



FUTURE
CIRCULAR
COLLIDER



Combined effect of impedance and beam-beam

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Outline

- Introduction
- Review of CDR Parameters
- Different Schemes
- Summary

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

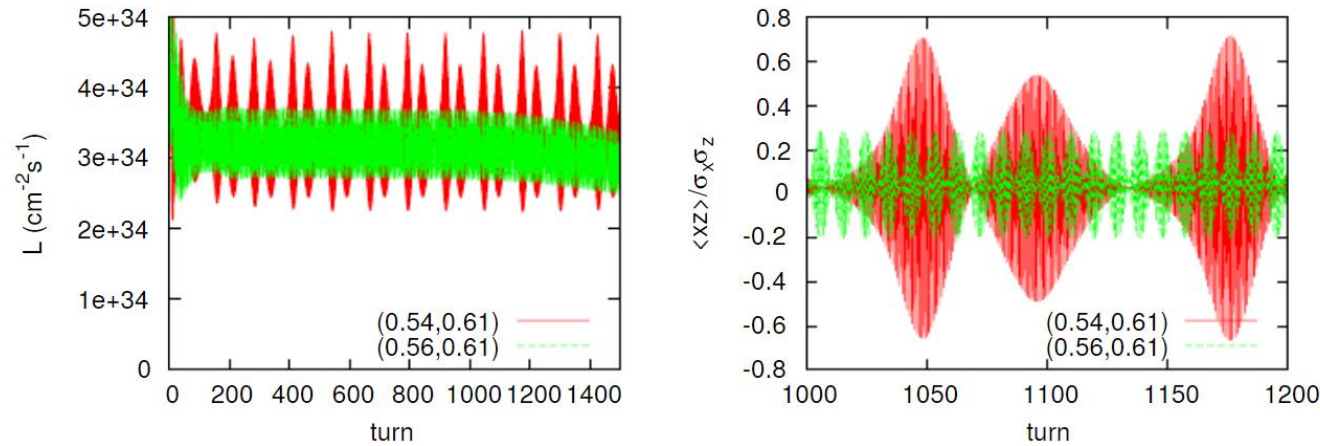


Fig. 5. Luminosity and $\langle xz \rangle$ evolutions given by a strong-strong simulation using BBSS code.

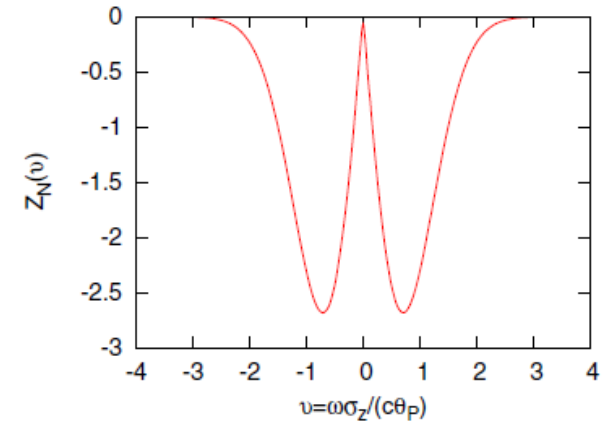


FIG. 3. Imaginary part of normalized cross impedance, where $v = \omega \sigma_z / (c \theta_p)$.

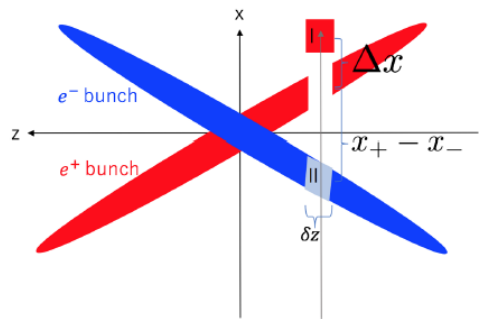


FIG. 1. Illustrative representation of the evaluation of the cross-wake force.

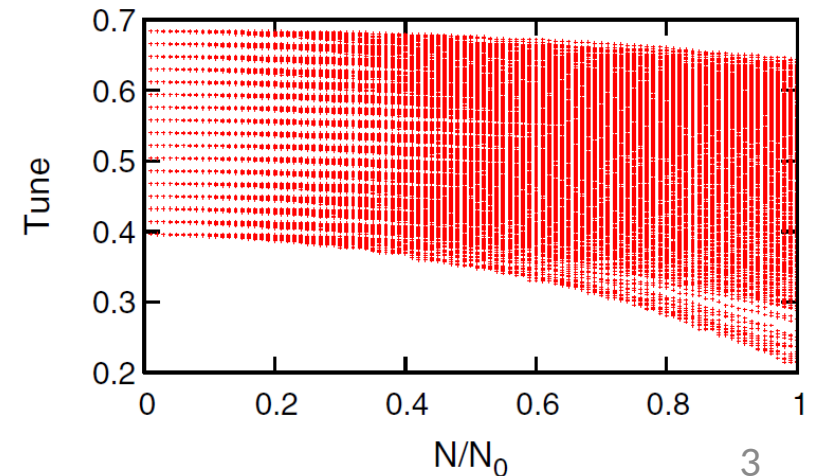
- Usual wake force gives correlation between bunch head to tail. Head-tail instability is induced by synchrotron motion

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

- **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.



