Combined Effect of Beam-Beam Interaction and Beam Coupling Impedance in Future Circular Colliders

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Thanks: Kazuhito Ohmi(KEK), Dmitry Shatilov(BINP), Chuntao Lin(IHEP)

Outline

- Introduction
- Review of CDR Parameters
- Mitigation Schemes
- Conclusion & Discussion

P. Raimondi , *2nd SuperB Workshop, March 2006*
M. Zobov et al., PRL 104, 174801 (2010)

Crab-waist collision

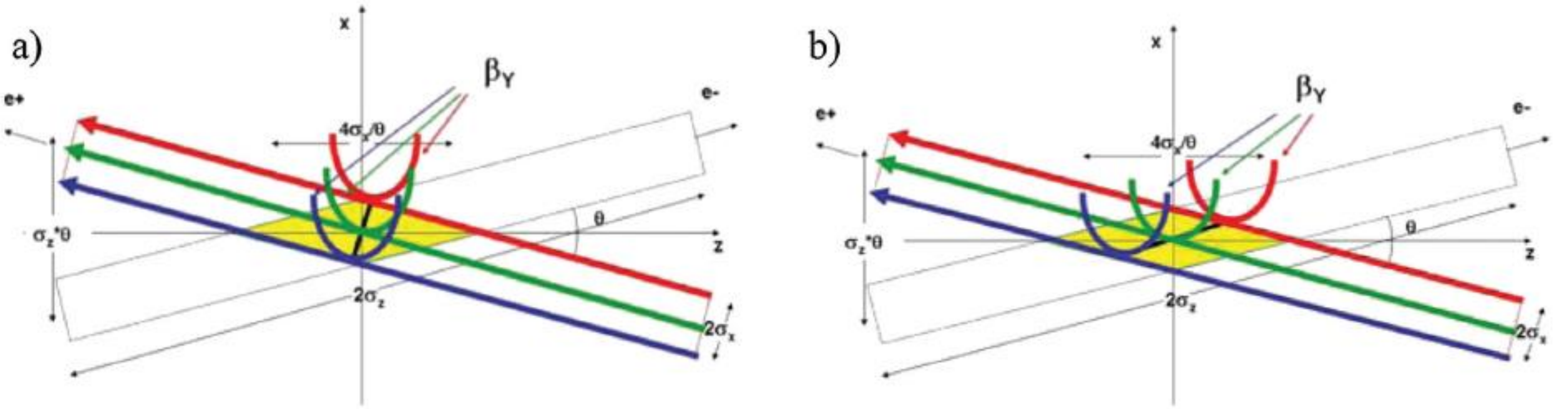


FIG. 1 (color). Crab-waist collision scheme. The color straight lines show directions of motion for particles with different horizontal deviations from the central orbit. The arrows indicate the corresponding β function variations along these trajectories.

$$L \propto \frac{N\xi_y}{\beta_y^*}; \qquad \xi_y \propto \frac{N\sqrt{\beta_y^*/\varepsilon_y}}{\sigma_z\theta}; \qquad \xi_x \propto \frac{N}{(\sigma_z\theta)^2},$$

$$\varphi = \frac{\sigma_z}{\sigma_x}\tan\left(\frac{\theta}{2}\right) \approx \frac{\sigma_z}{\sigma_x}\frac{\theta}{2}.$$

$$\beta_y^* \approx \frac{\sigma_x}{\theta} \ll \sigma_z.$$

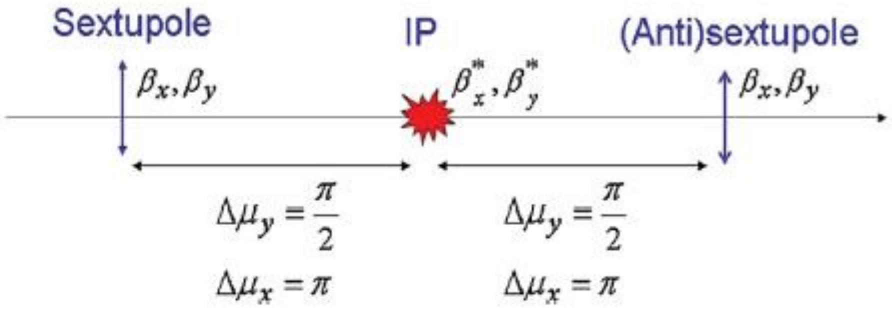


FIG. 2 (color). Crab sextupole locations.

Coherent Beam-Beam Instability with a Large Crossing Angle

K. Ohmi, Int. J. Mod. Phys. A, 31, 1644014 (2016).
K. Ohmi and et al., PRL 119, 134801 (2017)
N. Kuroo et al, PHYS. REV. ACCEL. BEAMS 21, 031002 (2018)
K. Ohmi, eeFACT 2018

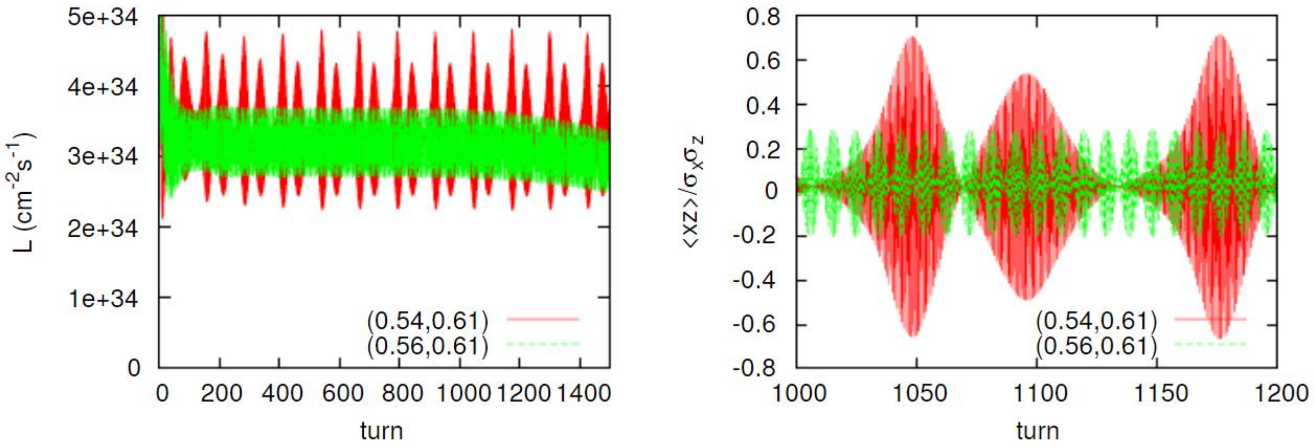


Fig. 5. Luminosity and $\langle xz\rangle$ evolutions given by a strong–strong simulation using BBSS code.

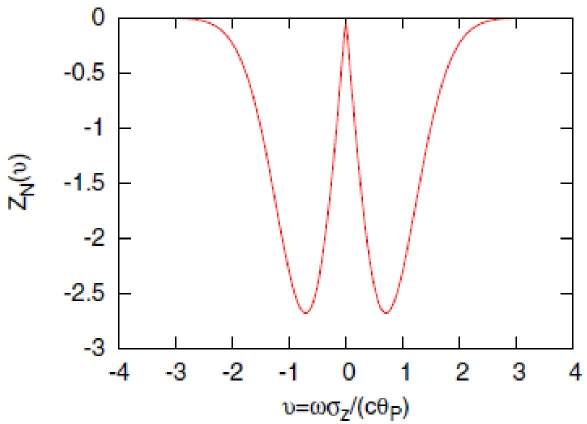


FIG. 3. Imaginary part of normalized cross impedance, where $\upsilon = \omega\bar{\sigma}_z/(c\theta_P)$.

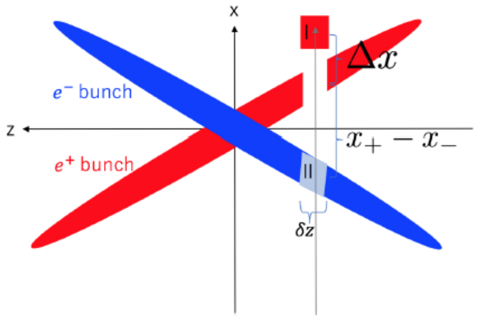


FIG. 1. Illustrative representation of the evaluation of the cross-wake force.

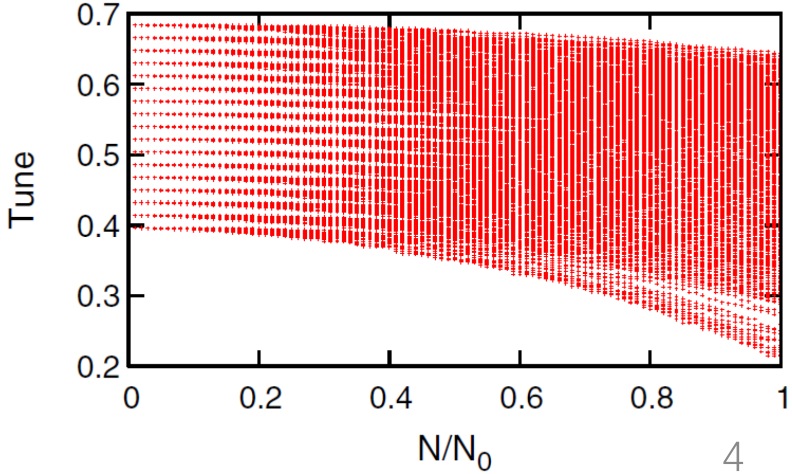
- Usual wake force gives correlation between bunch head to tail. Head-tail instability is induced by synchrotron motion

$$\Delta p_x(z) = -\int_z^{\infty} W(z-z')\rho_x(z')dz'$$

- Cross wake field gives correlation of two colliding beam by convolution of each dipole moment.

$$\Delta p_{x,\mp}(z_\mp) = -\int_{-\infty}^{\infty} W_x^{(\mp)}(z_\mp - z'_\pm)\rho_x^{(\pm)}(z'_\pm)dz'_\pm$$

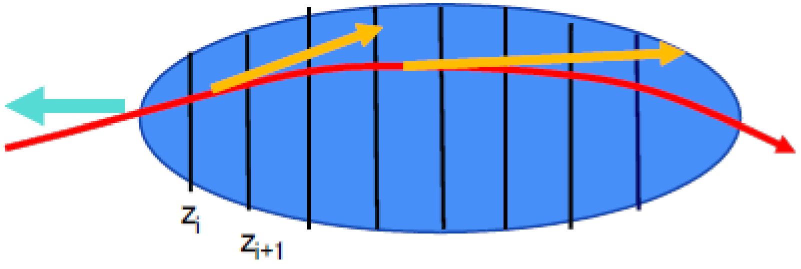
- Cross wake force induced by the beam-beam interaction is localized at IP.

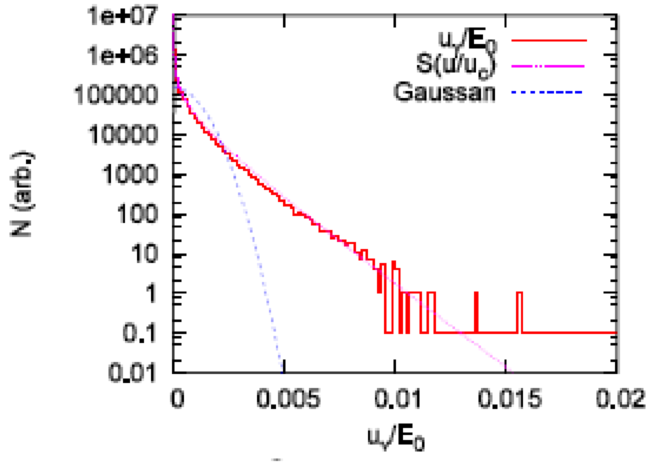


V. I. Telnov, PRL 110, 114801 (2013)
A. Bogomyagkov et al., Phys. Rev. ST Accel. Beams 17, 041004 (2014)
D. Shatilov, ICFA Beam Dyn. Newslett. 72, 30 (2017).

Beamstrahlung Effect & 3D flip-flop

- Synchrotron radiation during beam-beam interaction
- High energy photon -> Momentum acceptance -> Lifetime
- Longer bunch length and Higher energy spread
- Asymmetrical beam blowup: 3D flip-flop





Why have we started with the longitudinal impedance?

