ICFA mini workshop: Beam-Beam Effects in Circular Colliders BB24

Beam-beam effect study of crab cavity in EicC

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Outline

1. EicC layout and parameters
2. Simulation program: Athena
3. Self-consistent simulations of crab cavities in EicC
   – Effect of crab cavity on luminosity and bunch size
   – Crab cavity induced orbit effects
   – RF noise of crab cavity
   – Phase advance error
4. Summary

1. Electron-ion collider in China: EicC

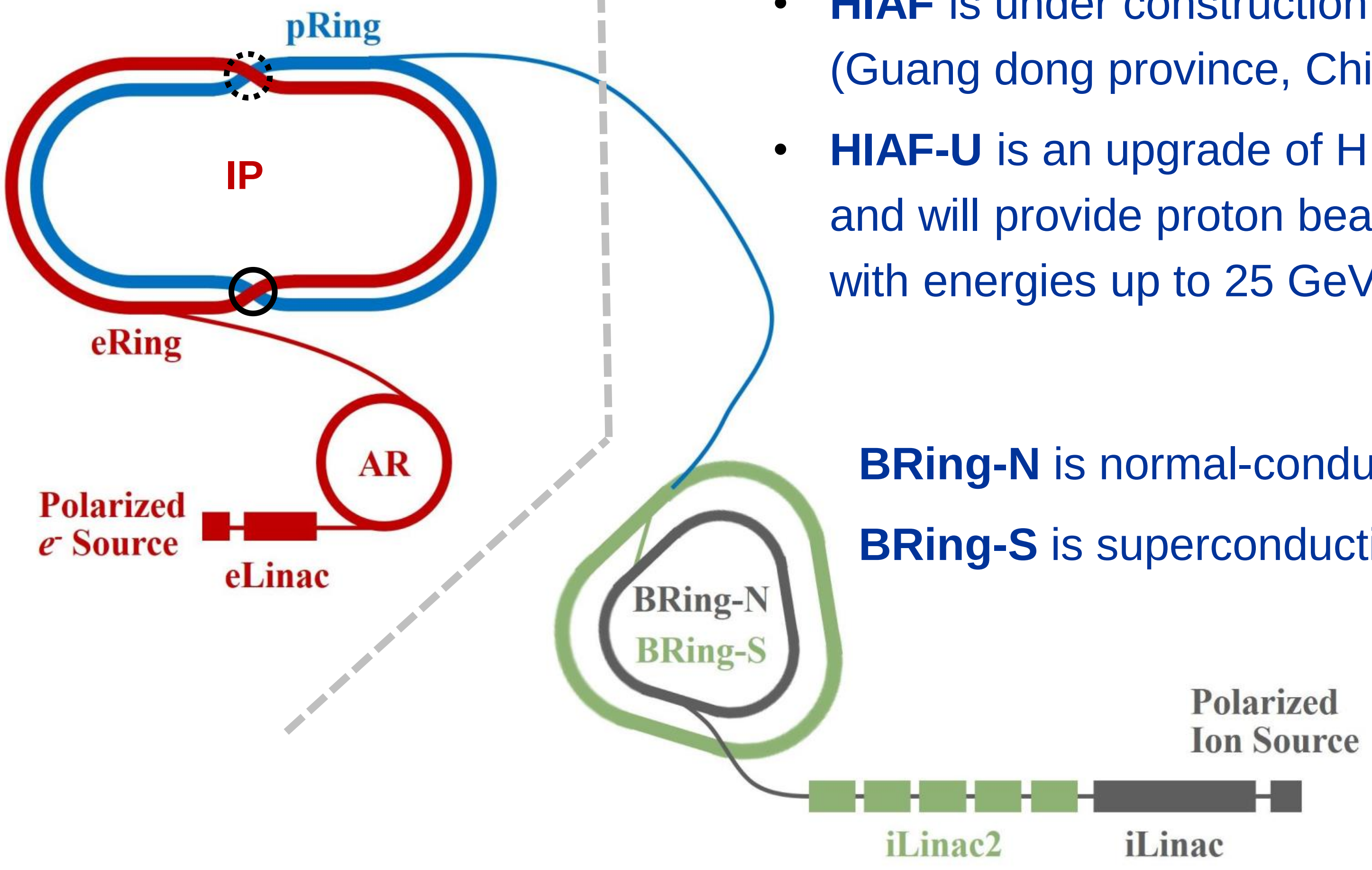
EicC

pRing
- Full energy swep-out injection
- 1149.07 m, 12 - 25 GeV

eRing
- Full energy swep-out injection
- 1151.20 m, 2.8 - 5.0 GeV

AR
- Accumulate the charge to 28 nC
- Accelerate electrons from 300 MeV to 2.8 - 5.0 GeV
- 287.80 m

eLinac and **eSource**
- Generate a 7-10 nC electron bunch and accelerate it to 300 MeV



(detailed in Jie Liu's talk)

HIAF and HIAF-U

- **HIAF** is under construction (Guang dong province, China).
- **HIAF-U** is an upgrade of HIAF and will provide proton beams with energies up to 25 GeV.

BRing-N is normal-conducting

BRing-S is superconducting

1. Main beam parameters at optimal energy

Particle	e	p
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·m)	11.7	67.2
Particles per bunch (×10^{11})	1.7	1.05
$\varepsilon_x/\varepsilon_y$ (nm·rad, rms)	50/15	100/50
β_x^*/β_y^* (cm)	10/4	5/1.2
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	-	0.066/0.105
Energy loss per turn (MeV)	1.46	-
Total SR power (MW)	3.97	-
Average Current (A)	2.7	1.68
Full crossing angle (mrad)	50	
Luminosity ($cm^{-2} \cdot s^{-1}$)	4.25×10^{33} (H=0.52)	

- **From the luminosity viewpoint, there are some important considerations:**
  - To achieve high luminosity (> 4×10^{33}) ➡ N ↑, β* ↓, ε ↓
  - But proton is low energy ➡ Space charge effect ↑
  - To mitigate the SC effect ➡ charge density λ↓, σ_z ↑
  - σ_z↑ makes the luminosity loss caused by hourglass effect and cross-collision stronger

◆ **Rh = 0.52, Rc = 0.035**

$$\mathcal{L} = \frac{N_1 N_2 f_c}{2\pi\sqrt{\sigma_{1x}^2+\sigma_{2x}^2}\sqrt{\sigma_{1y}^2+\sigma_{2y}^2}} R$$

$$\xi_{x,y}^{\pm} = \frac{N^{\mp} r_0^{\pm} \beta_{x,y}^{*\pm}}{2\pi\gamma^{\pm}\sigma_{x,y}^{\mp}(\sigma_x^{\mp}+\sigma_y^{\mp})}$$

Hourglass factor Rh

$$R_h = \int_{-\infty}^{+\infty} \frac{1}{\sqrt{\pi}} \frac{\exp(-t^2)}{\sqrt{(1+t^2/t_x^2)(1+t^2/t_y^2)}} dt$$

$$t_u^2 = \frac{2(\sigma_{1u}^2+\sigma_{2u}^2)}{(\sigma_{1s}^2+\sigma_{2s}^2)(\sigma_{1u}^2/\beta_{1u}^2+\sigma_{2u}^2/\beta_{2u}^2)} \quad (u = x, y)$$

Crossing factor Rc and Piwinski angle θp:

$$R_c = \frac{1}{\sqrt{1+\theta_p^2}}$$

$$\theta_p = \frac{\sigma_z}{\sigma_x}\theta_{half}$$

EicC proton: θp=28.3

1. Recovery of geometric luminosity loss

- **Hourglass:**
  - Use RFQs to modulate the longitudinal position of the beam waist near the collision point
  - Lumi.: from ~ $4\times10^{33}\text{cm}^{-2}\text{s}^{-1}$ to > $6\times10^{33}\text{cm}^{-2}\text{s}^{-1}$ (float waist scheme, detailed in Lei Wang's talk)
- **Crossing angle:**
  - Use local crab cavities (CC) to recover the geometric luminosity loss

Crab cavity kick

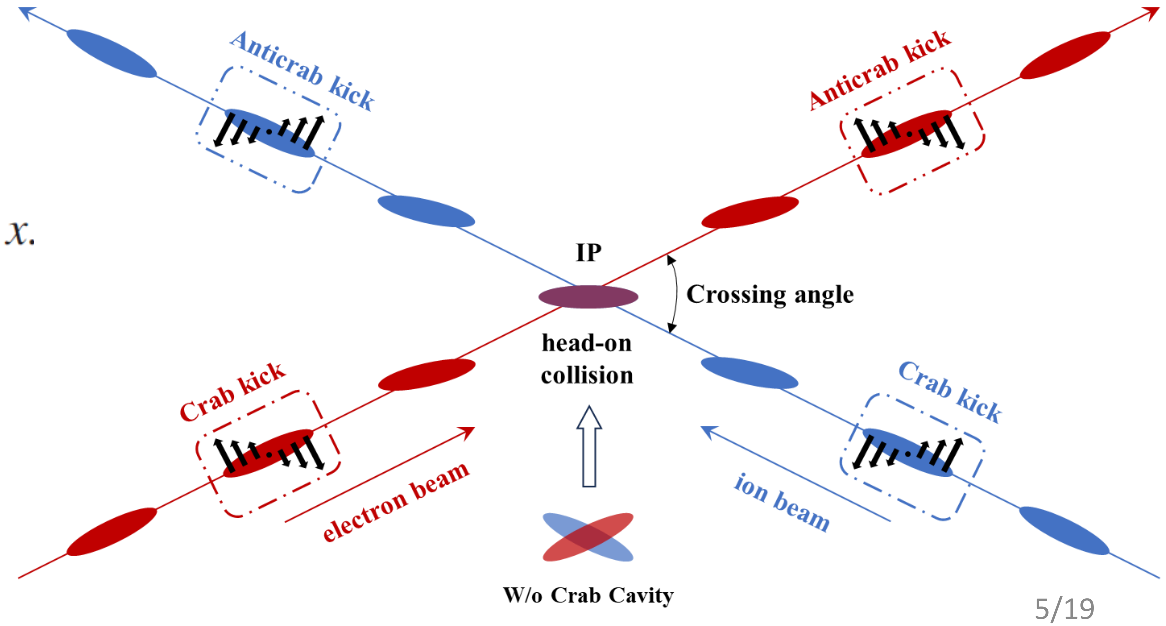
$$\Delta p_x = -\frac{\partial H_{\text{crab}}}{\partial x} = -\frac{qV}{P_s}\cdot\sin\left(\phi_s + \frac{\omega z}{c}\right)$$

$$\Delta p_z = -\frac{\partial H_{\text{crab}}}{\partial z} = -\frac{qV}{P_s}\cdot\cos\left(\phi_s + \frac{\omega z}{c}\right)\cdot\frac{\omega}{c}\cdot x.$$

