Self-consistent simulation of coupling impedance and beam-beam interaction in future e+/e- collider

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Many thanks: K. Ohmi(KEK), M. Zobov(INFN/LNF), D. Shatilov(BINP)

Outline

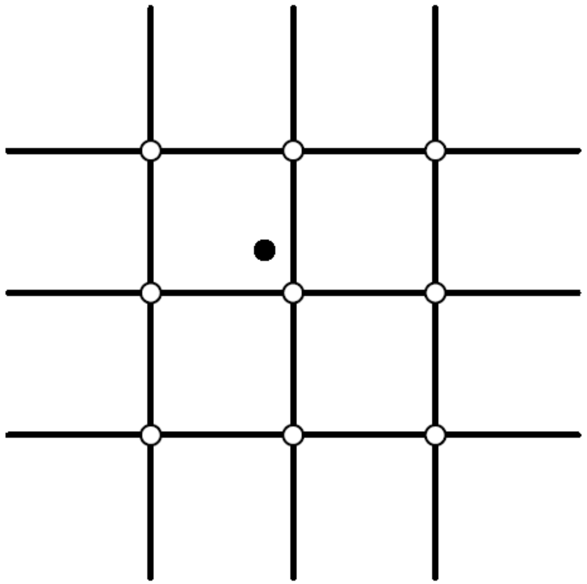
- Introduction of beam-beam simulation
- New effects in future e+/e- collider
- Simulation result
- Summary

Classical Beam-Beam Simulation

- Macro-particles, Particles-in-cell
- Poisson Solver

（FFT, Fourier-Analysis Cyclic Reduction Method）

$$\nabla^2 \phi = -\rho/\epsilon_0$$

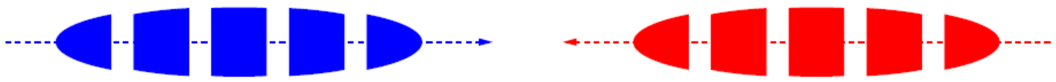


$$\mathcal{E}_x = -\frac{\partial \phi(x,y)}{\partial x} = \frac{Q}{2\epsilon_0\sqrt{2\pi(\sigma_x^2 - \sigma_y^2)}} \cdot \mathrm{Im}(\Gamma)$$

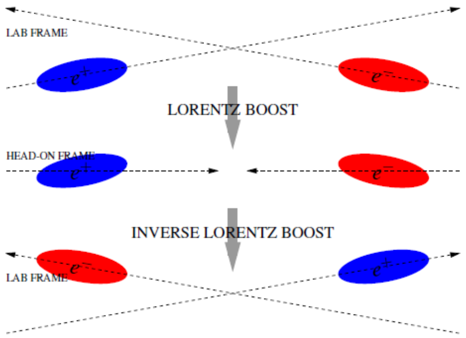
$$\mathcal{E}_y = -\frac{\partial \phi(x,y)}{\partial y} = \frac{Q}{2\epsilon_0\sqrt{2\pi(\sigma_y^2 - \sigma_y^2)}} \cdot \mathrm{Re}(\Gamma)$$

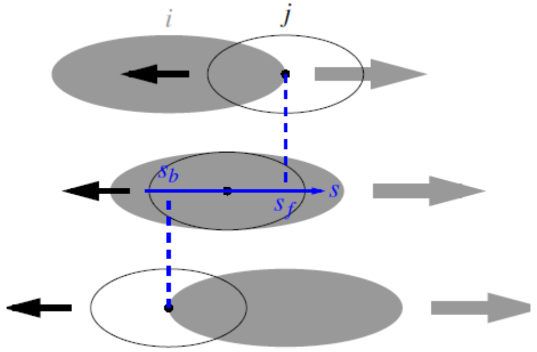
$$\Gamma = \mathrm{w}\left(\frac{x + \mathrm{i}y}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}}\right) - \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right)\mathrm{w}\left(\frac{x\frac{\sigma_y}{\sigma_x} + \mathrm{i}y\frac{\sigma_x}{\sigma_y}}{\sqrt{2(\sigma_x^2 - \sigma_y^2)}}\right)$$

Classical Beam-Beam Simulation



- Bunch Length => Hourglass effect => Slices & Interpolation
- Horizontal Crossinalg Angle

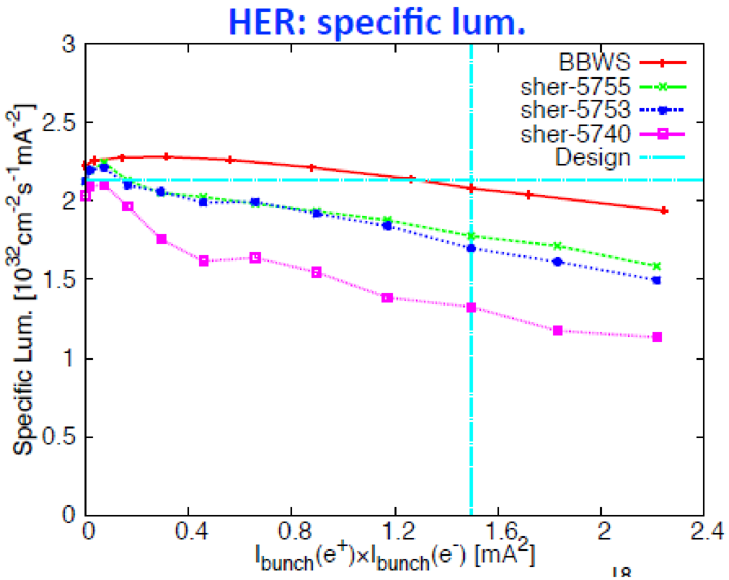




- With approximation of Gaussian distribution, Symplectic beam-beam map is given by Synchro-beam mapping method（Hirata）
- With Large Piwinski Angle, strong-strong PIC is very time-consuming, quasi-strong-strong is a feasible method

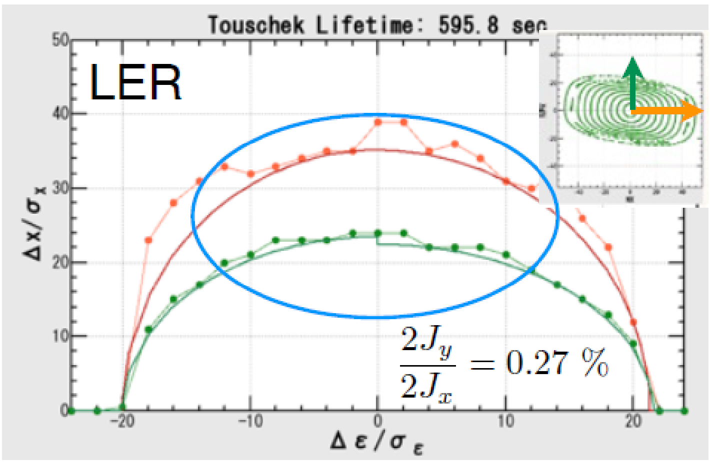
Crosstalk between beam-beam and Lattice nonlinarity

- Element-by-element tracking in lattice + beam-beam map at IP.

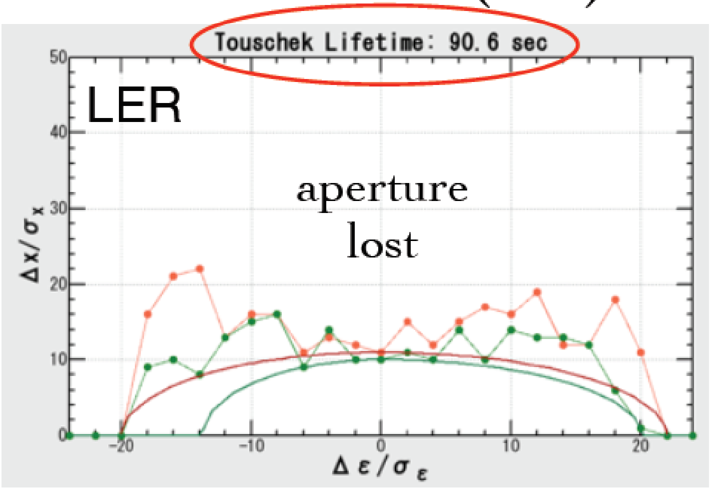


D. Zhou, ICFA Mini-Workshop on Commissioning of SuperKEKB and e+e- Colliders, 2013

w/o beam-beam



with beam-beam (W-S)



Transverse aperture is reduced significantly.

Y. Ohnishi, 18th KEKB Review, 2014

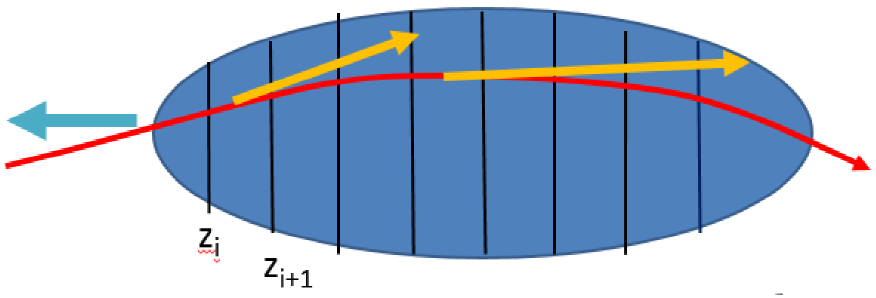
V.I. Telnov, DOI:10.1103/PhysRevLett.110.114801

Beamstrahlung Effect is New!

