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Beam-beam dynamics with strong hourglass effect

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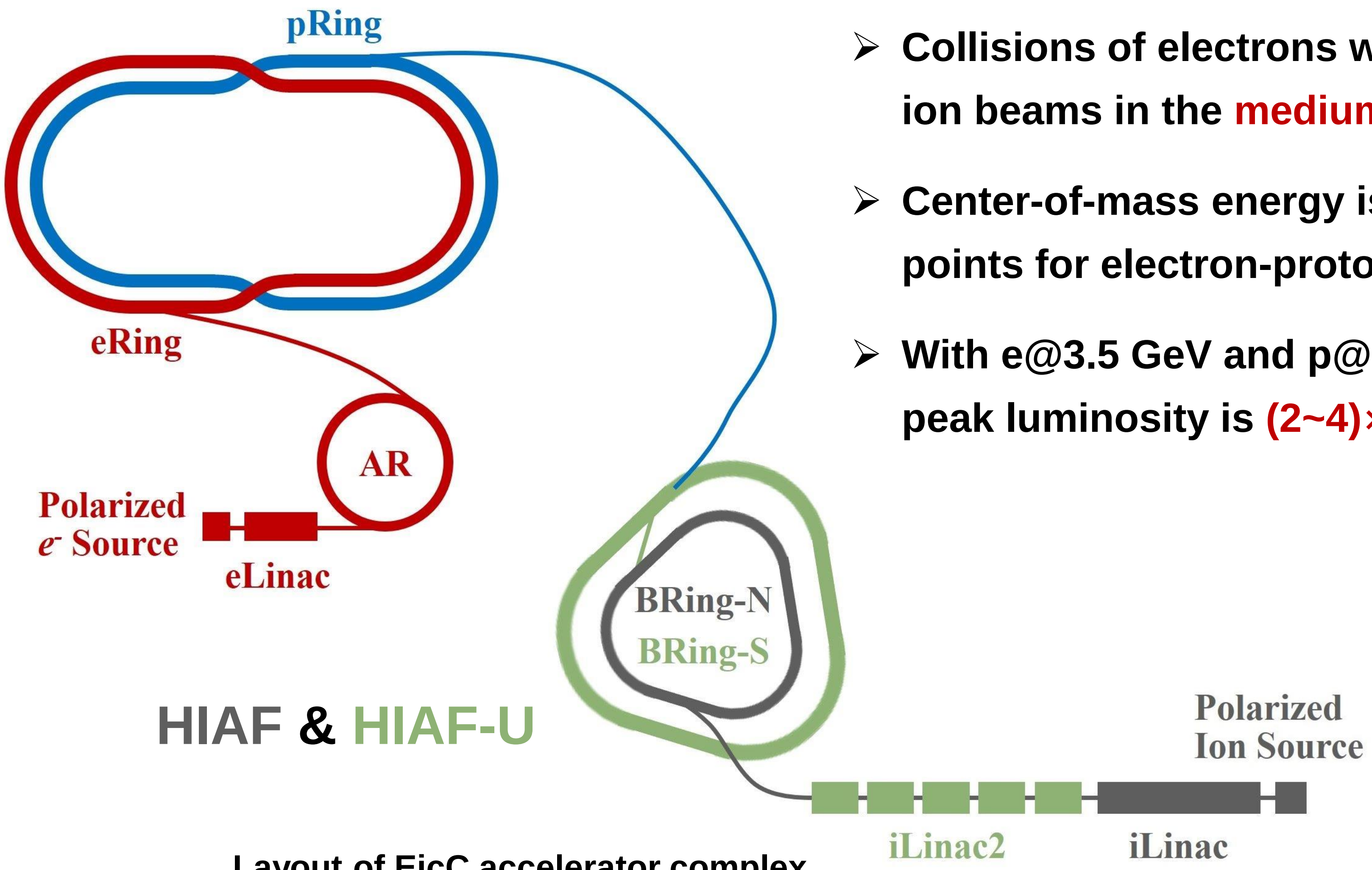
ICFA mini workshop Beam-Beam Effects in Circular Colliders, Sep. 2-5, EPFL, Lausanne

Outline

1. Hourglass effect in EicC
2. Simulation model
3. Head-tail instability of asymmetric colliding beams
    - Numerical observations
    - Key parameter scans and instability mechanism
    - Mitigation methods
4. Float waist collision scheme
    - Compensation principles of the hourglass effect
    - Numerical proofs and application to the head-tail instability
5. Summary

1. Introduction of EicC accelerators

Electron-Ion Collider in China



Layout of EicC accelerator complex

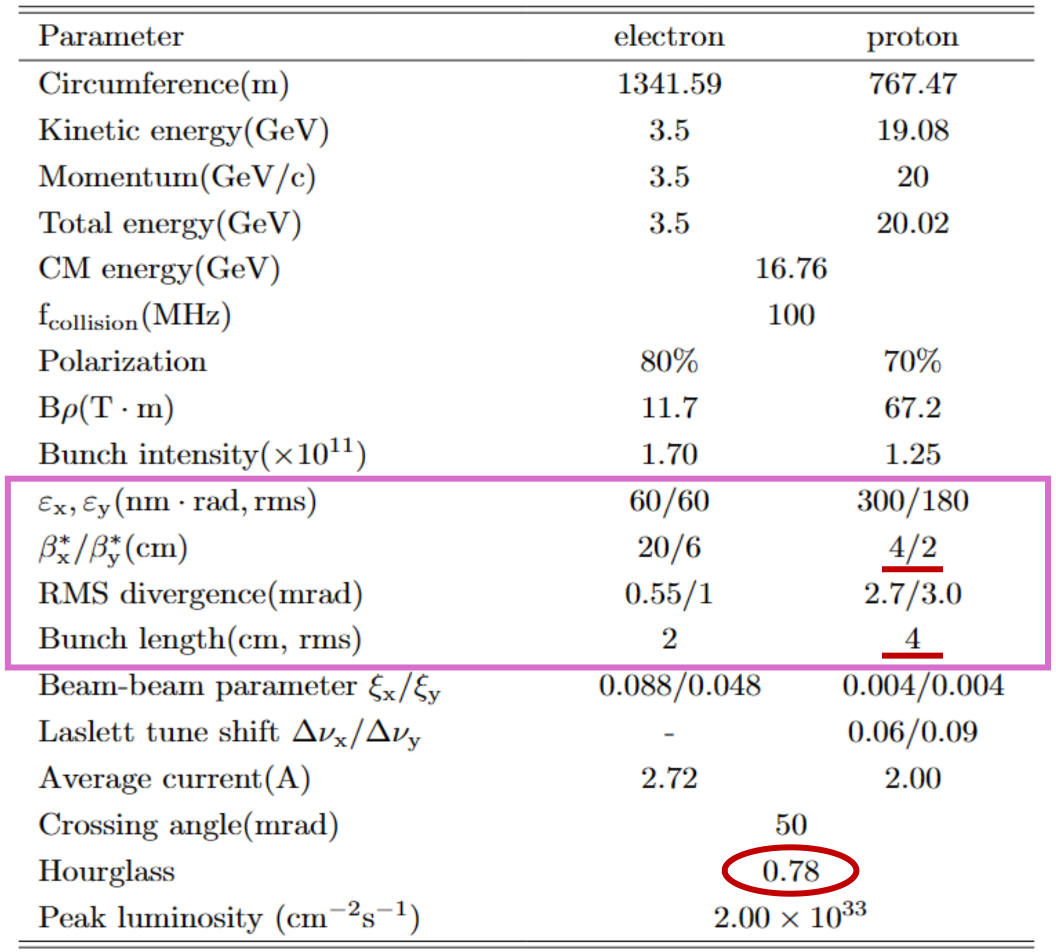
- ➢ Collisions of electrons with a large range of light to heavy ion beams in the medium energy region.
- ➢ Center-of-mass energy is between 12~23 GeV at specific points for electron-proton collisions.
- ➢ With e@3.5 GeV and p@19.08 GeV (CM energy 16.67 GeV), peak luminosity is $(2\sim4)\times10^{33}$ cm^{-2}s^{-1}.

- ● High luminosity, high polarization
- ● Quasi-full acceptance for reaction product detections
- ● Rapid cycling operation mode and swap-out injection

More details in Jie Liu's talk.

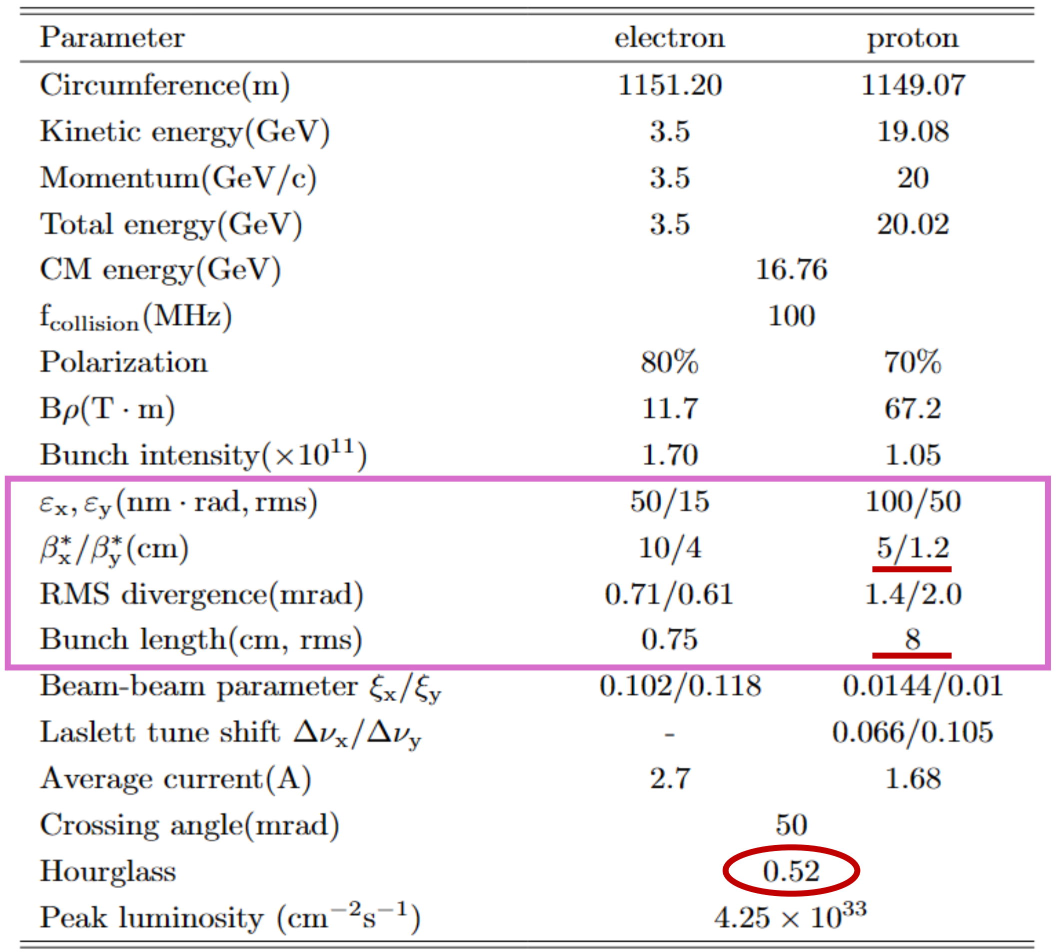
1. Introduction of EicC accelerators

Old parameters



Parameter	electron	proton
Circumference(m)	1341.59	767.47
Kinetic energy(GeV)	3.5	19.08
Momentum(GeV/c)	3.5	20
Total energy(GeV)	3.5	20.02
CM energy(GeV)	16.76	
$f_{collision}$(MHz)	100	
Polarization	80%	70%
$B\rho(T \cdot m)$	11.7	67.2
Bunch intensity($\times 10^{11}$)	1.70	1.25
$\varepsilon_x, \varepsilon_y$(nm · rad, rms)	60/60	300/180
β_x^*/β_y^*(cm)	20/6	4/2
RMS divergence(mrad)	0.55/1	2.7/3.0
Bunch length(cm, rms)	2	4
Beam-beam parameter ξ_x/ξ_y	0.088/0.048	0.004/0.004
Laslett tune shift $\Delta\nu_x/\Delta\nu_y$	-	0.06/0.09
Average current(A)	2.72	2.00
Crossing angle(mrad)	50	
Hourglass	0.78	
Peak luminosity ($cm^{-2}s^{-1}$)	2.00×10^{33}	