Crab cavity voltage

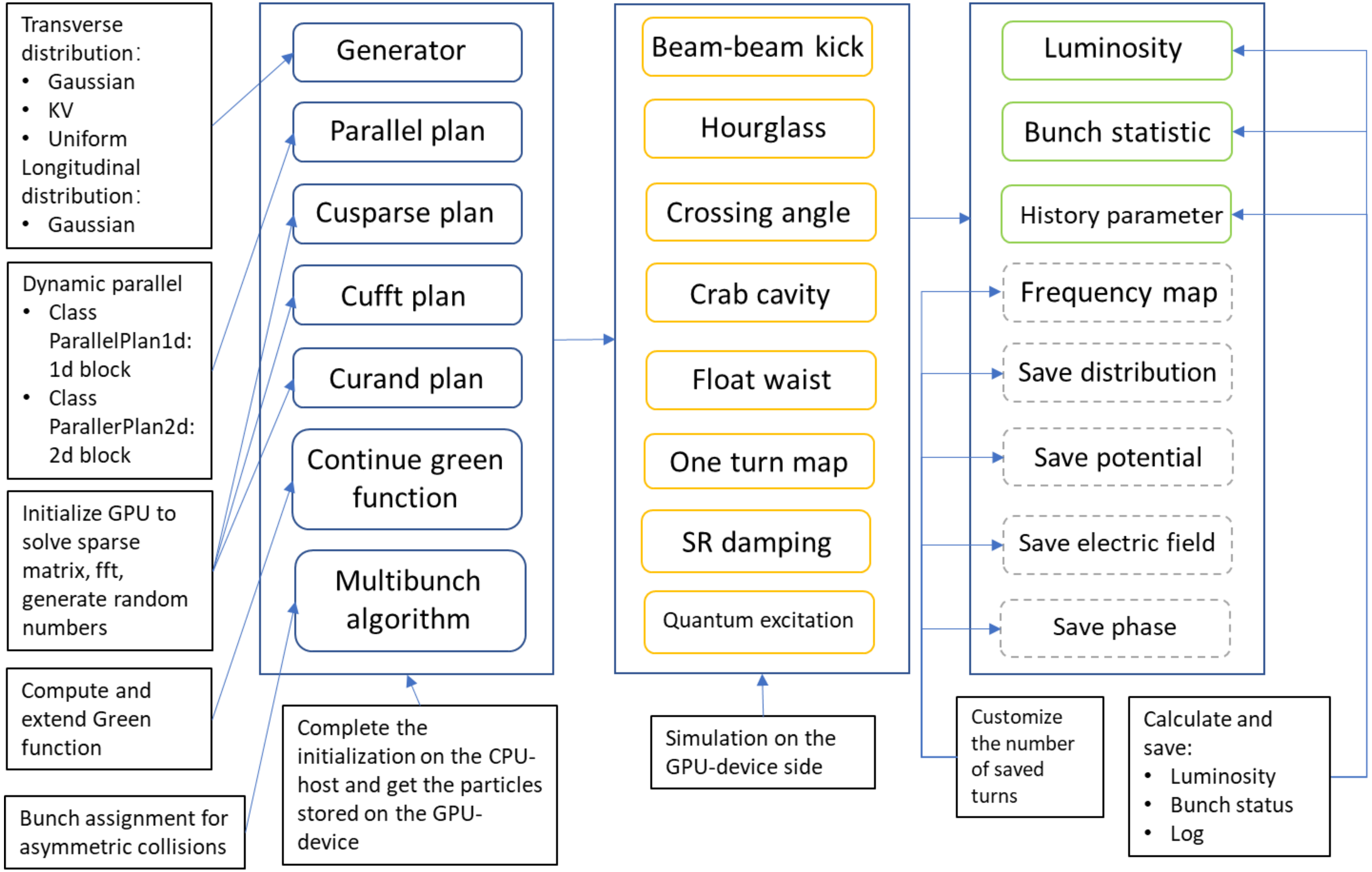
$$V_1 = \frac{c^2\cdot p_s\cdot\tan(\frac{\theta}{2})}{q\cdot\omega\cdot\sqrt{\beta^*\cdot\beta_{\text{crab}}}\cdot\sin(\Delta\varphi_0)}$$

$$V_2 = -R_{22}\cdot V_1$$



2. Simulation program: Athena

- **Athena is a gpu-based simulation program**



The complete bb map:

$$
\begin{aligned}
M \quad &= (T_{RFQ2}^{-1} M_{RFQ2} T_{RFQ2}) \\
&\cdot (T_{cc2}^{-1} M_{cc2} T_{cc2}) \\
&\cdot L^{-1} M_{bb} L \\
&\cdot (T_{cc1} M_{cc1} T_{cc1}^{-1}) \\
&\cdot (T_{RFQ1} M_{RFQ1} T_{RFQ1}^{-1})
\end{aligned}
$$

M: kick maps of beam-beam, crab cavity and RFQ

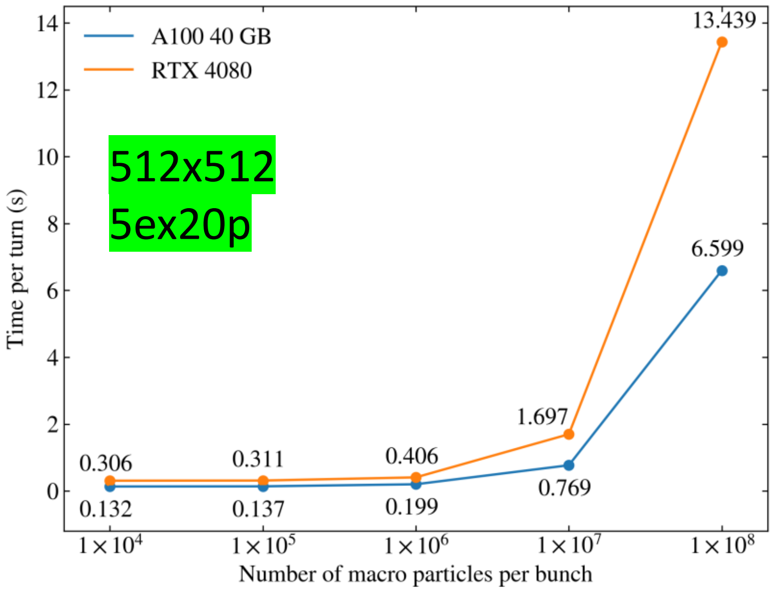
T: transfer maps between IP and cc, IP and RFQ

L: Lorentz transfer map

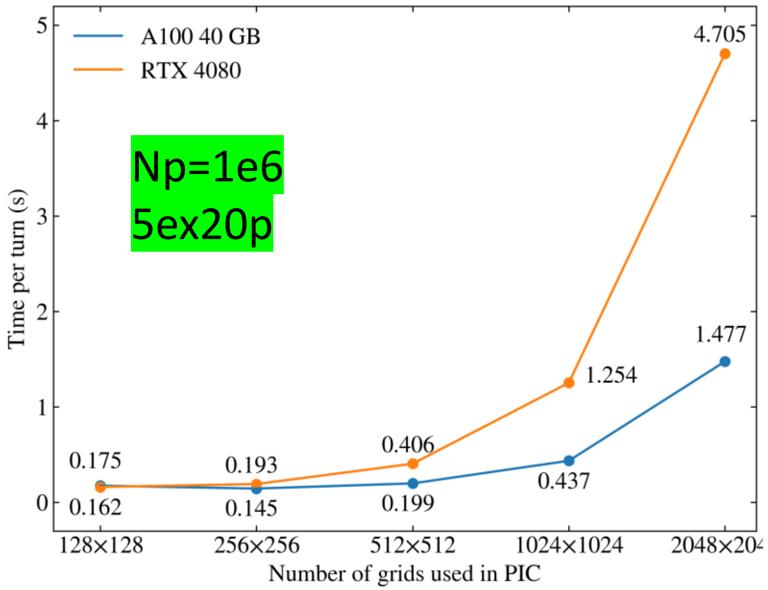
2. Performance test of Athena

- In the macro particle number testing, computational performance is limited by double-precision computing speed (Np≤1e7) and bandwidth (Np=1e8).
- In the grid number testing, computational performance is limited by double-precision computing speed (Np>1e7).
- In the slice number testing, when the number of calculations >100, the performance is mainly limited by the data transmission bandwidth.