1. In the collision scheme with Crab Waist and Large Piwinski Angle the luminosity and tune shifts strongly depend on the bunch length

$$L \propto \frac{N\xi_y}{\beta_y^*}, \quad \xi_y \propto \frac{N\sqrt{\beta_y/\varepsilon_y}}{\sigma_z\theta}, \quad \xi_x \propto \frac{N}{(\sigma_z\theta)^2}$$

2. For the future circular colliders with extreme beam parameters in collision several new effects become important such as beamstrahlung, coherent X-Z instability and 3D flip-flop. The longitudinal beam dynamics plays an essential role for these effects

K. Hirata et al., PA 40, 205-228 (1993)
K. Hirata, PRL, 74, 2228 (1995)
Y. Zhang et al., PRST-AB, 8, 074402 (2005)
K. Ohmi, IPAC16
Y. Zhang et al., 23, 104402, (2020)

Simulation

- Linear Arc Map with SR radiation
- Horizontal crossing angle: Lorentz boost map
- Bunch slice number is about 10 times Piwinski angle
- Slice-Slice collision: Synchro-beam mapping method
- Synchrotron radiation during collision
- Longitudinal wake potential is calculated in frequency domain before IP each turn

K. Oide, IPAC2017
D. Shatilov, *ICFA Beam Dyn.Newslett.* 72 (2017) 30-41

Parameter Optimization

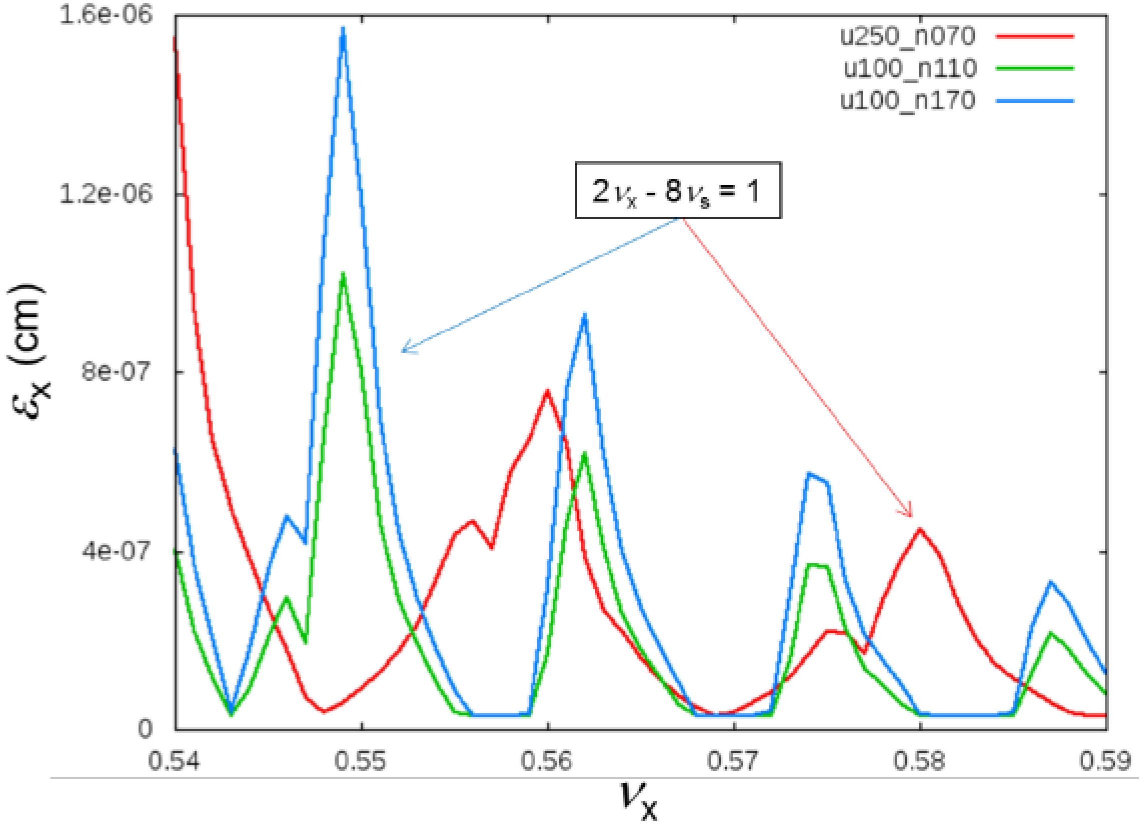
$$N_{th} \propto \frac{\alpha_p \sigma_\delta \sigma_z}{\beta_x^*},$$

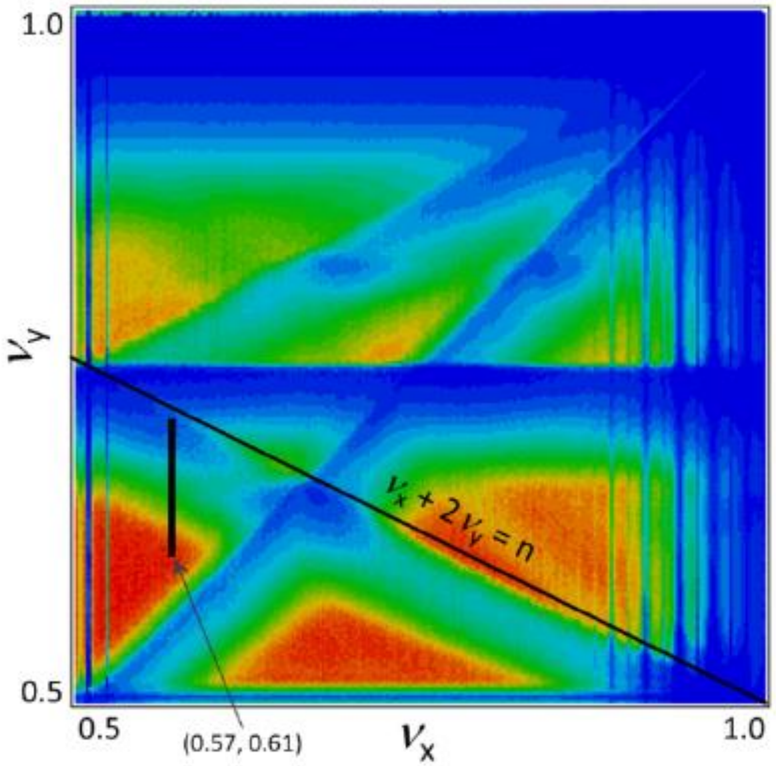
$$\alpha_p \sigma_\delta \propto \nu_s \sigma_z$$

$$\xi_x \propto N_p \beta_x^* / \sigma_z^2$$

Larger ν_s/ξ_x is preferred!