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

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

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

Simulation

CODE: IBB

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)

- 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

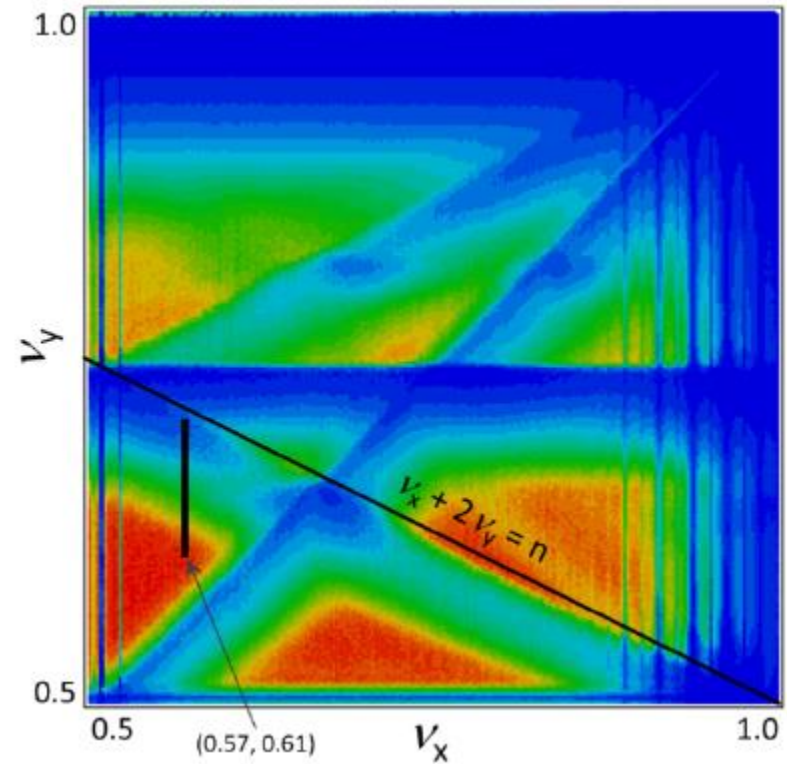
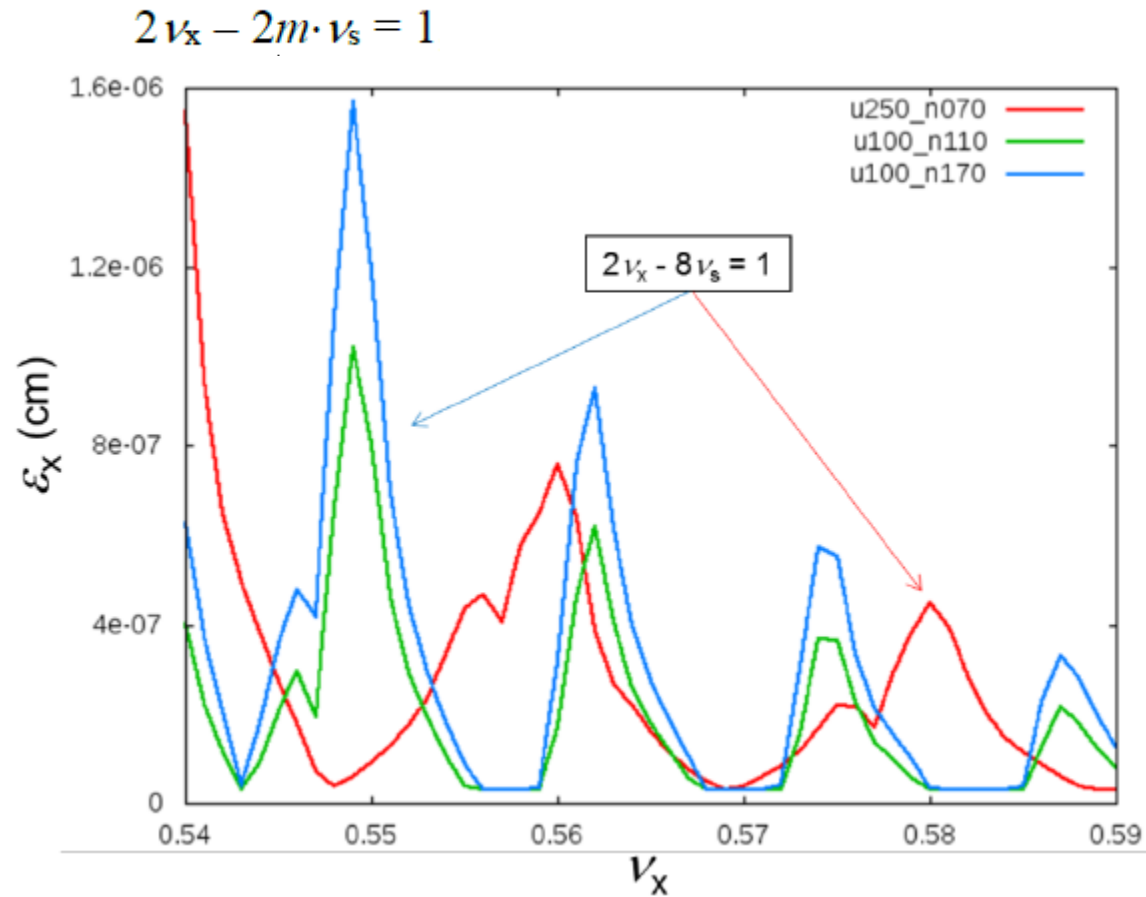
Parameter Optimization