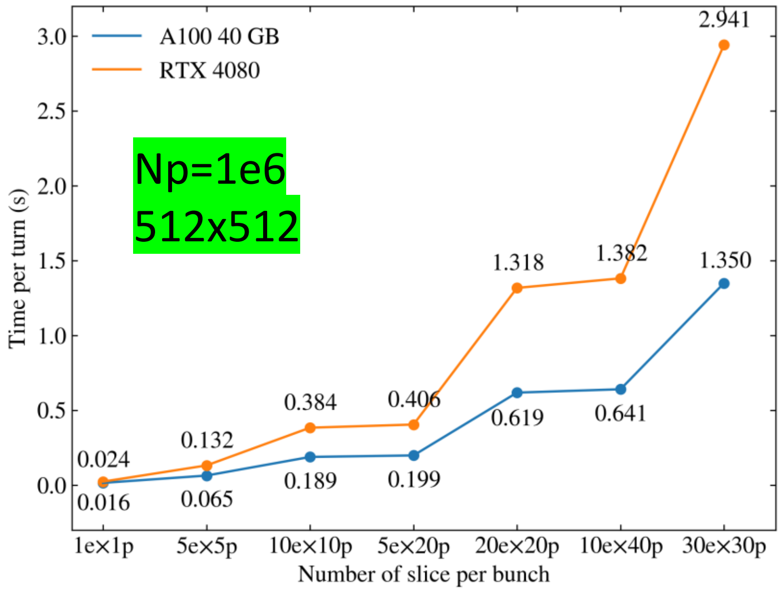
Macro particle number testing



Grid number testing



Slice number testing

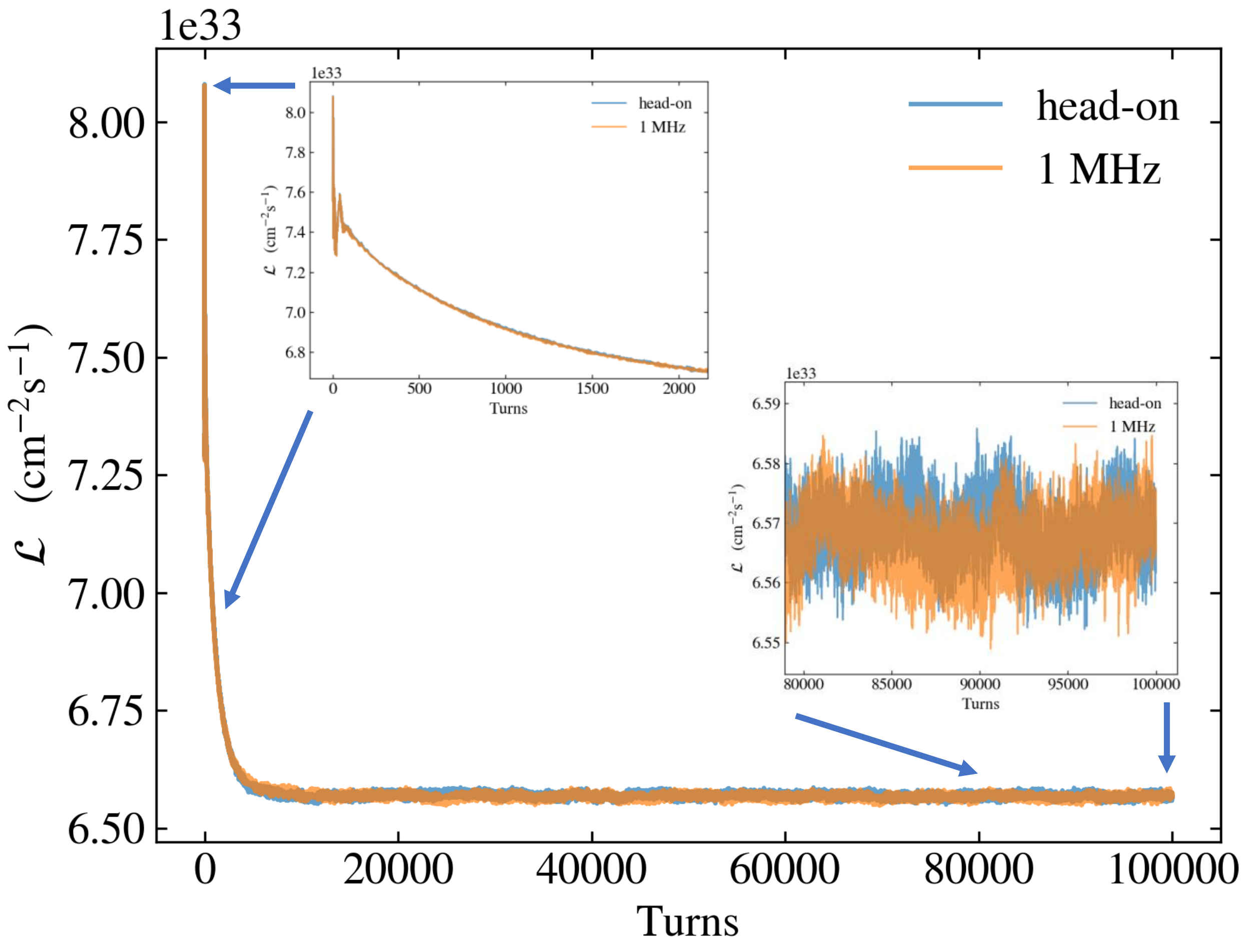


Athena shows good computing performance.

2. Simulation results verification and simulation parameters

- When the crab cavity frequencies of both the proton and electron beams are 1 MHz, their effects can be considered linear, and the simulated luminosity is the same as that in the head-on case.

Verify the correctness of crab cavity calculation



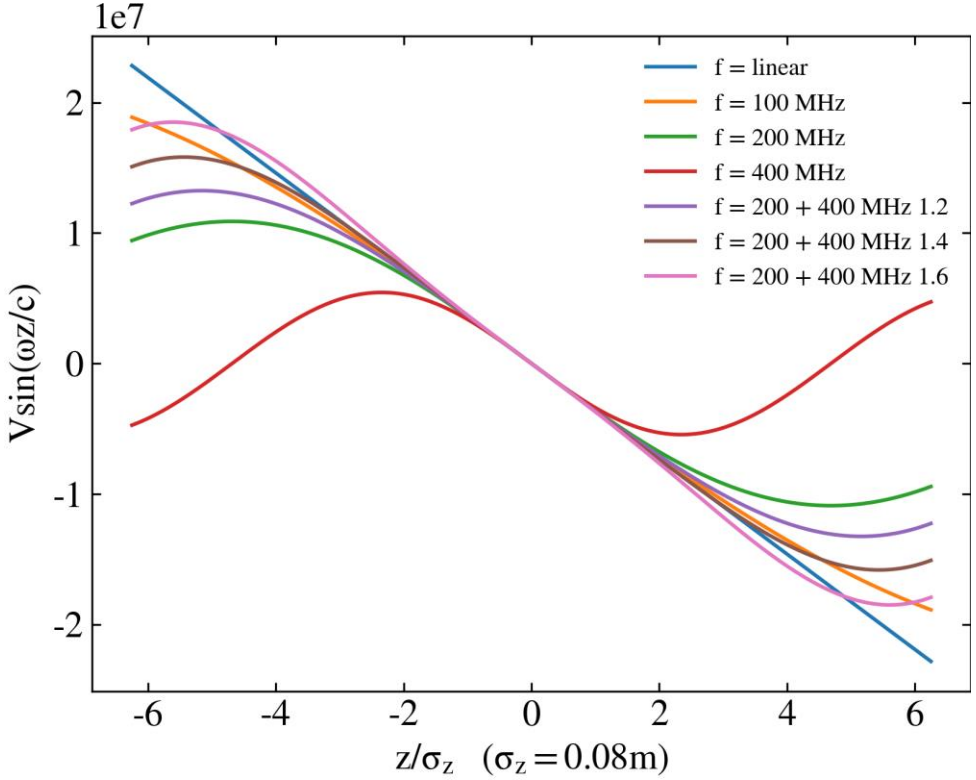
Parameters used in strong-strong simulation

Particle	e	p
# macro particles Np	1e6 /1e7 (growth rate)	
# grid size Nx/Ny	512/512	
Grid length Lx/Ly	10e-6/3.5e-6	
Number of slice	5	20
Hor. Damping turns	4000	-
$\varepsilon_x/\varepsilon_y$ (nm·rad, rms)	50/15	100/50
β_x^*/β_y^* (cm)	10/4	5/1.2
Bunch length (cm, rms)	0.75	8
Δp (‰)	0.65	1.62
Qx/Qy/Qz	0.08/0.06/0.035	0.31/0.32/0.0125
β_x at cc (1/2 pi) (m)	800	2400
β_x/β_y at RFQ (1/2 pi) (m)	-	2400/1200
β_x/β_y at RFQ (3/2 pi) (m)	-	532.36/21.82

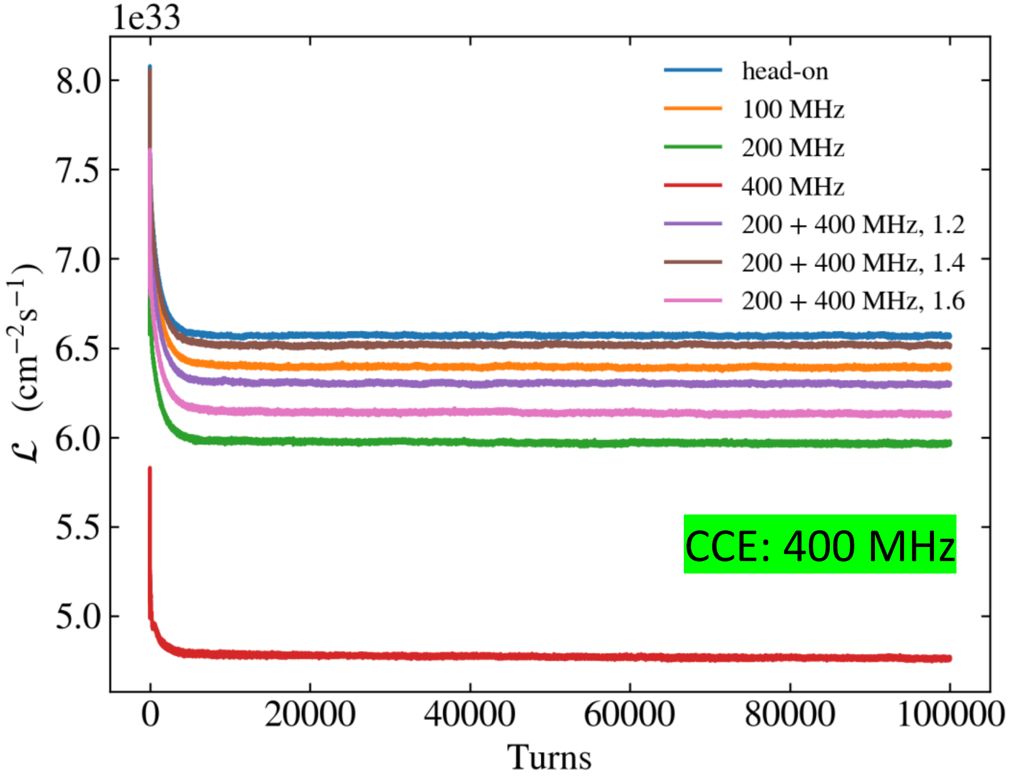
3. Simulation of different proton crab cavity (CCP) frequencies

- Due to the long length of proton bunch, the impact of the non-linear crabbing force of the crab cavity is very obvious. The lower the frequency, the better the linearity, but also the larger the cavity size.
- Although the beams are stable in these simulations, in order to achieve high luminosity, for CCP, 100MHz and 200+400MHz (1.4) are better.