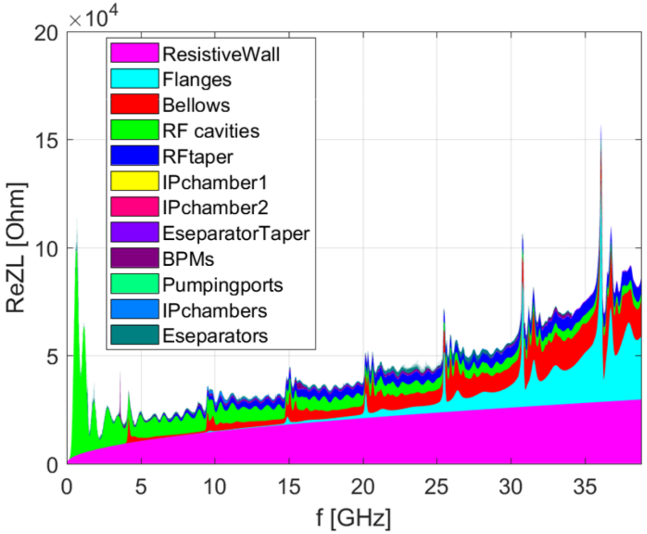
$$2\nu_x - 2m \cdot \nu_s = 1$$

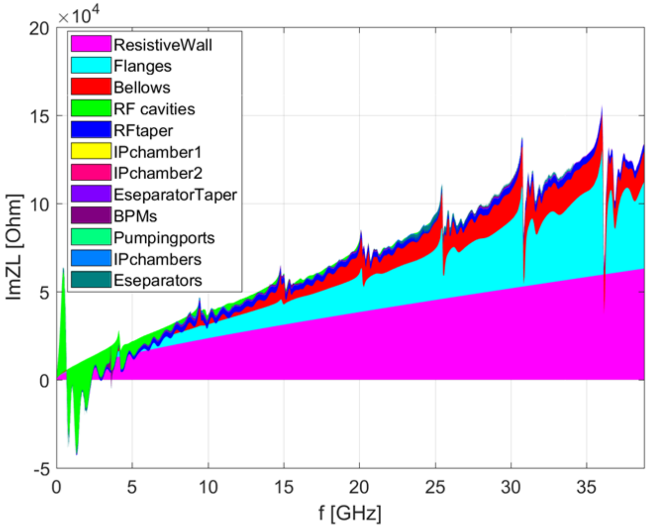


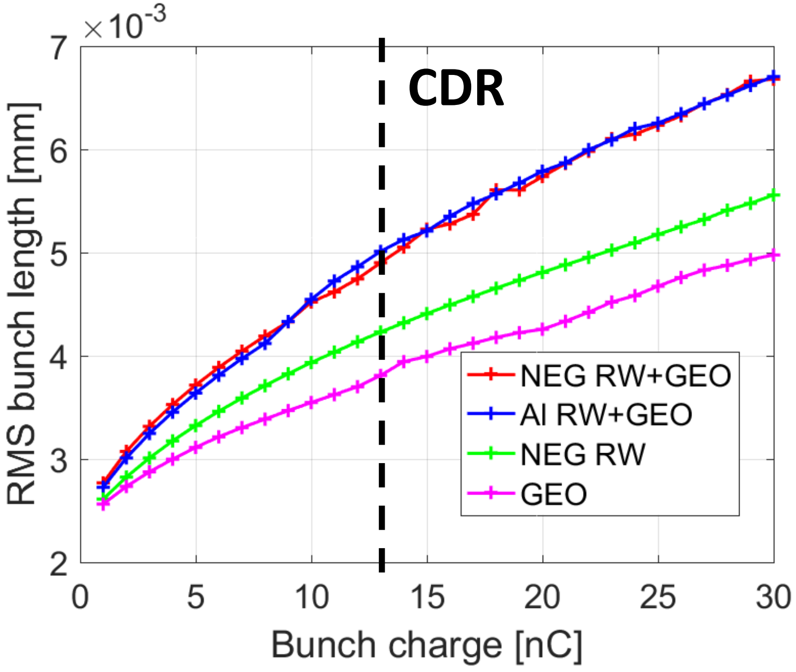


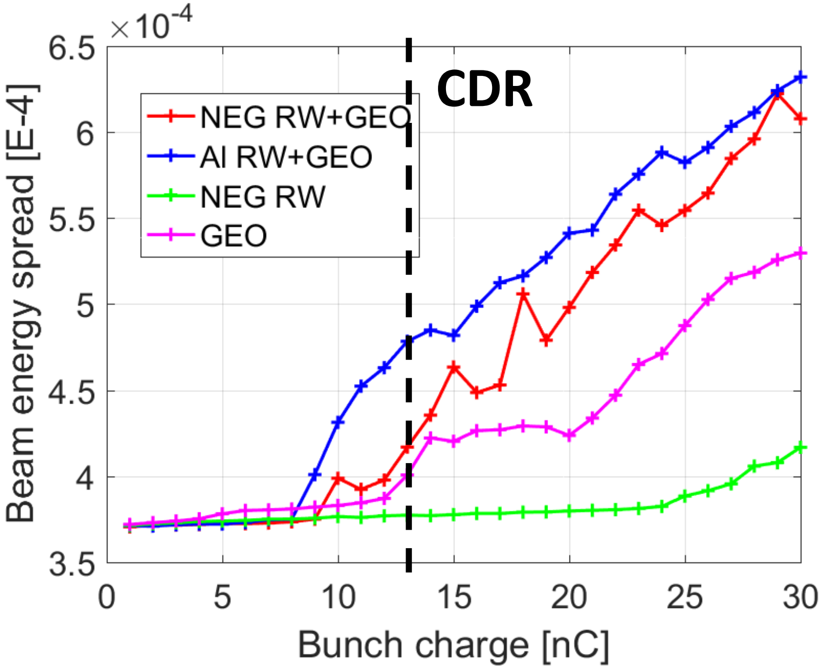
Single bunch Instability at CEPC-Z

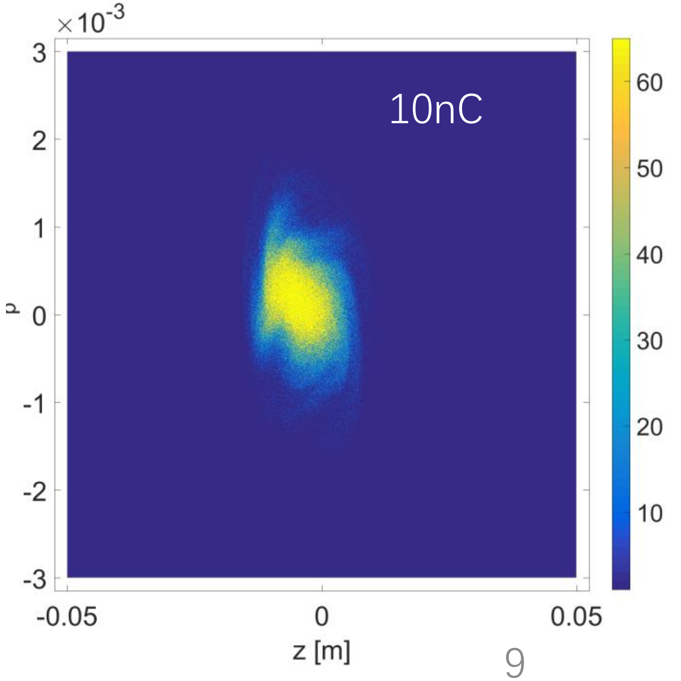
N. Wang, MCBI 2019 Workshop





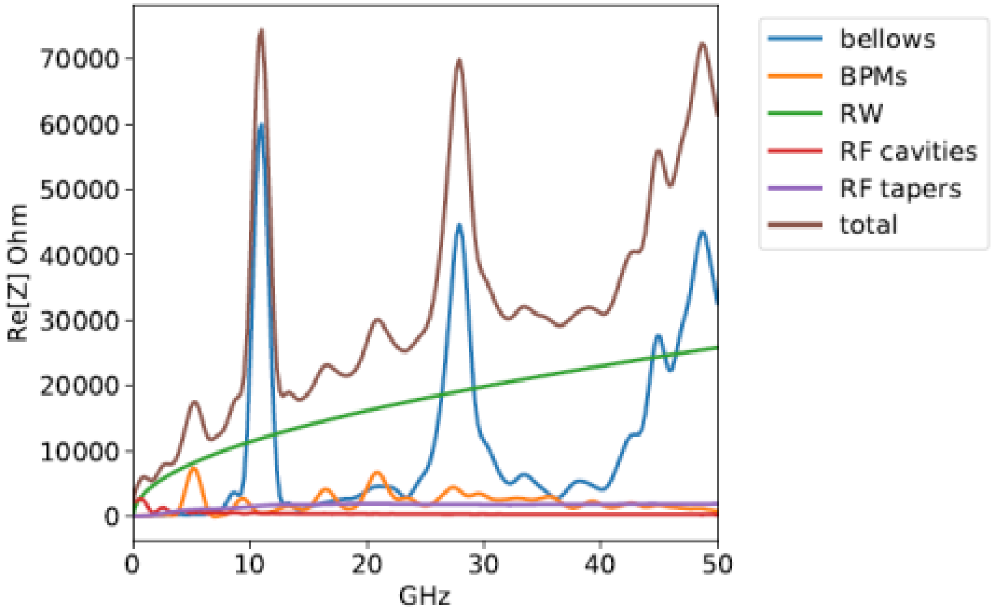


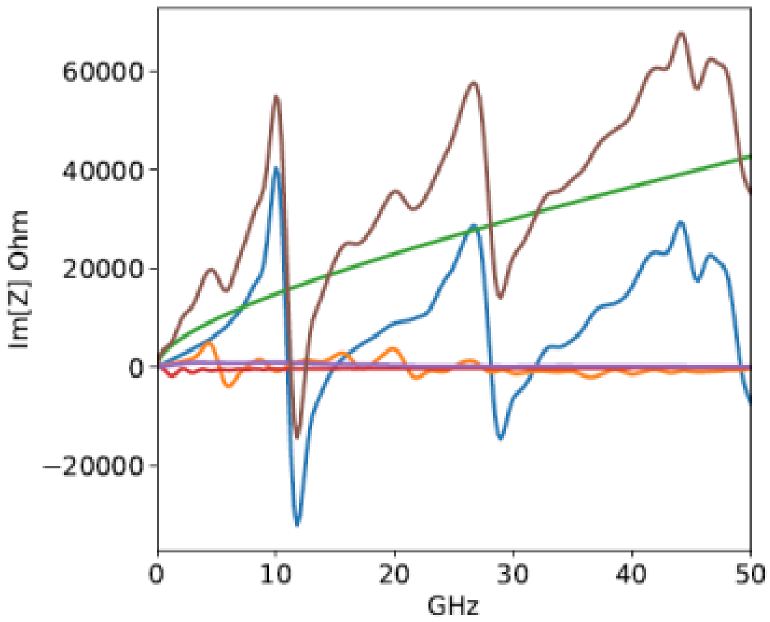


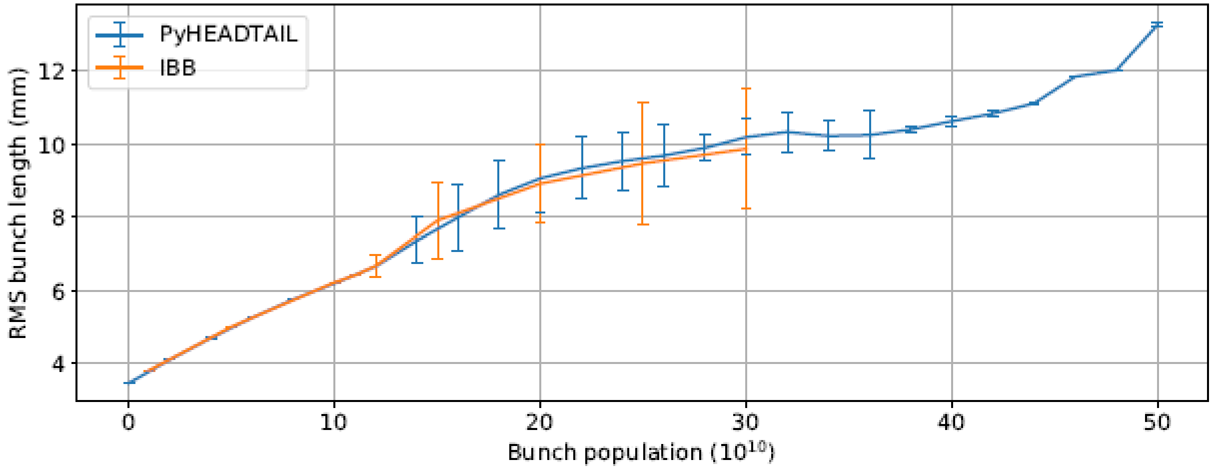


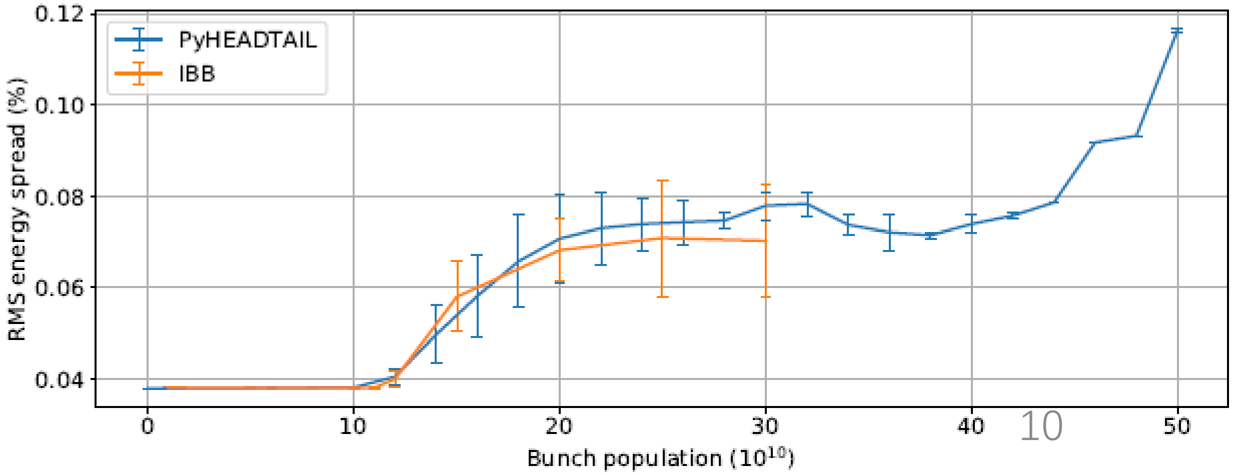
M.Migliorati and et al., Phys.Rev.Accel.Beams 21 (2018) 041001
M. Migliorati, 133rd FCC-ee optics design meeting

Single Bunch Effect at FCCee-Z









Interplay between beam-beam interaction, beamstrahlung and longitudinal impedance

X-Z Instability

1. Tune shift of stable tune areas due to the impedance related synchrotron frequency reduction
2. Reduction of sizes of the stable tune areas
3. Smaller beam blowup presumably due to the synchrotron frequency spread induced by the impedance

In Stable Areas

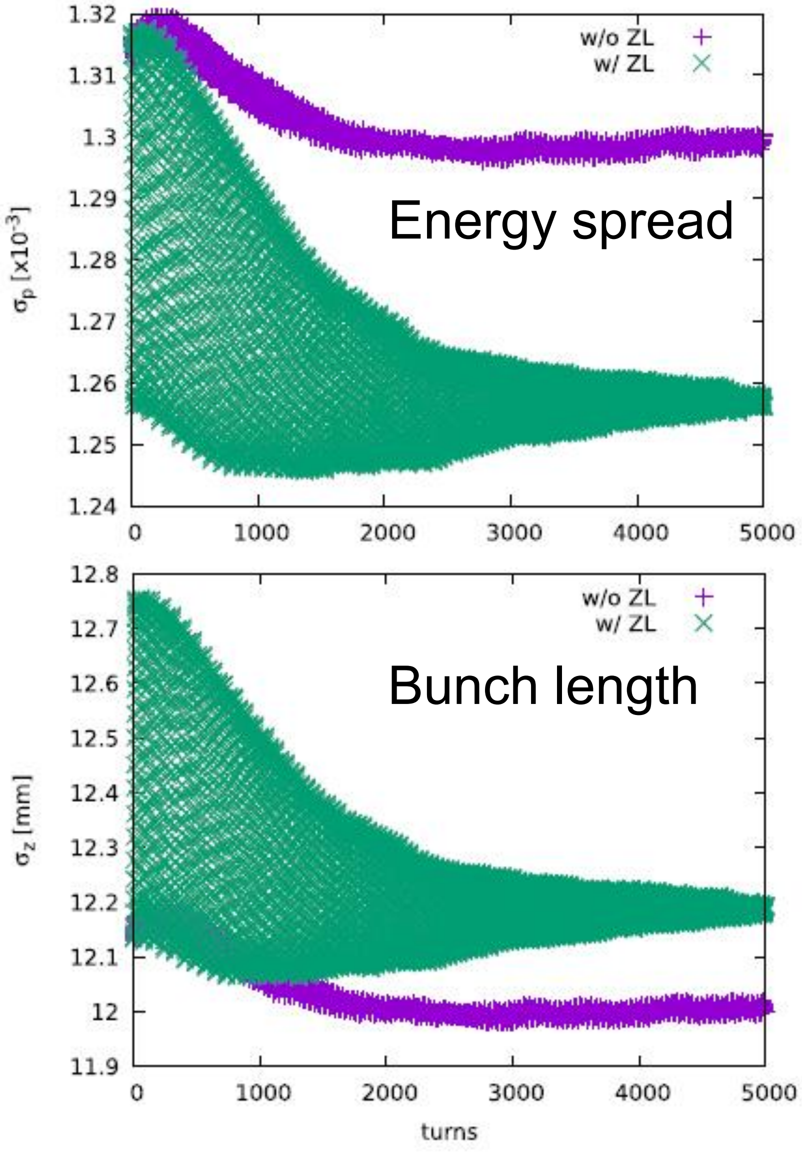
1. Longer bunch length
2. Smaller energy spread than that due to beamstrahlung alone
3. Eventual damping of the microwave instability due to longer bunches and overall higher energy spread

Machine Parameter (CDR version)

	CEPC-Z	FCCee-Z
Beam Energy	45.5 GeV	45.6 GeV
Bunch Population	8e10	17e10
Arc Cell	$90°/90°$	$60°/60°$
$\beta^*_{x/y}$	0.2 m/ 1mm	0.15 m/0.8 mm
ϵ_x/ϵ_y	0.18 nm/1.6 pm	0.27 nm/1.0 pm
ν_s/superperiod	0.014	0.0125
σ_z [SR/BS]	2.42 / 8.5 mm	3.5 / 12.1 mm
σ_p [SR/BS]	3.80 / 8 $\times 10^{-4}$	3.8 / 13.2 $\times 10^{-4}$
ξ_x [BS]	0.004	0.004
ξ_y [BS]	0.079	0.133
Piwinski Angle [SR/BS]	6.6 / 23	8.2 / 28.5

D.Leshenok and et al. PHYS. REV. ACCEL. BEAMS 23, 101003 (2020)

Combined effect of beamstrahlung and longitudinal impedance in stable tune areas



Semianalytical calculations are in reasonable agreement with numerical modeling

TABLE IV. The FCC-ee beam energy spread and length as well as the synchrotron tune parameter due to the combined effect of SR, BS, and PWD.