- Increase of Energy spread
- Bunch lengthening
- Beam Lifetime

$$\tau_{BS} \approx \frac{1}{n_{IP} f_{rev}} \frac{4\sqrt{\pi}}{3} \sqrt{\frac{\delta_{acc}}{\alpha r_e}} \exp\left(\frac{2}{3} \frac{\delta_{acc}\alpha}{r_e \gamma^2} \frac{\gamma \sigma_x \sigma_z}{\sqrt{2} r_e N_b}\right) \frac{\sqrt{2}}{\sqrt{\pi} \sigma_z \gamma^2} \left(\frac{\gamma \sigma_x \sigma_z}{\sqrt{2} r_e N_b}\right)^{3/2}$$

- The longitudinal oscillaion is strongly distorted by transverse dynamics.

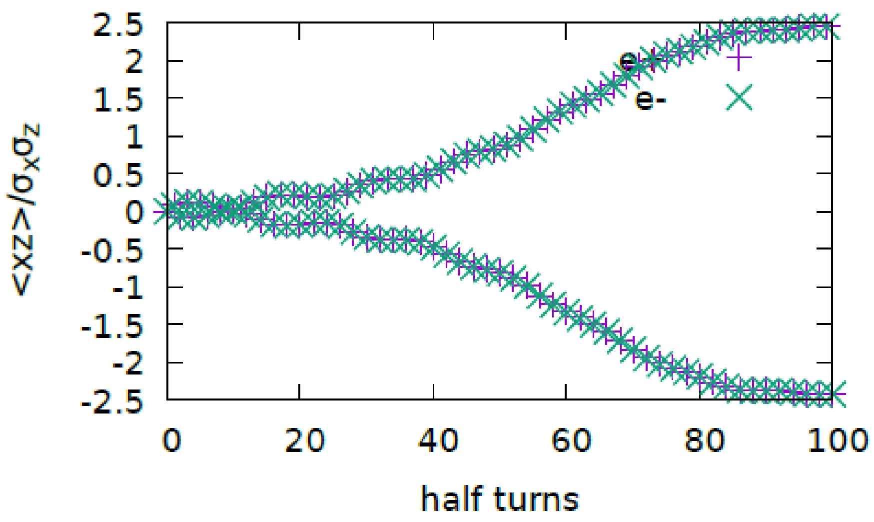


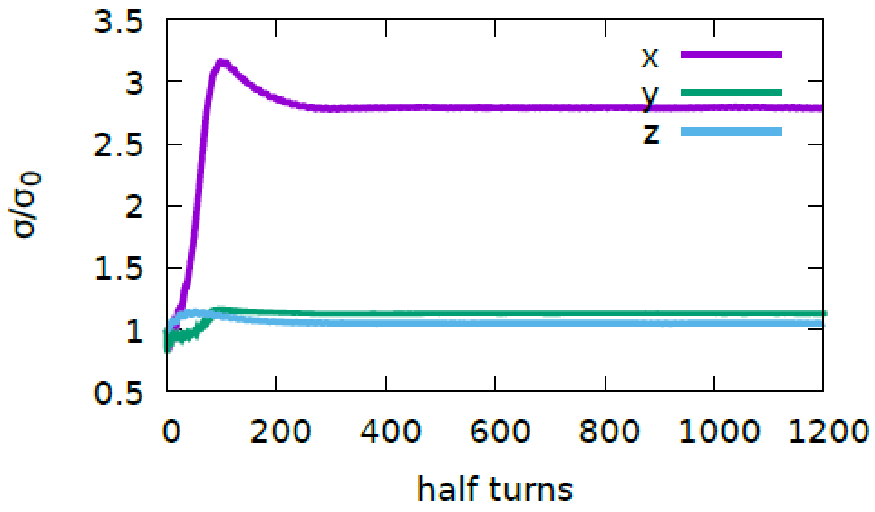
K. Ohmi and etal., DOI:10.1103/PhysRevLett.119.134801
K. Ohmi, eeFACT18 @ HKUST, Hongkong

New found X-Z coherent instability

Horizontal oscillations may also be distorted by longitudinal direction even with a Large Piwinski angle.

- It is believed the crab-waist scheme help to suppress the transverse and synchro-beatron resonance in collision
- Correlated head-tail instability in beam-beam collisions with a large Piwinski angle
- Blowup of horizontal beam size
- Resonance occur near $\nu_x = 0.5 + n\nu_s$
- Some benchmarking experiments has been done at SKEKB





Combined effect of Beam-Beam Interaction & Coupling Impedance

Conventional Method:

- Calculate bunch length with longitudinal impedance: $\sigma_z(I)$
- $\sigma_z(I)$ is an input parameter as the equilibrium bunch length w/o collision in the beam-beam simulation, since the longitudinal dynamics is nearly not affected by beam-bam interaction. (Gaussian Approximation in longitudinal direction)

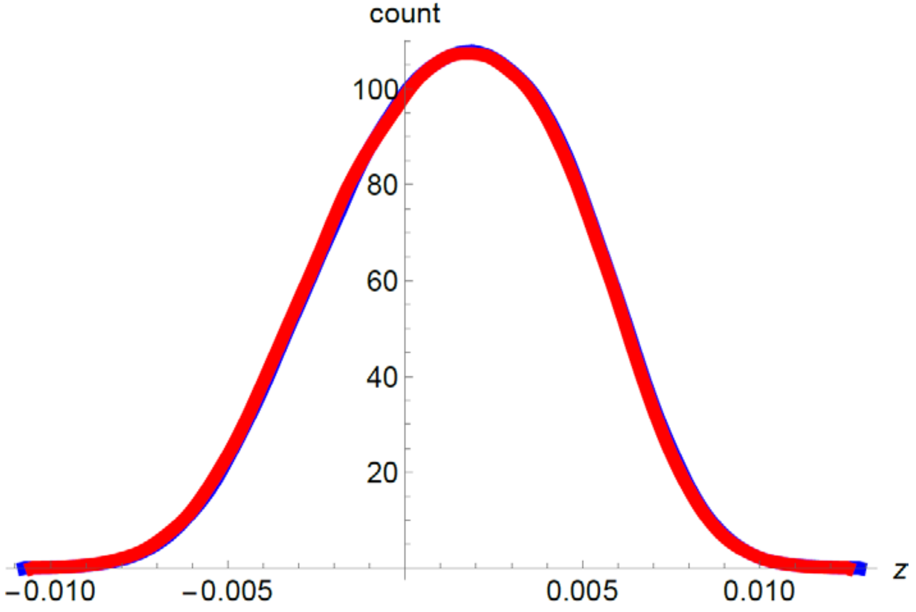
$$I(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} e^{-i\omega t} \tilde{I}(\omega)$$

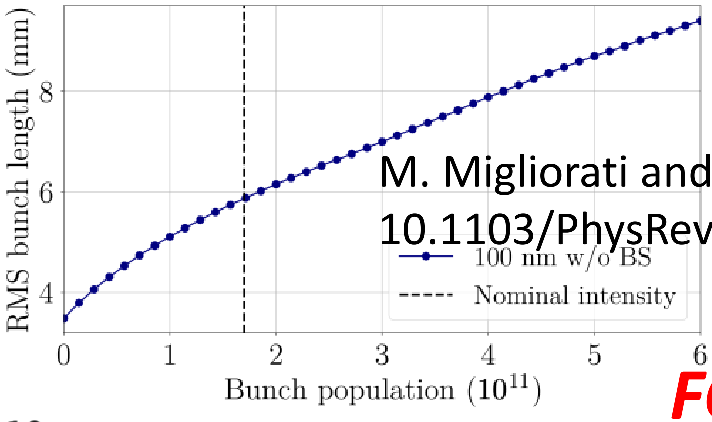
Self-consistent Method in future lepton collider:

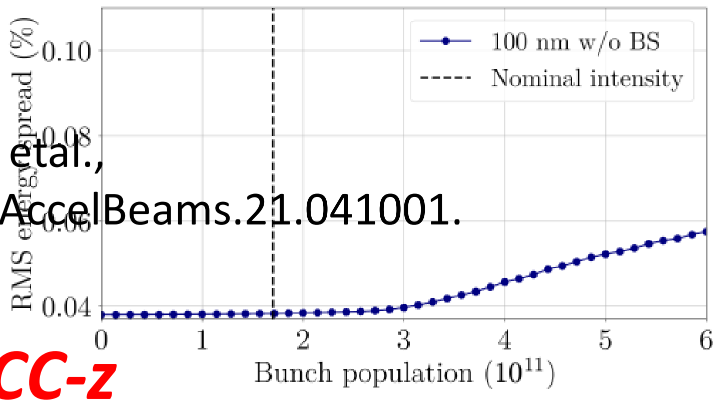
- The effect of longitudinal wake field is considered directly $\tilde{V}(\omega) = -\tilde{I}(\omega) Z_{\|}(\omega)$
- (The beamstrahlung effect during collision is also considered)