New parameters

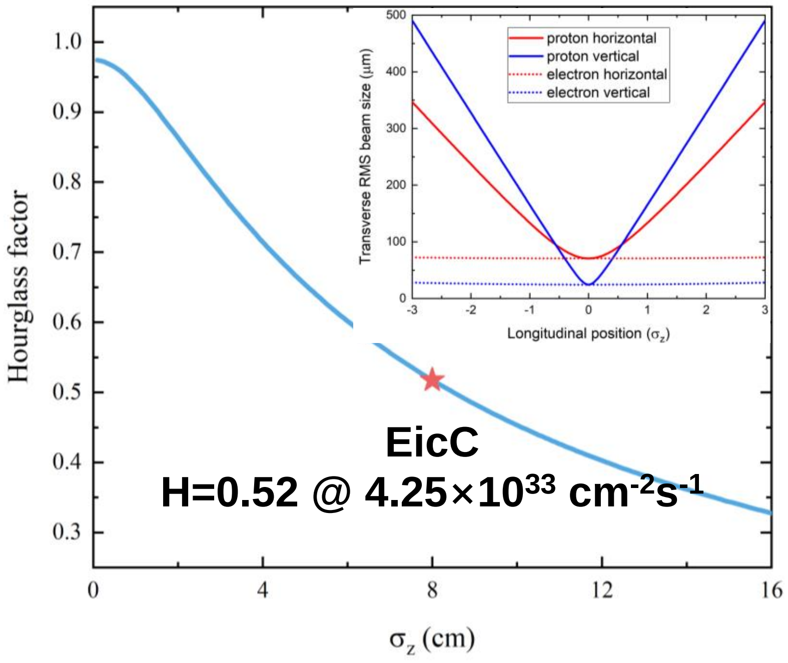


Parameter	electron	proton
Circumference(m)	1151.20	1149.07
Kinetic energy(GeV)	3.5	19.08
Momentum(GeV/c)	3.5	20
Total energy(GeV)	3.5	20.02
CM energy(GeV)	16.76	
$f_{collision}$(MHz)	100	
Polarization	80%	70%
$B\rho(T \cdot m)$	11.7	67.2
Bunch intensity($\times 10^{11}$)	1.70	1.05
$\varepsilon_x, \varepsilon_y$(nm · rad, rms)	50/15	100/50
β_x^*/β_y^*(cm)	10/4	5/1.2
RMS divergence(mrad)	0.71/0.61	1.4/2.0
Bunch length(cm, rms)	0.75	8
Beam-beam parameter ξ_x/ξ_y	0.102/0.118	0.0144/0.01
Laslett tune shift $\Delta\nu_x/\Delta\nu_y$	-	0.066/0.105
Average current(A)	2.7	1.68
Crossing angle(mrad)	50	
Hourglass	0.52	
Peak luminosity ($cm^{-2}s^{-1}$)	4.25×10^{33}	

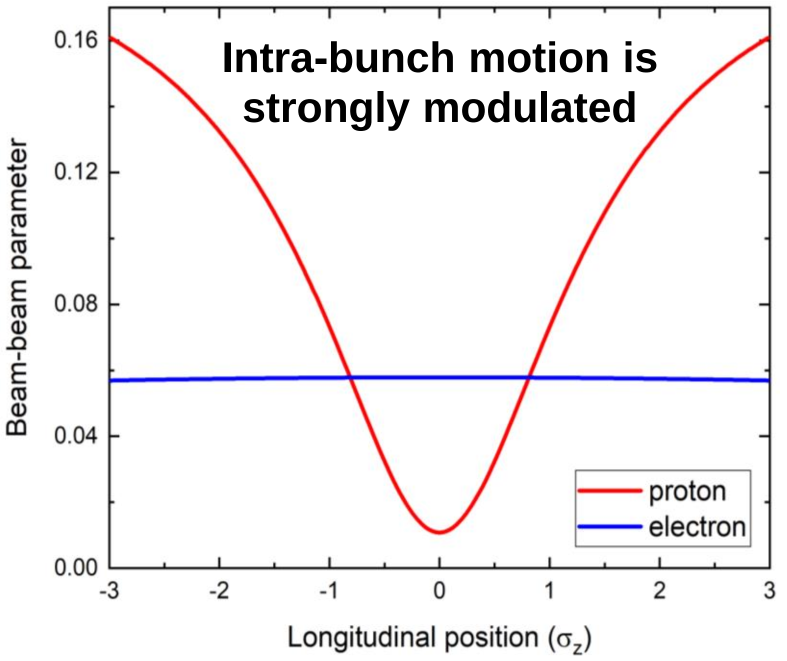
Both designs adopt asymmetric beam parameters and feature very strong hourglass effects.

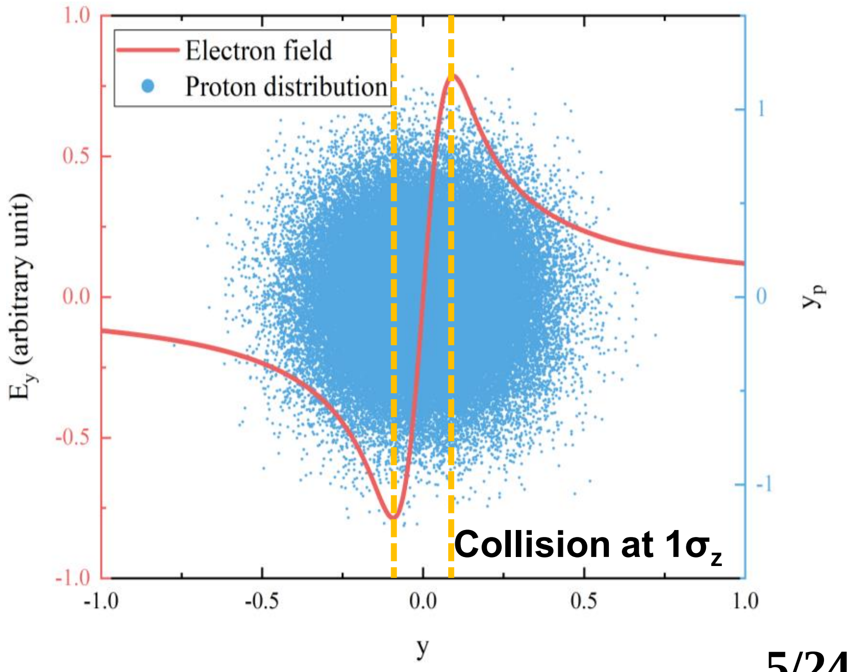
1. Hourglass effect in EicC

- **Geometric effect: Hourglass effect will lead to beam sizes growth, lower beam density and therefore cause peak luminosity reduction.**
- **Dynamic effect: Beam size mismatch will induce a very strong modulation of proton beam-beam parameters, interplay with transverse wakefield? Most protons will see the nonlinear part of electron beam-beam forces, excite resonances?**



EicC
H=0.52 @ 4.25×10^{33} cm^{-2}s^{-1}


Intra-bunch motion is strongly modulated


Collision at $1\sigma_z$

Outline

1. Hourglass effect in EicC

2. **Simulation model**

3. Head-tail instability of asymmetric colliding beams

   Numerical observations

   Key parameter scans and instability mechanism

   Mitigation methods

4. Float waist collision scheme

   Compensation principles of the hourglass effect

   Numerical proofs and application to the head-tail instability

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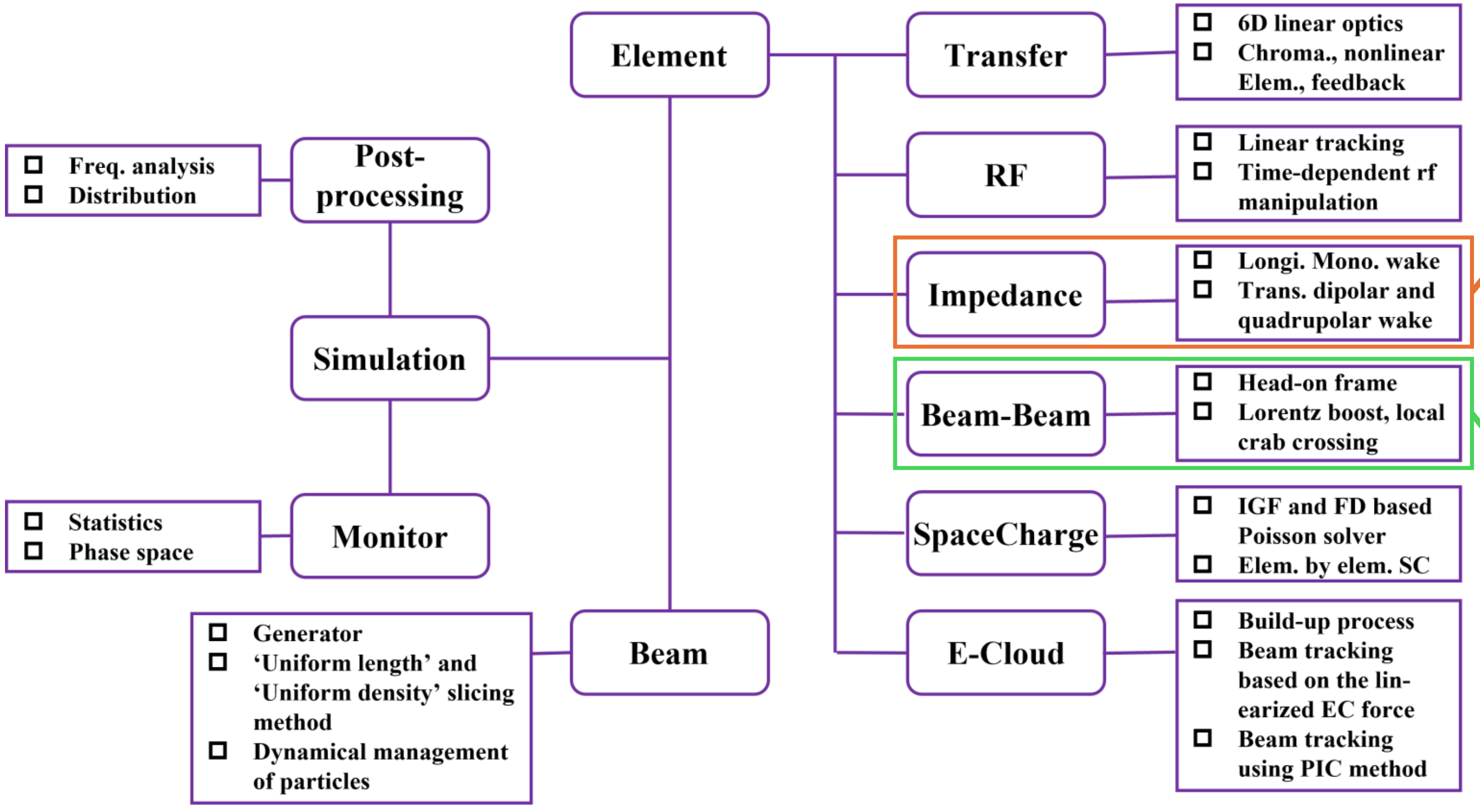
2. GOAT code and numerical model

- ➢ **Developed for interplays of multiple high-intensity single-bunch beam dynamics, including beam-beam, impedance, electron-cloud, and space charge.**
- ➢ **Upgrade to GPU version for better performance, extension to cover multi-bunch dynamics are in progress.**

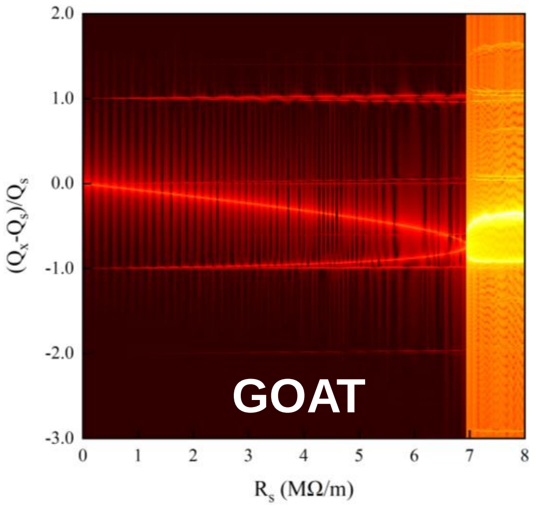


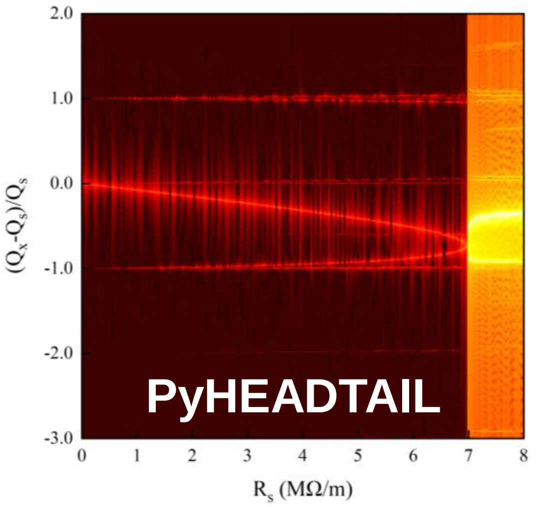
- ✓ **Wakefield is lumped at the IP and kicks are applied to the particles once per turn**
- ✓ **Arbitrary impedance model**