E [GeV]	45.6
σ_E	0.00126[a]
	0.00132[b]
σ_z [mm]	12.2[a]
	12.6[b]
ν_s/ν_{s0}	0.964[b]

[a]Beam-beam simulation [21].
[b]Semianalytical model (SR + BS + PWD).

Longitudinal Impedance induces
- Longer bunch length
- Lower energy spread
- Lower incoherent synchrotron tune

Review of CDR parameters of CEPC-Z Considering Impedance

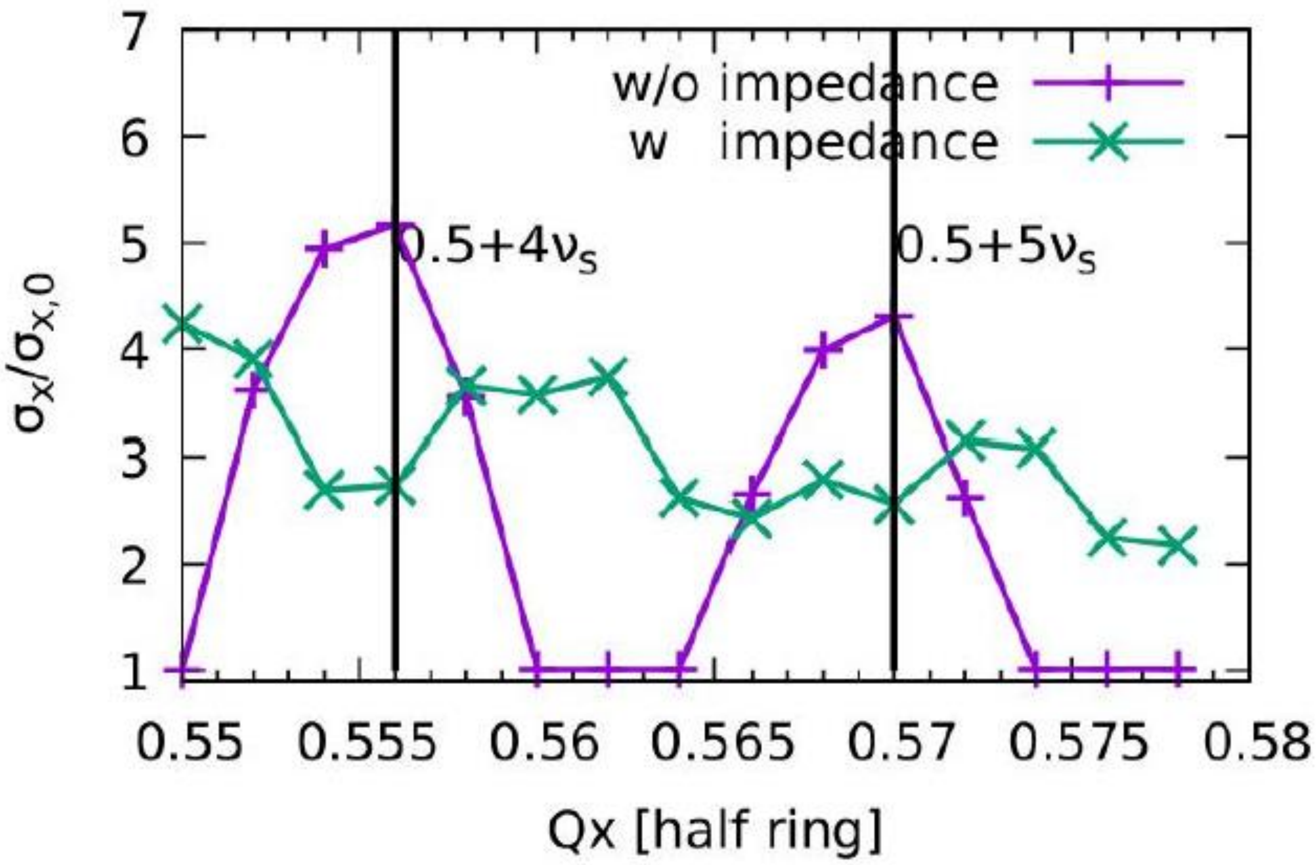


Figure 13: Horizontal beam size blow up in collision obtained by simulation with and without impedance.

X-Z instability tune scan with and without beam coupling impedance (CEPC)

By including the impedance stable areas become narrower and are shifted in frequency

After the horizontal beta function reduction from 0.2 m down to 0.15 m

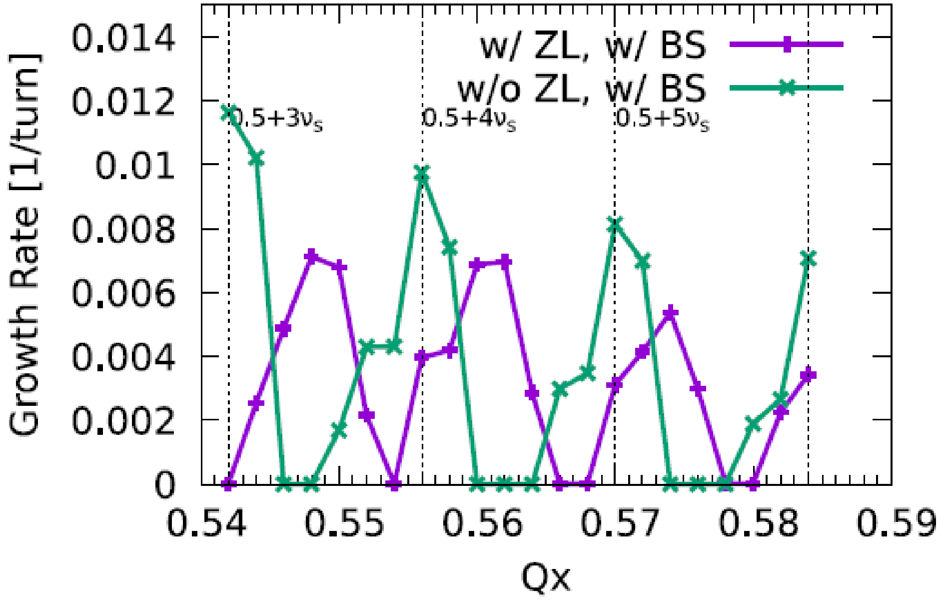
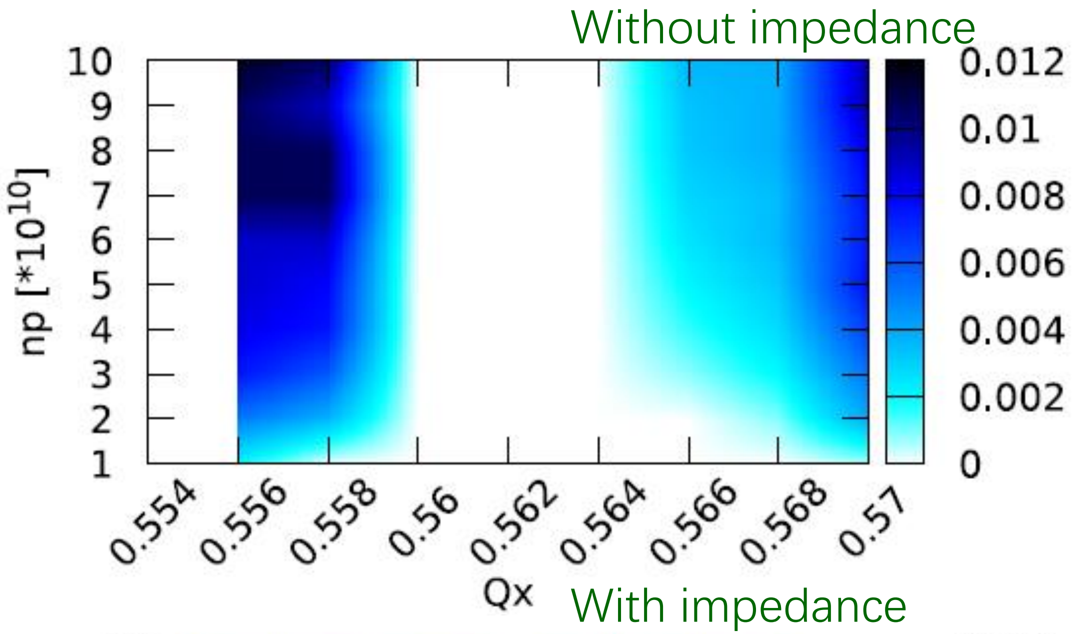
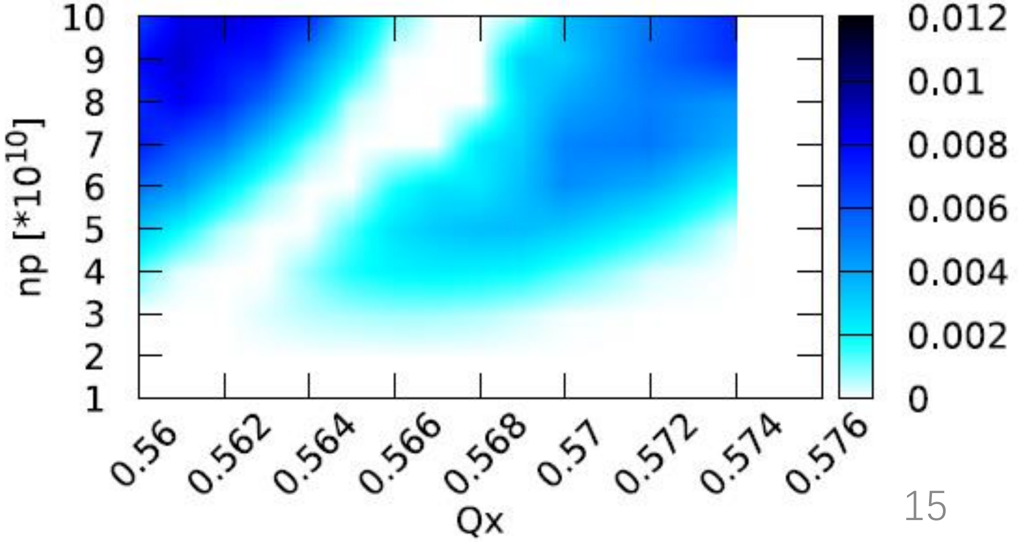
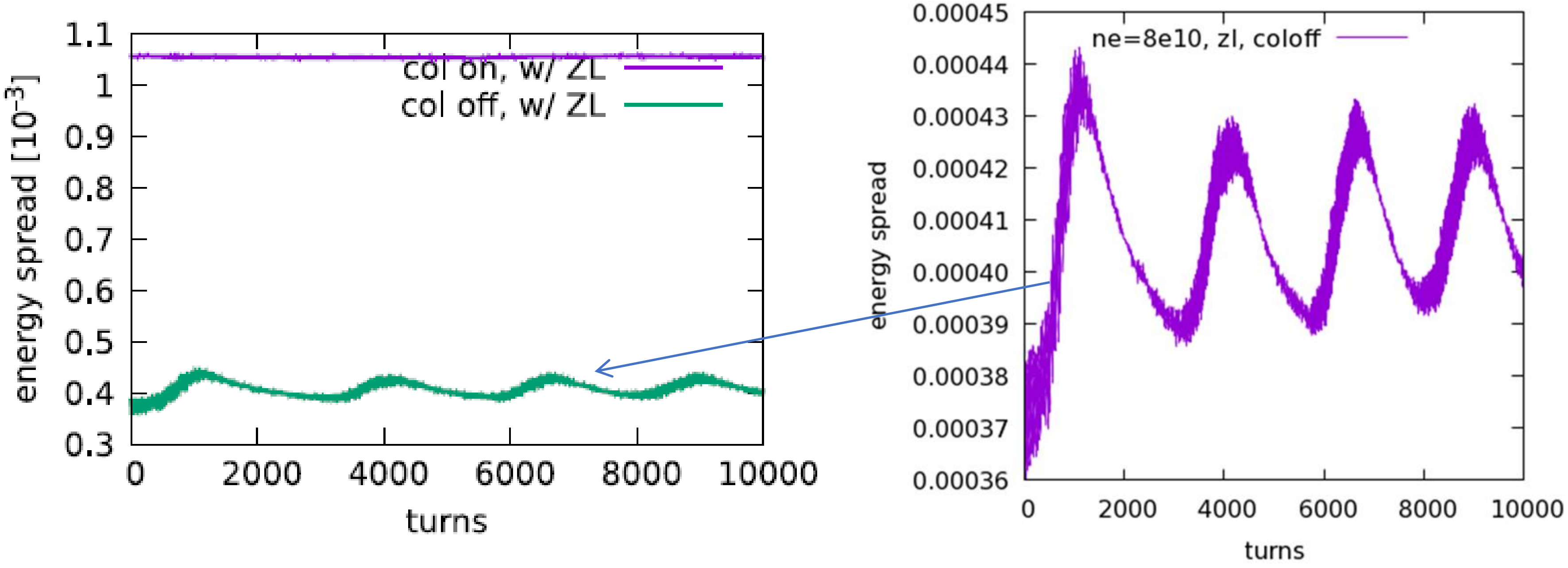


FIG. 3. The horizontal beam size growth rate versus horizontal tune with and without longitudinal coupling impedance (ZL) Beamstrahlung (BS) effect is turned on.



