# EIC Beam-Beam Simulations and Collision Scenarios

**Derong Xu**


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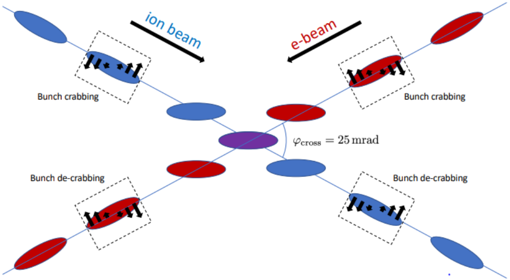
Electron-Ion Collider

# Luminosity and beam-beam interaction

- **Luminosity** characterizes the ability of a collider to produce events for a given physical process: $\mathrm{d}N/\mathrm{d}t = \mathcal{L} \cdot \sigma_p$. Achieving high luminosity is a central goal of collider design across the **energy**, **precision**, and **QCD** frontiers.
- **Beam-beam interaction** refers to the electromagnetic force exerted by one beam on the other during collisions.
  - Dynamic, highly non-linear, 6-Dimensional
  - In circular colliders, the **beam-beam parameter**, which characterizes the maximum tune shift induced by collisions, quantifies the strength of beam-beam interaction.
  - In lepton colliders, beam-beam limit is a well-defined empirical threshold for the beam-beam parameter, typically: $\xi \lessapprox 0.10 - 0.15$
  - In hadron machines, due to the lack of effective cooling, the achieved beam-beam parameter is much smaller than in lepton colliders. Beam quality can degrade over time due to the beam-beam interaction.
- The EIC enters an unprecedented regime with large beam-beam parameters for both electron and hadron beams — beyond existing operational experience.

# Crab crossing

- A large crossing angle is essential to avoid parasitic collisions, reduce background, and accommodate the detector and IR magnets.
- The geometric luminosity loss can be restored by crab cavities.
- Crab crossing of electron and positron beams at KEKB enabled record luminosities in lepton colliders.
- Crabbing of proton bunches has been demonstrated at CERN's SPS.




Crab crossing has become a key feature in modern collider designs, including HL-LHC, EIC, and EicC.

# Flat hadron beam

The **flat hadron beam** — vertical emittance ten times smaller than horizontal emittance — is a unique feature of the EIC. Demonstrated at RHIC @Phys. Rev. Lett. 132, 205001

- **Emittance** quantifies the beam distribution in phase space. Emittance plays a role analogous to temperature:

$$\rho(x, p_x) \propto \exp\left(-\frac{\gamma x^2 + 2\alpha x p_x + \beta p_x^2}{2\epsilon_{x,\mathrm{rms}}}\right), \qquad p_i \propto \exp\left(-\frac{E_i}{k_\mathrm{B} T}\right)$$

- In electron storage ring, the emittance is determined by machine design. The electron beam is naturally flat.
- In hadron storage ring, without an external cooling mechanism, the beam emittance is determined by the particle sources and is typically round.
- Defining flatness as the aspect ratio at the IP, $\kappa \equiv \sigma_y^*/\sigma_x^*$, the luminosity and beam-beam parameters scale as $\mathcal{L} \propto \frac{1}{\kappa}$, $\xi_x \propto \frac{\beta_x^*}{1+\kappa}$, $\xi_y \propto \frac{\beta_y^*}{\kappa(1+\kappa)}$. By scaling $\beta_{x,y}^*$, one can increase luminosity while keeping the beam-beam parameters constant.

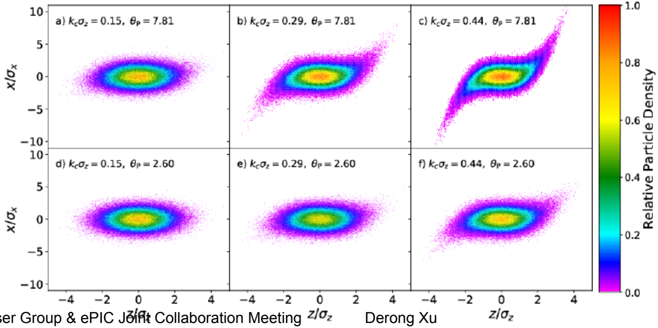
# Finite bunch length effect @Phys. Rev. Accel. Beams 24, 041002

Sinusoidal kick from the crab cavity $\Delta p_x = -\frac{\theta_c}{k_c\Lambda}\sin(k_c z)$, $\Delta p_z = -\frac{x\theta_c}{\Lambda}\cos(k_c z)$