Thanks M. Migliorati for the FCC-ee Resistive Wall Impedance data

Crosscheck of the code(IBB) w/o Collsion

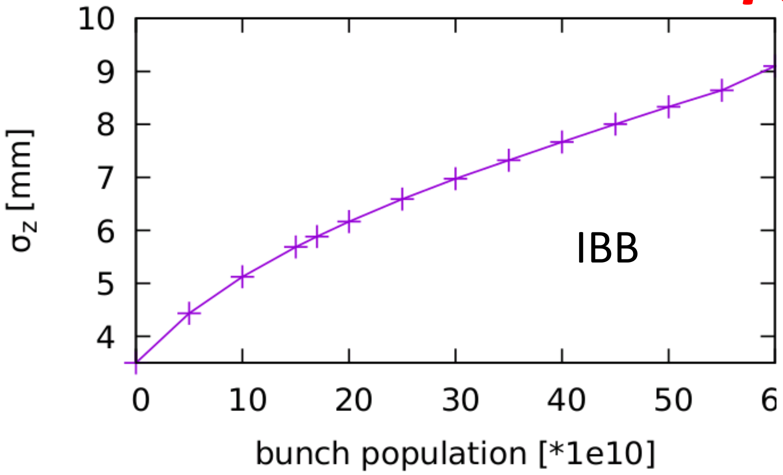


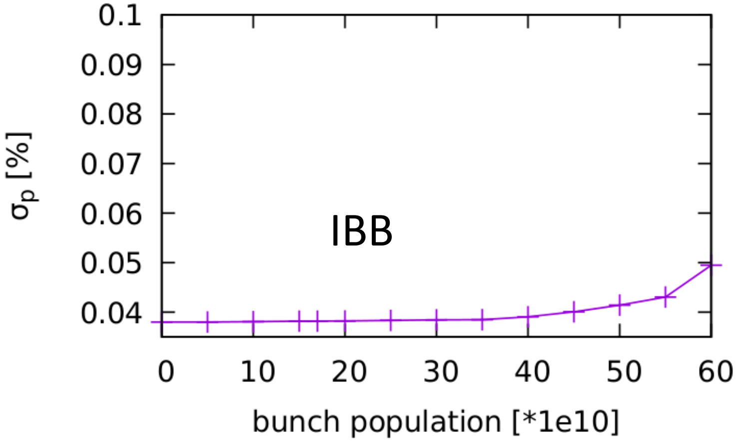




M. Migliorati and etal., 10.1103/PhysRevAccelBeams.21.041001.

FCC-z

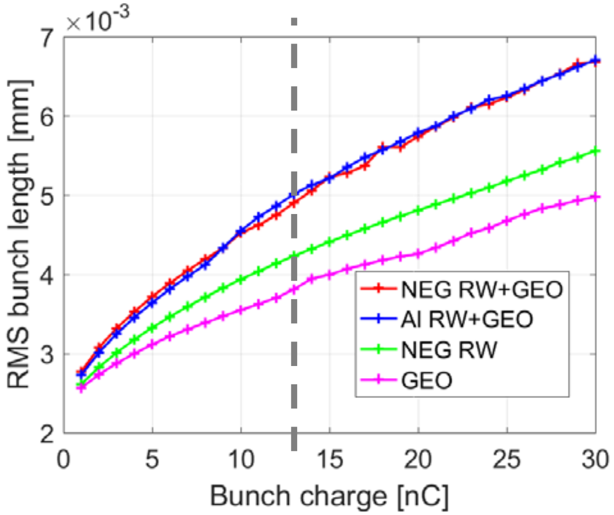


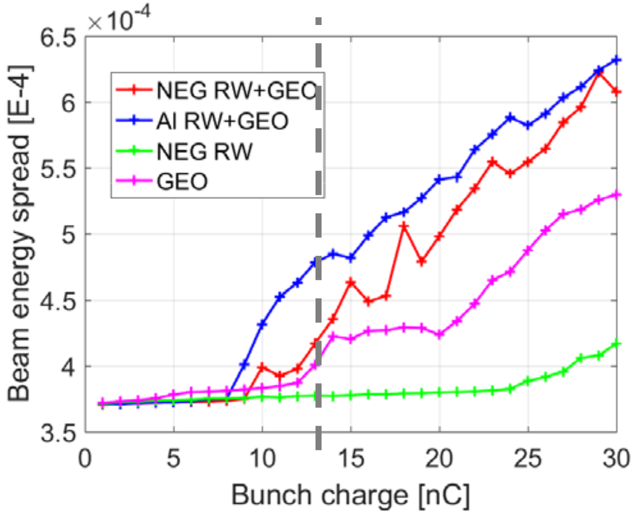


Longitudinal Impedance is Considered in Beam-Beam Code. Crosscheck of longitudinal distribution between IBB and Elegant.

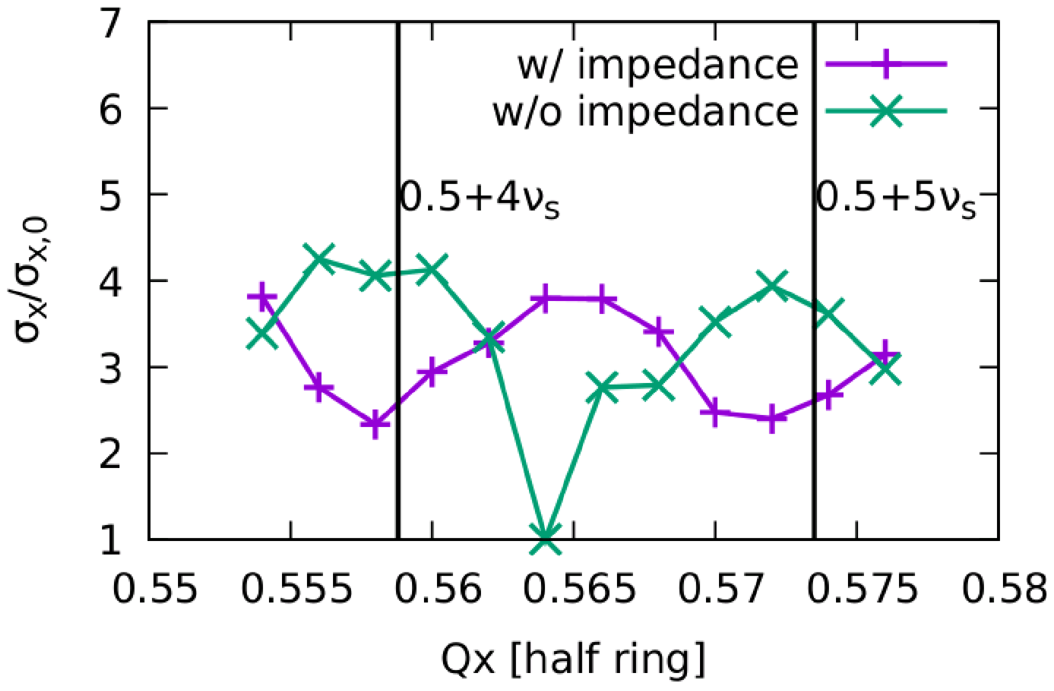
- Microwave instability and bunch lengthening
  - The microwave instability will rarely induce beam losses, but may reduce the luminosity due to the deformed beam distribution and increasing of the beam energy spread.
  - With the impedance model developed, the microwave instability and bunch lengthening are simulated with the code Elegant => the design bunch intensity is just above the threshold, and turbulent distributions are observed above the threshold.
  - To mitigate the effect:
    - Impedance reduction
    - Beam parameter optimization

Keil-Schnell criterion: $$I_{th} = \frac{\sqrt{2\pi}\alpha_p \frac{E}{e} \sigma_{e0}^2 \sigma_l}{R \left| \frac{Z_\parallel}{n} \right|_{eff}}$$





Recheck of CEPC-Z (cdr)

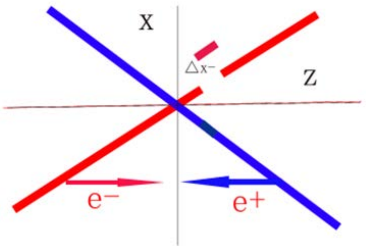


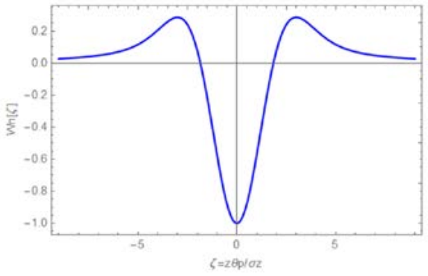
- Only one working point is stable without impedance: where the input parameter of $\sigma_z(I) = \sigma_z(0)$ in simulation.
- The beam-beam interaction gets more unstable with longitudinal impedance due to the X-Z coupling.
- Bootstrapping method with impedance is also tried, stable threshold of bunch population is about 3e10.

Crosscheck of the simulation with longitudinal impedance

The e- and e+ bunches with a tilt angle move head on to each other in the Lorentz boosted frame[1]. The transverse momentum kick induced by the cross wake force is represented as follows[2],where we have ignore a term that induces a tune shift.