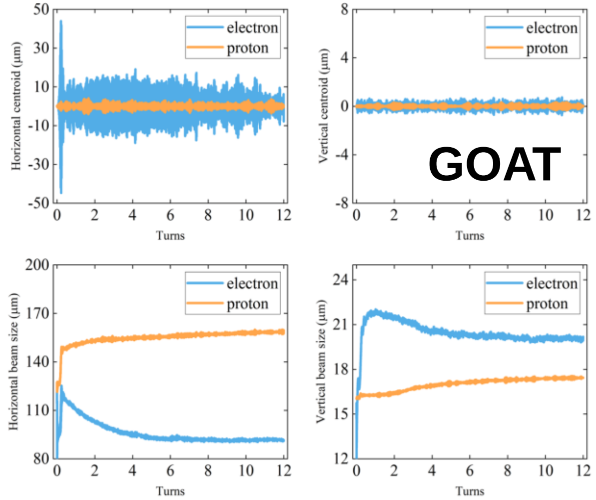
- ✓ **Only strong-strong model, slice-by-slice collisions for hourglass effect, integrated Green function and linear interpolation methods for beam-beam potential**
- ✓ **Particles are transferred from IP to IP using 6D linear matrix**

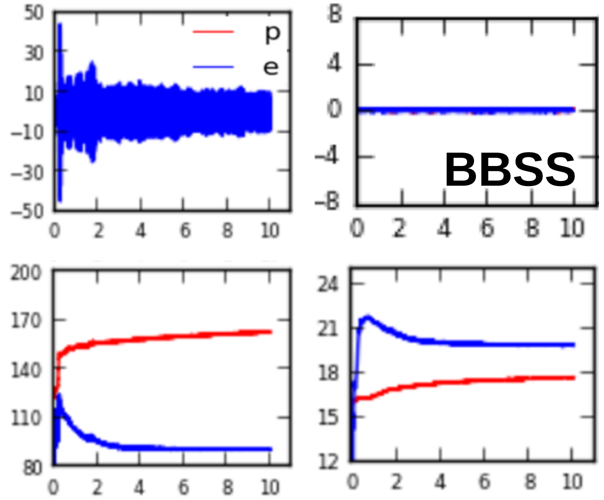
2. GOAT code and numerical model

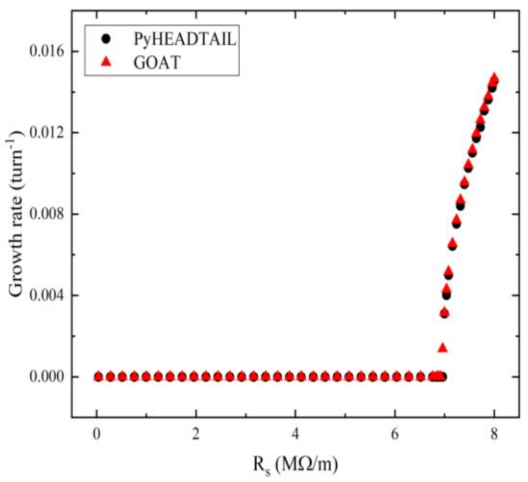
- **Benchmarks**





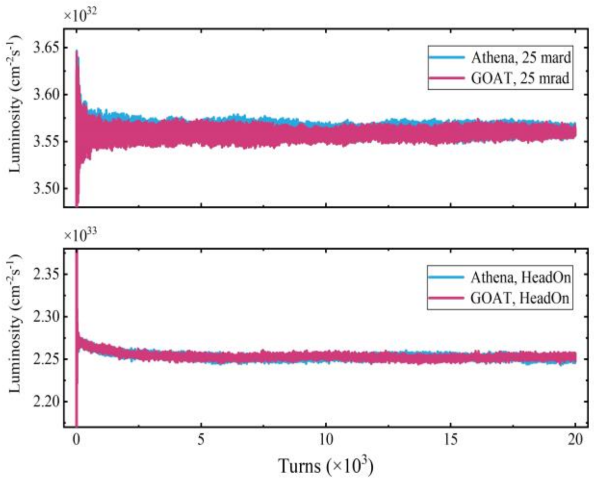






Benchmarks with the PyHEADTAIL using a broadband resonator impedance model

Spectra and growth rates are the same



Benchmarks with BBSS (copy from other slides) and AthenaGPU codes for beam-beam effect

Luminosities and beam motions are the same

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    - **Mitigation methods**
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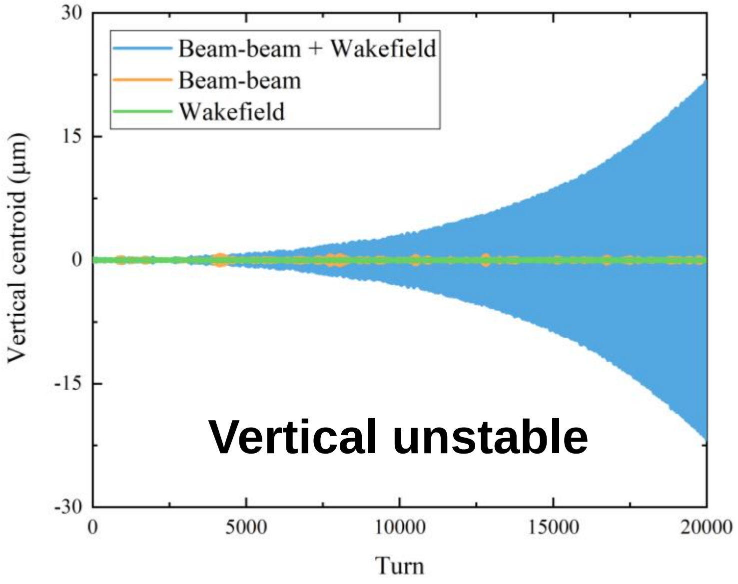
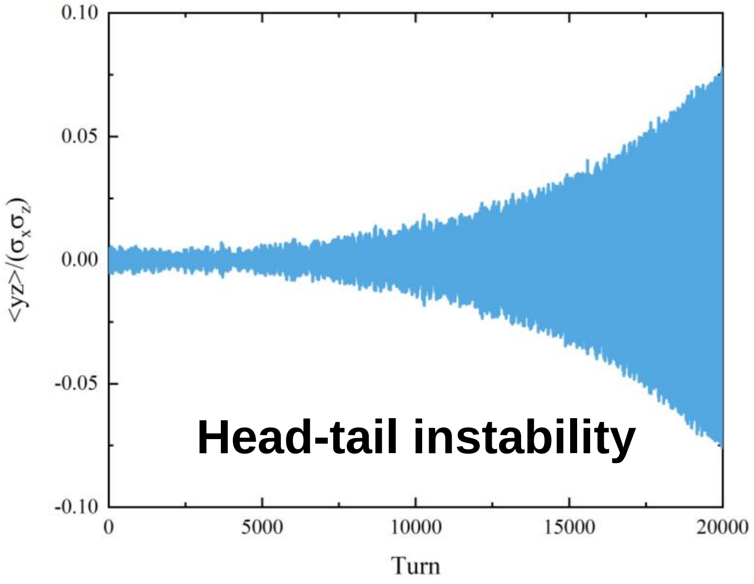
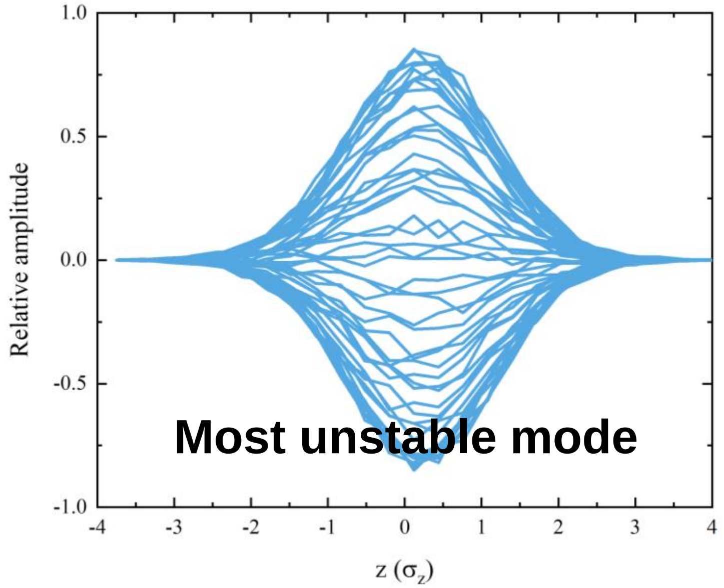
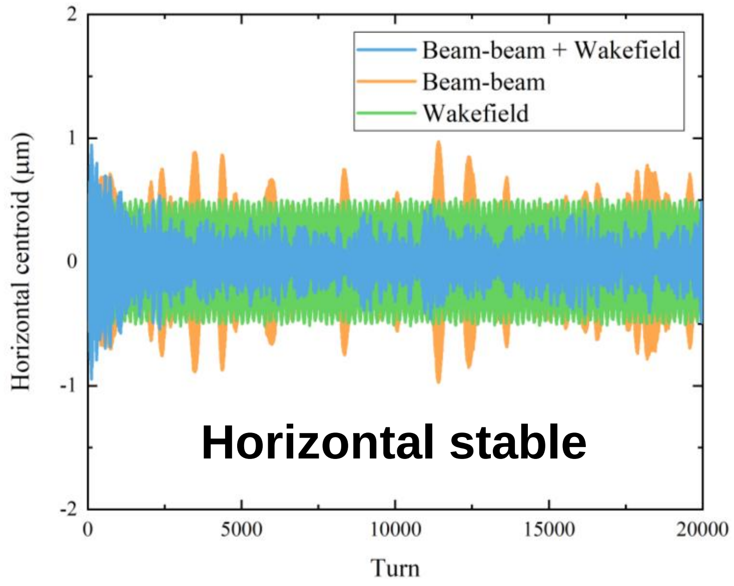
3. Instability observation


Vertical unstable

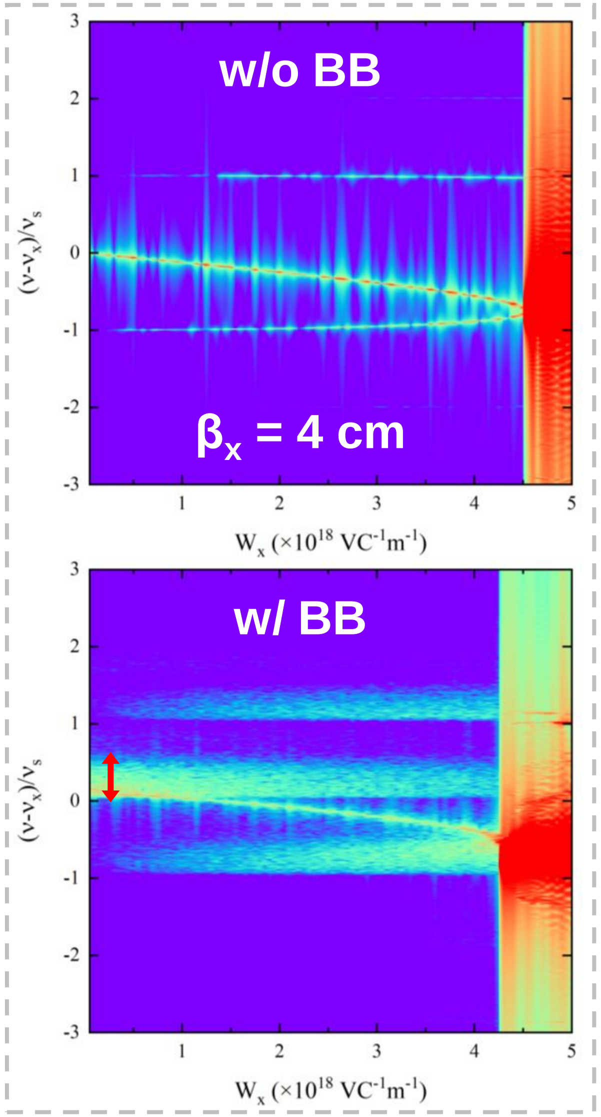

Head-tail instability


Most unstable mode

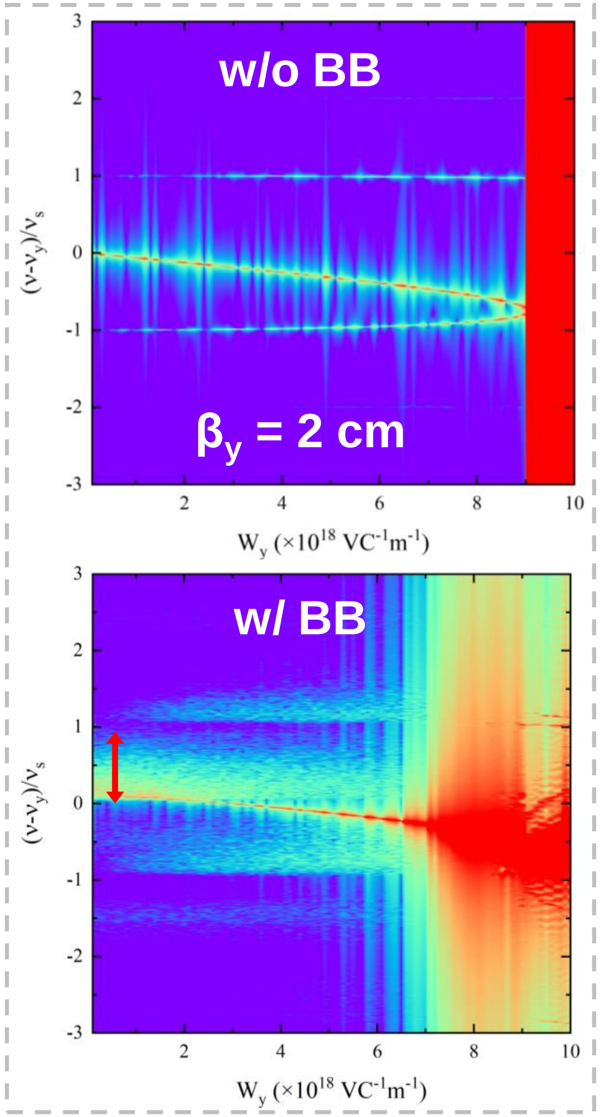

Horizontal stable

- **Old designs, beam-beam for e+p and wakefield only for p**
- **With beam-beam interactions or transverse wakefields (below TMCI threshold) alone, the beam keeps stable, but a head-tail type instability is stimulated by their interplay.**
- **Under similar conditions (the same ξ and ΔQ_{coh}). The instability occurs only in the vertical plane, but not seen in the horizontal plane (even a damping effect).**