Crabbed offset at IP

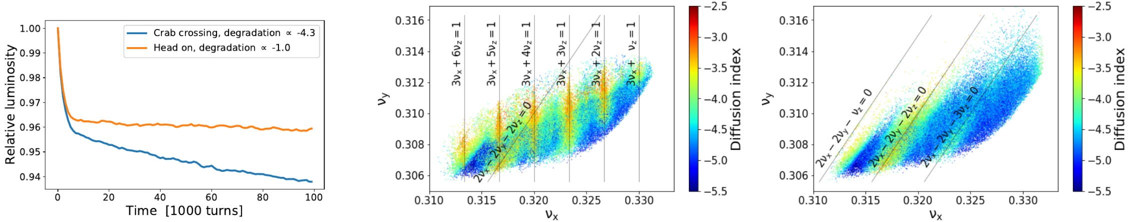
$$\Delta x = -\theta_c\left[\frac{\sin(k_c z)}{k_c} - z\right] \approx \frac{1}{6}\theta_c k_c^2 z^3$$

$x - z$ motion is coupled when $|k_c z| \sim 1$, applicable for EIC hadron beam



# Finite bunch length effect @Phys. Rev. Accel. Beams 24, 041002

Left: luminosity, middle: frequency map of crab crossing, right: frequency map of head-on




- The luminosity degradation is much faster in crab crossing than in head-on collision.
- There are 2 kinds of resonances existing in the footprint

$$3\nu_x + p\nu_z = 1, \qquad 2\nu_x - 2\nu_y + p\nu_z = 0$$

  The first kind only exists in crab crossing scheme.
- The second kind in head-on scheme comes from the chromaticity and hourglass effect.

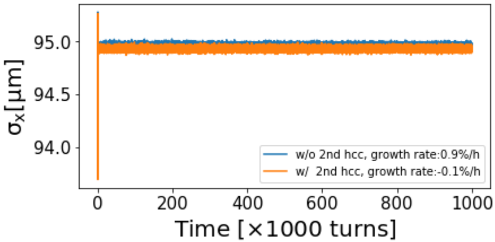
# Finite bunch length effect @Phys. Rev. Accel. Beams 24, 041002

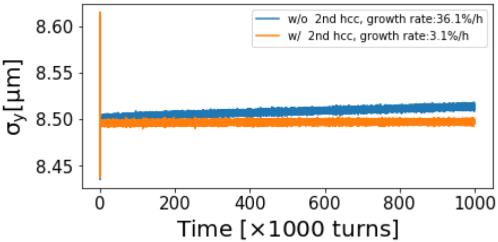
Mitigation methods:

- Moving the proton working point from $(0.310, 0.305)$ to $(0.228, 0.210)$
- Including second order harmonic crab cavity:

$$\Delta x = -\theta_c \left[ \frac{4\sin(k_c z)}{3k_c} - \frac{\sin(2k_c z)}{6k_c} - z \right]$$

Proton beam size evolution in weak-strong simulation



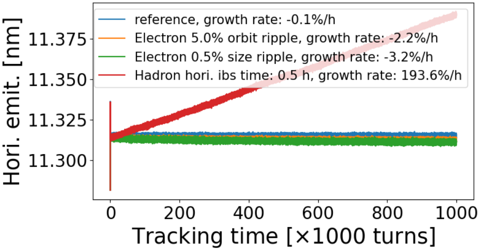



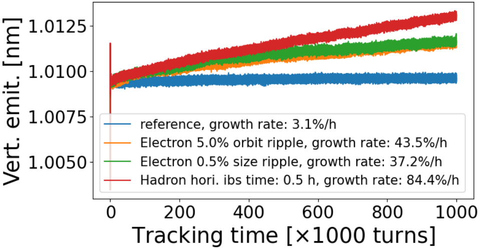
# Converging of EIC baseline design @EIC CDR

| Parameter | proton | electron |
|---|---|---|
| Ring circumference [m] | 3833.8451 | |
| Particle energy [GeV] | 275 | 10 |
| Lorentz energy factor $\gamma$ | 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) |
| $\beta^*$ at IP (H, V) [cm] | (80, 7.2) | (45, 5.6) |
| RMS bunch size $\sigma^*$ at IP (H, V) [μm] | (95, 8.5) | |
| RMS bunch length $\sigma_l$ 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 | |

- The first kind of resonance has been mitigated via parameter optimization.
- However, the second kind of resonance becomes a problem when taking external noise into consideration.