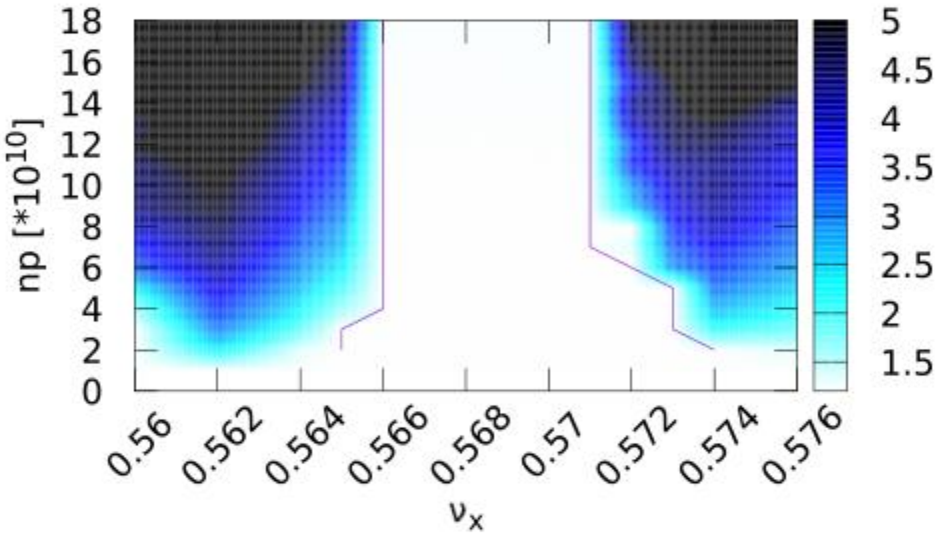


Microwave instability suppression in collision (CEPC example)

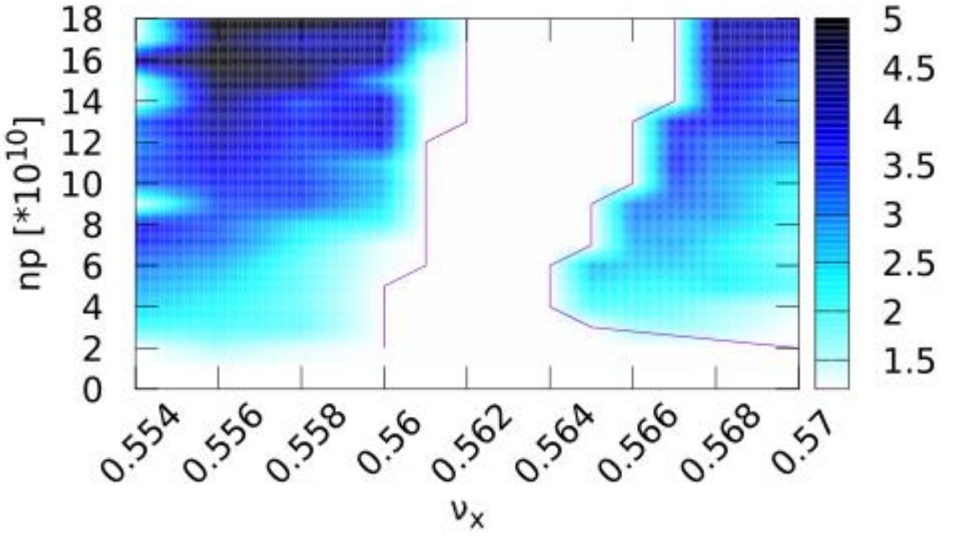


X-Z instability tune scan with and without beam coupling impedance (FCC-ee, Horizontal size blowup)

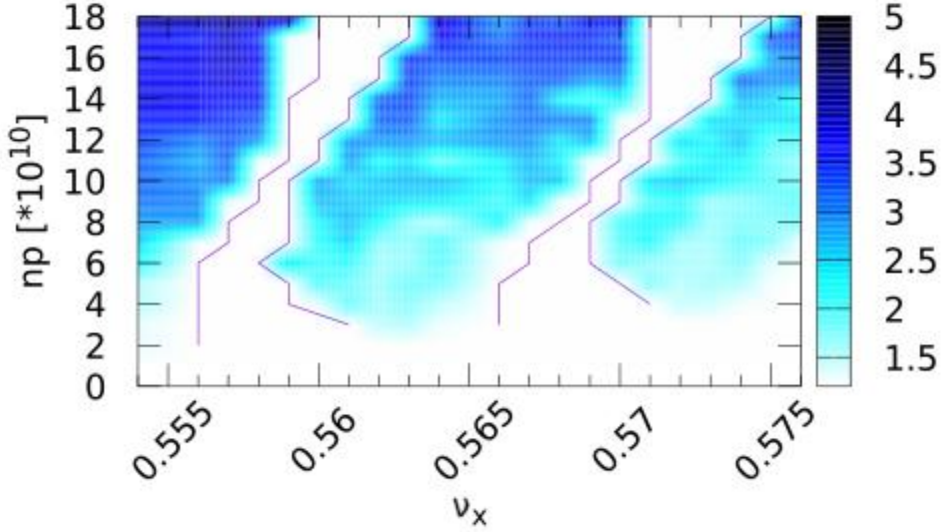
w/o ZL

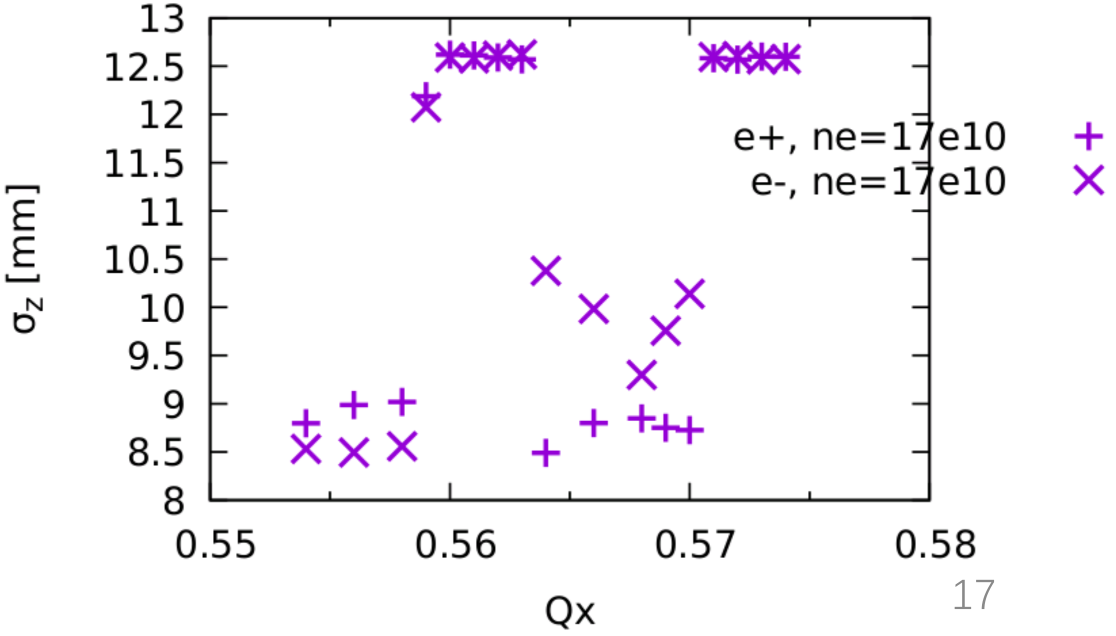


Only with RW



with full impedance (so far)





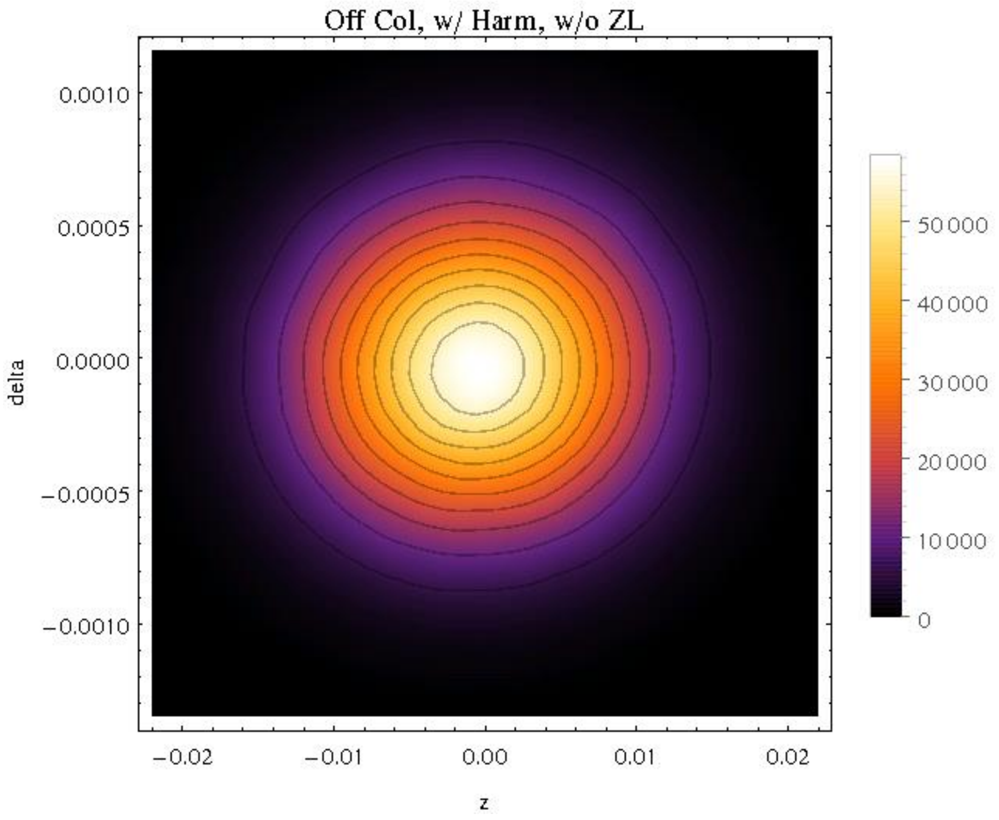
Idea of using harmonic cavities

- With harmonic cavities the lower synchrotron tune can be achieved without momentum acceptance reduction, differently from the main cavities voltage reduction alone.
- So higher order X-Z resonances nQx-mQs take place for the same betatron working points, i.e. a weaker X-Z instability is expected.
- The harmonic cavities provide a higher synchrotron frequency spread (Landau cavities). This may help to suppress the X-Z instability and provides additional damping of the longitudinal multi-bunch instabilities.
- The microwave instabilities are expected to be weaker with the harmonic cavities as is the case of several synchrotron light sources.
- Longer bunches reduce the horizontal tune shift, since it scales inversely to the second power of the bunch length. This also helps in suppressing the X-Z instability.
- Longer bunches in collision result in a smaller energy spread due to beamstrahlung.