Voltage waveform at different CCP frequency



Lumi. at different CCP frequencies.

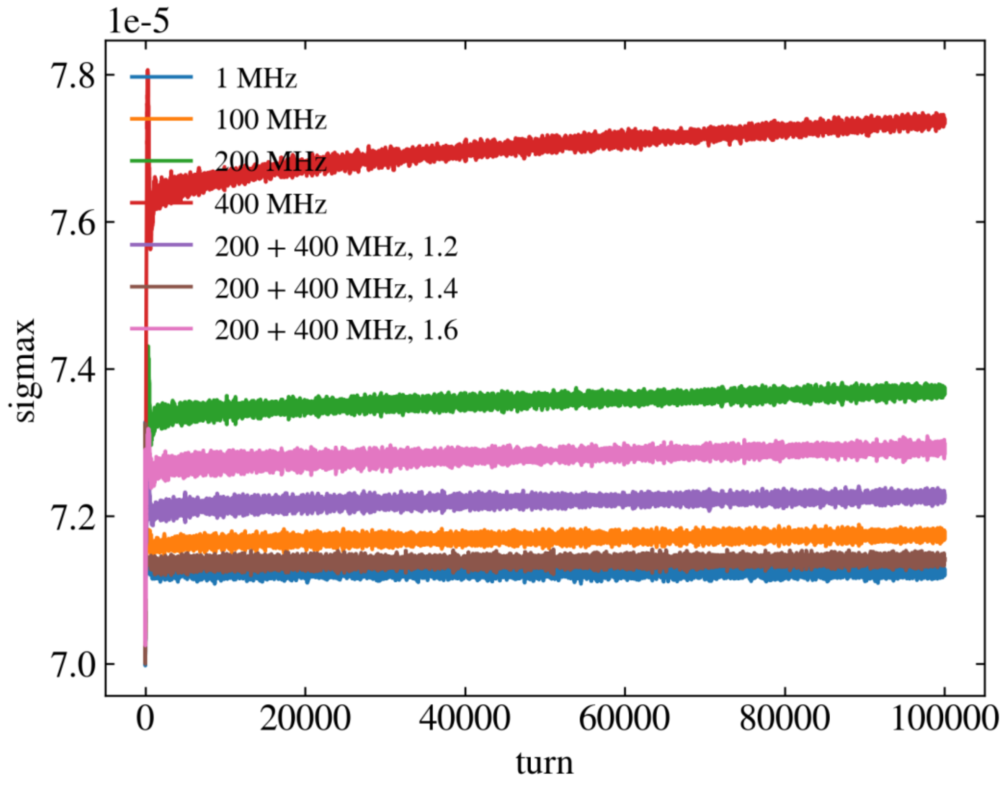


When the second harmonic cavity is used, 1.2, 1.4, 1.6 indicates that the crabbing angles of the 200 MHz crab cavity are 1.2θ, 1.4θ, and 1.6θ, and the crabbing angles of the 400 MHz crab cavity are -0.2θ, -0.4θ, and -0.6θ.

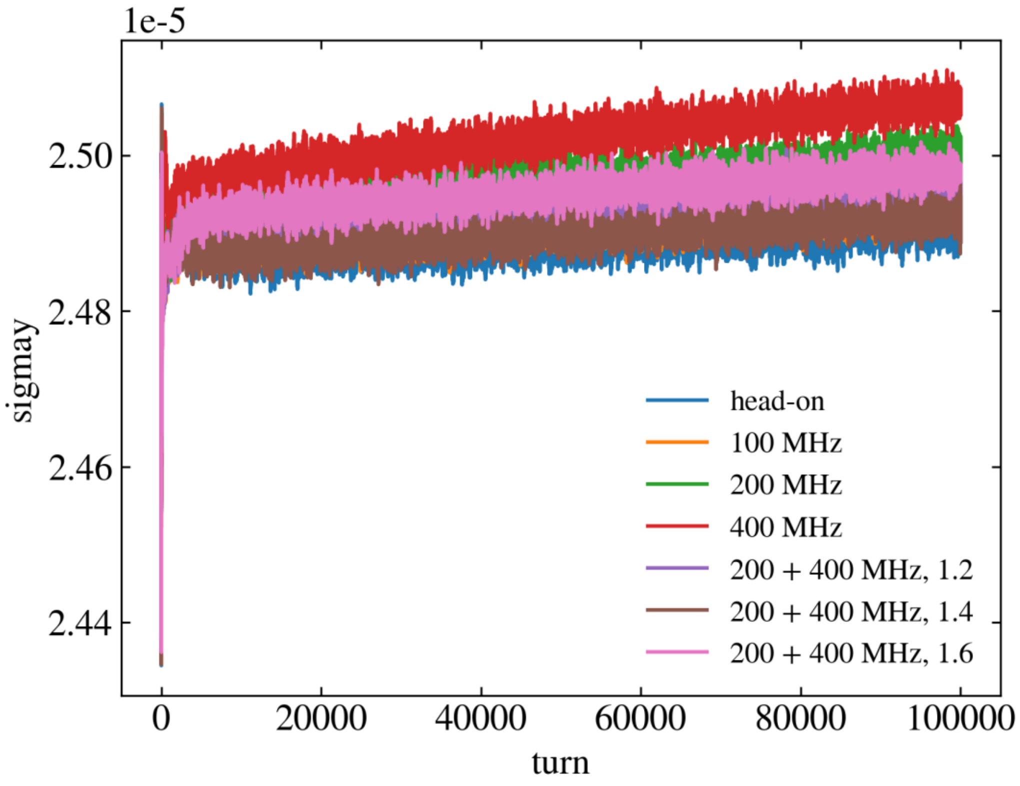
3. Simulation of different CCP frequencies

- When the frequency of CCP increases, the horizontal equilibrium size of the proton bunch will increase, and the growth rate will be faster.
- Although the crab cavity will not directly affect the particle in the vertical direction, changes in horizontal distribution will eventually change the growth rate of the vertical bunch size.

σx of proton bunch at different CCP frequencies.



σy of proton bunch at different CCP frequencies.

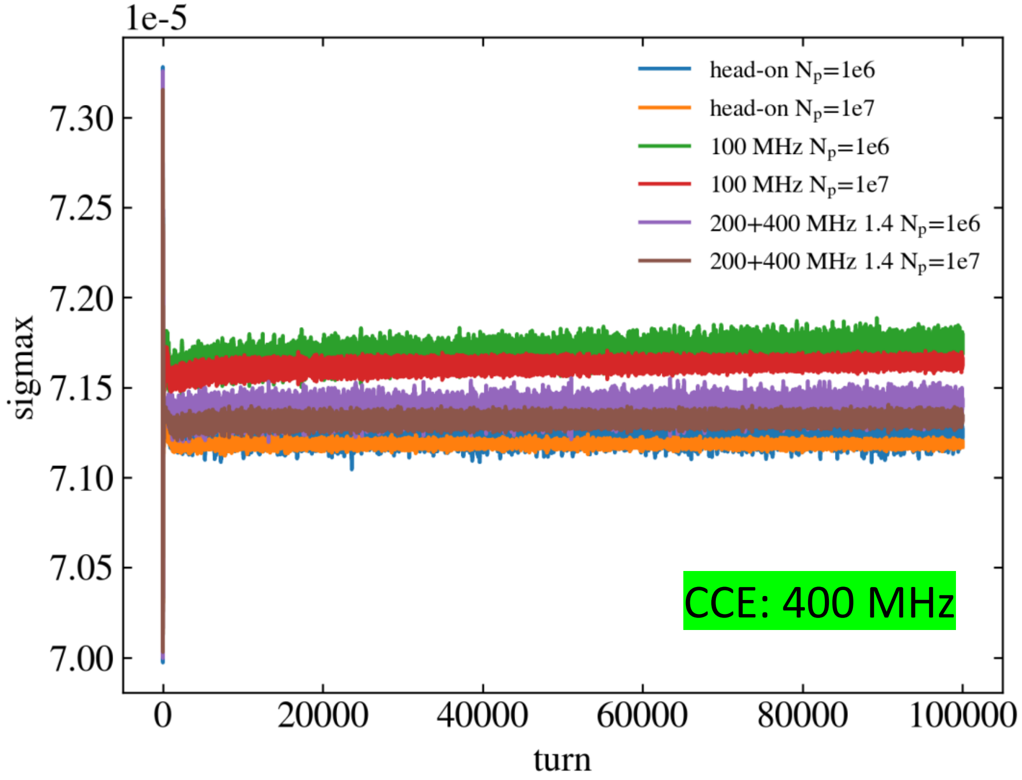


CCE: 400 MHz

3. Simulation of different CCP frequencies

- The effects of numerical noise caused by PIC calculation on bunch size growth rate and luminosity degradation rate are obvious.
- Increasing the number of macro particles can reduce the numerical noise (but severely reduce the calculation speed, use the spectral method, etc.).