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

$$\alpha_p \sigma_\delta \propto v_s \sigma_z$$

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

Larger v_s / ξ_x is preferred!



Interplay between beam-beam interaction, beamstrahlung and longitudinal impedance

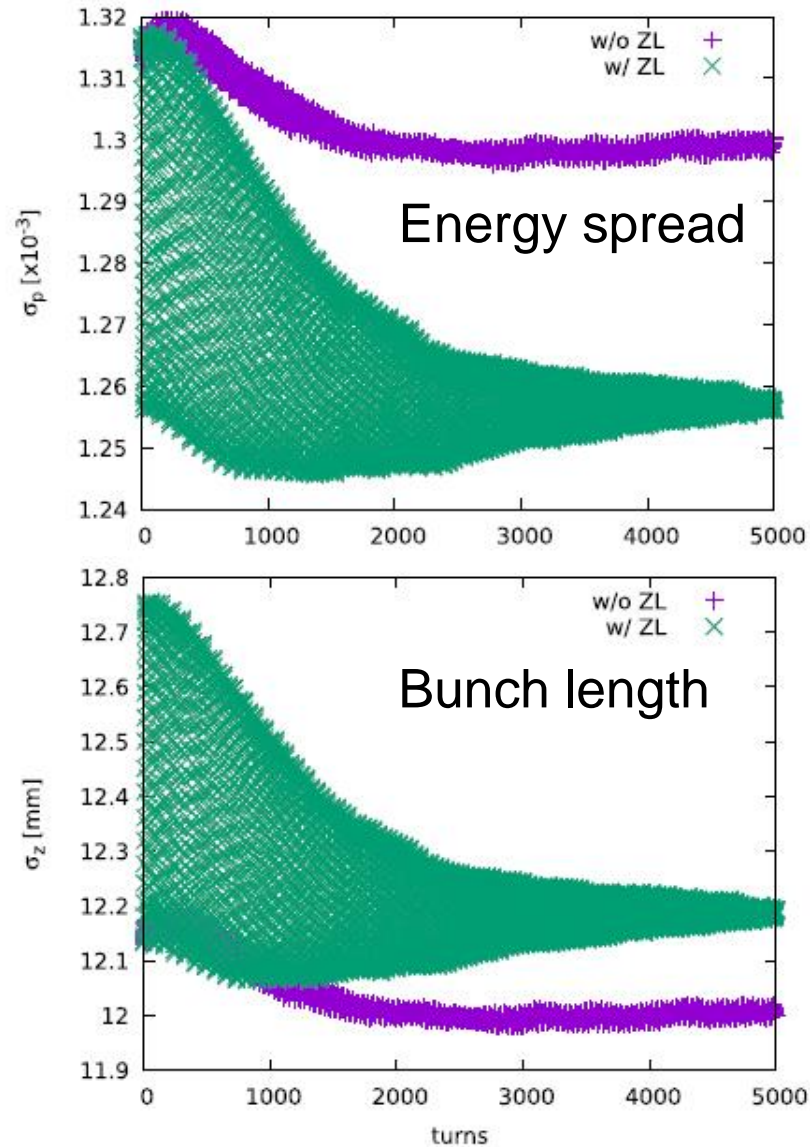
X-Z Instability

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

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

^aBeam-beam simulation [21].