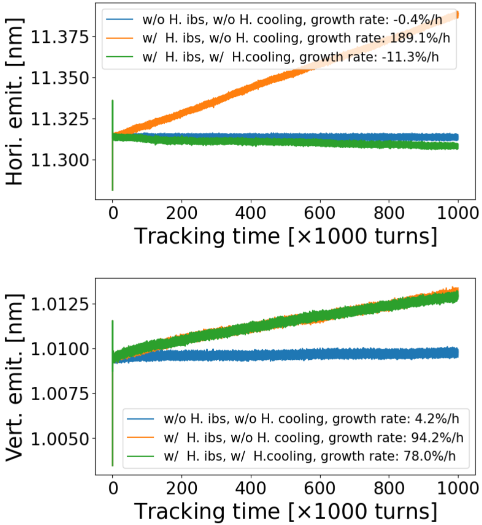
# Emittance transfer @arXiv:2506.21289



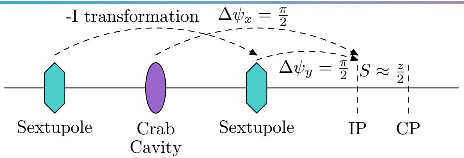

- The vertical emittance growth is always accompanied with horizontal emittance decrease.
- In real-world accelerator operations, physical noise is unavoidable. For simplicity, we examine robustness against three representative types.
- Electron orbit ripple: proton diffusion via beam-beam interaction.
- Electron size ripple: diffusion + tune modulation
- Proton intra-beam scattering (IBS) diffusion: broadband, white noise source covering betatron tunes
- Emittance transfer imposes more stringent requirements on systems such as magnet power supplies, crab cavity phase noise, and RF phase and amplitude stability.

# Emittance transfer @arXiv:2506.21289




- Unequal transverse emittances, synchro-betatron resonance, and physical fluctuations form the essential ingredients for driving emittance transfer.
- Unlike dispersion-based mechanisms that redistribute diffusion or cooling rates, the emittance always flows from hot to cold plane.
  - Orange: Without cooling, both horizontal and vertical emittances grow over time.
  - Green: With horizontal cooling applied, the horizontal emittance is stabilized, but vertical emittance still increases.
- Although cooling is not within the EIC scope any more, the emittance transfer necessitates dedicated and strong vertical cooling.

# Dynamic focusing @arXiv:2506.21289




$$K_2L = \frac{\sqrt{\beta_x^*/\beta_{s,x}}}{4\theta_c \beta_{s,y}\beta_y^* \cos\psi_x}$$

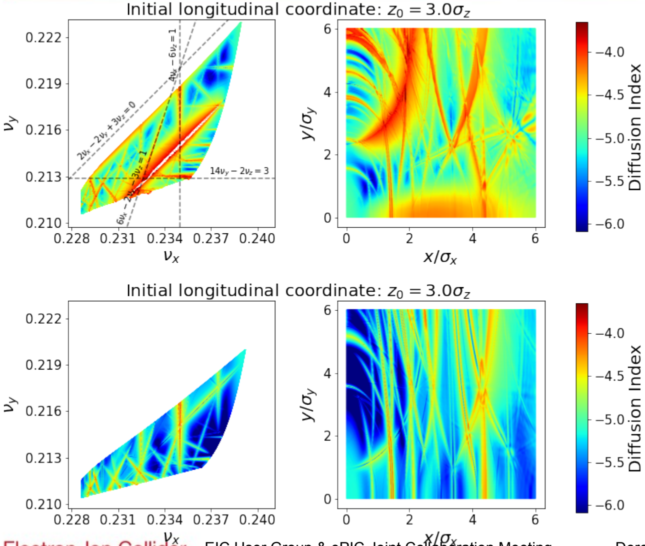
How it works:

- The crab cavity correlates $x$ and $z$ motion: at the downstream of crab cavity, there is an time-dependent offset $\Delta x = \zeta z$
- The feeddown effect of sextupole produces time-dependent focusing:

$$\Delta p_x = -K_2L\left(x^2 - y^2\right) = -2K_2L\zeta xz + \ \dots, \qquad \Delta p_y = 2K_2Lxy = 2K_2L\zeta yz + \ \dots$$

- After $\psi_y = \pi/2$, the time-dependent focusing translates into vertical drift, which exactly compensates the virtual drift from IP to CP
- Another sextupole cancells the geometry term from this sextupole