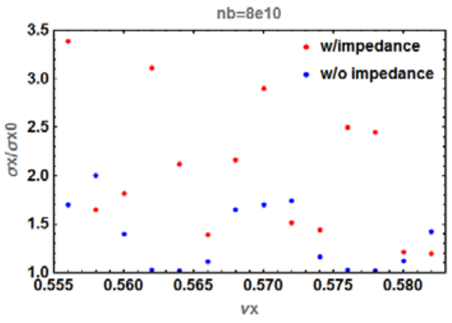
$$\Delta p_x^{(\pm)}(z) = -\frac{N r_e}{\gamma}\int_{-\infty}^{\infty} W_x^{(\pm)}(z-z')\,\rho_x^{(\mp)}(z')\,dz'$$



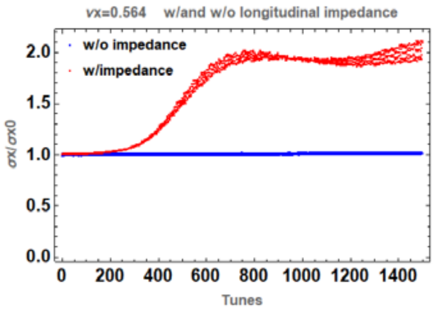


Normalized cross wake function

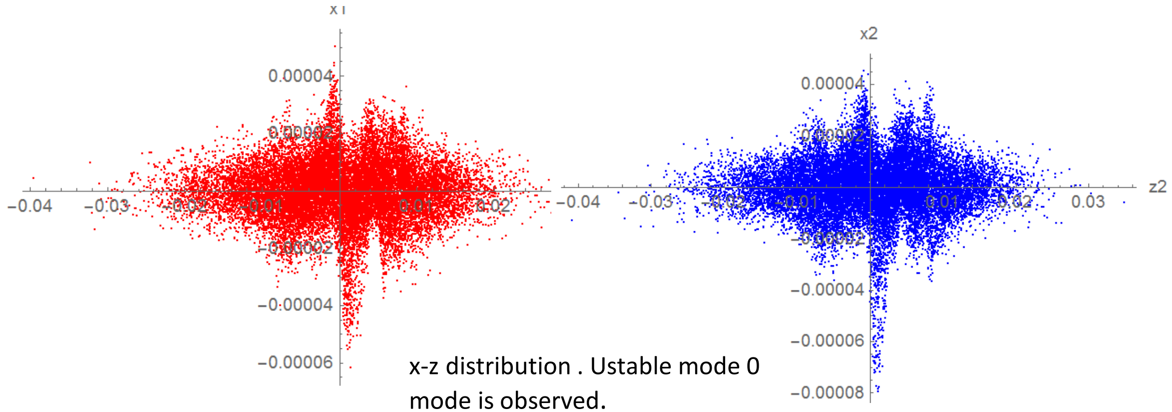
This cross wake force is caused by the beam-beam interaction and is a linear part of beam-beam force. We use this localized force for particle tracking. The tracking results become worse when we consider the longitudinal impedance. The following show the tracking result.



Normalized beam size at different horizontal tune



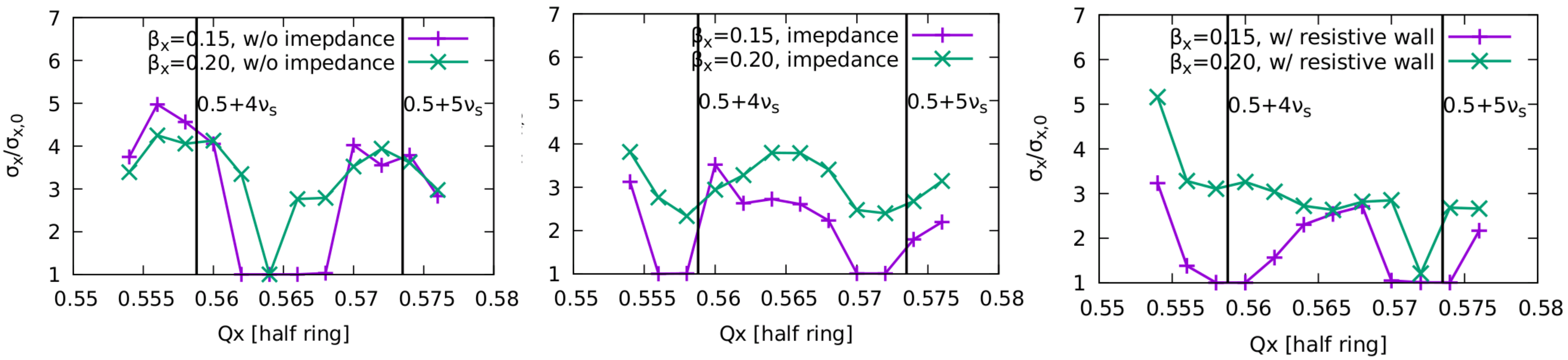
Evolutions of horizontal beam size with and without longitudinal impedance at υx=0.564



x-z distribution . Ustable mode 0 mode is observed.

[1] K. Hirata, Phys. Rev. Lett.74,2228(1995).
[2] K. Ohmi, N. Kuroo, K. Oide, D. Zhou, and F. Zimmermann,"Coherent Beam-Beam Instability in Collisions with a Large Crossing Angle", Phys .Rev. Lett.119,134801(2017).

- smaller $\beta_x{}^*$ is preferred for X-Z coupling[#*].
  - Larger stable region is obtained by reducing the $\beta_x{}^*$ from 0.2m to 0.15m
- By including the longitudinal impedance
  - The stable region is reduced and shifted
  - With only RW, a smaller tune shift and larger stable region are observed
- **Beam parameters and impedance should be further optimized.**

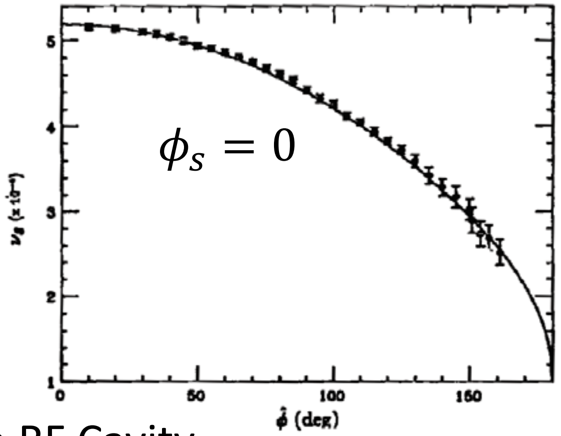


K. Ohmi, et al., Coherent Beam-Beam Instability in Collisions with a Large Crossing Angle, Phys. Rev. Lett. 119, 134801 (2017).

* D. Shatilov, FCC-ee parameter optimization, ICFA Beam Dynamics Newsletter 72, 30 (2017).

Nonlinear Kick in Local RF Cavity

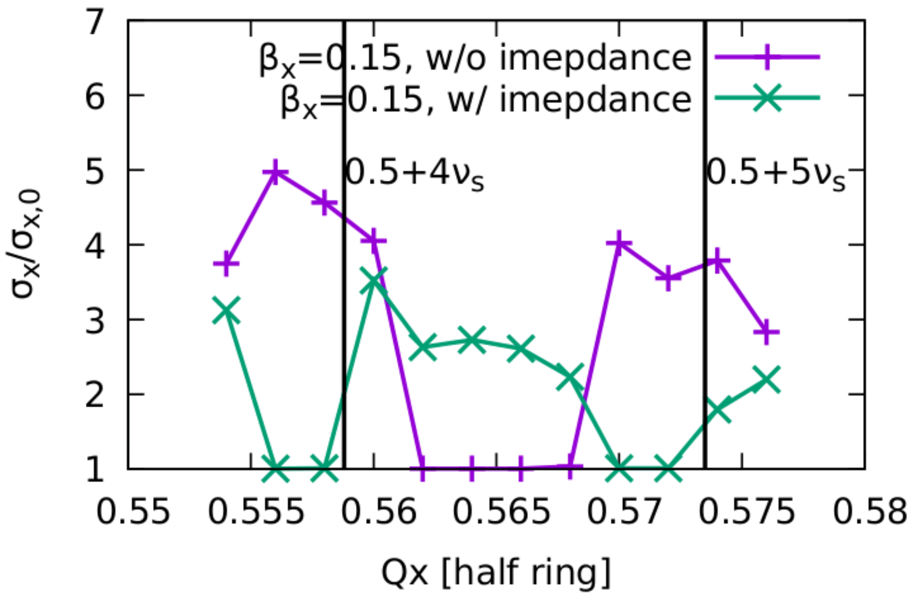
$$\nu(\hat{\phi}) \approx \nu_s\left(1 - \frac{\hat{\phi}^2}{16}\right)$$