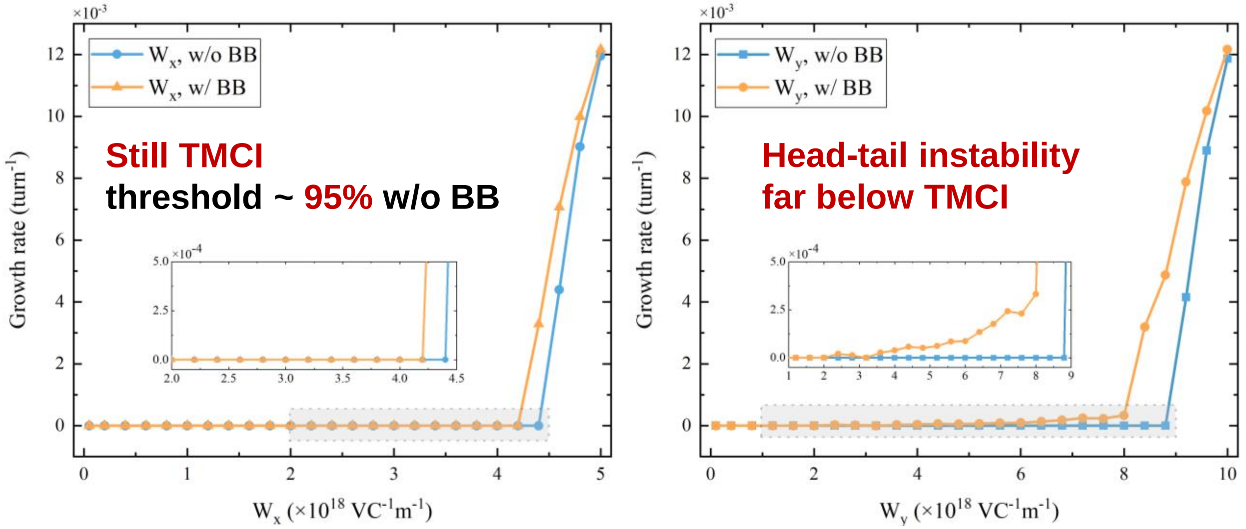
3. Transverse wakefield scan



Horizontal



Vertical

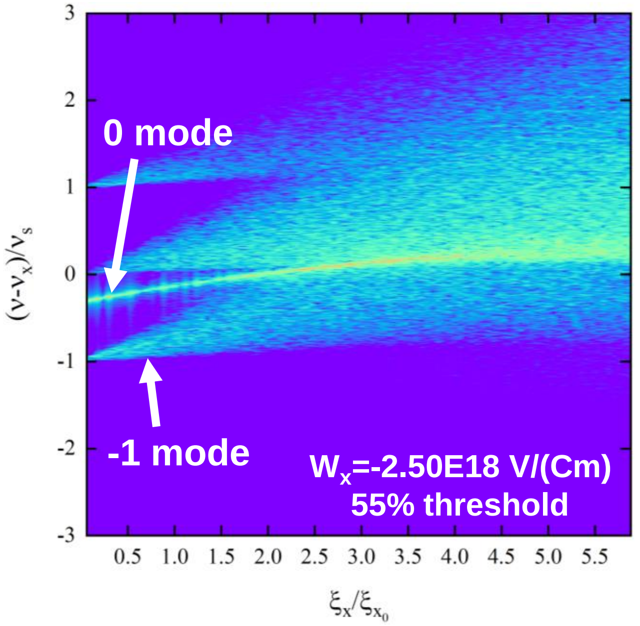


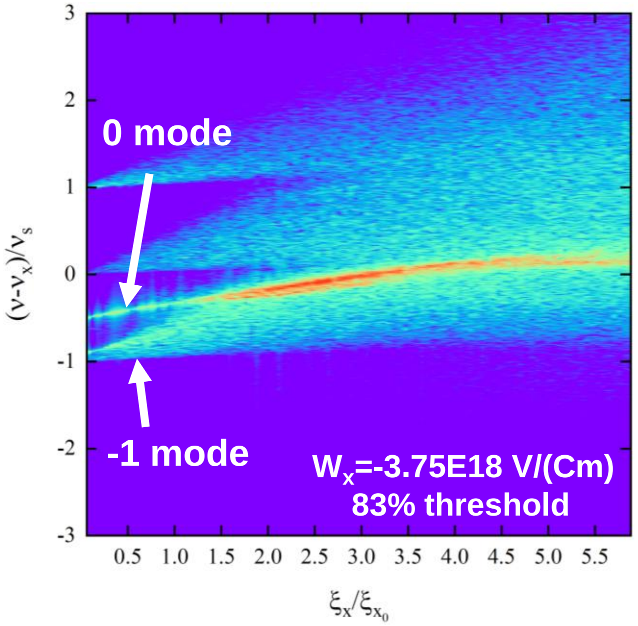
Still TMCI
threshold ~ 95% w/o BB

Head-tail instability far below TMCI

- **Constant wakefield is used to exclude the effect of bunch length on TMCI threshold (∝ $W_{x,y} \times \beta_{x,y}$) same ΔQ_{coh} when $W_y = 2W_x$.**
- **With beam-beam, longitudinal sidebands become more spread. The widening is more evident in the vertical direction.**
- **Beam-beam is responsible for the difference in the horizontal and vertical directions.**

3. Horizontal beam-beam parameter scan

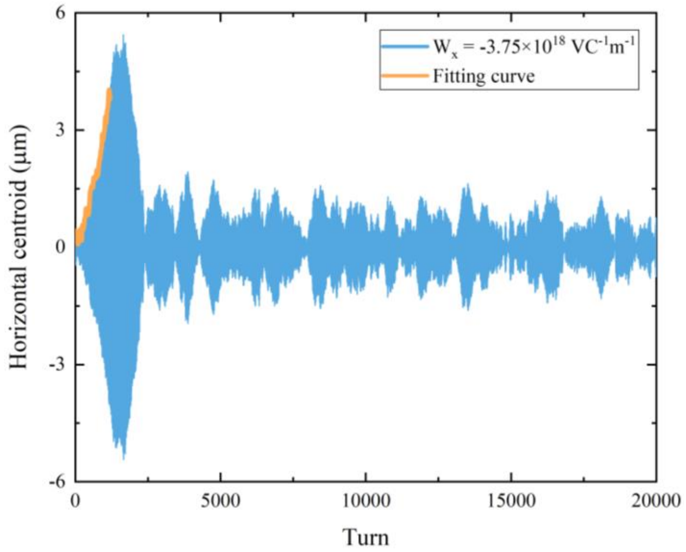


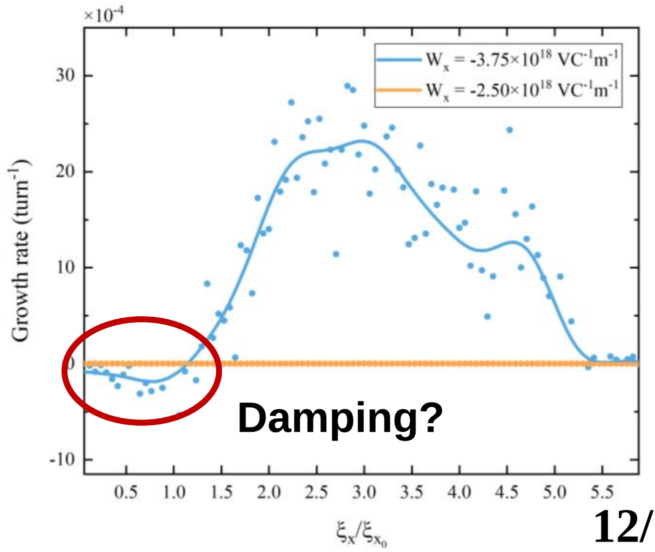


The -1 sideband grows much faster than the coherent mode, very different from the case for symmetric colliding beams

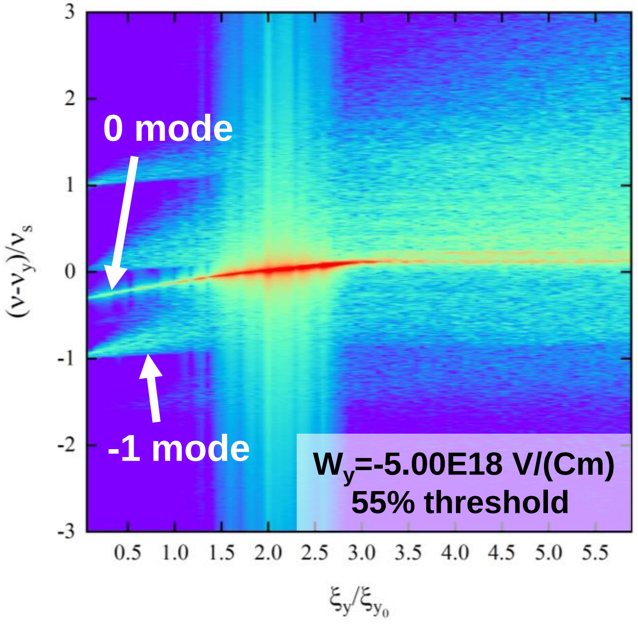
Mode frequency shift	W_x=-2.50E18 V/(Cm)	W_x=-3.75E18 V/(Cm)
Coherent mode	0.56348 ξ_x	0.56537 ξ_x
-1 sideband	1.52035 ξ_x	1.49056 ξ_x

- Beam is stable at small wakefield, and gets unstable at higher wakefield.
- With large wakefield, beam instabilities appear only in the first 2000 turns and then they are self-damped.
- Need further understandings.

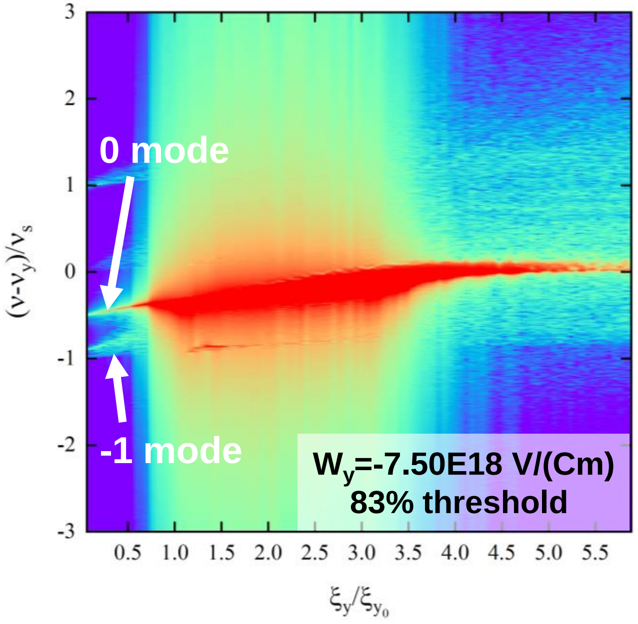




3. Vertical beam-beam parameter scan



W_y=-5.00E18 V/(Cm)
55% threshold

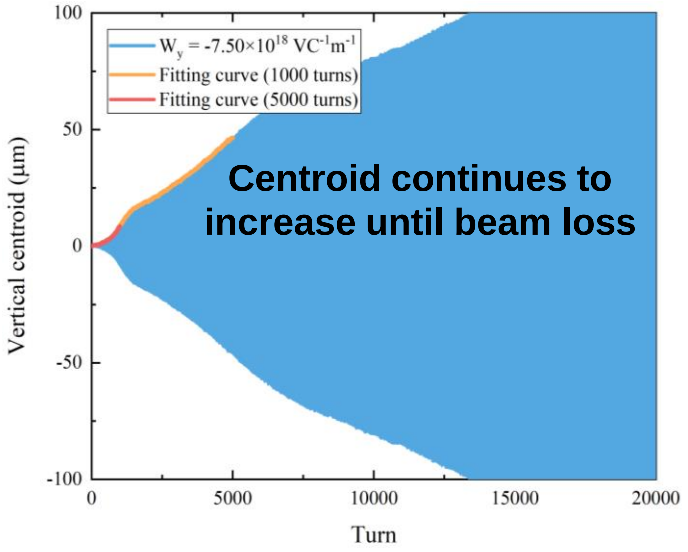


W_y=-7.50E18 V/(Cm)
83% threshold

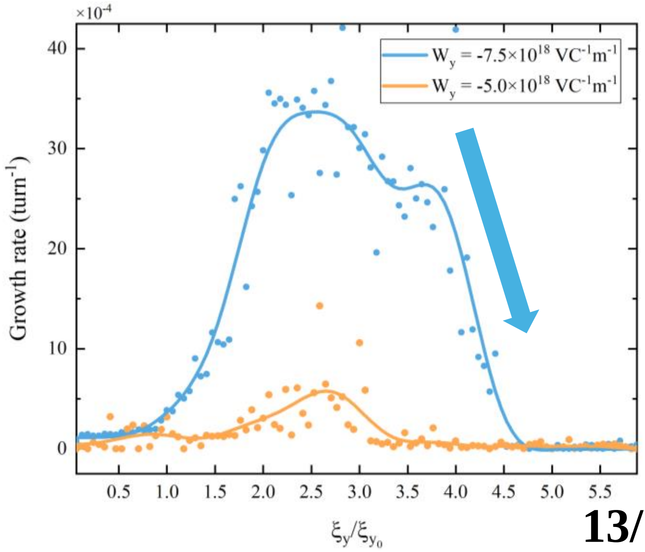
The vertical -1 sideband moves 4 times faster than the coherent mode, and the beam stabilities are different