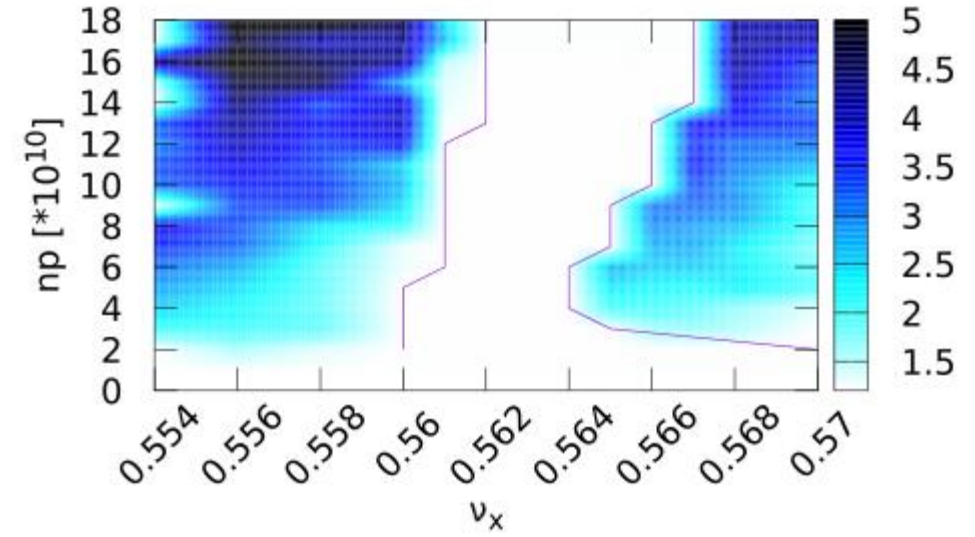
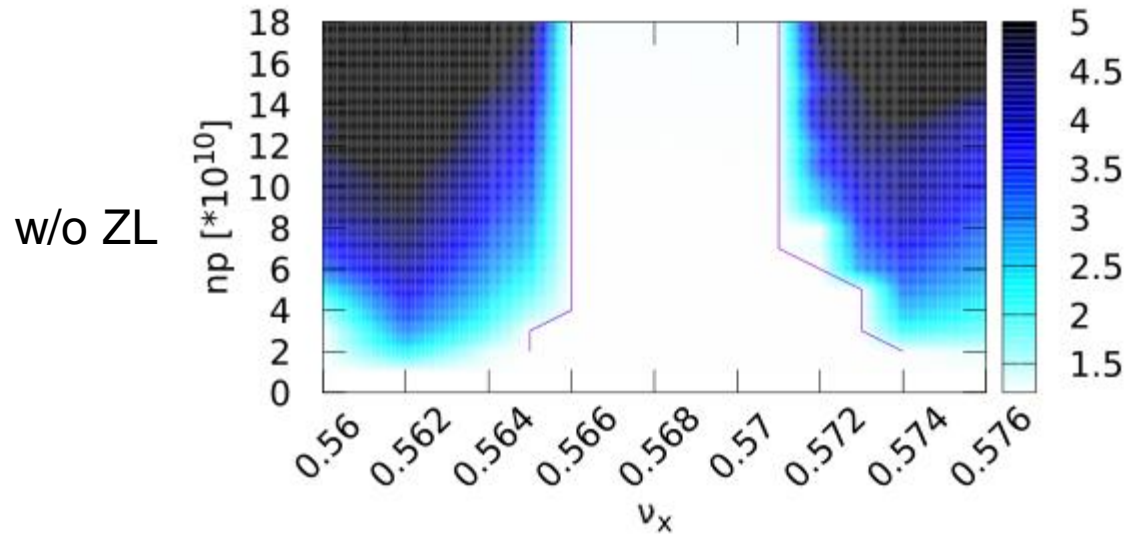
^bSemianalytical model (SR + BS + PWD).

