic nonlinear field errors, multipoles in crab cavities, nonlinear fields in arc dipoles (important for radially shifted design orbits), etc.
- **Noises**: phase and voltage noises of crab cavities, power supply current ripples, 10Hz orbit oscillations due to cryo-flows (observed in RHIC), RF phase noises, etc.

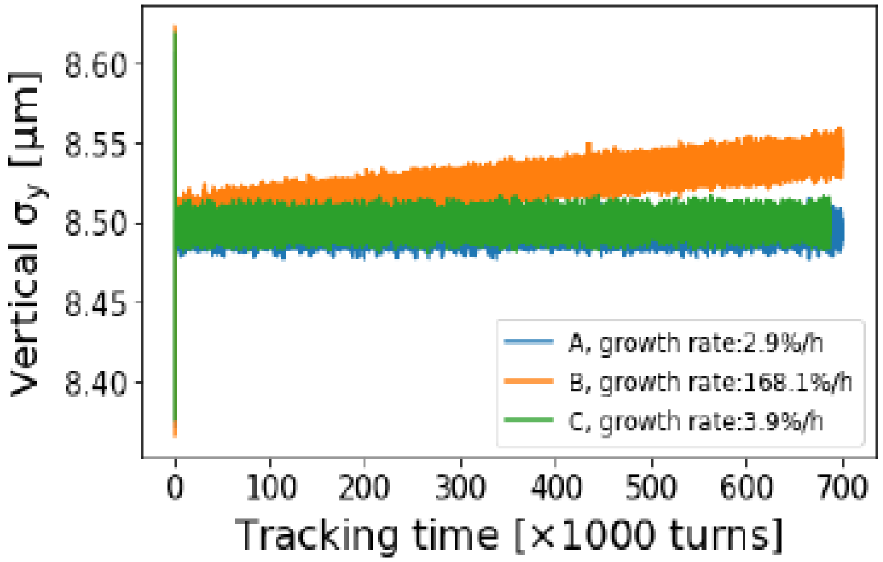
Crabbing Bump Closure in HSR

- Phase advance between crab cavities: 175 degrees, 5 degrees off 180 degrees.
- The beam-beam performance can be restored by adjusting crab cavity voltages.
- Dynamic aperture studies show no significant difference between unclosed and artificially closed crabbing bumps. Mostly likely, the HSR will live with the crabbing leakage.