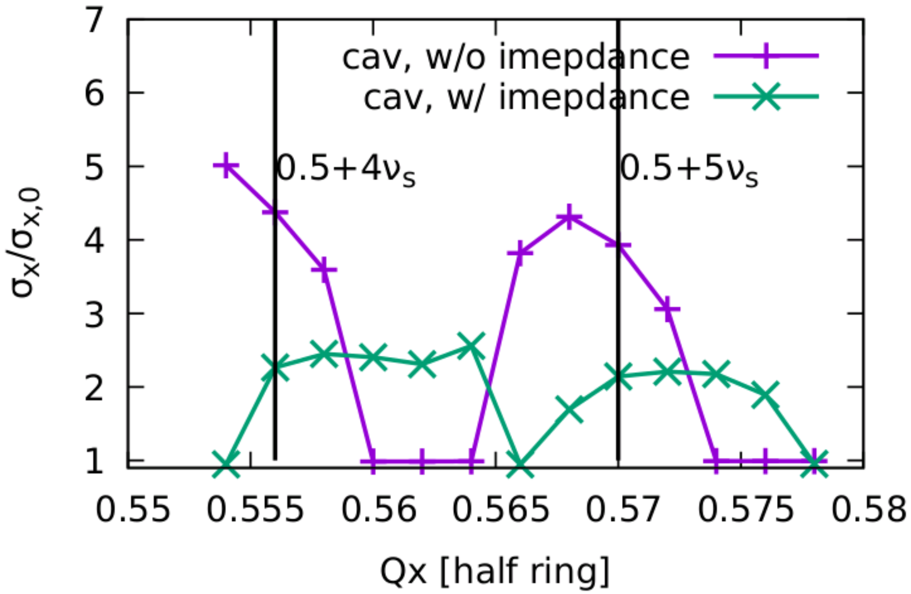
- With cavity's nonlinear kick(Sin wave): $3\sigma_z$=22mm~3 deg, ϕ_s=158.9 deg <z> shift 3.6mm

  only one working point is stable considering impedance

Linear Oscillation in Longitudinal Direction



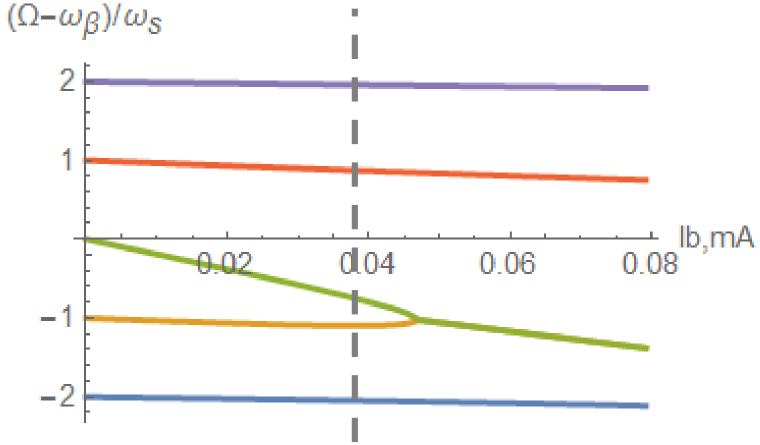
Nonlinear Kick in RF Cavity



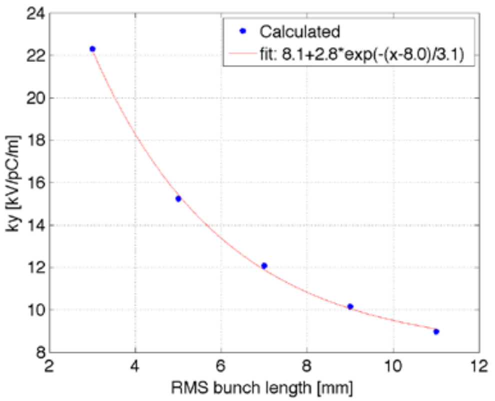
- Transverse mode coupling instability
  - The threshold for the TMCI is estimated using both analytical formula and Eigen mode analysis.

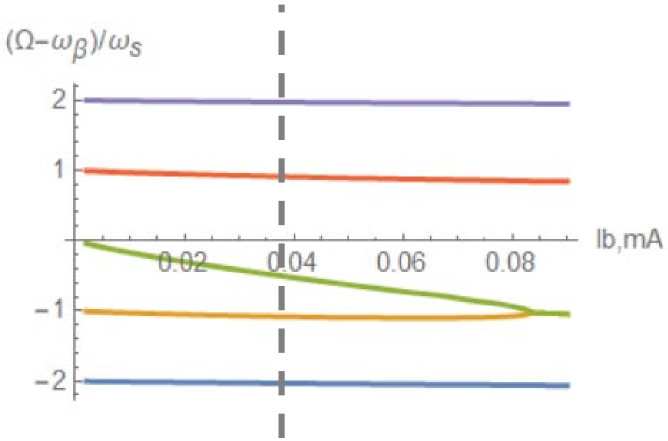
$$I_0^{th} = \frac{2Q_s\omega_0 E/e}{\sum_j \beta_{\perp,j}\kappa_{y,j}}\Theta$$

  - When considering bunch lengthening due to the impedance or beamstrahlung, the transverse effective impedance decreases due to its dependence on the bunch distribution => TMCI threshold increases.



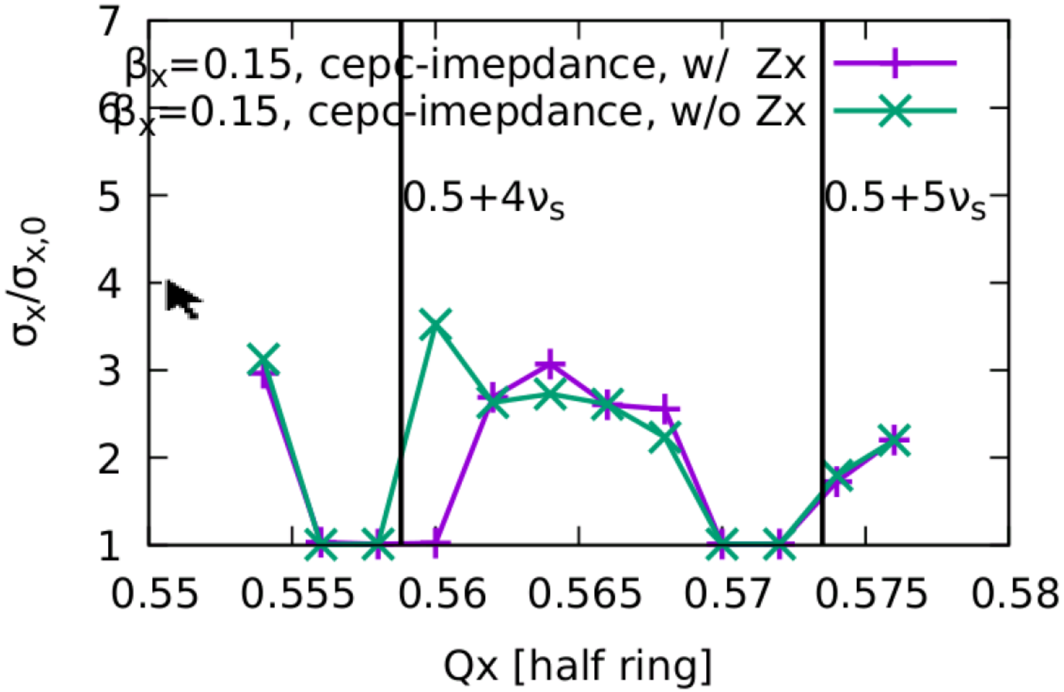
Threshold is comparable with the design current without considering bunch lengthening.





Larger safety margin obtained when considering bunch lengthening effects.

- No significant influence of the transverse wake field on collision.
  - $\beta_x{}^*$= 0.15m
  - With longitudinal and horizontal impedance



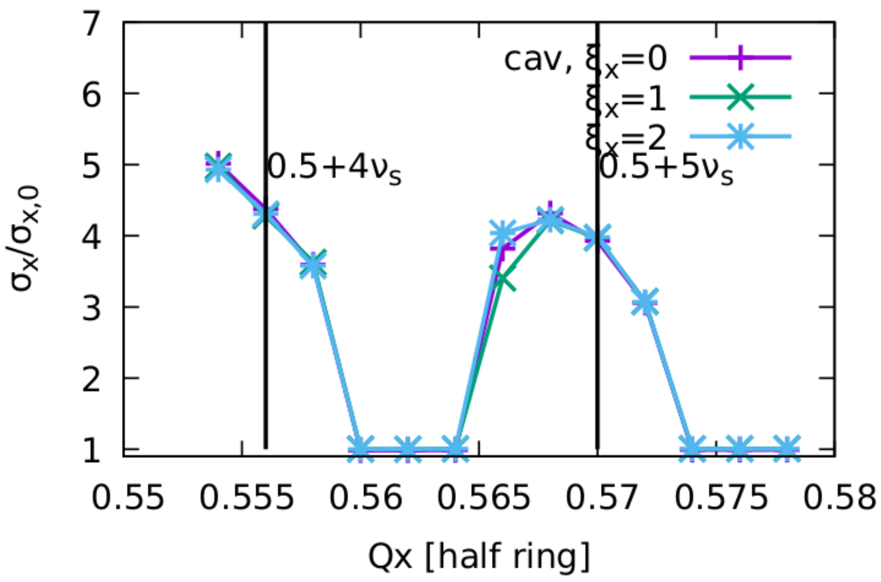
General Chromaticity

Y. Seimiya and etal., "Symplectic Expression for Chromatic Aberrations", PTP 127, 1099(2012)

- Here only include a linear horizontal tune chromaticity to check if the chromaticity could affect the X–Z instablitiy.