Longitudinal Impedance induces

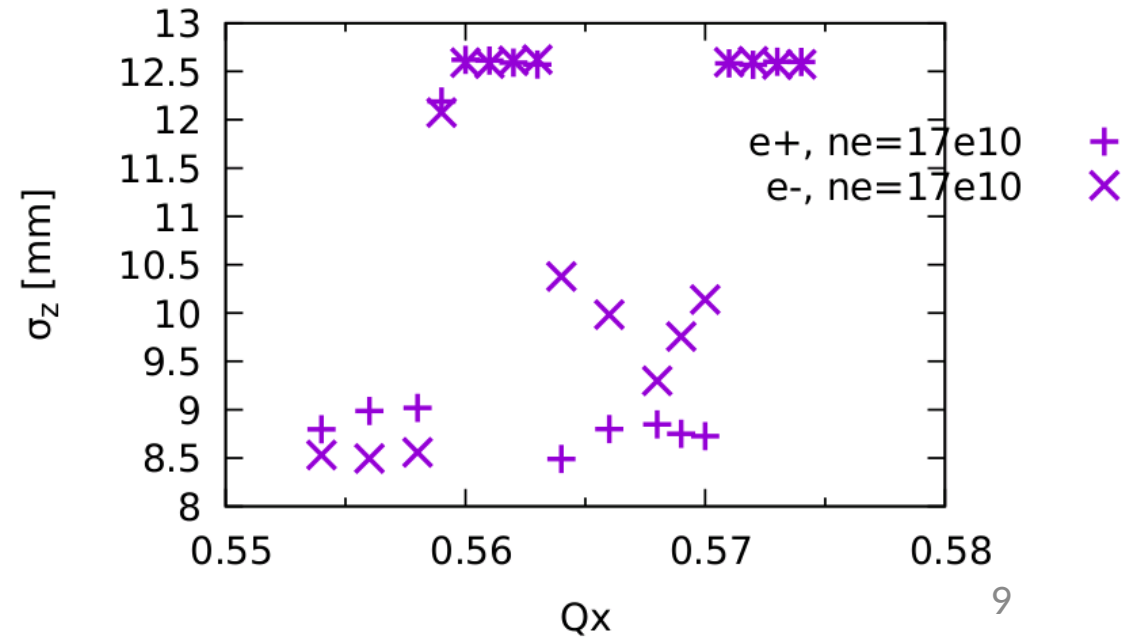
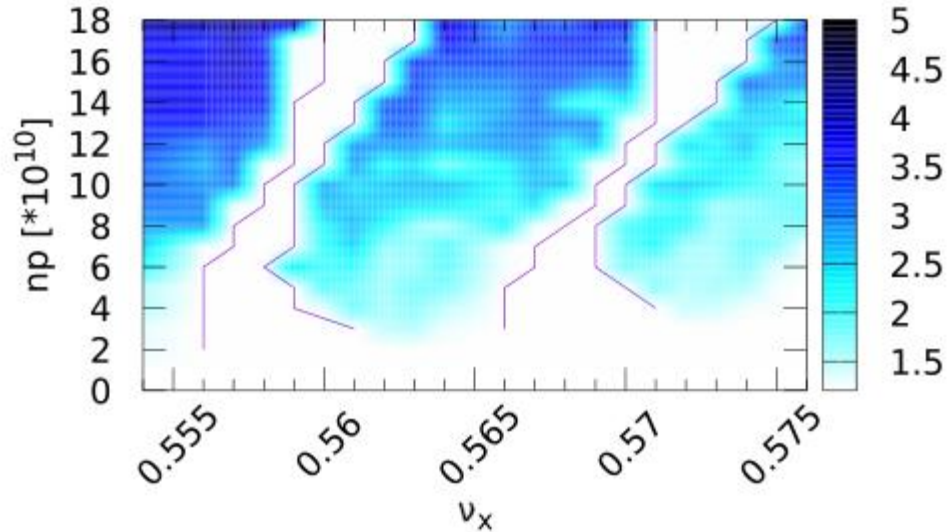
- Longer bunch length
- Lower energy spread
- Lower incoherent synchrotron tune

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

Only with RW



with full impedance
(so far)



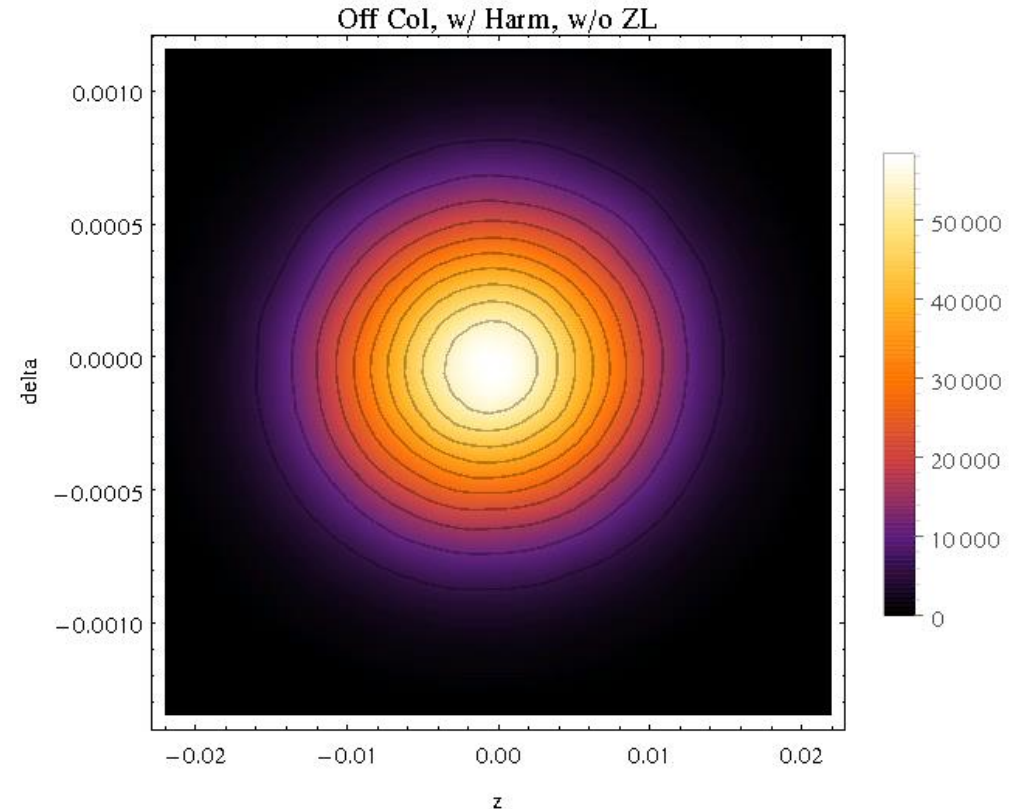
Idea of using harmonic cavities

- 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 $nQ_x - mQ_z$ 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