Crab dispersion leakage in HSR

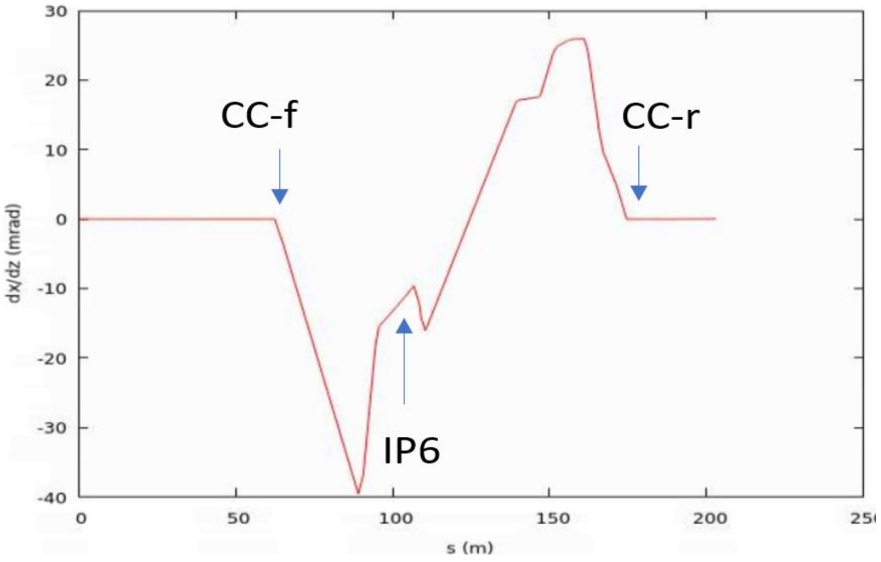


A: reference, B: w/o voltage adjustment, C: w/ voltage adjustment

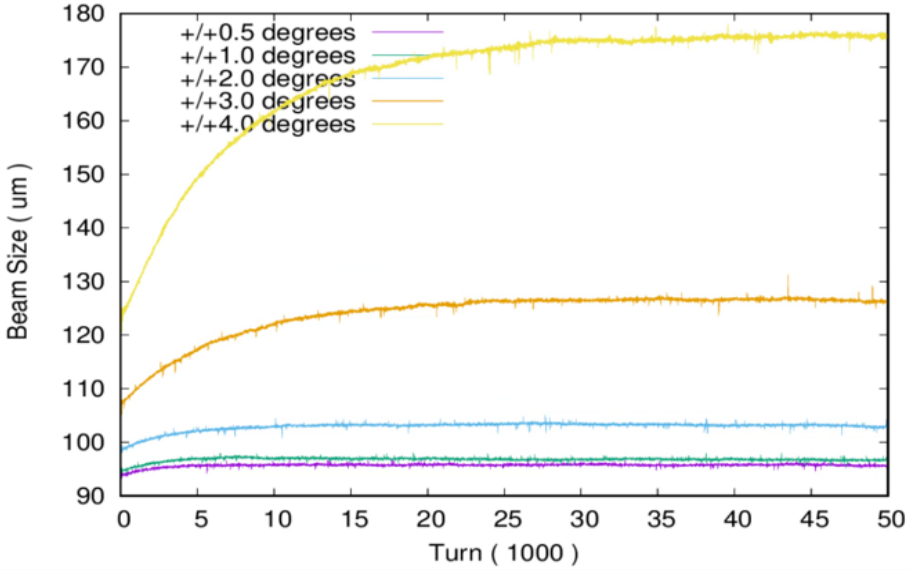


Crabbing Bump Closure in ESR

- The crabbing bump is closed in ESR with current lattice design: 360 degrees between crab cavities on both sides of IR6.
- A very tight tolerance for the crabbing bump closure: 1-2 degrees off the closure condition. The reason is that the horizontal tune 0.08 and synchrotron tune 0.069 are very close.