Harmonic cavity configuration of FCC-ee-Z

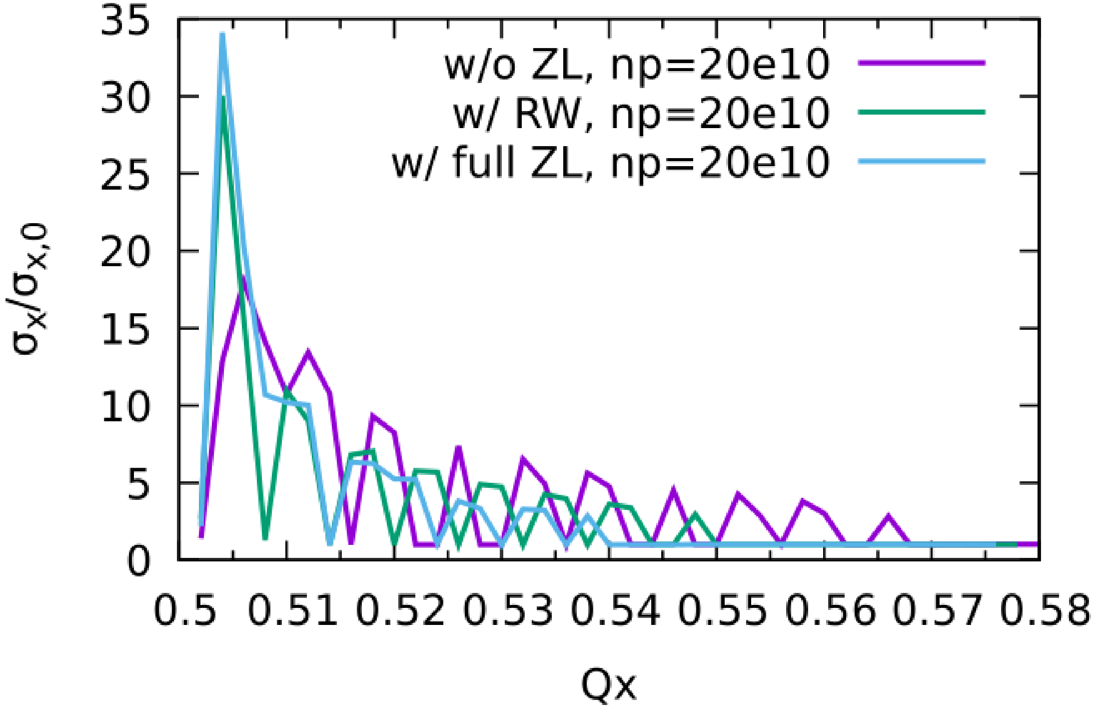
Bunch is lengthened about a factor of 2 (without collision)

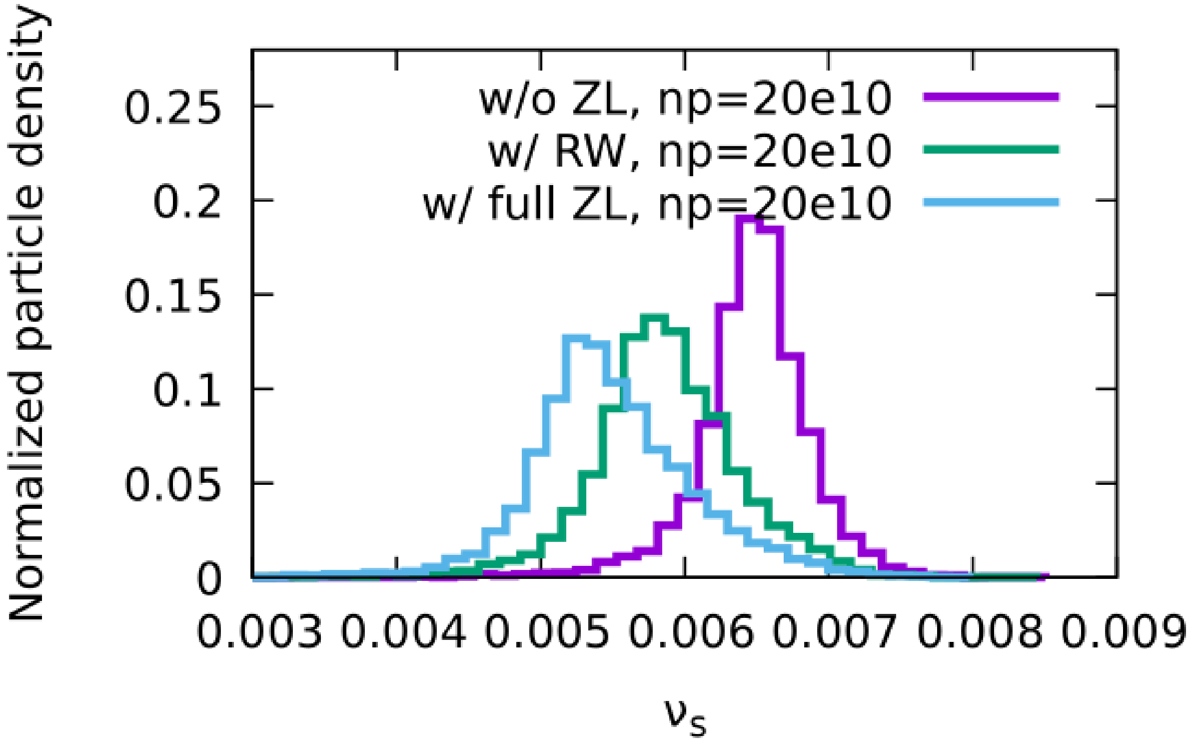
- E0 = 45.6 GeV
- U0 = 18 MV (half ring)
- Main Cavity,
  - Vrf = 50 MV
  - ϕ=156.1^{o} ($50 \sin\phi = 20.3$)
- 3rd Harmonic, 1.2GHz
  - Vrf_3 = 11.7 MV
  - ϕ_3=-11.1^{o} ($11.7 \sin\phi_3 = -2.3$)



Horizontal size blowup with Harmonic Cavity @ FCC-ee-Z

With full impedance, it is all stable at different bunch population （Qx: 0.554-0.576/0.001）



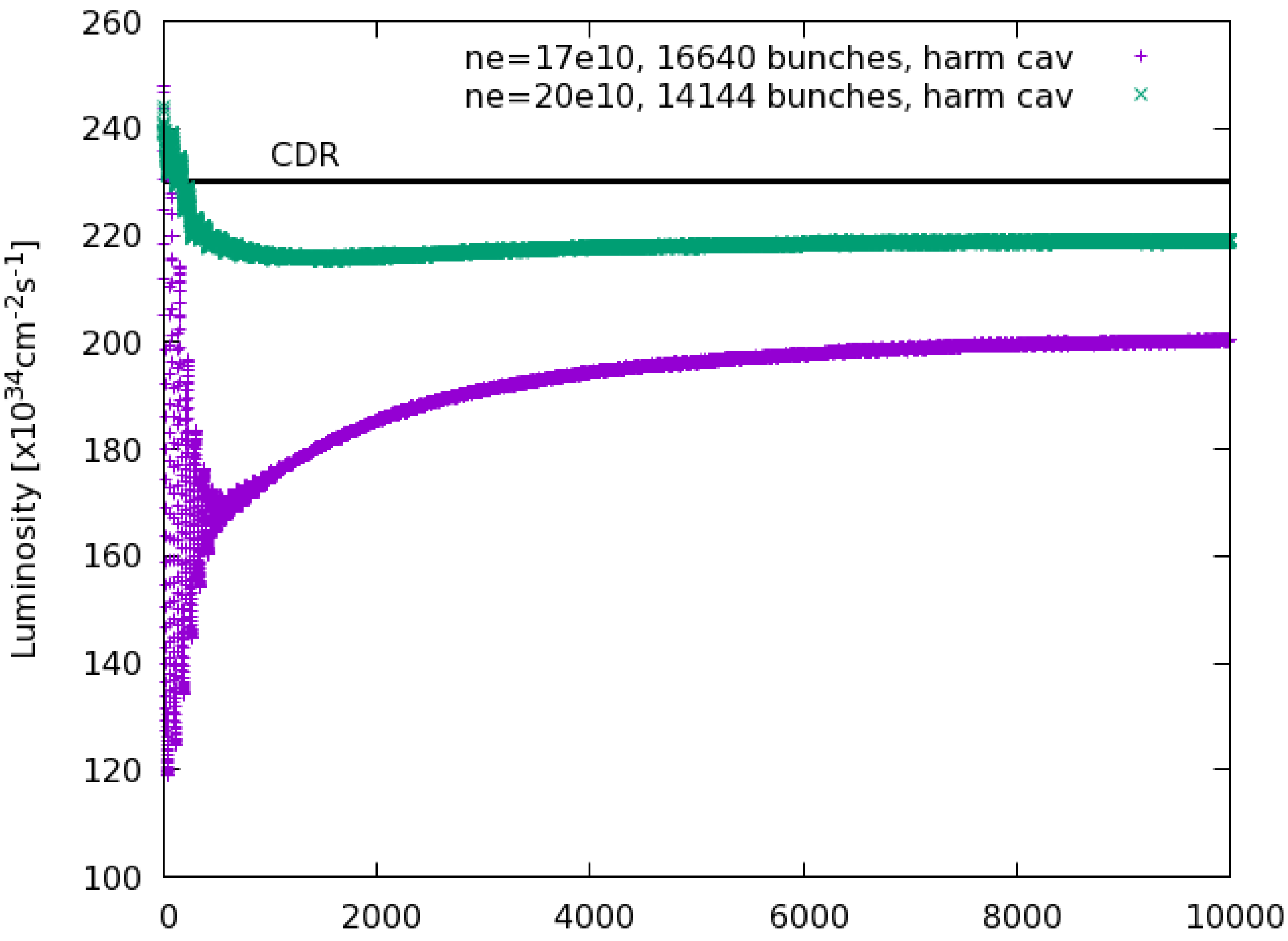


σ_z = 18 mm (CDR: 12 mm)

σ_p = 9.2e-4 (CDR: 13e-4)

ξ_x = 2.0e-3 (CDR: 4e-3)