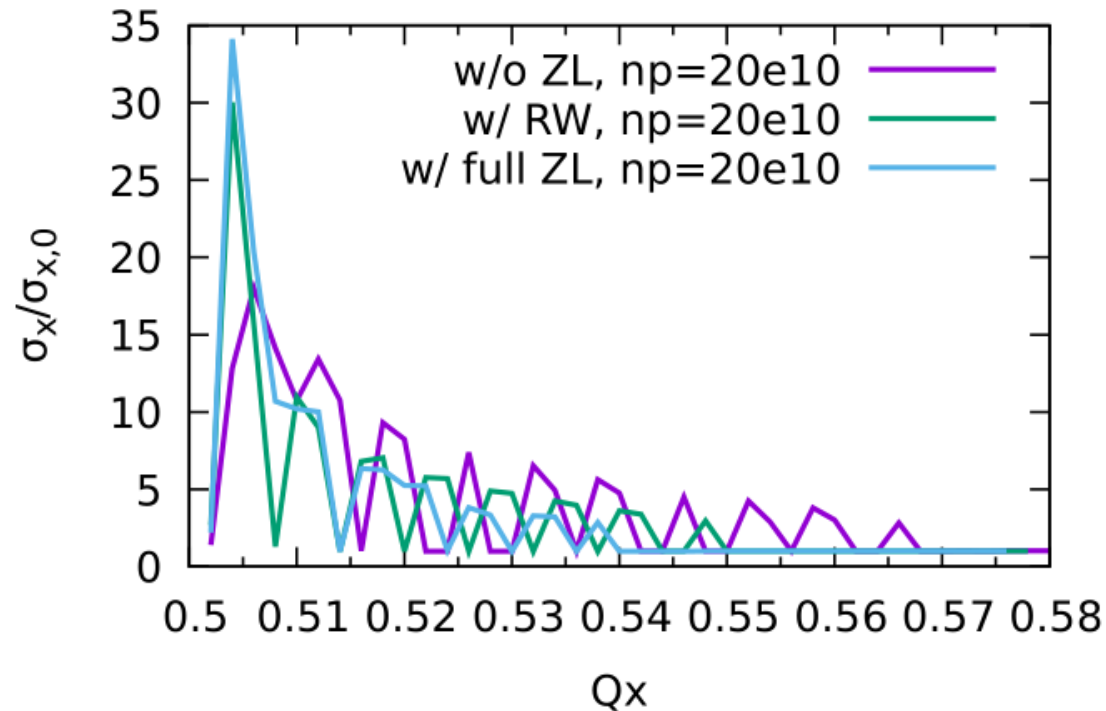
Bunch is lengthened about a factor of 2 (without collision)

- $E_0 = 45.6 \text{ GeV}$
- $U_0 = 18 \text{ MV}$ (half ring)
- Main Cavity,
 - $V_{rf} = 50 \text{ MV}$
 - $\phi = 156.1^\circ$ ($50 \sin \phi = 20.3$)
- 3rd Harmonic, 1.2GHz
 - $V_{rf_3} = 11.7 \text{ MV}$
 - $\phi_3 = -11.1^\circ$ ($11.7 \sin \phi_3 = -2.3$)