Mode frequency shift	W_y=-5.00E18 V/(Cm)	W_y=-7.50E18 V/(Cm)
Coherent mode	0.60242 ξ_y	0.61566 ξ_y
-1 sideband	2.33555 ξ_y	2.46351 ξ_y

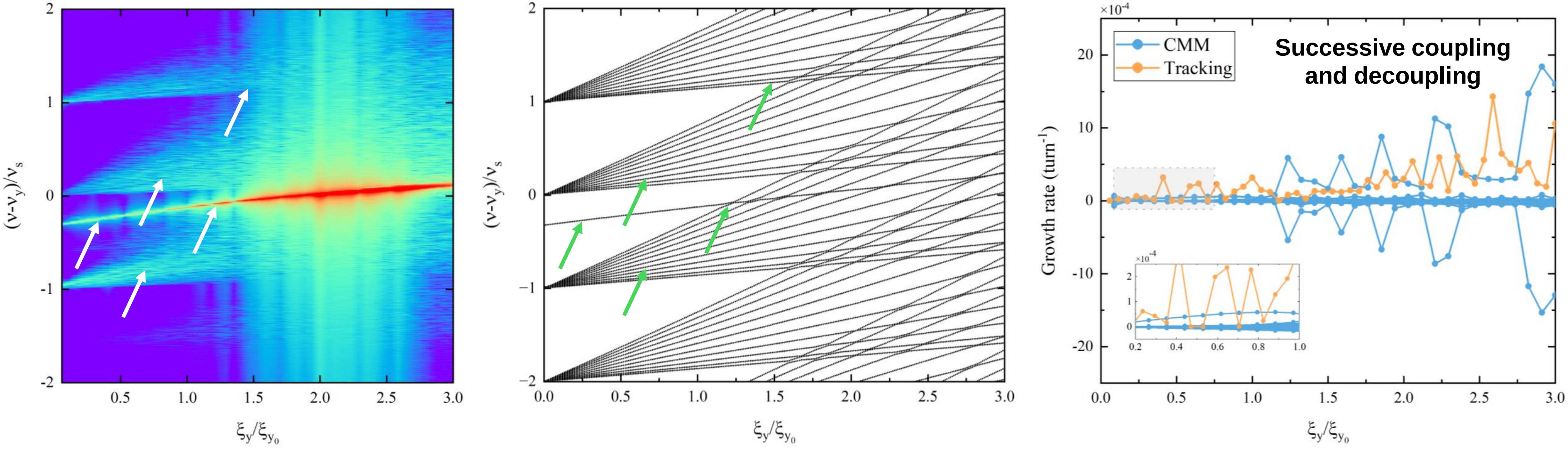
- **The -1 sideband interacts with coherent mode much earlier, and therefore result in head-tail instabilities far below TMCI threshold.**
- **Instability occurs without threshold and weakens as the overlaps of -1 sideband and coherent mode become larger.**



Centroid continues to increase until beam loss



3. Tracking vs circulant matrix model



Successive coupling and decoupling

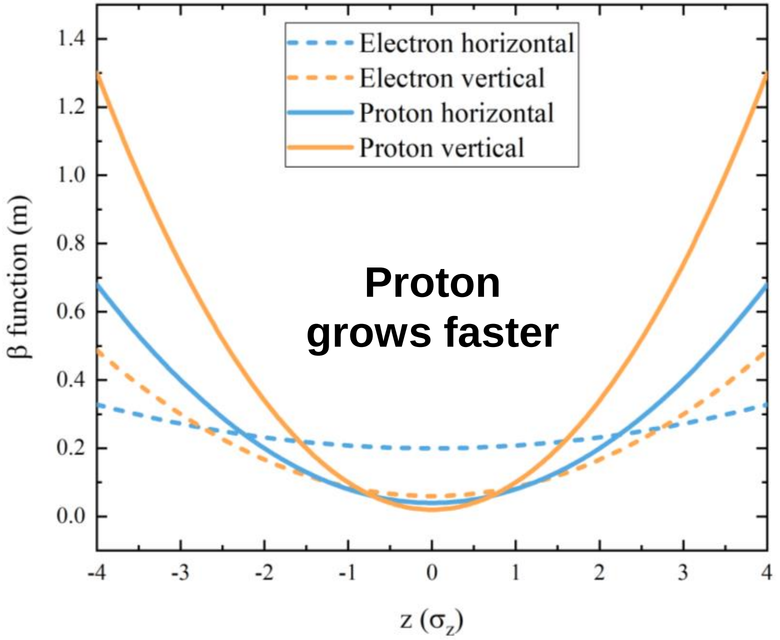
Mode frequency shift	Simulation	CMM
Coherent mode	0.60242 ξ_y	0.59746 ξ_y
-1 sideband	2.33555 ξ_y	2.32447 ξ_y

- ➢ **Predictions of the beam spectra and the instability growth rates are qualitatively the same for the two methods.**
- ➢ **The analytical approach confirms the existence of such a head-tail type instability.**

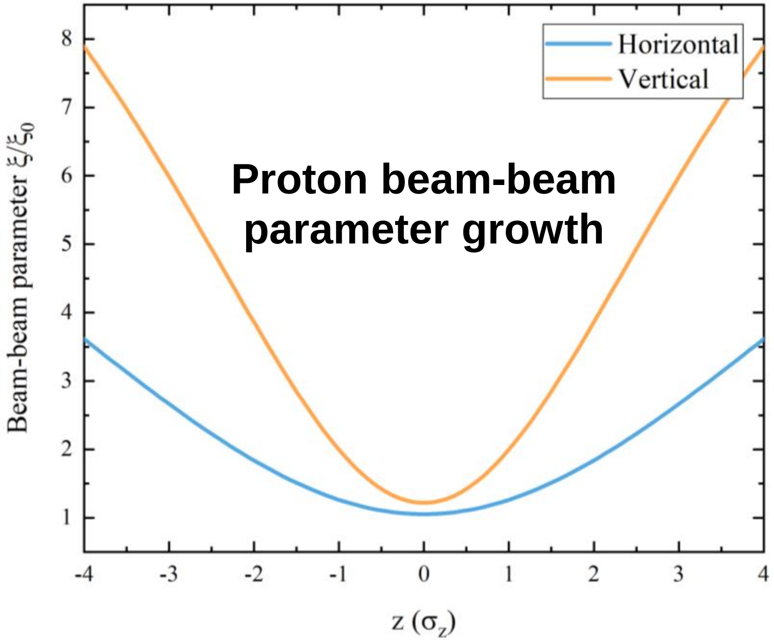
3. Instability mechanism

- For flat asymmetric colliding beams, these four β* grow at different rates due to hourglass effect, and beam sizes are no longer matched at CP (NOT IP). This results in a significant growth and modulation of proton beam-beam parameters.

$$\beta(z) = \beta^* + \frac{z^2}{\beta^*} \quad \Rightarrow \quad \xi_{x,y}(z_p)\uparrow \cong \int \frac{r_p \rho_e(s) \beta_{x,y}(s)\uparrow\uparrow\uparrow}{2\pi \gamma_p \sigma_{e,x,y}(s)\left[\sigma_{e,x}(s) + \sigma_{e,y}(s)\right]\uparrow} ds$$



Proton grows faster



Proton beam-beam parameter growth

Protons with larger synchrotron amplitude will experience much stronger bb forces.

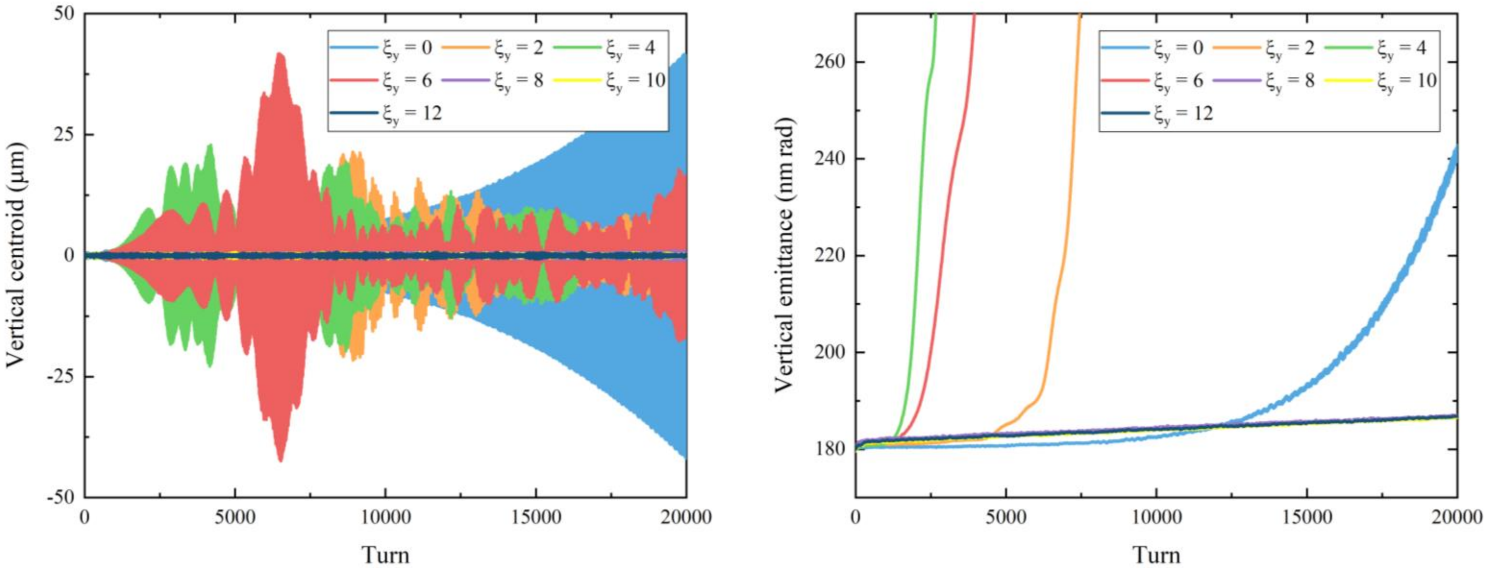
~ Responsible for the broadening of the longitudinal sidebands.

Vertical bb parameter growth and modulation are more severe.

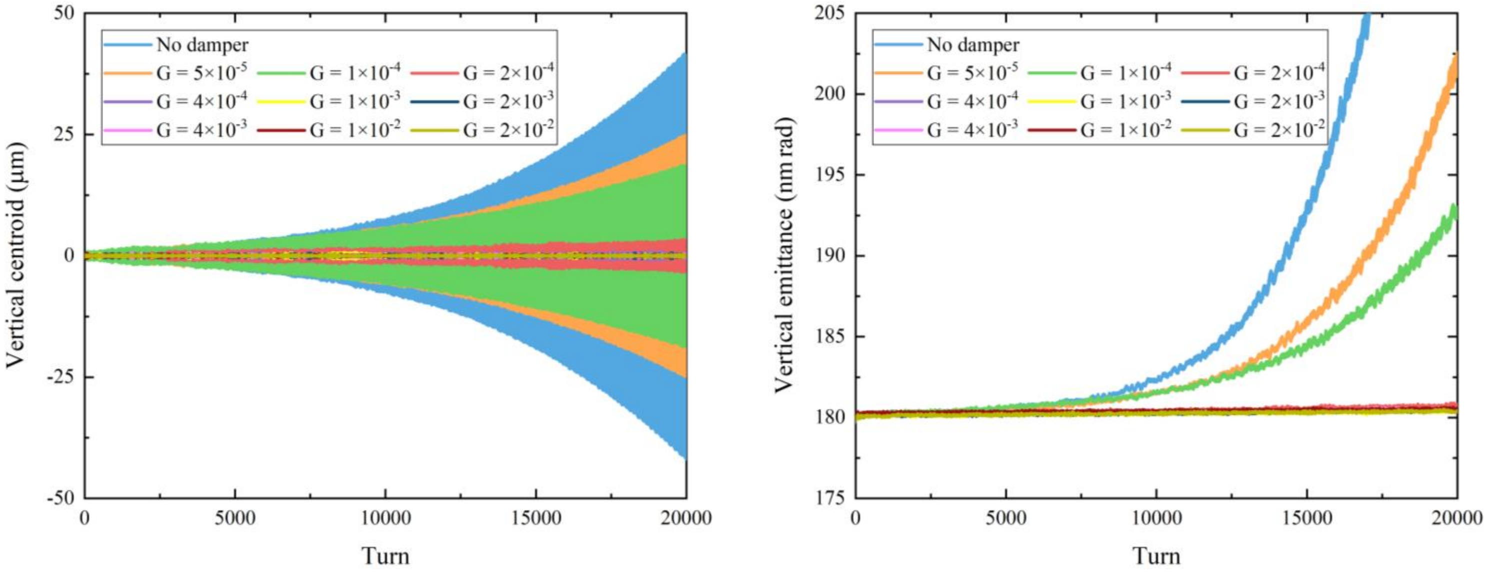
~ Responsible for beam stability and spectrum differences in two transverse planes.