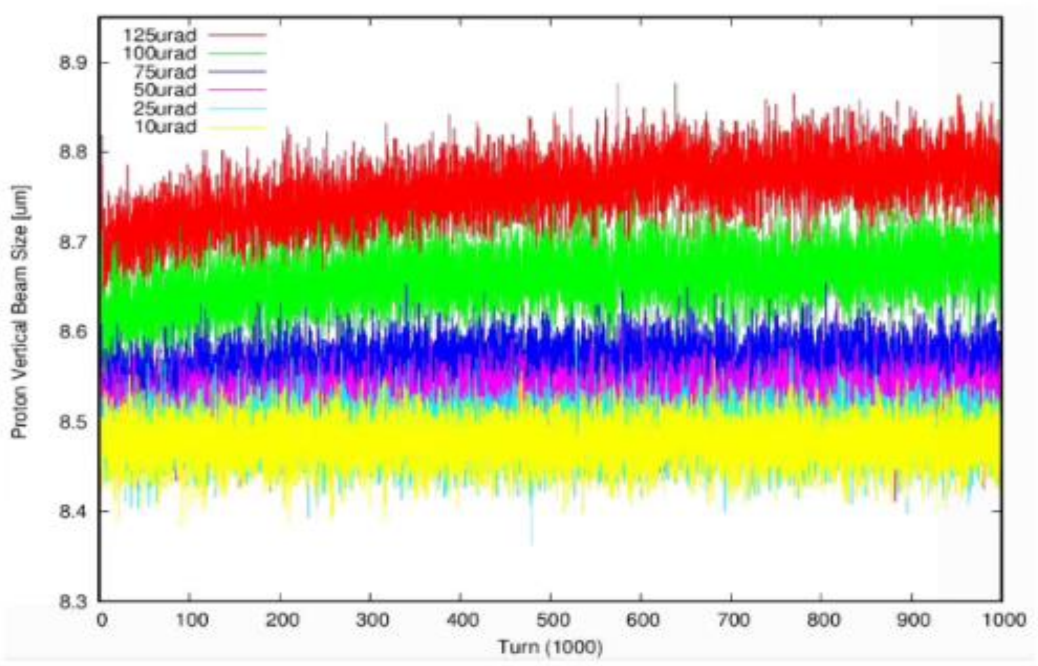
Crab dispersion bump in ESR



Tolerance study of crabbing bump closure

Vertical Crab Dispersion at IP in HSR

- Vertical crabbing can be introduced by horizontal crabbing and betatron coupling in the IR.
- Weak-strong beam-beam and dynamic aperture simulation studies show that the tolerance of vertical crab dispersion at IP is ~ 20 urad in the HSR, which requires effective correction.
- Vertical crab dispersion will be corrected with local skew quadrupoles in the IR. For the HSR, we will use local and global skew quadrupoles for a hybrid correction scheme.

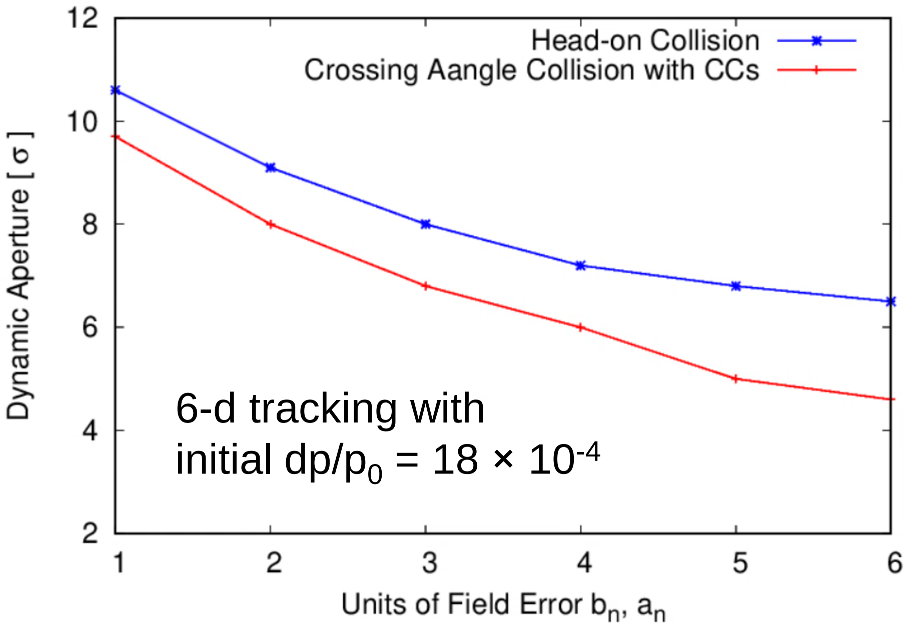


W-S simulation with different vertical crabbing

IR Magnetic Field Errors

- Based on RHIC's experience, IR magnetic field errors play an important role in DA reduction. To have a sufficient beam lifetime, DA with IR field errors and BB should be larger than 5 σ.
- Magnetic field errors:

$$\Delta B_y + \mathrm{i}\Delta B_x = B(R_{\mathrm{ref}}) \left[10^{-4} \sum_{n=0}^{N_{\max}} (b_n + \mathrm{i} a_n) \frac{(x+\mathrm{i}y)^n}{R_{\mathrm{ref}}^n} \right]$$



- Preliminary HSR DA results show that HSR DA is more than 6 σ even with 3 unit of IR field errors, which is sufficient for beam lifetime.