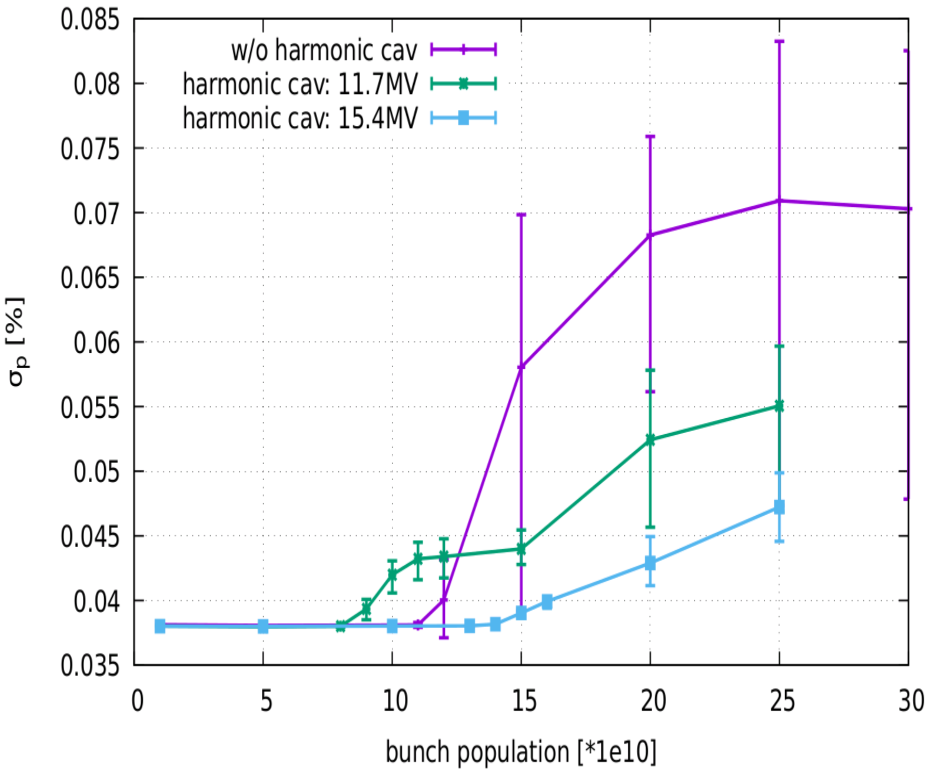
Luminosity with Longitudinal Impedance



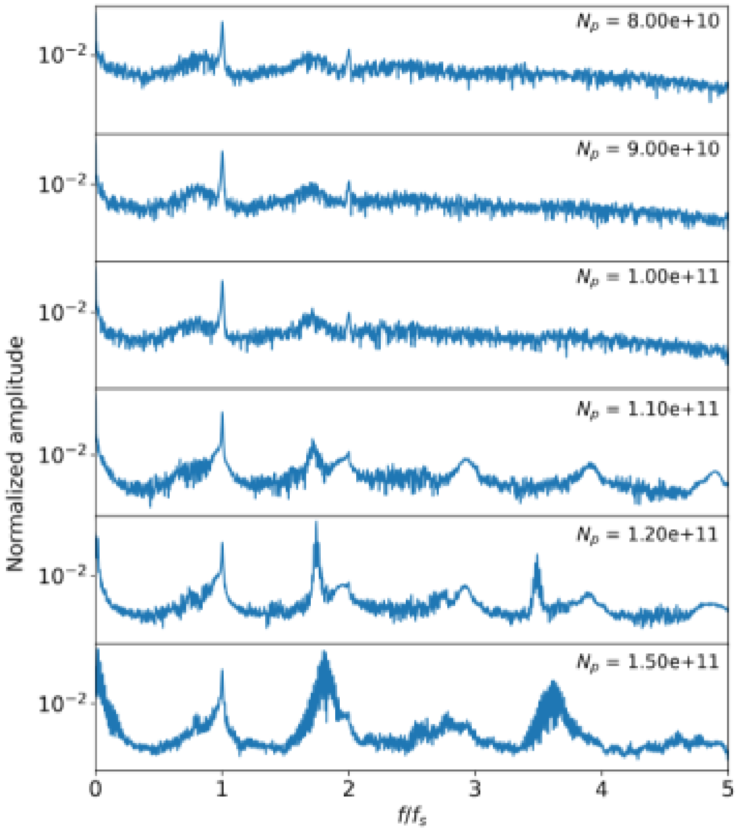
M. Migliorati

PRAB 23, 071001, 2020

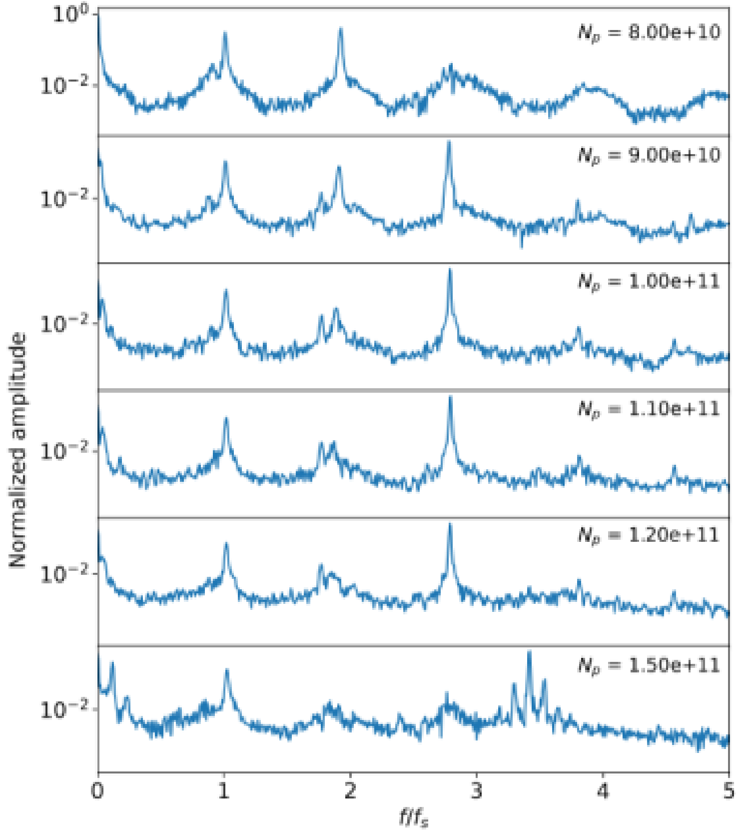
Single Bunch Instability w/ Harmonic Cavity at FCC-ee-Z



Frequency spectra of the momenta of the bunch distribution at different bunch intensity



w/o Harmonic Cavity



w/ Harmonic Cavity

Some Discussion

The X-Z instability is a multi-parametric problem:

- ξ_x affects the resonance strength, i.e. the width of the resonances
- ξ_x should be less than the distance between the resonance lines
- order of the resonances (Qx+nQs)
- spread of the synchrotron frequencies
- bunch shape is important for a head-tail instability
- Etc.

Many of these effects depend on the impedance frequency behavior and the effective impedance depends on the bunch length.

Issues to be solved/studied for harmonic cavity scheme

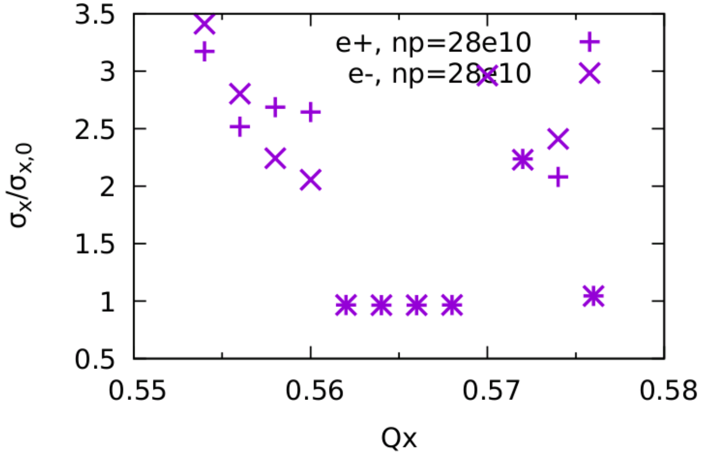
- Transient beam loading
- TMCI should be carefully investigated.
- Some luminosity loss due to longer bunches for the fixed total SR power.
- Additional impedance contribution of the harmonic cavities and other devices.
- Energy calibration.

Higher Momentum Compaction

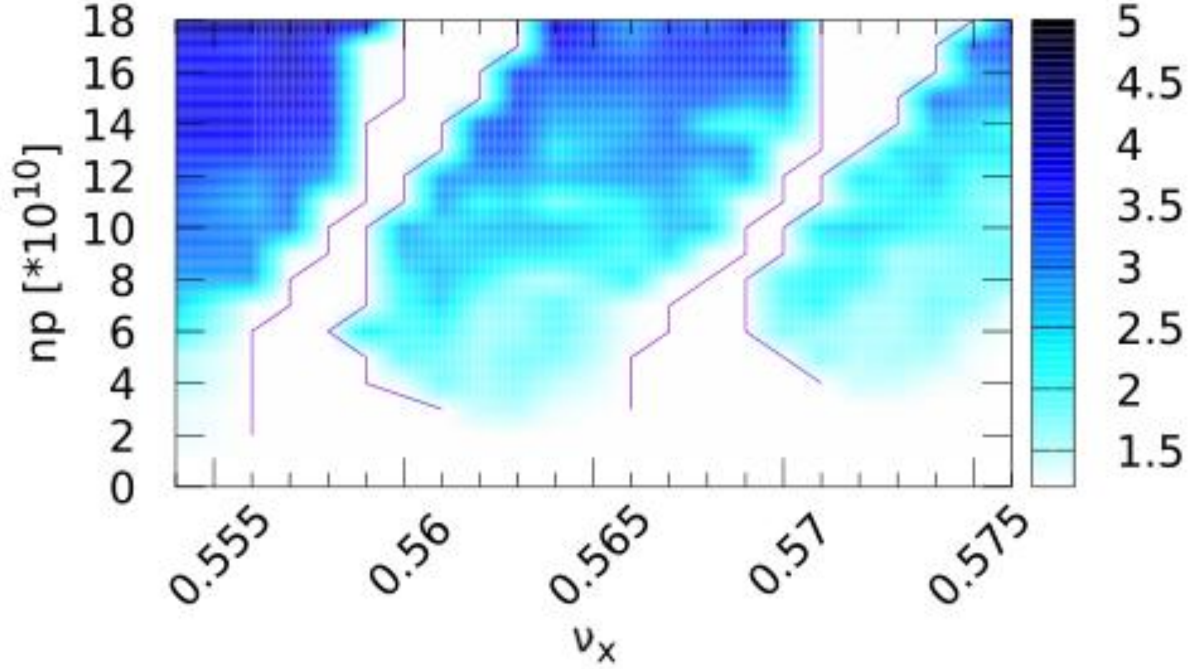
- CEPC-Z: $90°/90°$ (CDR) to $60°/60°$
- FCC-ee-Z CDR: $60°/60°$ FODO cell
- Switching from $60°/60°$ to $45°/45°$ arc cell lattice has been proposed for FCC-ee Z. The lattice for $45°/45°$ does not exist yet.
- To restore the luminosity of CDR, higher bunch population (28e10) has been proposed.

Arc Cell	α_p $[10^{-5}]$	ϵ_x [nm]	ϵ_y [pm]	ν_s	σ_{z0} [mm]	σ_z [mm]	σ_p $[10^{-4}]$	L/IP 10^{36}	ϕ	ξ_x
$45°$	2.5	0.6	1.5	0.0163	4.5	11.5	9.7	1.9	18.2	0.004
$60°$	1.48	0.27	1.0	0.0125	3.5	12	13	2.3	28.5	0.004