- Hourglass effect is a possible mechanism for this newfound head-tail instability.

3. Mitigation methods



- **Chromaticity**
  - ✓ **Above transition, a positive chromaticity larger than +8 can suppress this head-tail instability**
  - ✓ **Significant emittance growth is present**



- **Ideal feedback**
  - ✓ **Exponential centroid motion is mitigated with a feedback gain higher than 4×10^{-4}**
  - ✓ **Beam emittance is preserved**
  - ✓ **A more efficient method**

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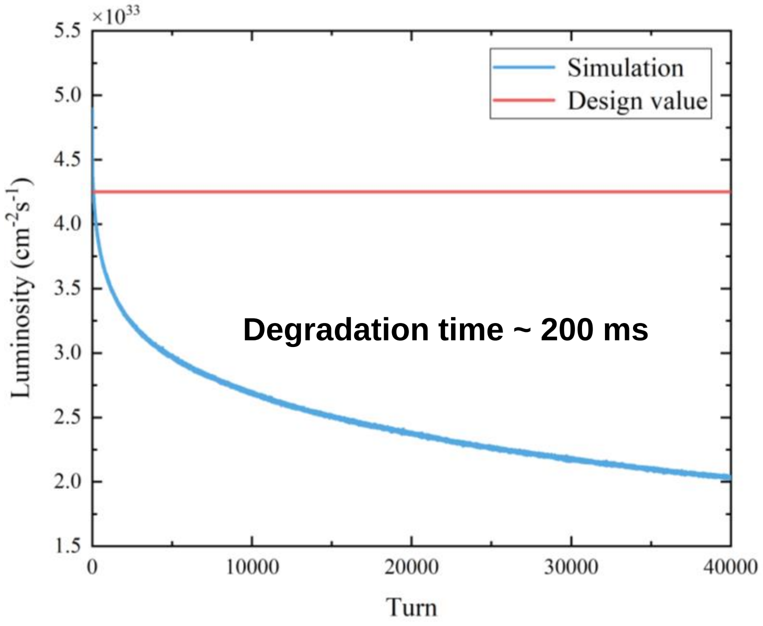
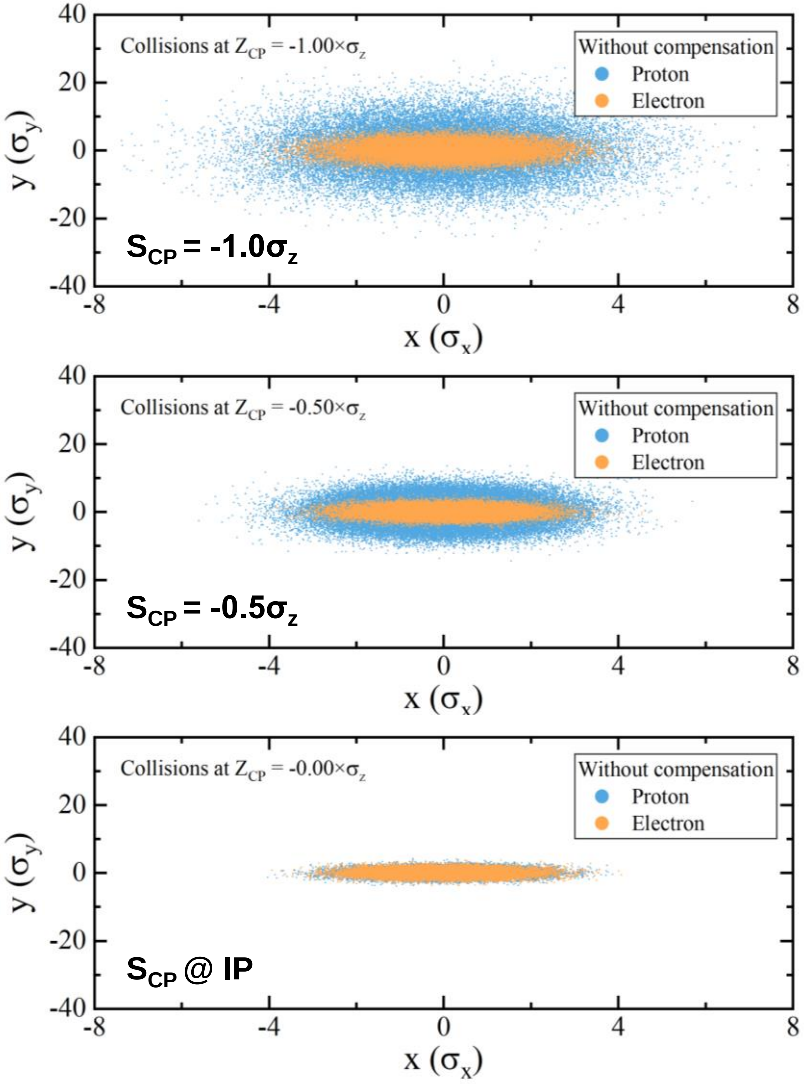
4. Difficulties with new parameters



Degradation time ~ 200 ms

- **Simulation predicts very bad luminosity lifetime.**
- **Beam sizes mismatch cause severe BB parameter growth and consequently large tune spread and a fair number of SB resonances.**

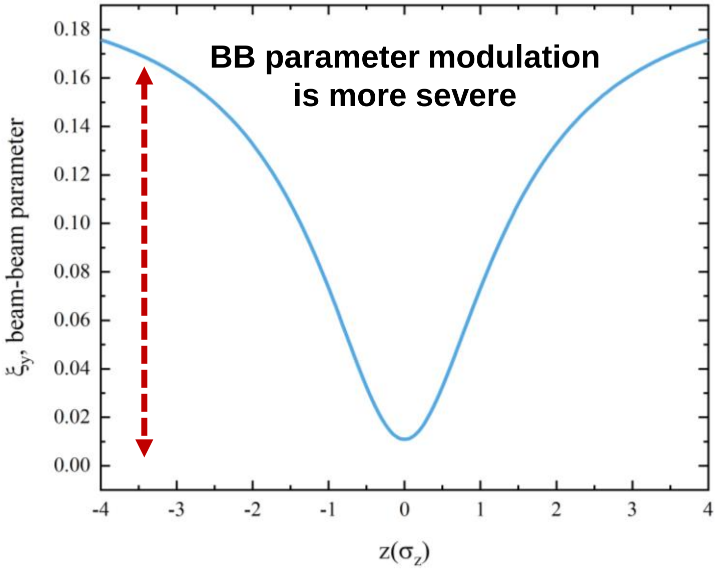


S_{CP} = -1.0σ_z

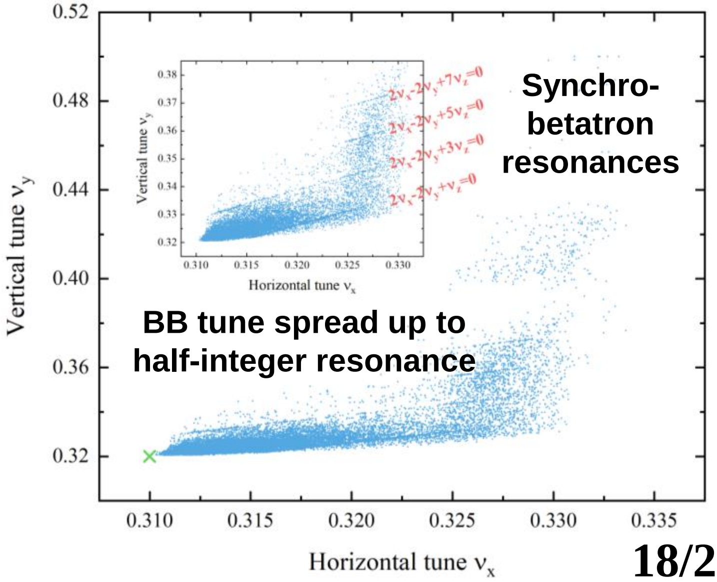
S_{CP} = -0.5σ_z

S_{CP} @ IP

Beam sizes mismatch in collisions



BB parameter modulation is more severe

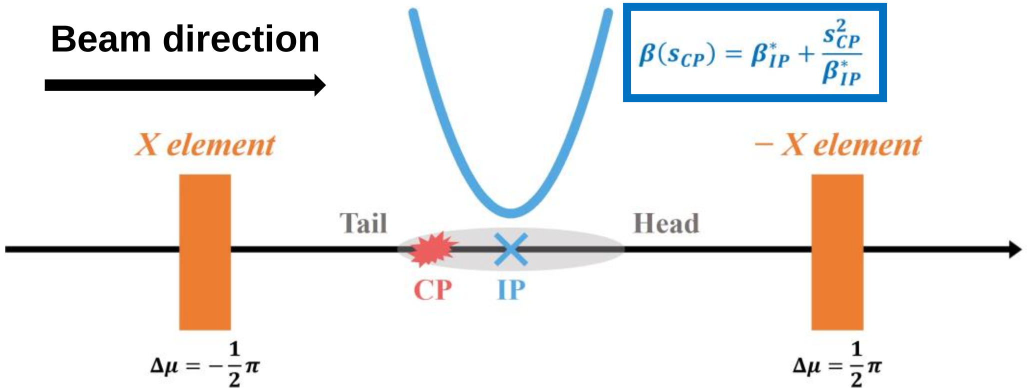


Synchro-betatron resonances

BB tune spread up to half-integer resonance

4. Hourglass compensation principles

- **Theoretical criterion**



Step 1: IP → X $\quad M_1 = \begin{bmatrix} 0 & -\sqrt{\beta_X\beta^*} \\ \frac{1}{\sqrt{\beta_X\beta^*}} & 0 \end{bmatrix}$

Step 2: Kicks @ X $\quad M_2 = \begin{bmatrix} 1 & 0 \\ \mathrm{K} & 1 \end{bmatrix}$

Step 3: X → IP $\quad M_3 = \begin{bmatrix} 0 & \sqrt{\beta_X\beta^*} \\ -\frac{1}{\sqrt{\beta_X\beta^*}} & 0 \end{bmatrix}$

Step 4: IP → CP $\quad M_4 = \begin{bmatrix} 1 & S_{CP} \\ 0 & 1 \end{bmatrix}$

The idea is initially proposed for HERA-TESLA collider.