The impact of macro particle # on numerical noise



Linear fit to data from turns 50k to 100k

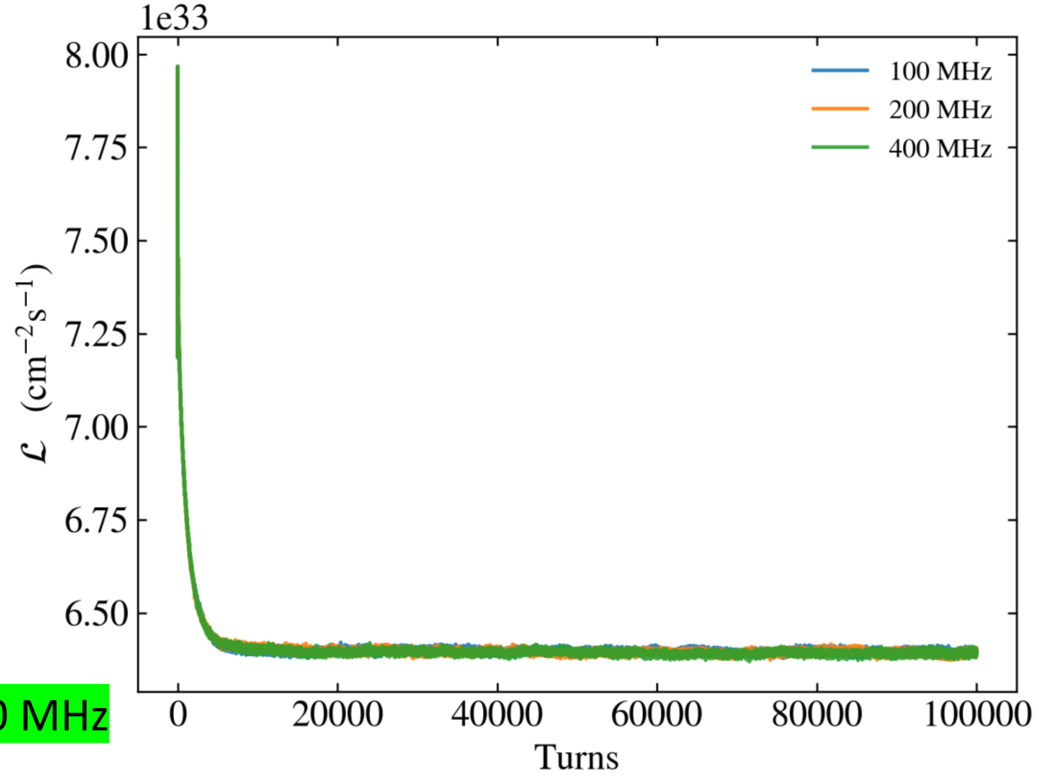
Linear fit of bunch size growth	
Head-on σx	0.05%/min
Head-on σy	4.02%/min
100 MHz σx	7.69%/min
100 MHz σy	7.73%/min
200+400 MHz (1.4) σx	3.51%/min
200+400 MHz (1.4) σy	6.46%/min

EicC adopts rapid cycling mode to replace all proton bunches in ~ minutes

3. Simulation of different electron crab cavity (CCE) frequencies

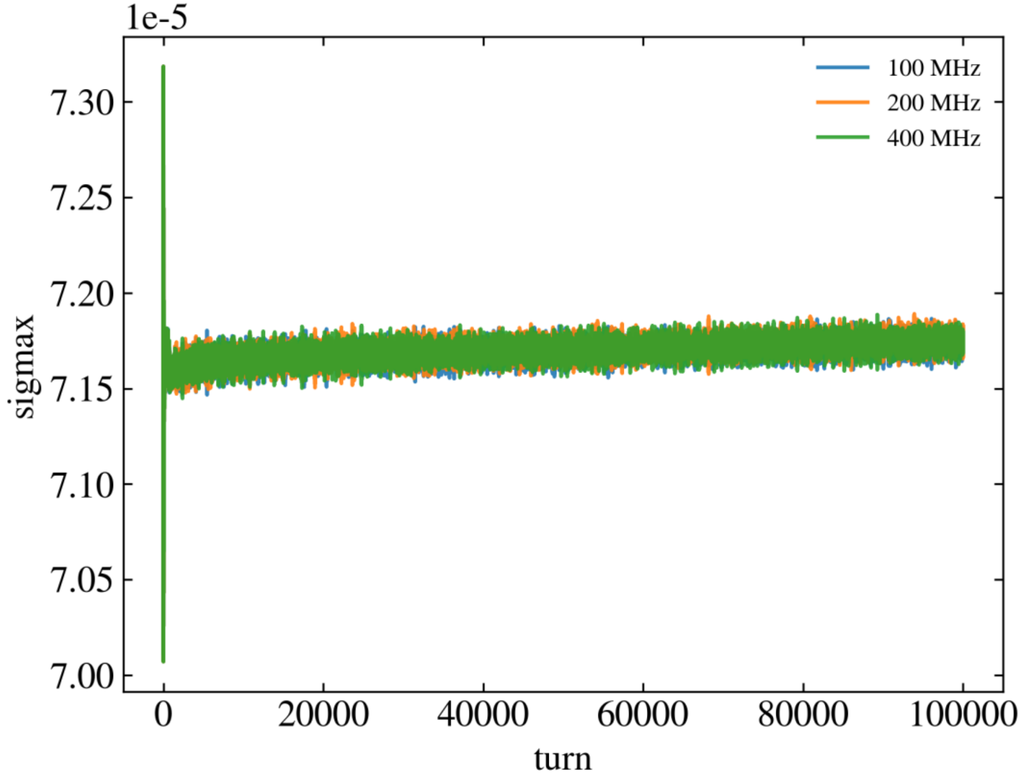
- When the CCP frequency is 100 MHz, the luminosity obtained from the simulations at different CCE frequencies is essentially the same, and the growth rate of the proton bunch size is also similar.

Lumi. at different CCE frequencies.



CCP: 100 MHz

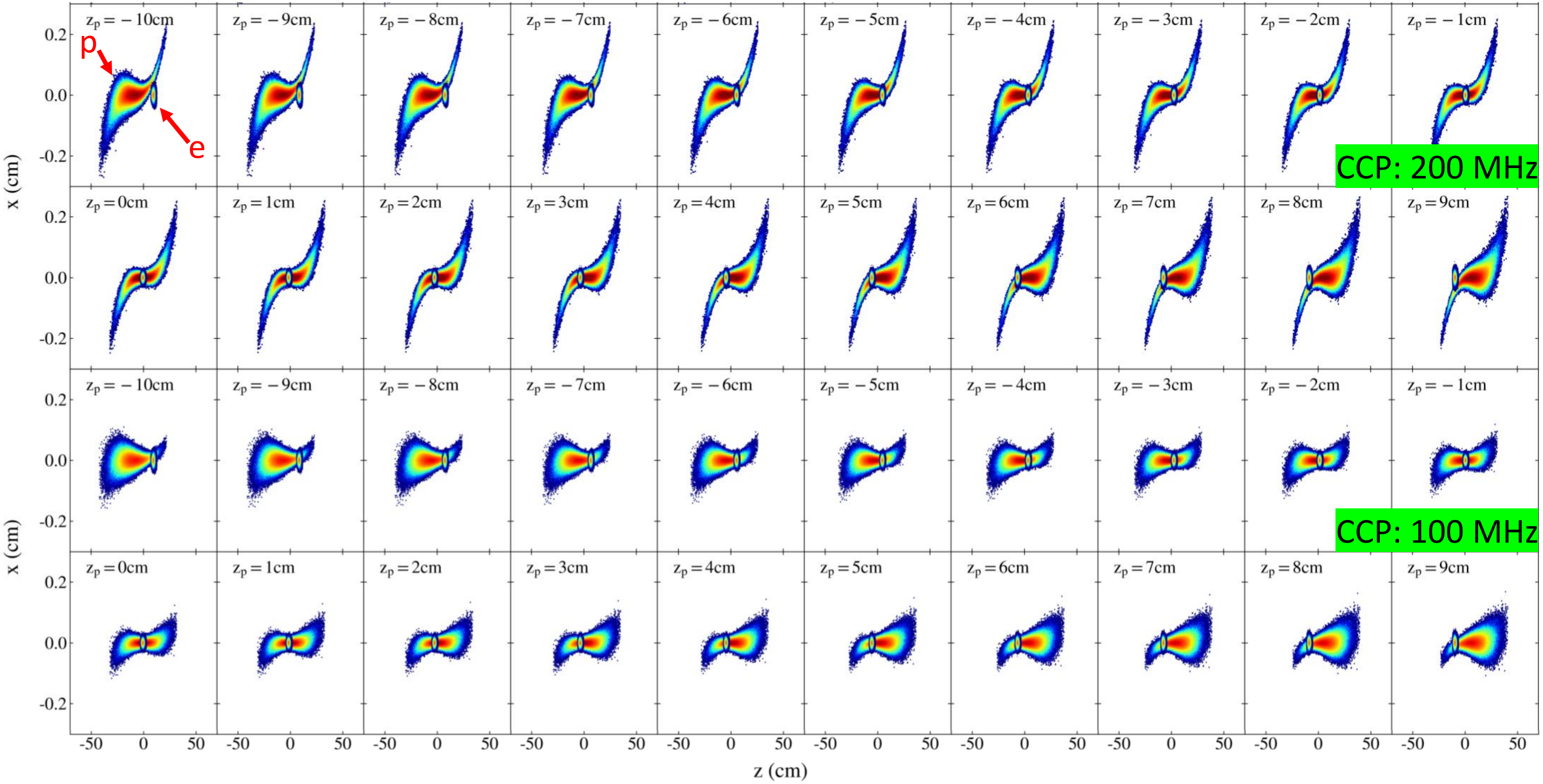
σx of proton bunch at different CCE frequencies.



➢ The crabbing force at 400 MHz is already quasi-linear for electron bunch. In order to reduce the cavity size, the CCE of EicC will adopt a frequency of 400MHz.

3. Crab cavity induced orbit effects

- The particles at the head and tail of the proton bunch that are not completely crabbed will apply a dipole force on the electron bunch, causing the center of mass of the electron bunch to change.



$$\Delta x' = \frac{\text{const}}{d} \cdot \left[1 - \frac{x}{d} + o\left(\frac{x^2}{d^2}\right)\right]$$