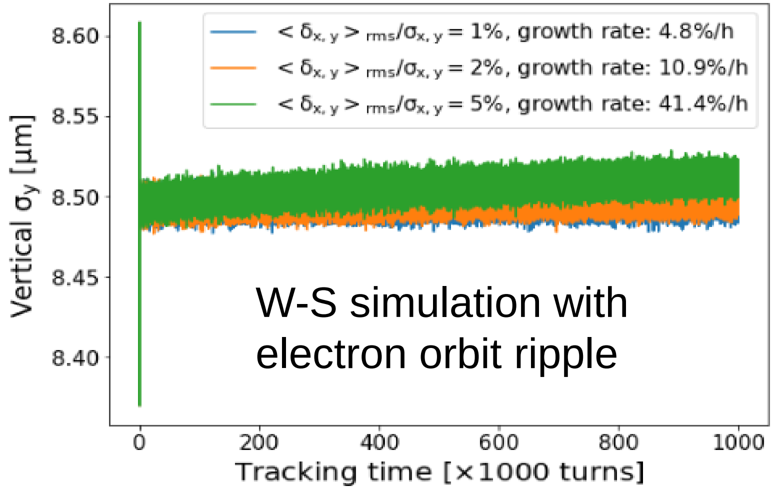
- Recently we are working on field error tolerances for individual HSR IR magnets, especially for these large aperture magnets (e.g. , B0PF). We are in a close collaboration with the EIC magnet design team.

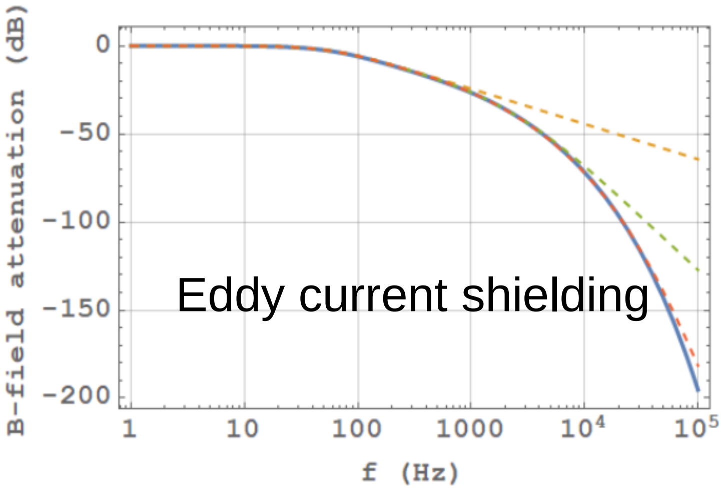
Machine Noises: Power Supply Current Ripples

- W-S BB simulation for highest luminosity collision mode: with proton beam size growth less than 10%/h, orbit oscillation at IP should be less than 5% $\sigma_{x,y}$ for low frequency band (<8kHz), and less than 10^{-4} $\sigma_{x,y}$ for high frequency band.

- The tolerance of dipole power supply current ripple at low frequency band is ~ 1 ppm. The high-frequency ripple is less worrisome due to very significant eddy current shielding.

- Solutions under investigation: grouping all dipoles on a same power supply, AC-couple all dipole PS, increase induction of ESR dipole PS, etc.