# Dynamic focusing @arXiv:2506.21289

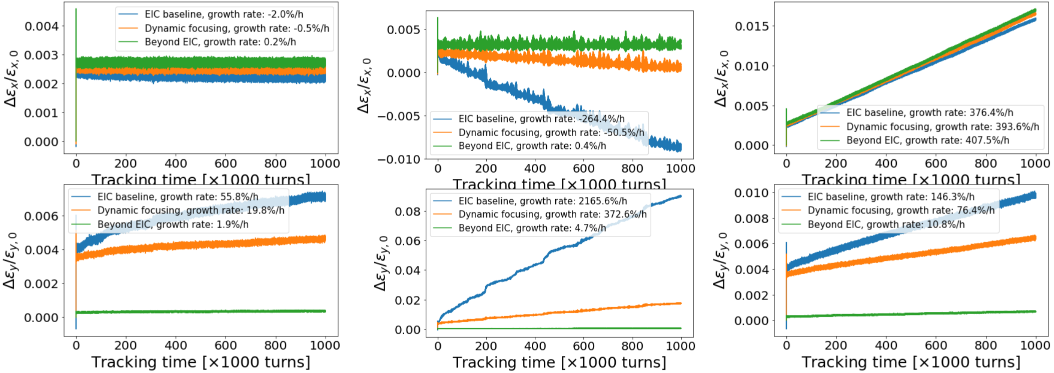



- The synchro-betatron resonance is suppressed.
- Tolerance to physical noise is improved by factors of two to three, accompanied by a slight gain in luminosity.

| Parameter | Unit | EIC Baseline | Dynamic Focusing |
|---|---|---|---|
| $\beta^*_{y,\mathrm{e}}$ | cm | 5.6 | 7.2 |
| Luminosity | $\frac{10^{34}}{\mathrm{cm}^2\mathrm{s}}$ | 0.93 | 0.97 |
| E. orbit ripple | $\sigma^*_{x,y}$ | 2.5% | 5.0% |
| E. size ripple | $\sigma^*_{x,y}$ | 0.3% | 1.0% |
| P. IBS time | hour | 4.5 | 1.5 |

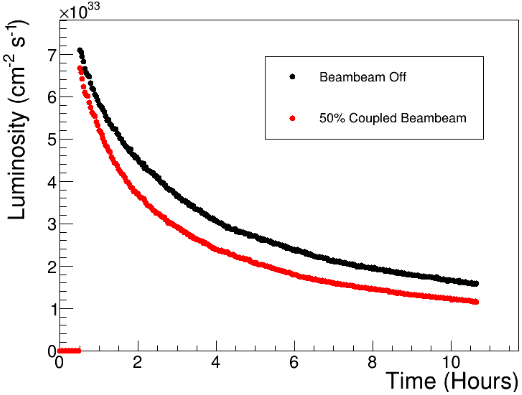
# Beyond EIC @arXiv:2506.21289

- In EIC beam parameter optimization, the detector constrains equal divergence in both planes. It leads to $\epsilon_y/\epsilon_x = \beta_y/\beta_x$
- The dynamic focusing allows us to further reduce proton vertical beta.




Left: E. orbit ripple of $5\%$, middle: E. size ripple of $5\%$, right: P. ibs diffusion of $0.25$ h

# Luminosity model @William Bergan




- Vertical emittance growth originates from resonance-driven emittance transfer.
- Assuming vertical growth is 50% of horizontal growth, the average luminosity is $2.2 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Applying a dynamic focusing scheme suppresses the transfer, raising average luminosity to $2.7 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Poor control of vertical growth can reduce luminosity to $1.5 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Once vertical growth is suppressed, luminosity is limited by horizontal and longitudinal emittance — effective high-energy cooling is required to reach $10^{34}$.

# Summary

- The EIC enters a novel regime with large beam-beam parameters for both beams, flat hadron profiles, and crab crossing — beyond existing collider experience.
- Finite bunch length effects cause significant luminosity degradation. This is mitigated by parameter optimization and the inclusion of a second-harmonic crab cavity.
- Emittance transfer emerges in beam-beam simulations with external noise, driven by resonance streaming around $2\nu_x - 2\nu_y + p\nu_z = 0$.
- A dynamic focusing scheme — combining crab cavities with sextupoles — suppresses synchro-betatron resonances and improves noise tolerance.
- Dynamic focusing shows promise in mitigating emittance transfer. We are exploring IR lattice solutions that implement this scheme without reconfiguring IR6.
- With resonance suppression and noise control, luminosity performance is limited by horizontal and longitudinal IBS diffusion. Achieving $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ will require effective high-energy cooling.

# Thank you!