Fig. z-x distribution at different collision points

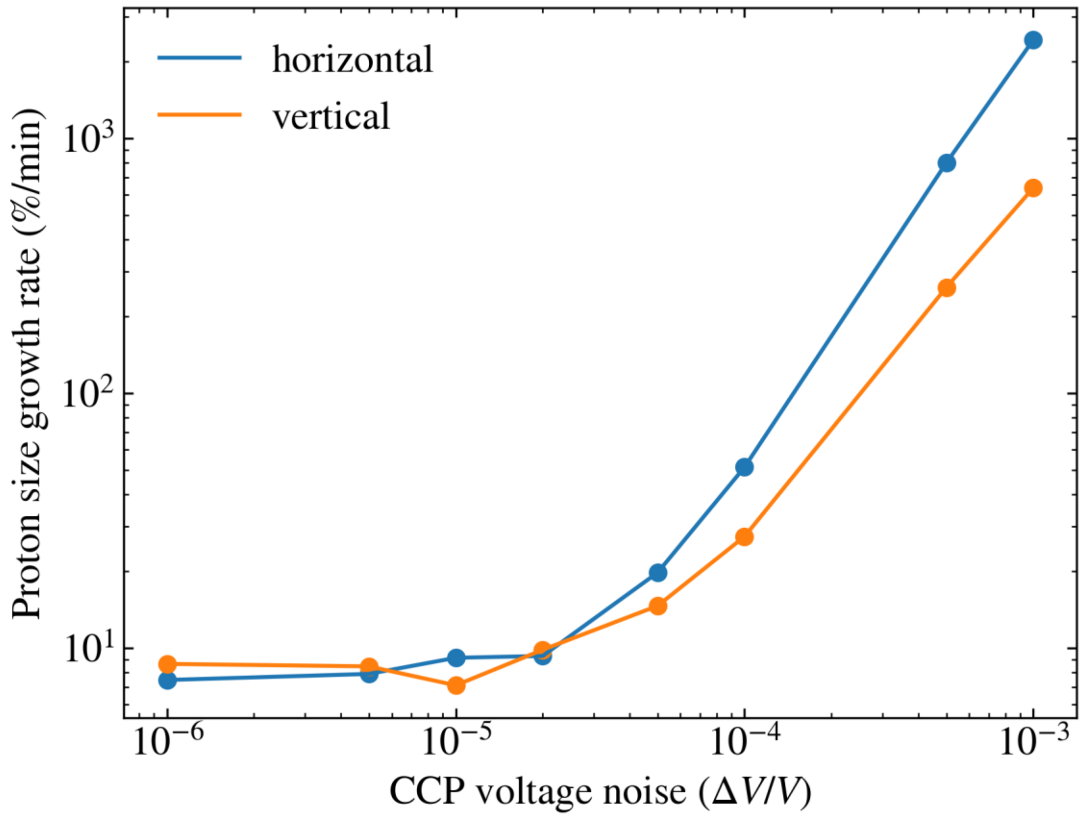
The electron bunch center position at IP:
100 MHz, $\overline{x}_e$=1.7μm
200 MHz, $\overline{x}_e$=3.6μm
400 MHz, $\overline{x}_e$=3.7μm

3. White noise of CCP's RF voltage and phase

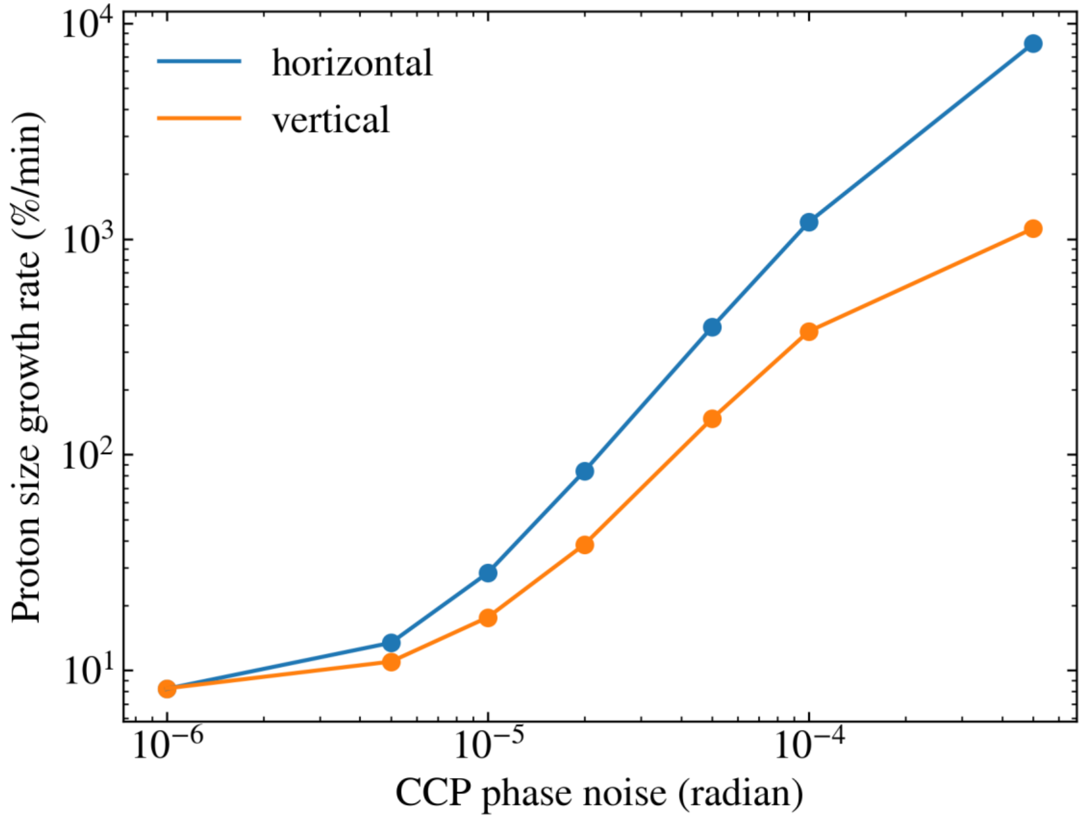
- Voltage errors cause the bunch distribution to become tilted at the IP, and phase errors cause the bunch center to have a transverse offset at the IP.

$$\delta x \approx \frac{c}{\omega} \tan(\theta_c/2)\delta\phi \qquad \delta x_i \approx \frac{\delta V}{V} \sin(\omega z_i^n/c + \phi)$$

Proton size growth rate vs. CCP voltage noise amp.



Proton size growth rate vs. CCP phase noise amp.



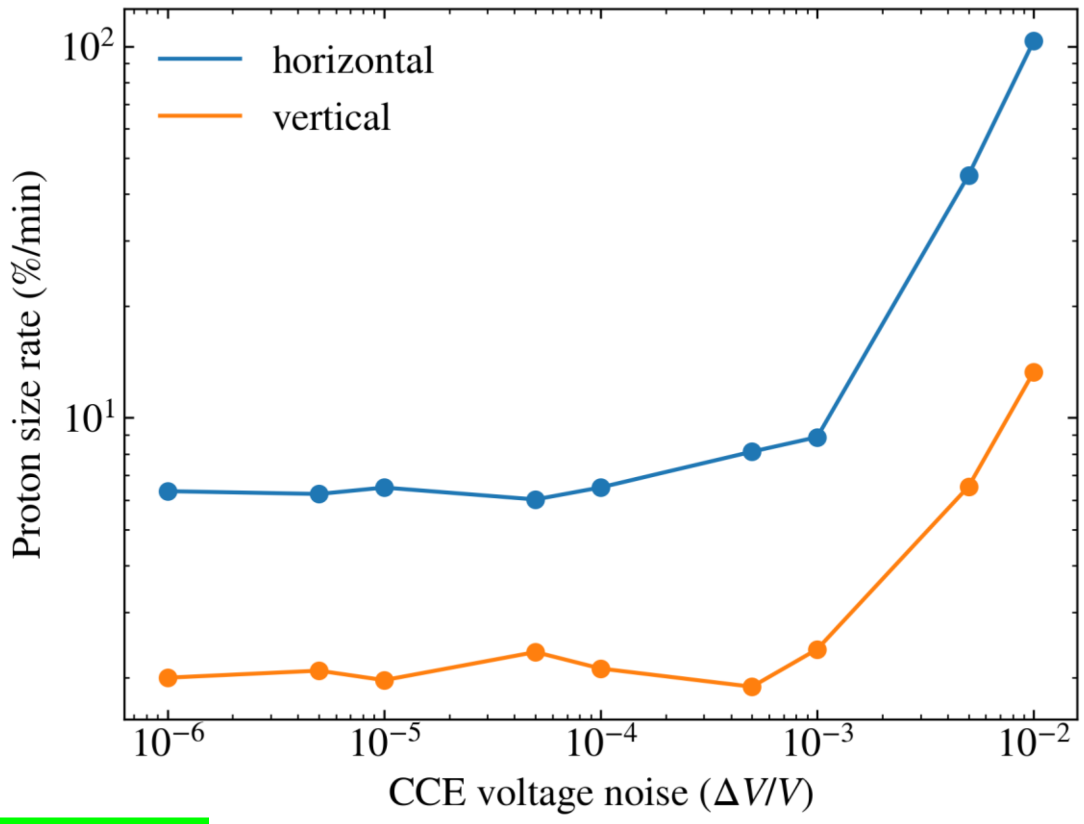
CCP: 100 MHz
CCE: 400 MHz

CCP RF white noise tolerance level: voltage ~ 1x10^{-5}, phase ~ 1x10^{-6}

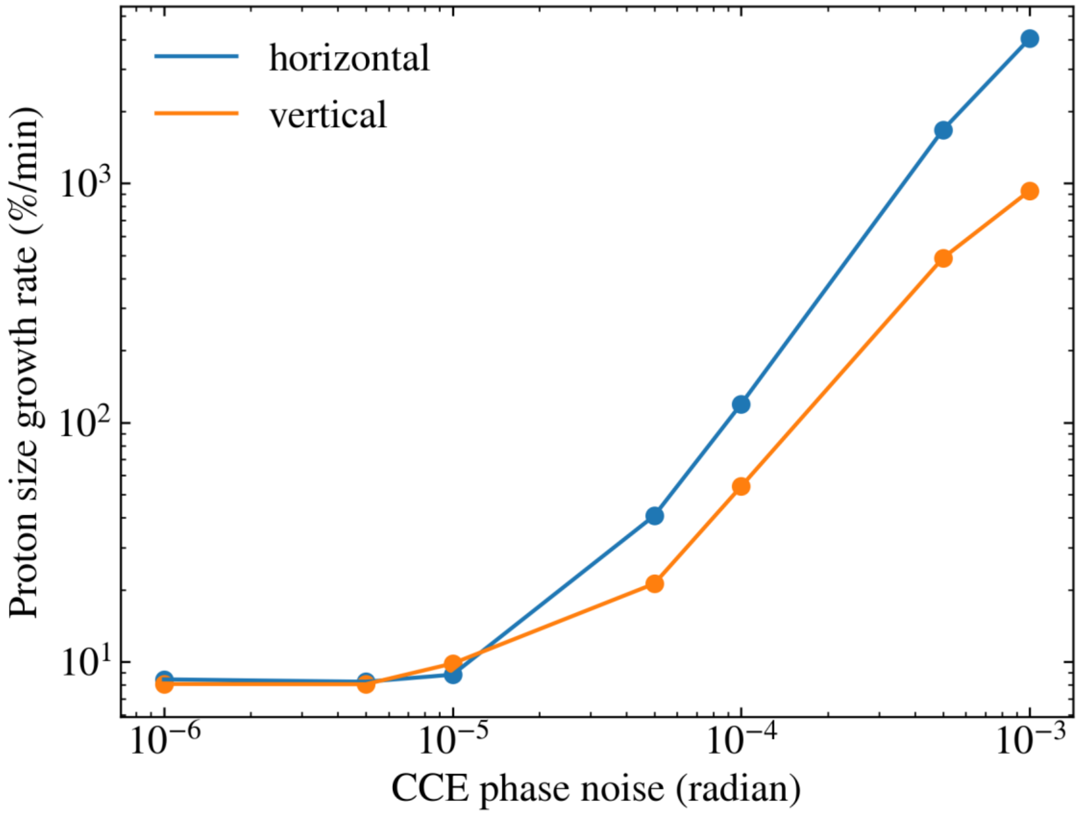
3. White noise of CCE's RF voltage and phase

- Due to the damping effect of synchrotron radiation, the electron beam has a greater tolerance to crab cavity noise.