$$\bar{\boldsymbol{x}} = M_4(\delta)\boldsymbol{x},$$
$$\bar{z} = z + g(x, p_x, y, p_y, z, \delta),$$
$$\delta = \bar{\delta},$$

$$g = -\boldsymbol{x}^T M_4^T(\delta) S_4 \big(\partial_\delta M_4(\delta)\big)\boldsymbol{x}/2$$



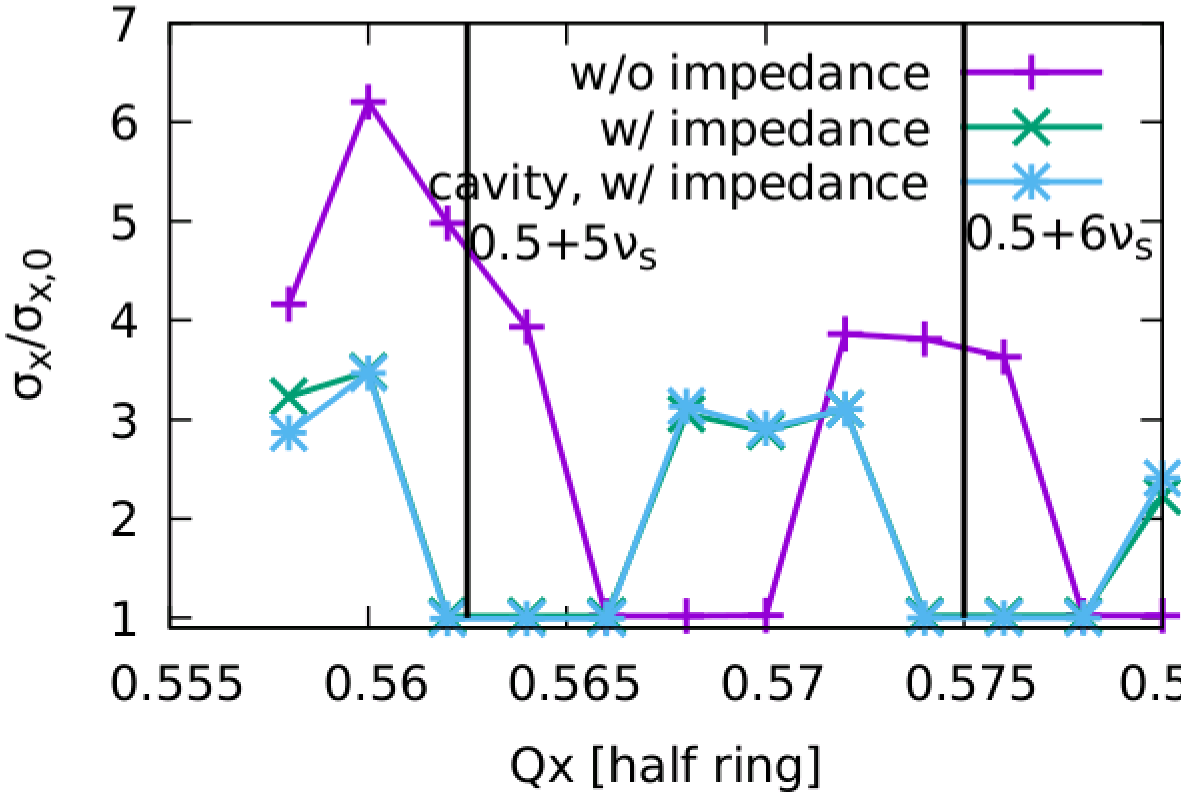
σ_p~1.1e-3,

Only resistive wall impedance of FCCee is considered.

FCCee-Z

Only a tune shift (~0.004) is found

Stable width of working point space: 0.004



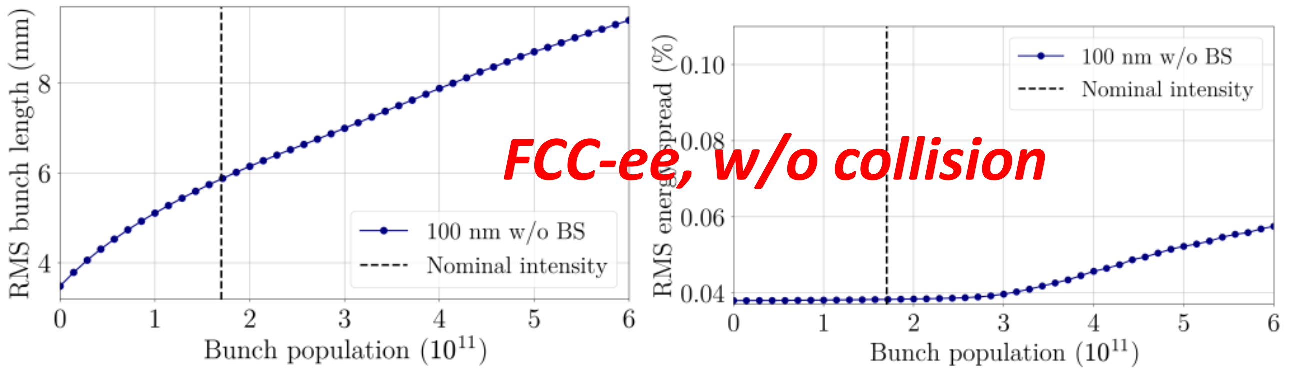
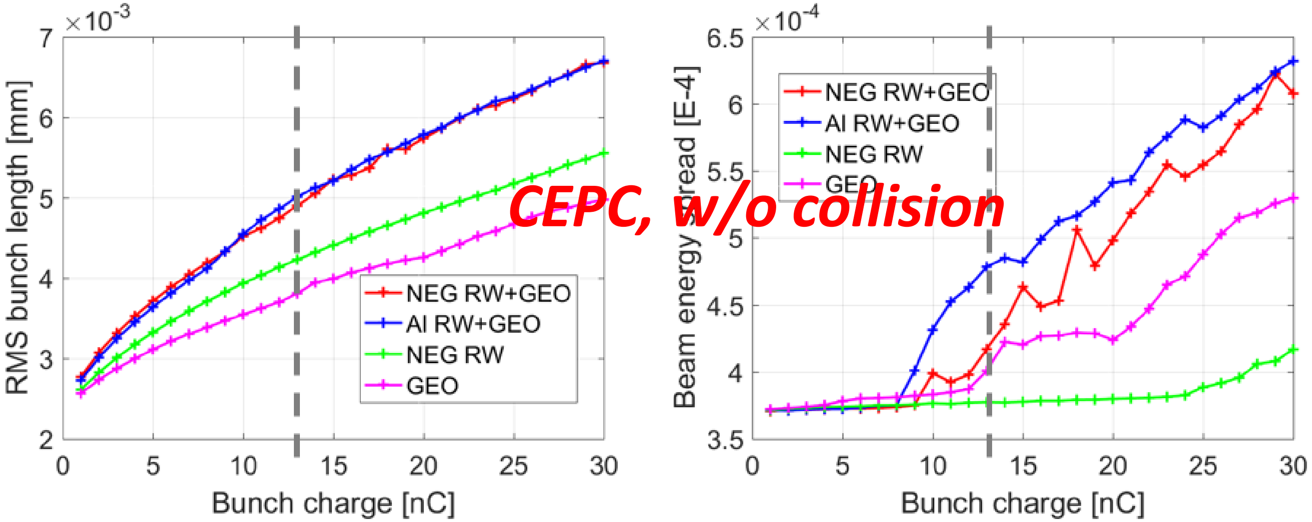


Figure 2.27: RMS bunch length (left) and RMS energy spread (right) as a function of the bunch intensity obtained from numerical simulations, without beamstrahlung (BS), considering only the RW impedance produced by a NEG film with 100 nm thickness.