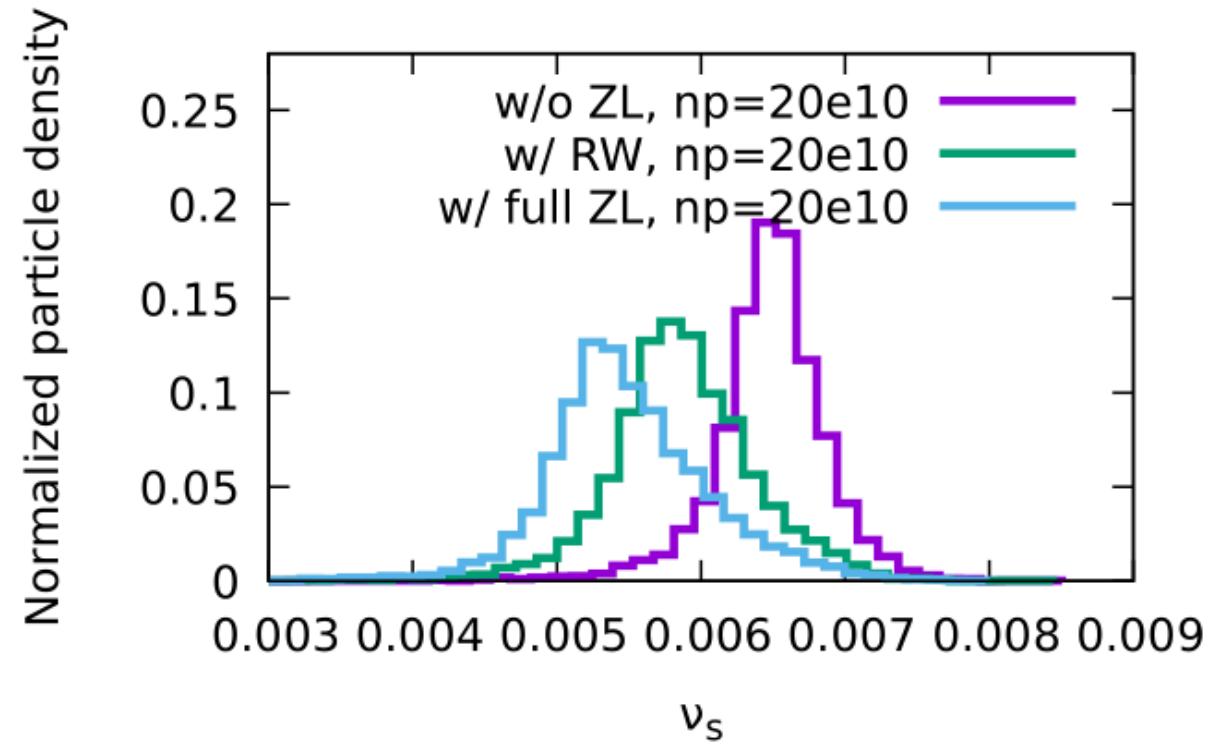


Horizontal size blowup with Harmonic Cavity @ FCC-ee-Z

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

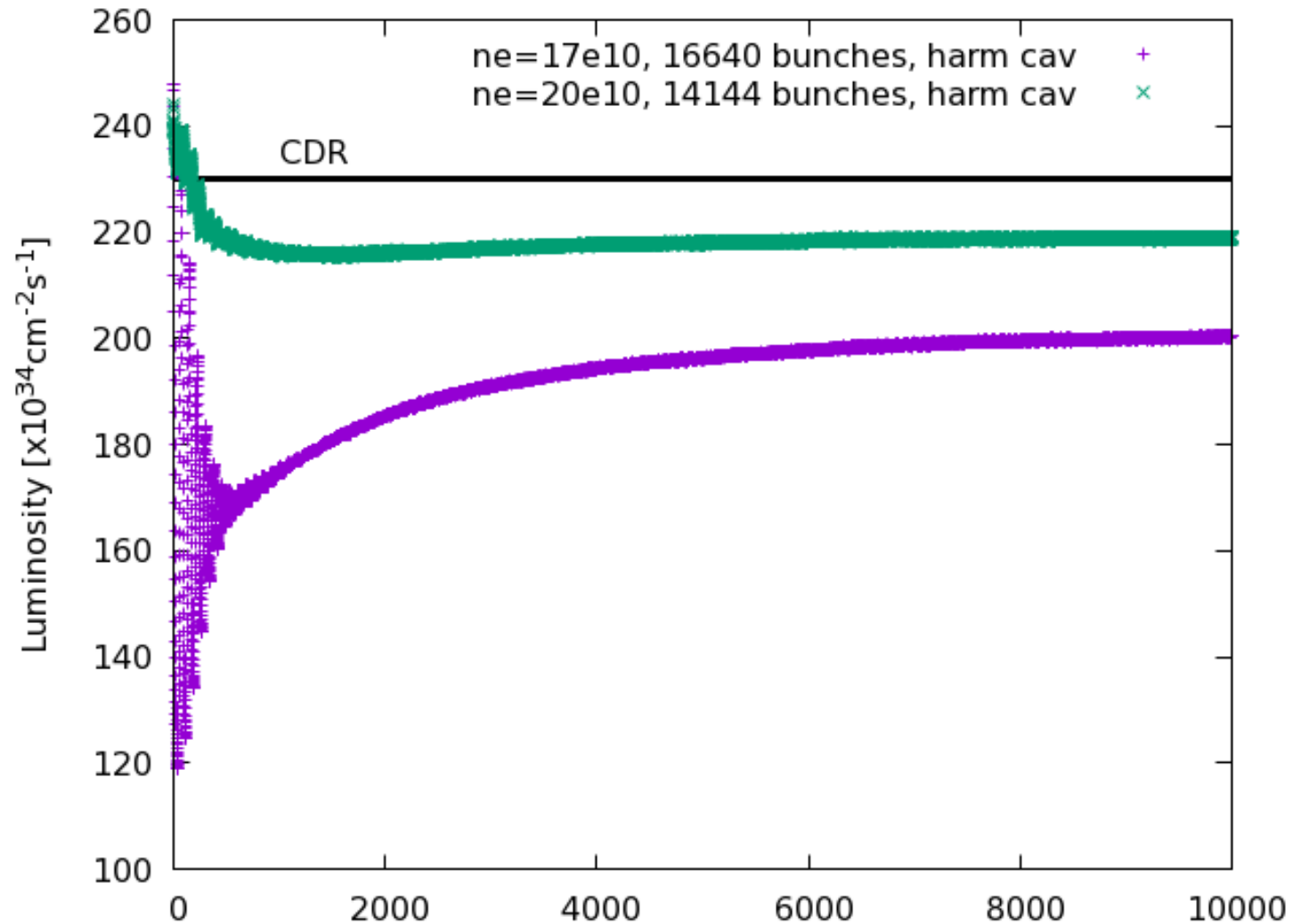


$\sigma_z = 18$ mm (CDR: 12 mm)
 $\sigma_p = 9.2e-4$ (CDR: $13e-4$)