Proton size growth rate vs. CCE voltage noise amp.



Proton size growth rate vs. CCE phase noise amp.



CCP: 100 MHz
CCE: 400 MHz

CCE RF white noise tolerance level: voltage ~ 1x10^{-3}, phase ~ 1x10^{-5}

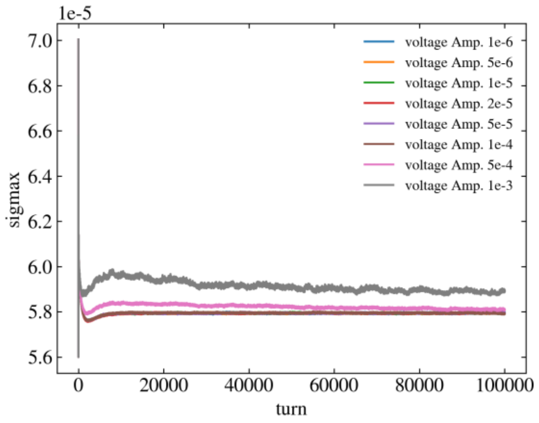
3. White noise of CCP and CCE's RF voltage and phase

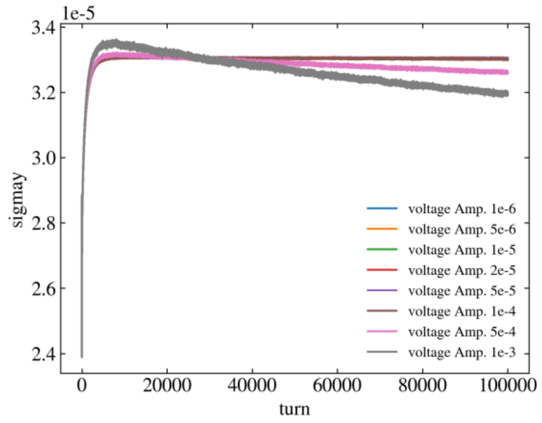
- As long as the RF white noise of CCP and CCE does not exceed the threshold we mentioned earlier, the electron bunch size will not increase significantly.

CCP: 100 MHz
CCE: 400 MHz

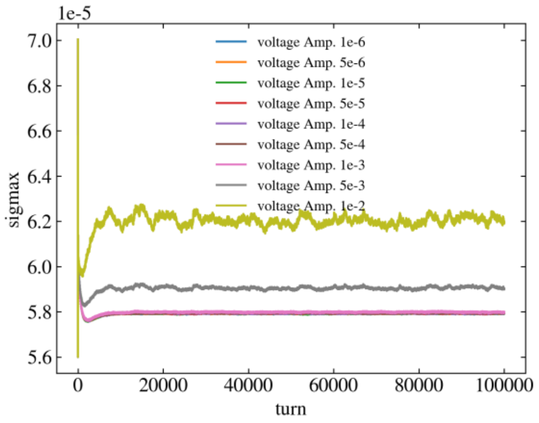
Electron bunch size at different CCP RF noise

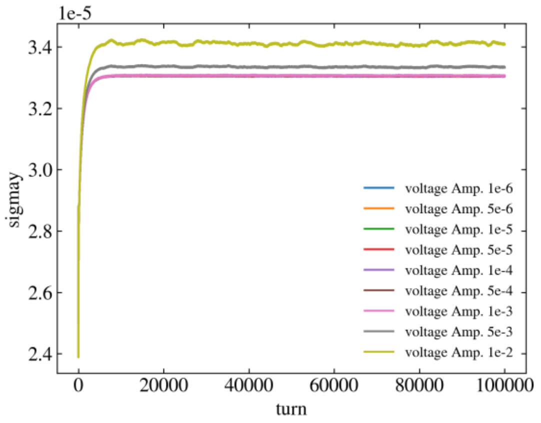
Electron bunch size at different CCE RF noise