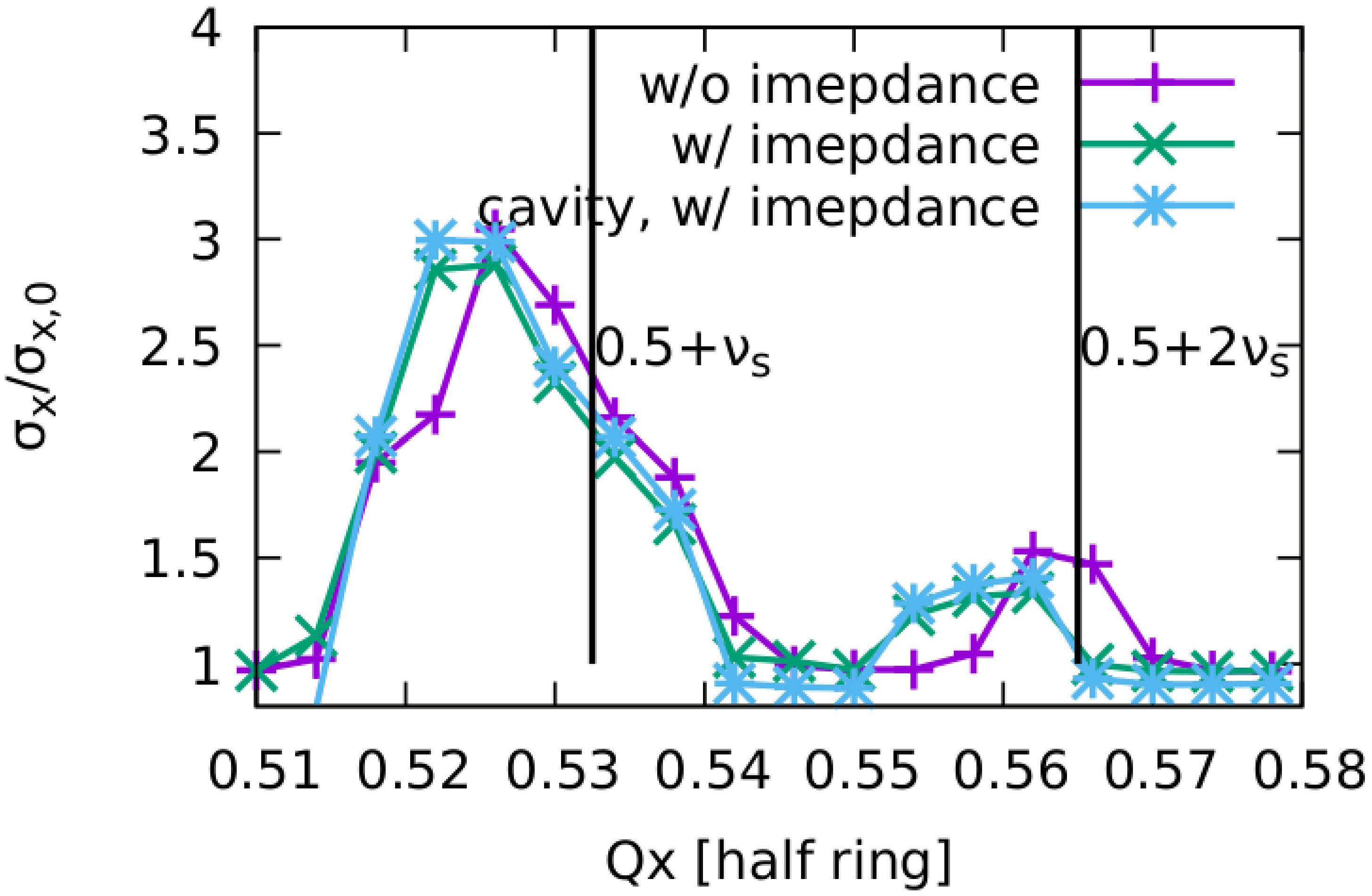


- D. Shatilov, FCC-ee parameter optimization, ICFA Beam Dynamics Newsletter 72, 30 (2017).

Parameter Optimization

- $\xi_x \ll Q_s$, to suppress X-Z coherent instability
- Since $\xi_x \propto \frac{\beta_x N}{\beta_x \epsilon_x + \sigma_z^2 \theta^2}$ & $\phi = \frac{\sigma_z \theta}{\sigma_x} \gg 1$, smaller β_x is more preferred .
- Longer bunch length σ_z is preferred for small ξ_x. Increasing α_p help increase bunch length (reduce ξ_x), and Q_s. To keep ξ_y unchanged, bunch population increase. $L \propto \frac{N\xi_y}{\beta_y}$ keep unchanged. Microwave instability threshold $N_{th} \propto \frac{\alpha_p \sigma_p^2 \sigma_z}{\mathrm{Re}\left[\frac{Z}{n}\right]}$ also increase.
- Without beamstrahlung and wakefield, decrease Vrf, do not change ξ_x / Q_s, but increase the synchro-betatron resonance order.

Higgs@CEPC



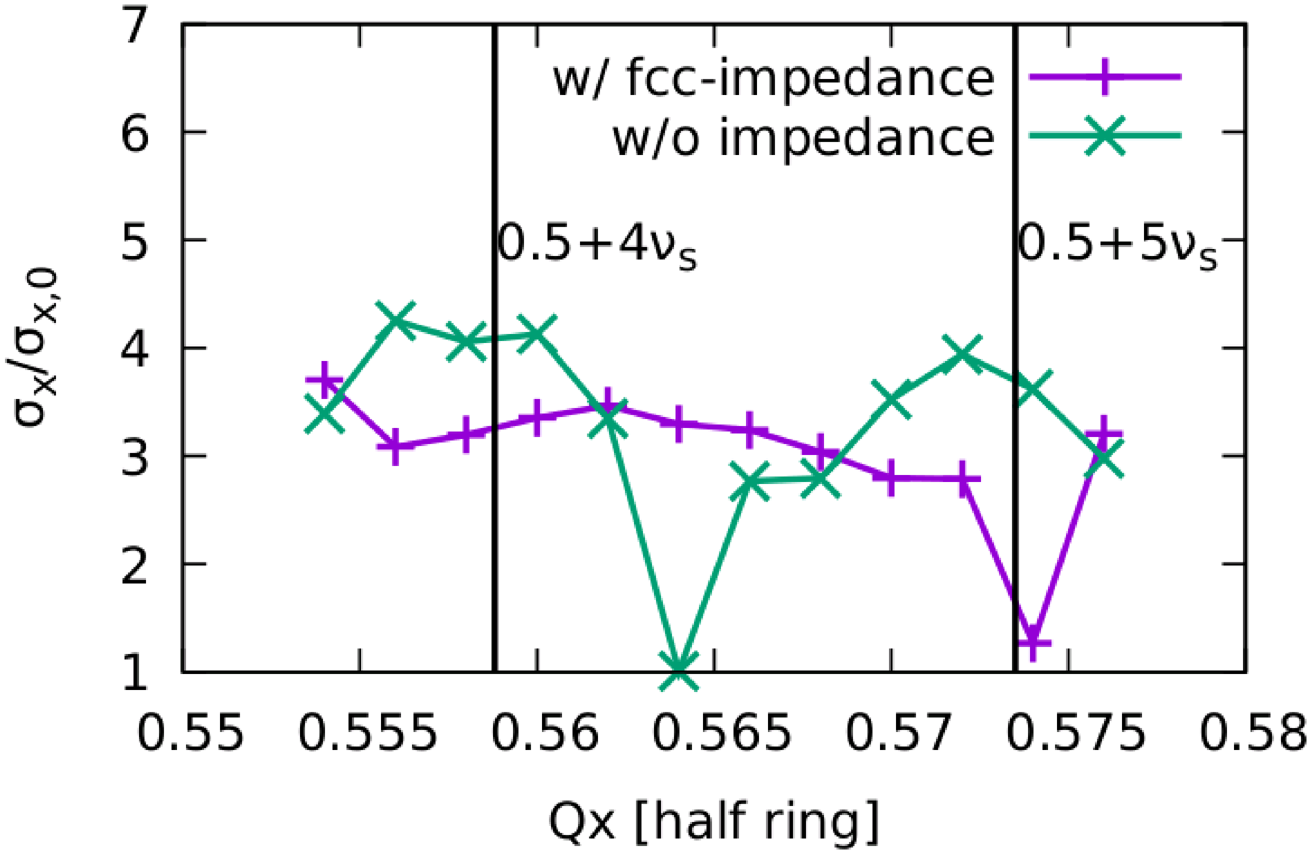
w/o imepdance
w/ imepdance
cavity, w/ imepdance
0.5+νs
0.5+2νs
σx/σx,0
Qx [half ring]
4
3.5
3
2.5
2
1.5
1
0.51
0.52
0.53
0.54
0.55
0.56
0.57
0.58