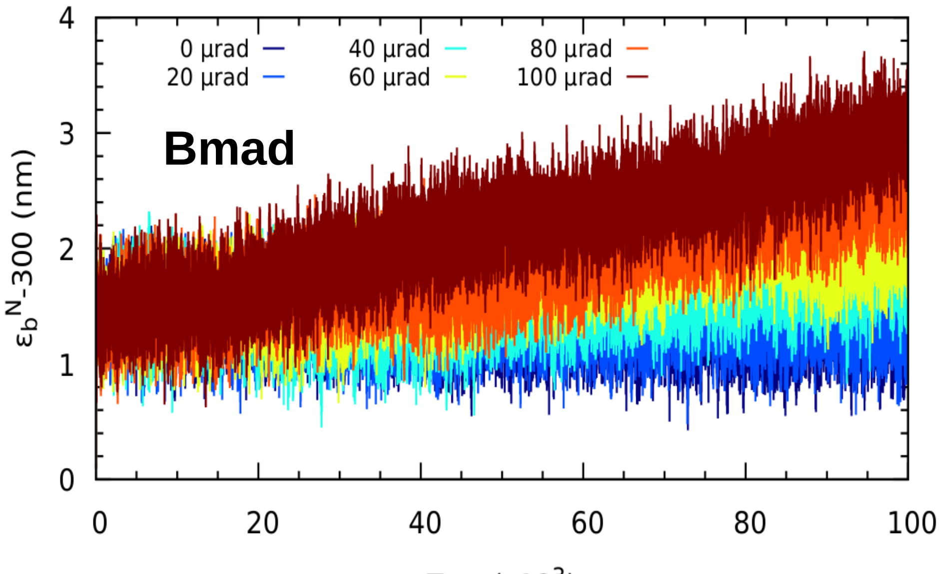


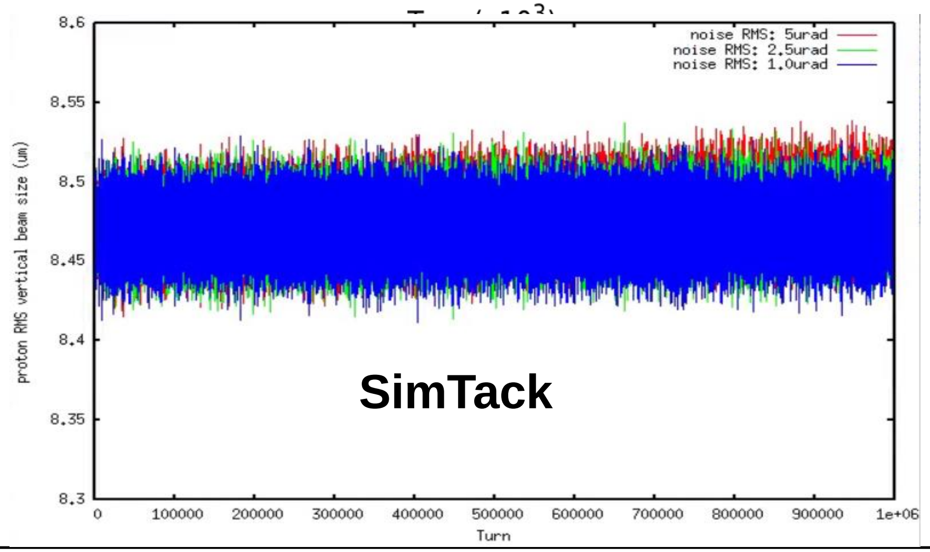
Tolerances for Crab Cavity Phase Noises

- Numerical simulations confirmed horizontal growth rates predicted by analytical calculation.
- Vertical emittance growth is observed when beam-beam interaction is included.

- To have proton beam size growth rate less than 10%/hour in both planes, **RMS of pink phase noises should be no more than 1 μrad**, which is beyond state-of-the-art.

- Countermeasures are under investigation: LLRF phase feedback, beam damper, high precision pickup, etc.





Additional Studies

- Luminosity sharing in two IRs, Y. Luo et al., IPAC2018, MOPMF011
- Electron bunch replacement with BB, J. Qiang et al., IPAC2021, WEPAB252
- Evaluation of tilted ESR on BB performance, D. Xu et al., IPAC2022, WEPOPT049
- Numerical noises in strong-strong beam-beam simulation, Y. Luo, et al, IPAC2022, WEPOPT038. D. Xu, et al, NAPAC2022, MOYD4.
- Interplay between beam-beam and impedances, J. Qiang, M, Blaskiewicz
- Interplay between beam-beam and polarization (*Please check M. Signorelli's talk on Thursday*)
- Scenarios and strategies / solutions for future EIC operation

And many more.

Summary

- In the past few years, we had addressed many beam-beam related issues for the EIC, including design parameter optimization, optics and machine imperfections, impacts of power supply current ripples and crab cavity phase noises, HSR dynamic aperture calculation and improvement, tolerances of magnetic field errors, and so on.

- There are still some topics we are currently working on, such as, numerical noises in beam-beam simulation, mechanisms for emittance growth with noises, online imperfection compensations, interplays between beam-beam and other fields, future EIC commissioning schemes and solutions, and so on.

- We warmly welcome inter-lab collaborations on EIC beam-beam studies.

  (*Please check C. Montag's talk Monday afternoon*)

Acknowledgements

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