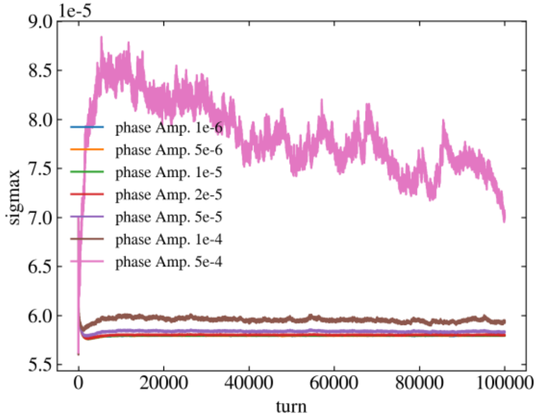


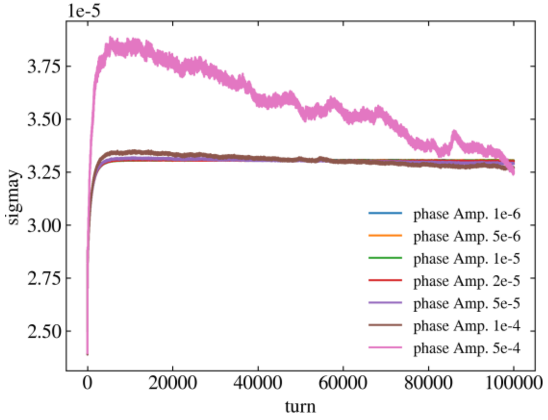


Voltage noise

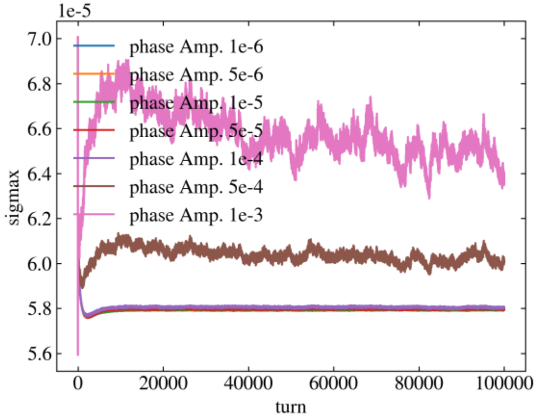


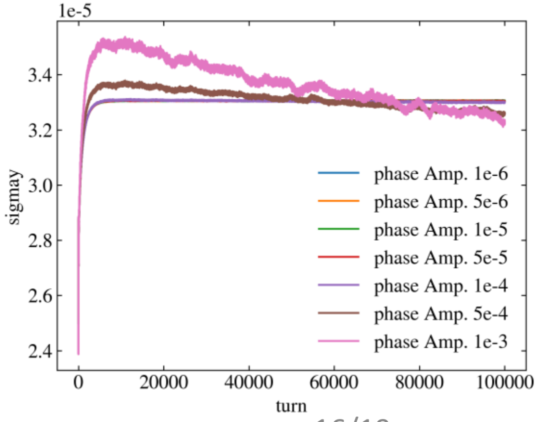






Phase noise

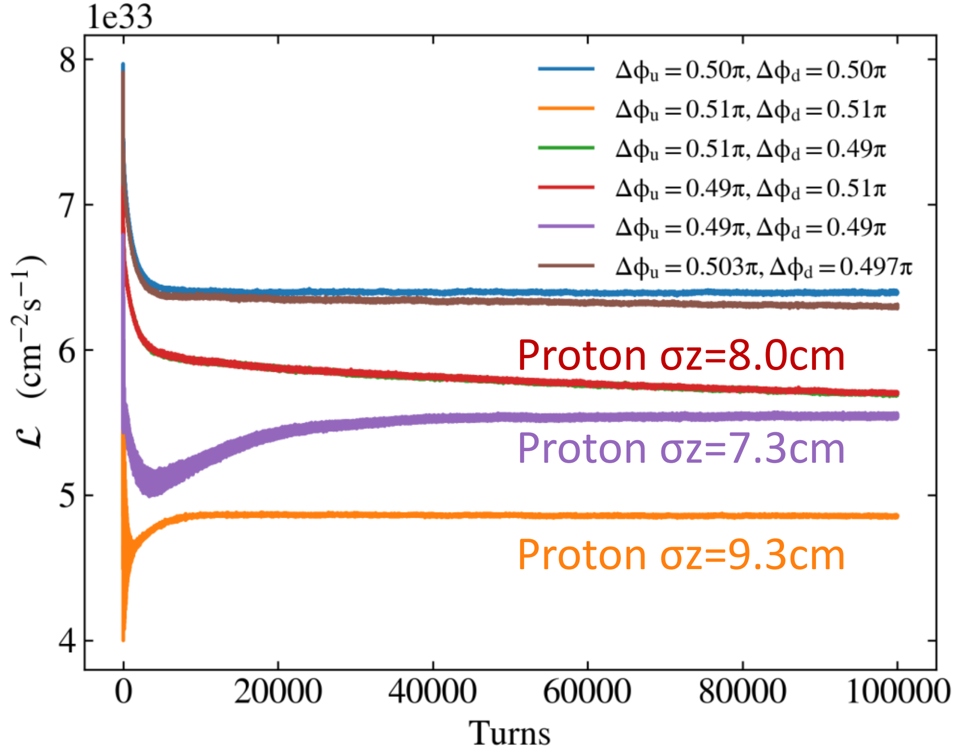




3. CCP phase advance error

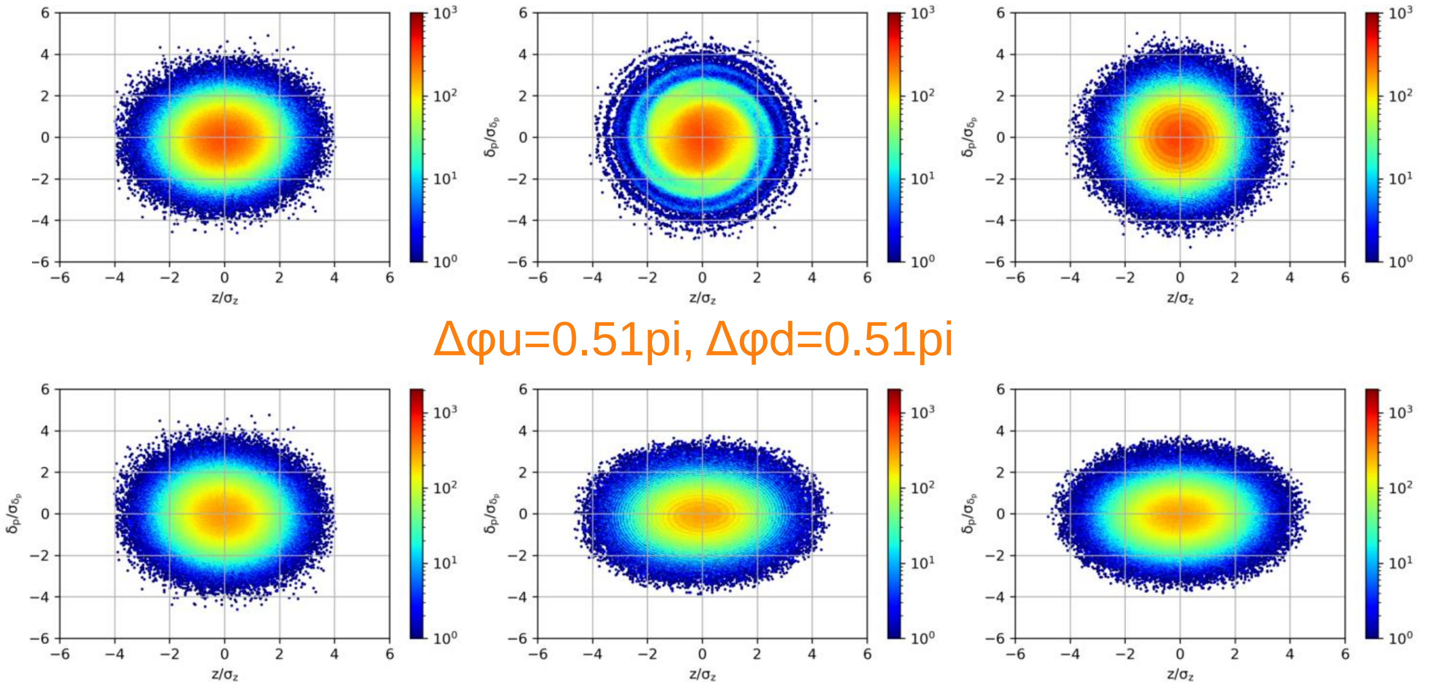
- When the phase advances between the two crab cavities and IP are less than pi/2, the bunch length will be compressed, otherwise it will be stretched.
- When the phase advance between the two crab cavities is pi, the bunch length will not be changed. For CCP, the phase shift error of any crab cavity cannot exceed 0.2°.

Lumi. at different CCP phase advance



Proton z-x dist. at different CCP phase advance

Δφu=0.49pi, Δφd=0.49pi

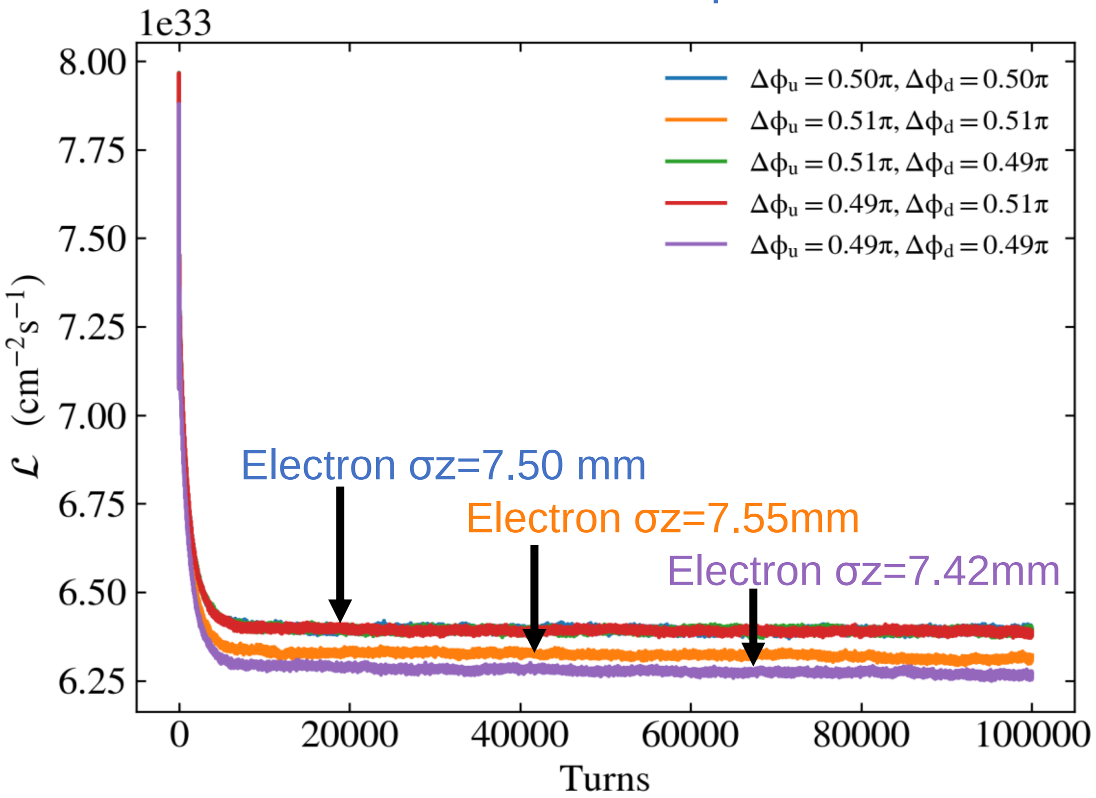


Turn 1 Turn 10k Turn 100k

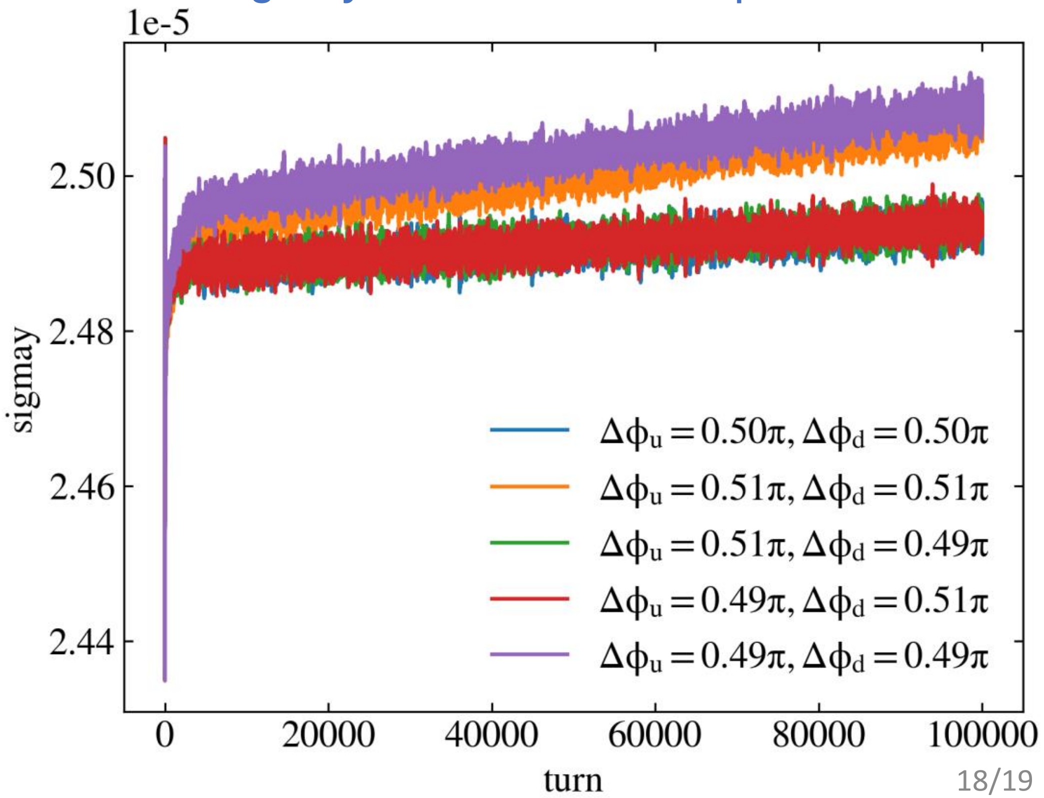
3. CCE phase advance error

- For electron beam, the phase advance error of the crab cavity will also affect the bunch length and luminosity, but the effect is weaker than that of the proton crab cavity.
- When the phase advance between the two crab cavities is pi, even if the phase advance error of a single crab cavity is 0.1pi, it will not have a significant effect on the luminosity and proton bunch size.

Lumi. at different CCE phase advance



Proton sigmay at different CCE phase advance



4. Summary

- To separate the two beams quickly, EicC will use a 50 mrad crossing angle for collision. A local crab cavity scheme will be used to restore the geometric luminosity loss.
- The proton crab cavity can restore the luminosity to a state close to head-on at frequencies of 100 MHz and 200+400 MHz (1.4θ-0.4θ). The electron crab cavity frequency does not have a significant effect on luminosity, and a frequency of 400MHz is planned to be used.
- The proton crab cavity RF white noise tolerance level: voltage ~ 1×10^{-5}, phase ~ 1×10^{-6}
- The electron crab cavity RF white noise tolerance level: voltage ~ 1×10^{-3}, phase ~ 1×10^{-5}
- The phase advance between proton crab cavities and electron crab cavities needs to be equal to pi, where the phase advance error of a single proton crab cavity does not exceed 0.2°, and that of a single electron crab cavity does not exceed 2°.
- We need to optimize parameters to reduce the vertical size growth rate of the proton bunch.

Thanks for your attention!