☐ **Without** "X-element", the transfer matrix from IP to CP is,

$$M = M_4 M_3 M_1 = \begin{bmatrix} 1 & S_{CP} \\ 0 & 1 \end{bmatrix}$$

☐ **With** additional defocusing force from "X-element", the transfer matrix becomes:

$$M' = M_4 M_3 M_2 M_1 = \boxed{\begin{bmatrix} 1 & S_{CP} - K\beta_X\beta^* \\ 0 & 1 \end{bmatrix}}$$

$$\boxed{K = \frac{S_{CP}}{\beta_X\beta^*}}$$

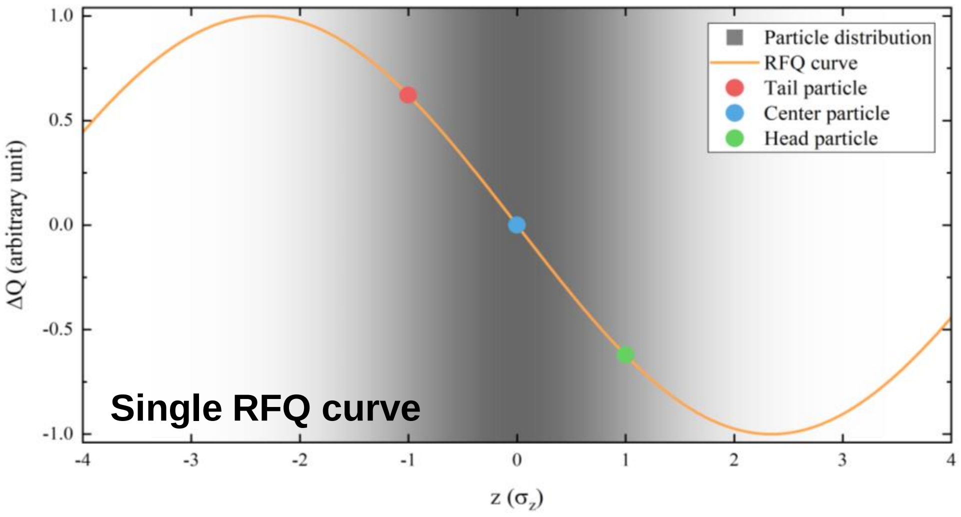
IP is no longer the fixed focusing point, proton beam waist locates at arbitrary CP

Proton bunch is much longer than electron bunch, K is foreknown:

$$S_{CP} = \frac{1}{2}(Z_p - Z_e) = \frac{1}{2}Z_p$$

4. Hourglass compensation principles

- **RF quadrupole magnets**



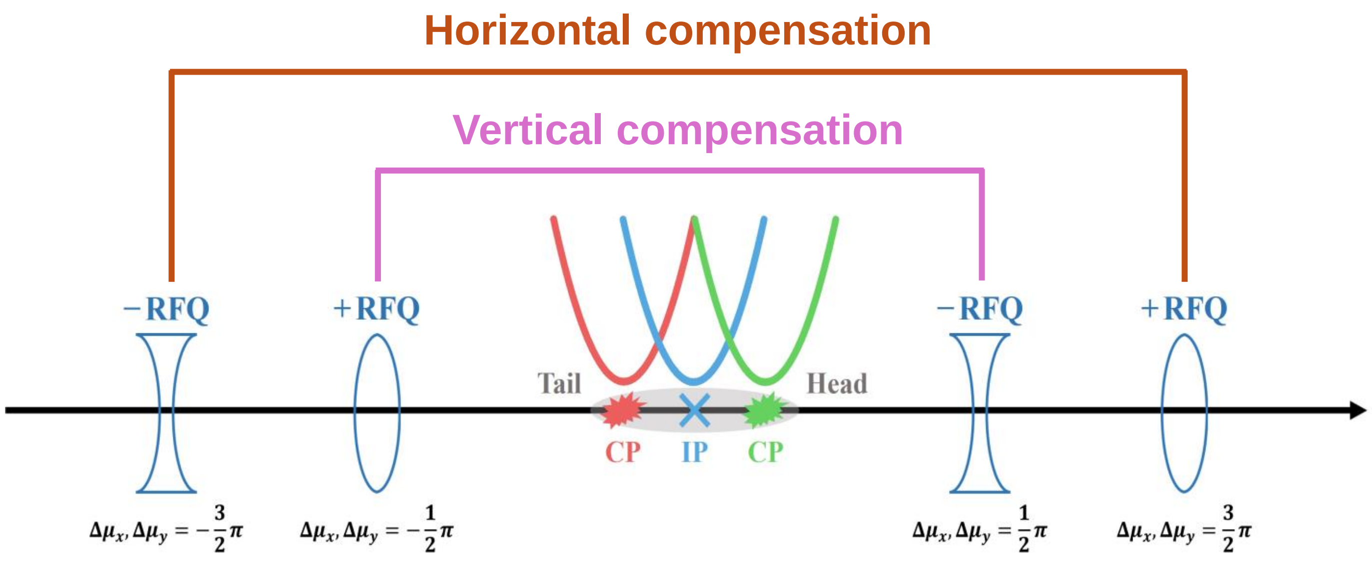
$$\Delta Q^{RFQ}_{x,y} = \pm\beta_{x,y}\frac{b^{(2)}}{4\pi B_0\rho}\cos\left(\frac{\omega}{\beta c}z+\frac{\pi}{2}\right)$$

$$= \pm\beta_{x,y}\frac{b^{(2)}}{4\pi B_0\rho}\left[\frac{2\pi f}{\beta c}z+O(z^3)\right] = \pm K_1 z$$

Inverse focusing properties for two planes

$$\Delta Q^{theory}_{x,y} = -\frac{z}{8\pi\beta^*}$$

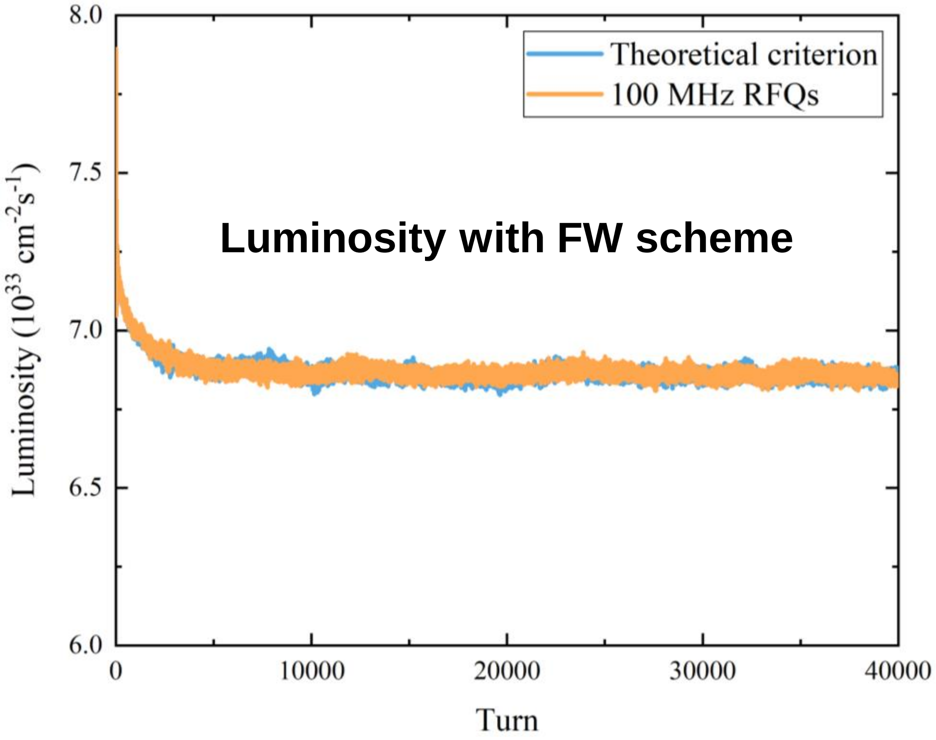
Head defocusing, tail focusing for both planes



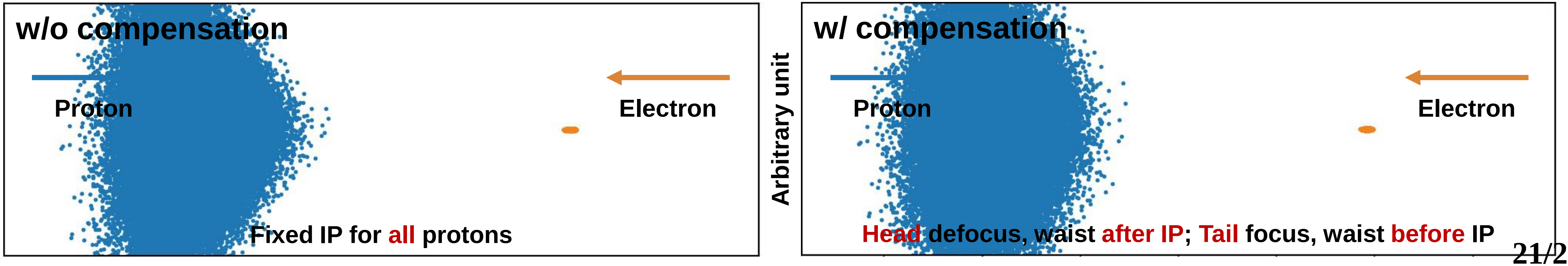
- **Float Waist collision scheme: Two pairs of RFQm with phase advances of π/2*(2n+1), one pair for x direction and one pair for y direction**

- **Similar to chromaticity correction, the hourglass effect is compensated simultaneously in x and y directions if @ ±π/2 over-floating for y direction, and @ ±3π/2 over-floating for x direction**

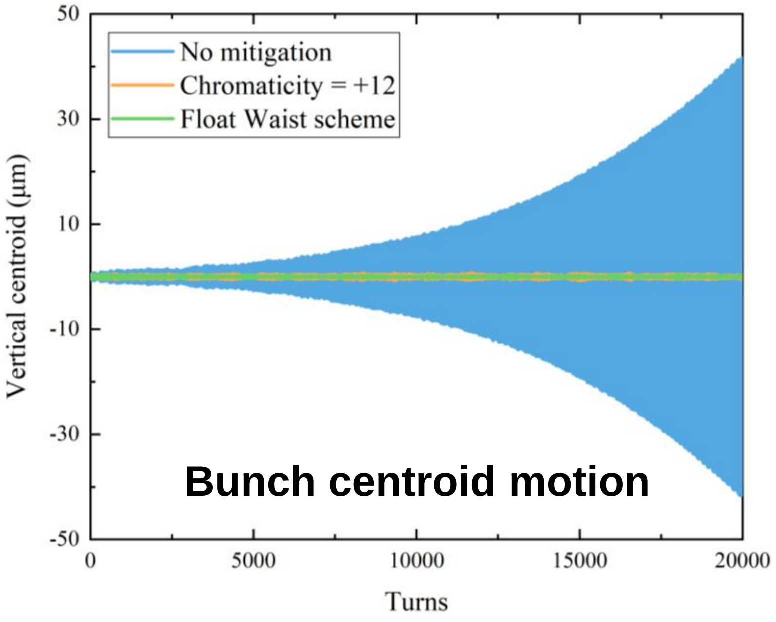
4. Numerical proofs

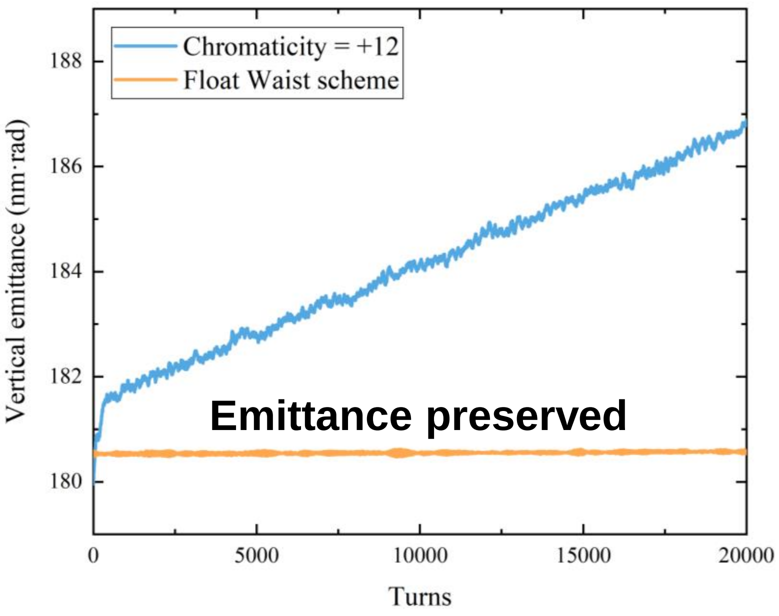


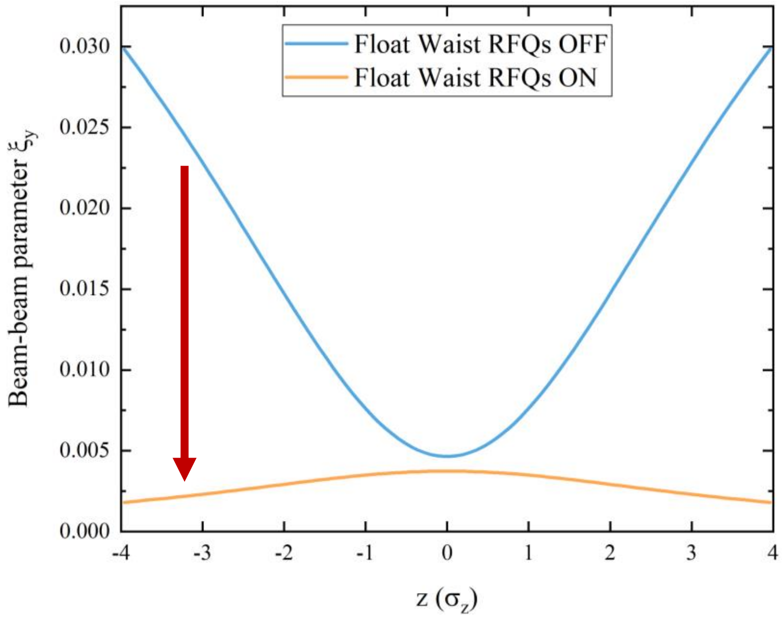
- **The theoretical criterion works very well, and two sets of RFQm with frequencies of 100 MHz (up to 300 MHz) can perfectly match the criterion.**
- **With Float Waist collision scheme, luminosity is partially restored (H > 0.8) and luminosity lifetime is significantly improved.**
- **The residual luminosity loss is caused by electron beam size growth at CP (unable to compensate ☹☹).**



4. Mitigation of the head-tail instability







- **With strong hourglass effect, the instability has actually been stimulated, chromaticity just provides tune spread for decoherence and causes emittance growth.**
- **In the Float Waist collision scheme, the hourglass effect is partially compensated, the proton beam-beam parameter modulation is significantly suppressed, so that this head-tail instability is avoided fundamentally.**
- **This verifies the explanation of the hourglass-induced instability mechanism from the side.**

Outline

1. Hourglass effect in EicC
2. Simulation model
3. Head-tail instability of asymmetric colliding beams
   - Numerical observations
   - Key parameter scans and instability mechanism
   - Mitigation methods
4. Float waist collision scheme
   - Compensation principles of the hourglass effect
   - Numerical proofs and application to the head-tail instability
5. **Summary**

5. Summary

- The interplay of beam-beam interactions and transverse wakefields is studied self-consistently for EicC with strong hourglass effect. A coherent head-tail instability is observed.