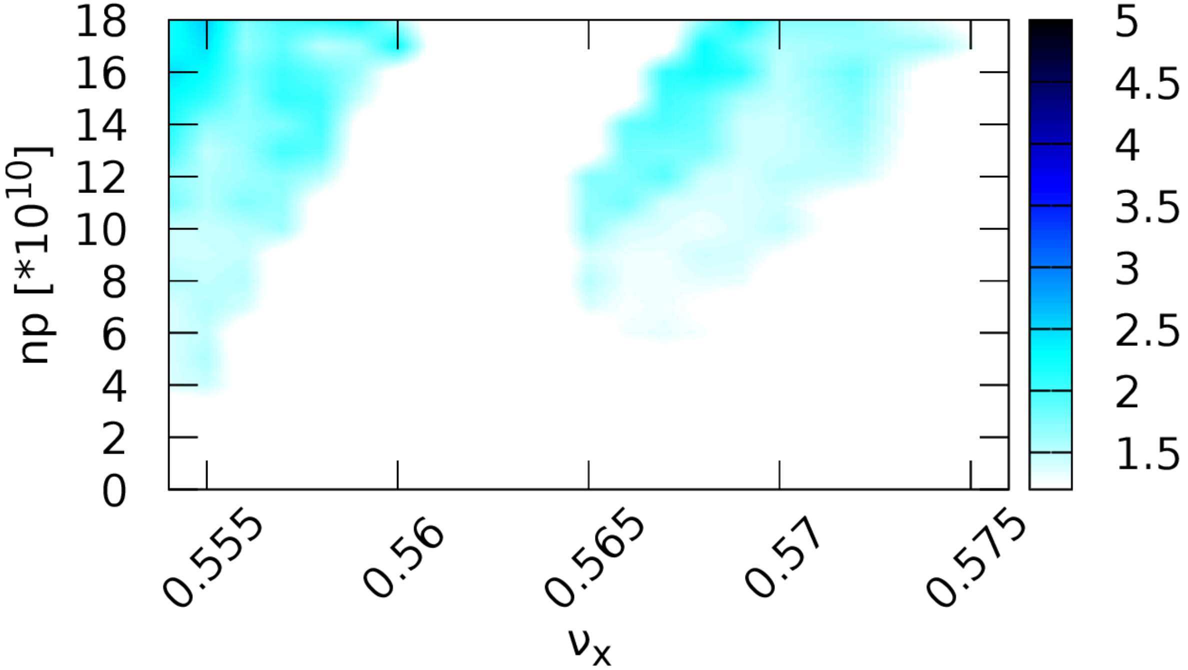
Bootstrapping Injection



- Horizontal size blowup

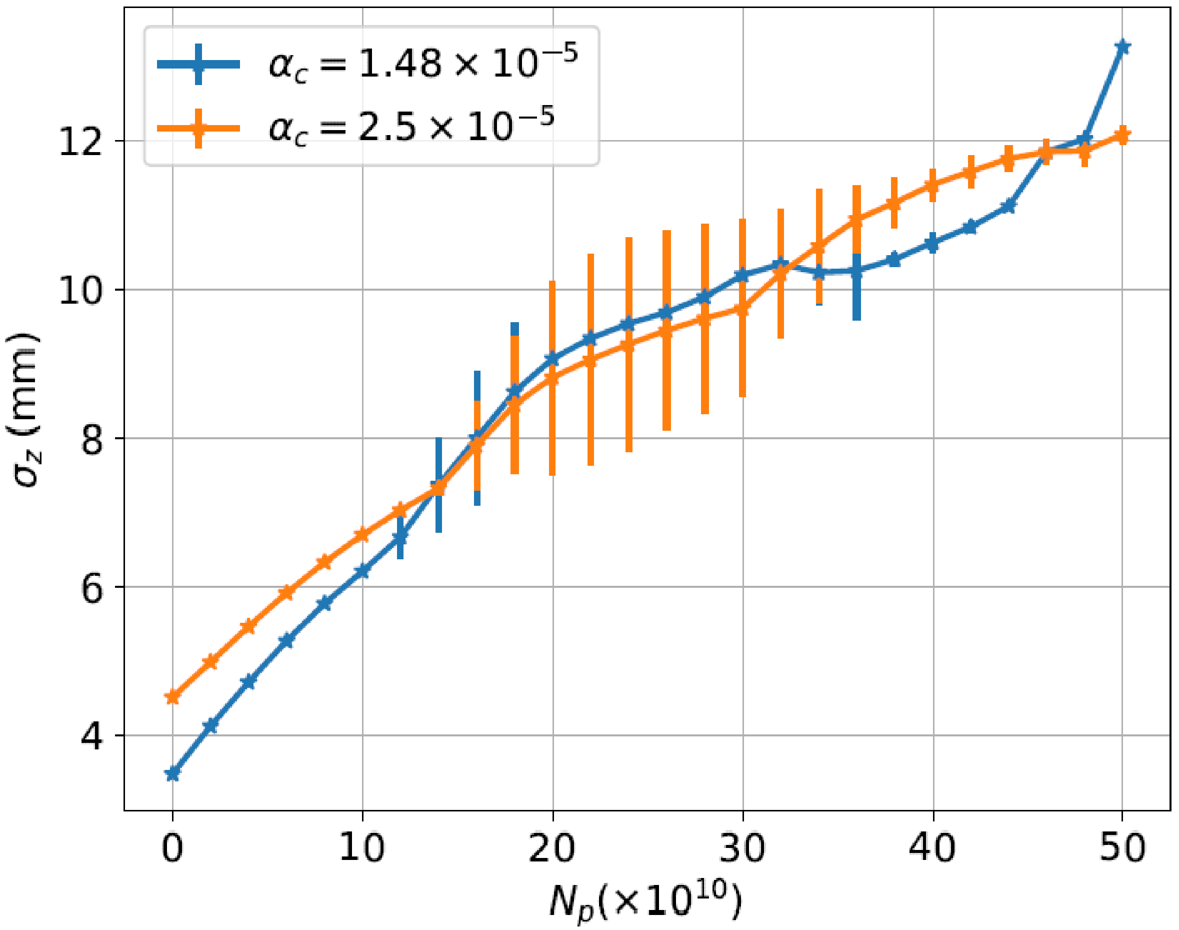


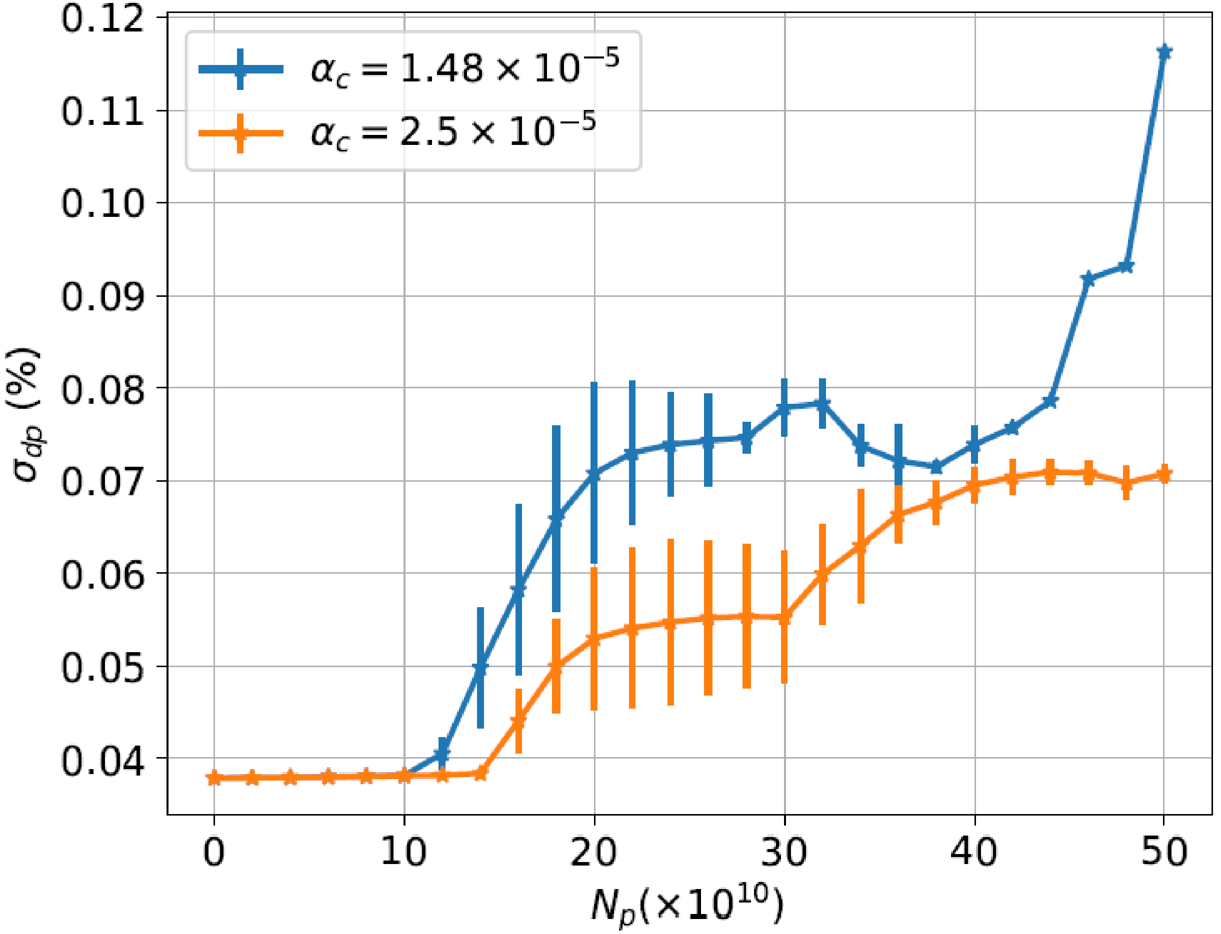
FODO CELL: $60°/60°$



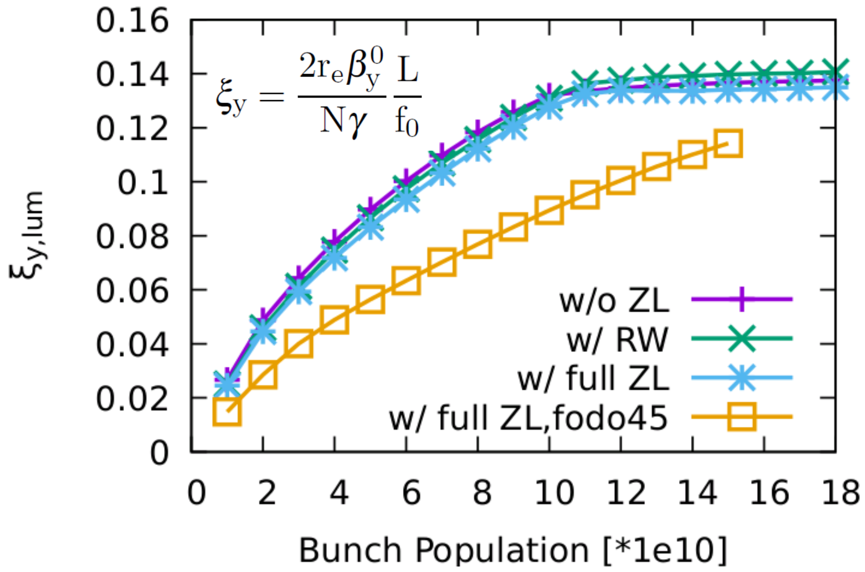
FODO CELL: $45°/45°$

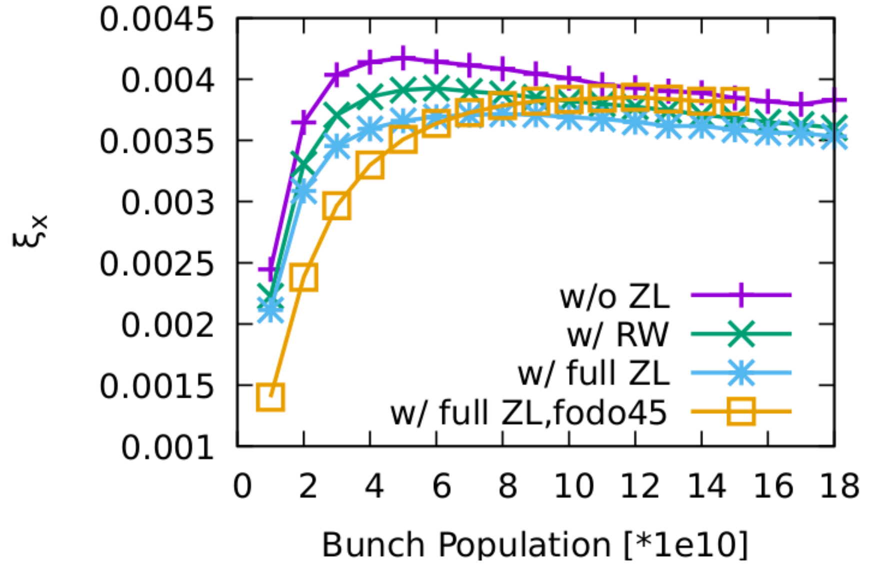
Single bunch instability at FCC-ee-Z

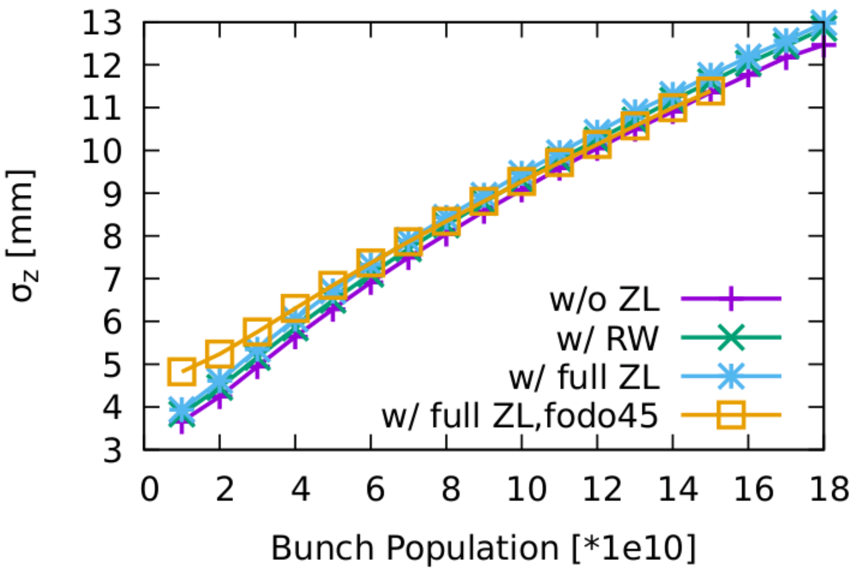


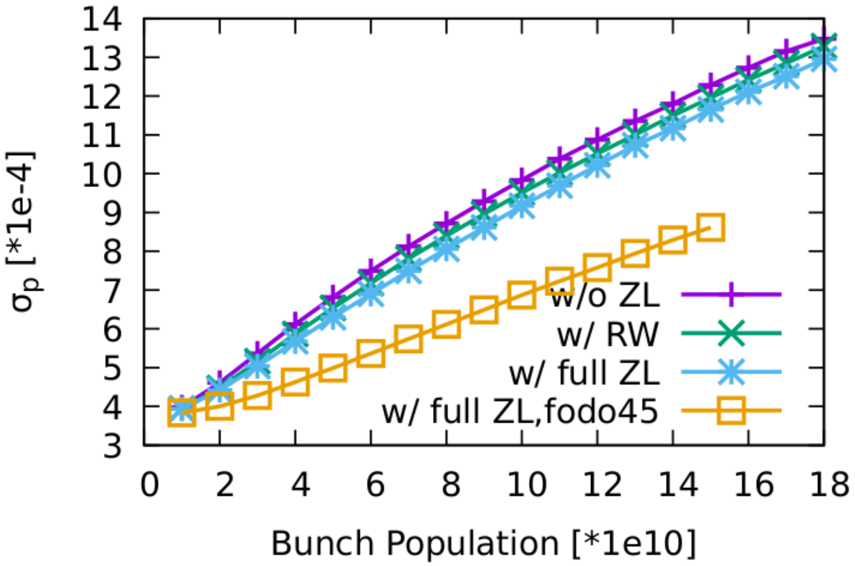


Evolution of Parameters during Injection









Discussion on High Momentum Compaction

- good tune areas
- less bunches and higher intensity per bunch
- Higher bunch separation and higher bunch intensity
    - e-cloud is much weaker
    - avoiding ion trapping
- Higher synchrotron frequency is better for the energy calibration

Conclusions

- The beam coupling impedance can have a substantial impact on the choice of beam parameters and the final collider performance.
- The principal effects are summarized:
  - Tune shift of stable tune areas
  - Smaller safe tune area
  - Smaller beam blowup
- Possible Mitigation Options:
  - Smaller β_x^*
  - Higher Harmonic Cavity (energy calibration?)
  - Higher Momentum compaction
- Both CEPC and FCC-ee are still in the design phase, and it is expected that longitudinal impedance will certainly increase. The combined effect of impedance and beam-beam needs particular care since it may cause unwanted instabilities.