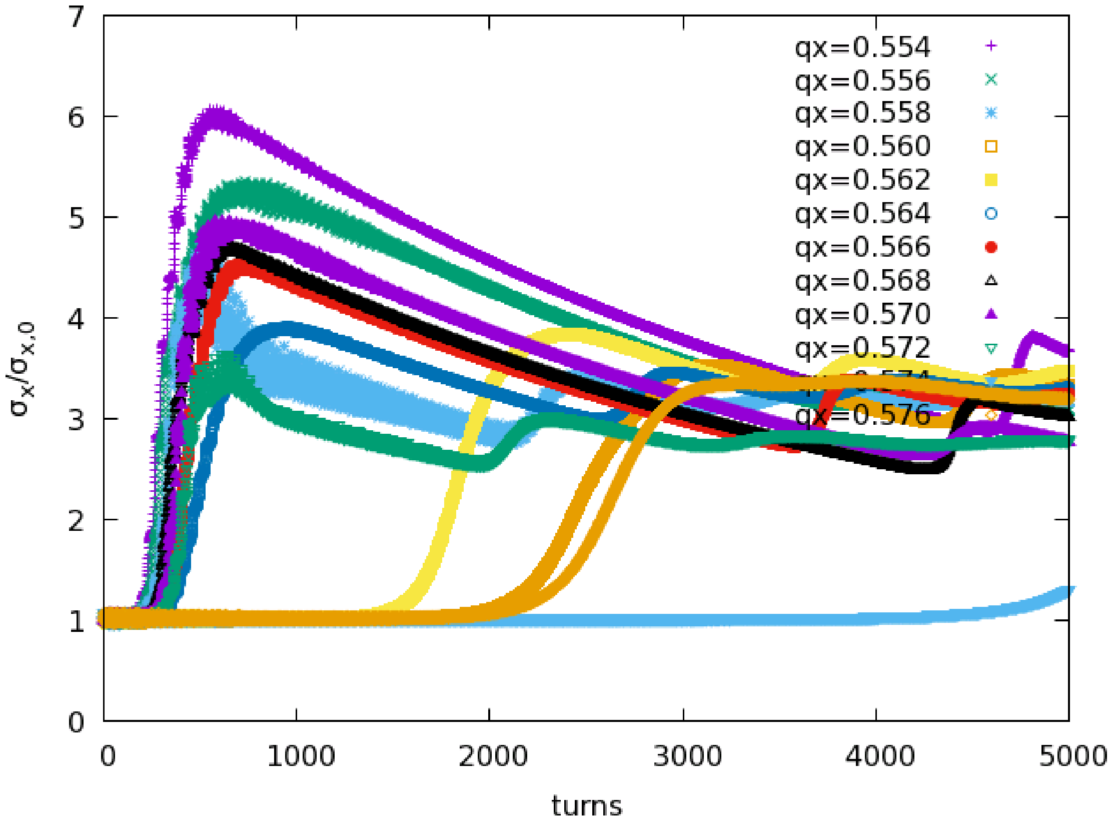
Summary

- Self-consistent simulation considering beam-beam interaction and single-bunch collective effect has been done.
- The longitudinal wakefield has a serious effect on the stability of collision for CEPC-Z
- The impedance budget needs to be further squeezed
- The machine parameters needs to be further optimized:
  - Squeeze β_x
  - Increasing α_p

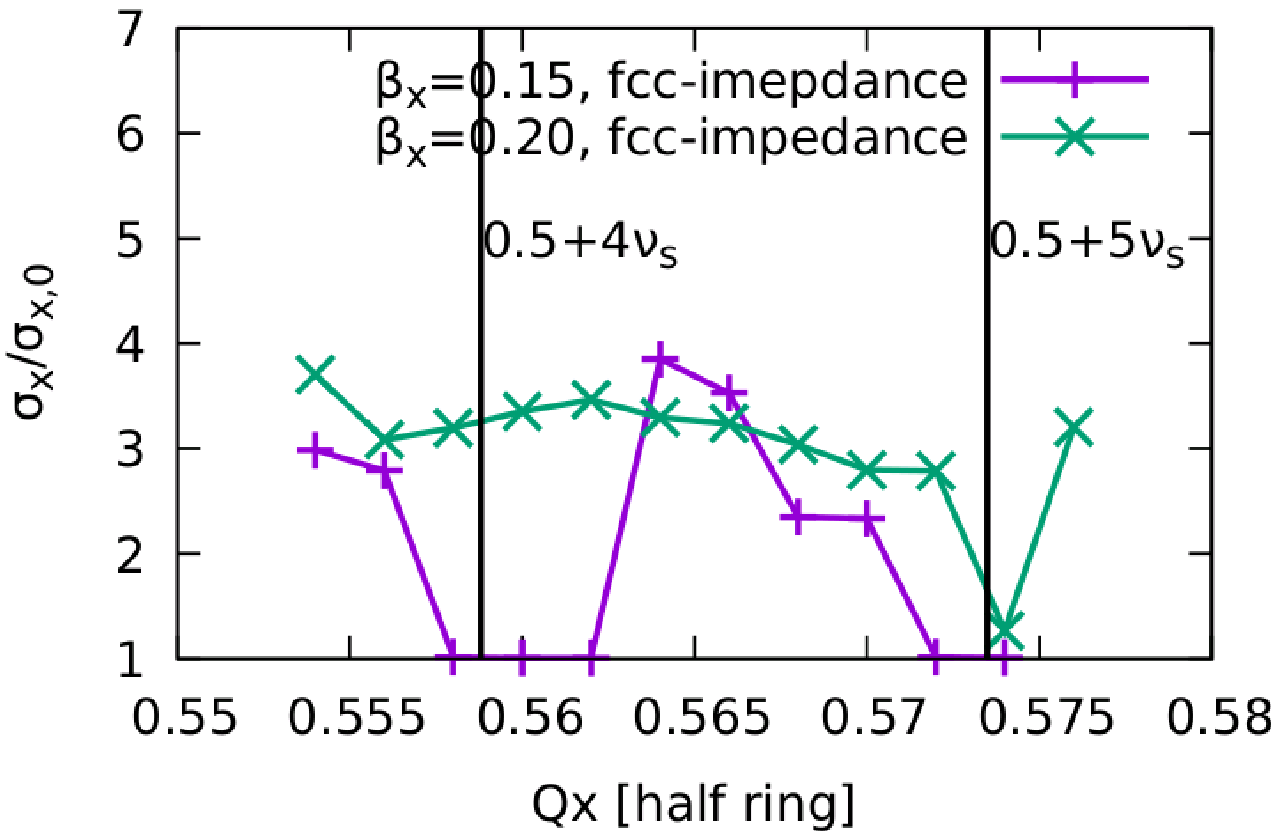
- Backup

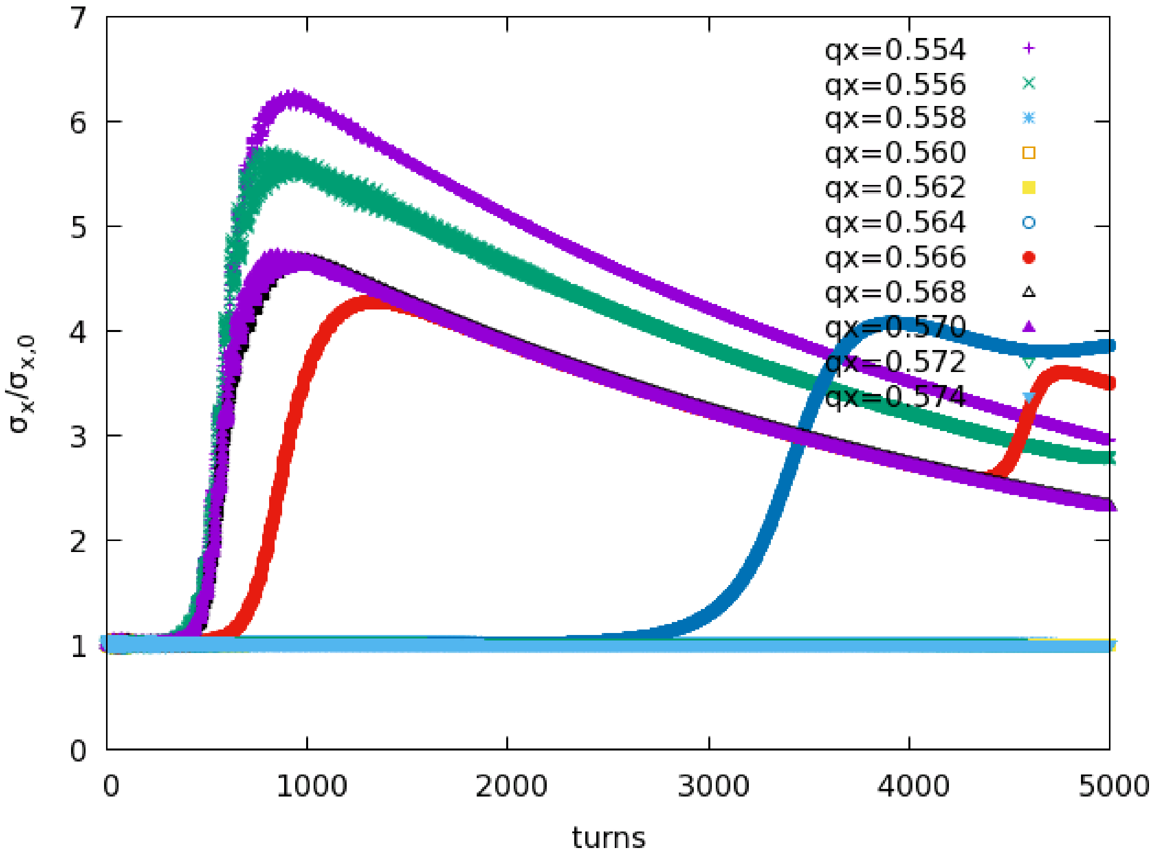
FCC IMPEDANCE + CEPC Z PARAMETER





FCC IMPEDANCE, BX=0.15, CEPC





CEPC VS FCC (CDR)

	CEPC	FCC
Bunch Popualtion	8e10	1.7e11
Horizontal Emittance	0.18 nm	0.27 nm
Vertical Emittance	1.6 pm	1.0 pm
Arc Cell Phase Advance	90/90	60/60 [deg]
Momentum Compaction	11.1e-6	14.8e-6
Horizontal β_x^*	0.2 m	0.15 m
Vertical β_y^*	1 mm	0.8 mm
Energy Spread [SR]	3.8e-4	3.8e-4
Bunch Length [SR]	2.4 mm	3.5 mm
Piwinski Angle [SR]	6.6	8.2
Synchrotron Tune Q_s	0.028	0.025
Beam-Beam Parameter $\xi_{x,0}/\xi_{y,0}$		
Beam-Beam Parameter ξ_x/ξ_y	0.004/0.079	0.004/0.133