- The coherent head-tail instability is studied by tracking simulations and confirmed by the analytical method. Different growth rates of the coherent mode and the -1 sideband are the main cause of this instability and responsible for the difference between two transverse planes.

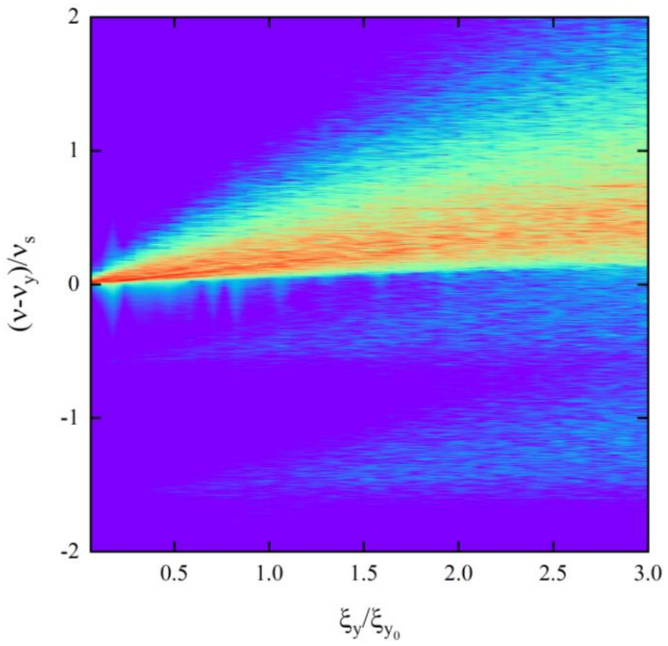
- The underlying mechanism is the hourglass effect for beam-beam parameters. For flat asymmetric beams, different growth rates of the β-functions result in a strong growth and modulation of proton beam-beam parameters.

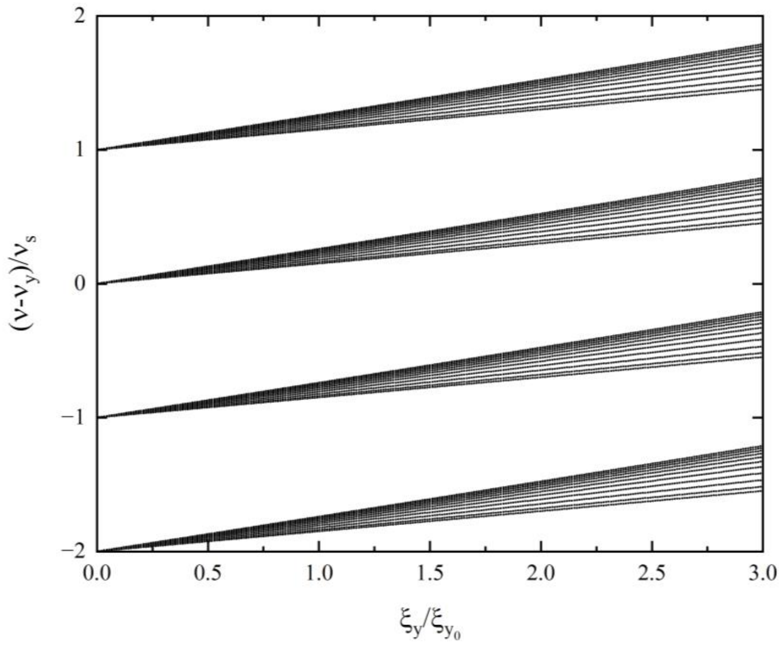
- The Float Waist collision scheme is developed based on two-sets of RFQm on both sides of the IP. The peak luminosity is partially restored, and the luminosity lifetime is significantly improved. This collision scheme can fundamentally mitigate the newfound head-tail instability.

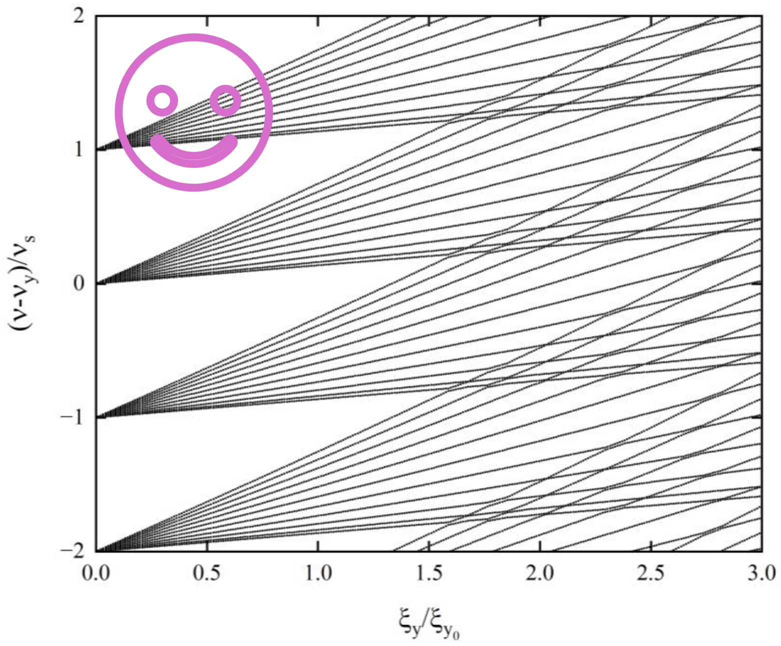
Thank you for your attention!

Back up

Modifications to coherent beam-beam kicks







Simulation results

$$\Delta Q_{coh,x,y} = \frac{N_e r_p \beta_{p,x,y}}{2\pi\gamma_p \Sigma_{x,y}(\Sigma_x + \Sigma_y)}$$

$$\Sigma_{x,y} = \sqrt{\sigma_{e,x,y}^2 + \sigma_{p,x,y}^2}$$

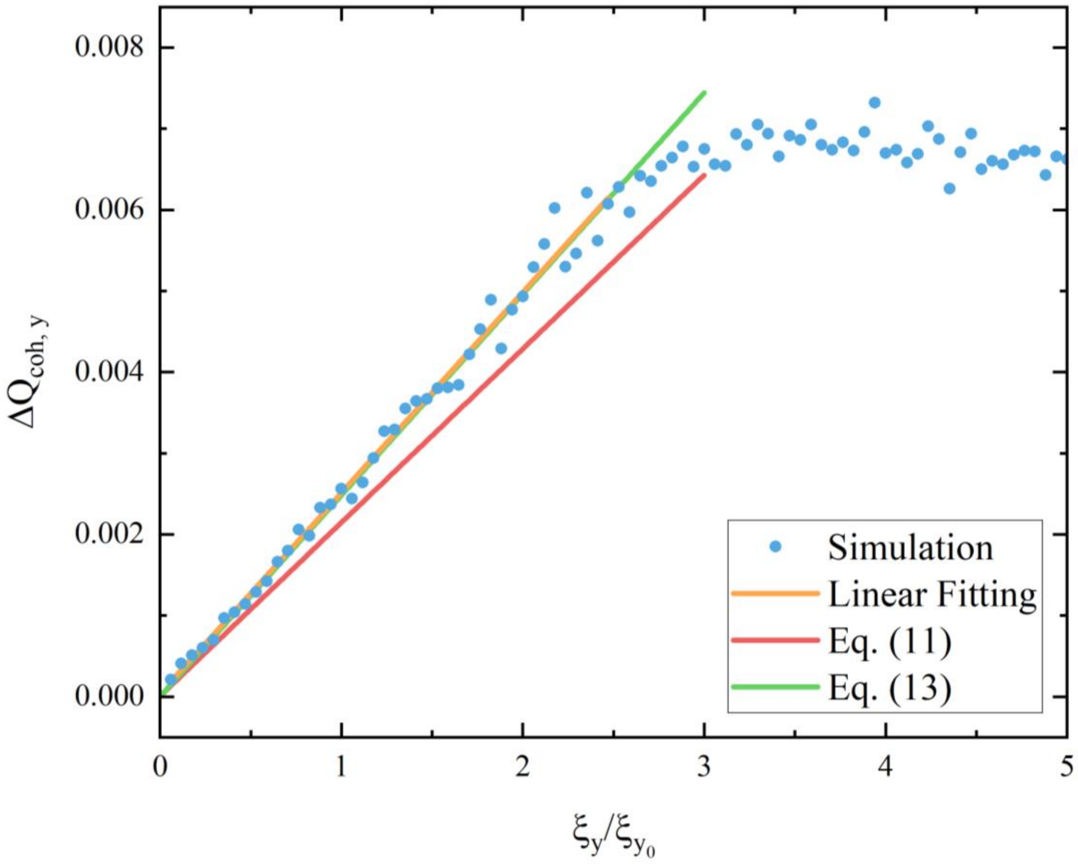
Do not consistent with simulations!

$$\Delta Q_{coh,x,y} = Y\frac{N_e r_p \beta_{p,x,y}}{2\pi\gamma_p \sigma_{e,x,y}(\sigma_{e,x} + \sigma_{e,y})}$$

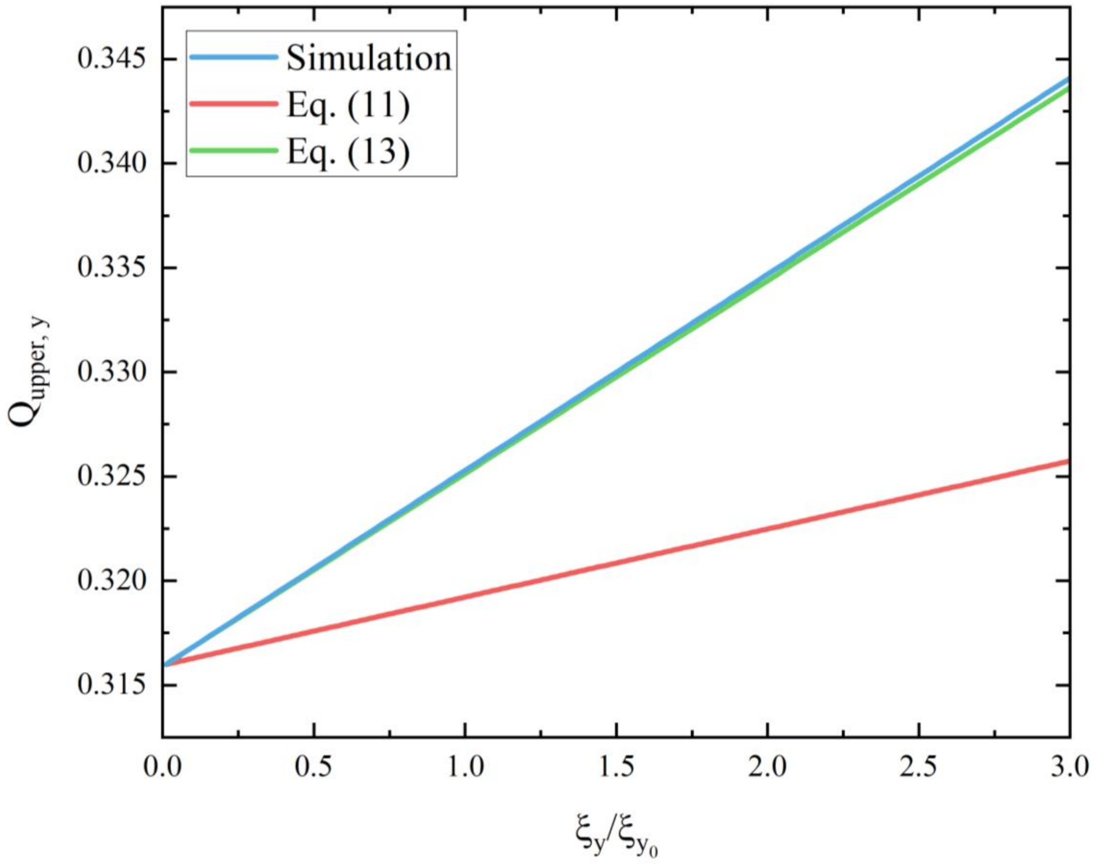
Y is the ratio of coherent tune shifts and incoherent tune shifts, Y is 0.35 in the vertical plane for old designs.

Physics? Further studies!

Modifications to coherent beam-beam kicks



Coherent mode frequency shifts obtained by tracking simulations, coherent formula, incoherent formula.



Mode frequencies of the upper bound of -1 sideband obtained by tracking simulations, coherent formula, incoherent formula.