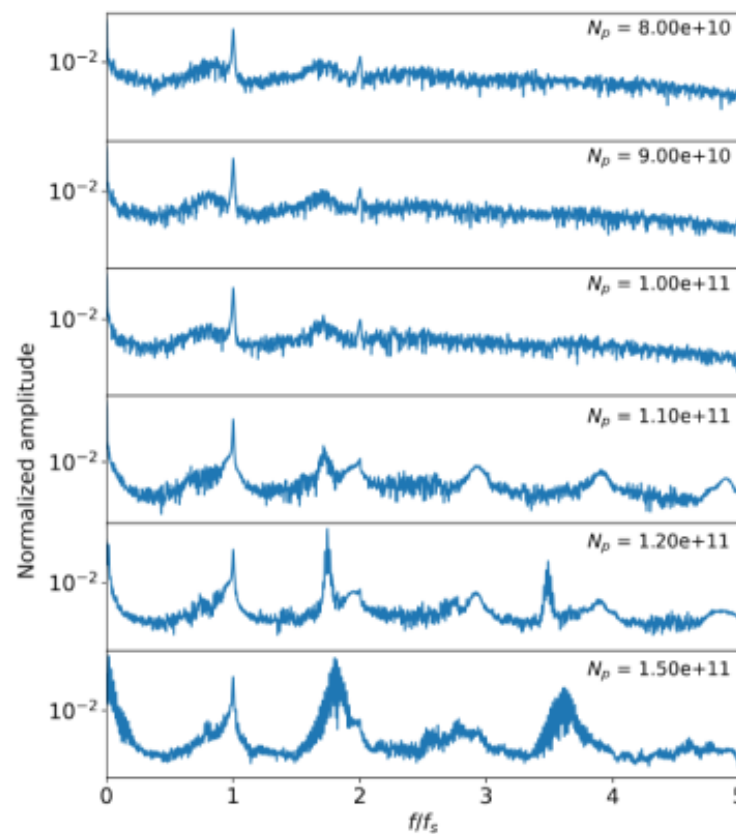
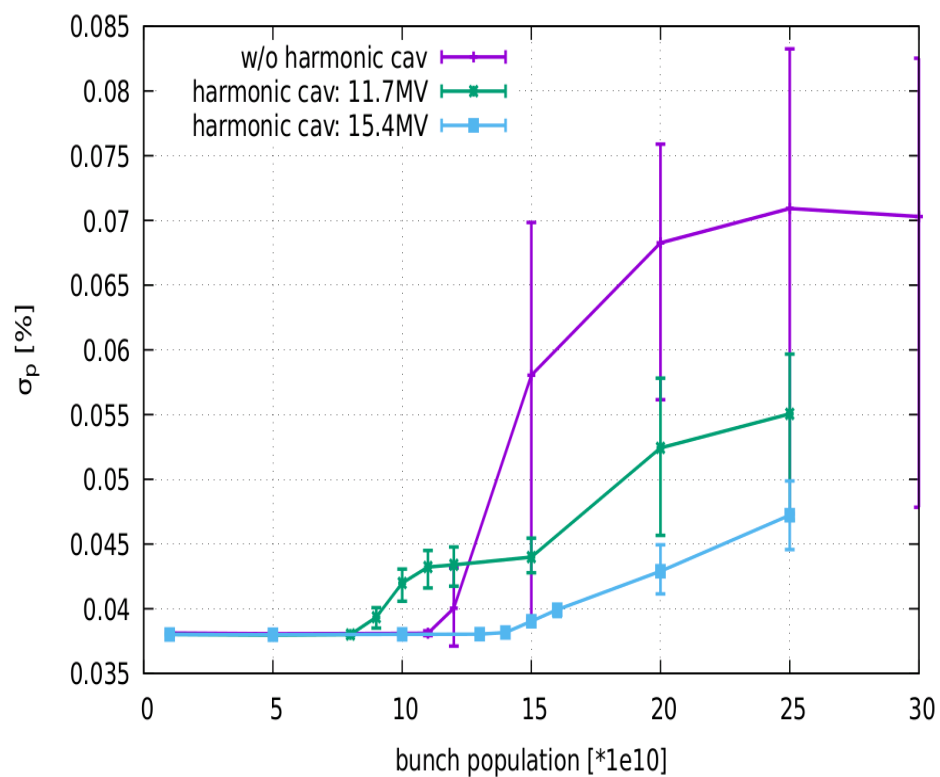
$\xi_x = 2.0e-3$ (CDR: $4e-3$)

Luminosity with Longitudinal Impedance

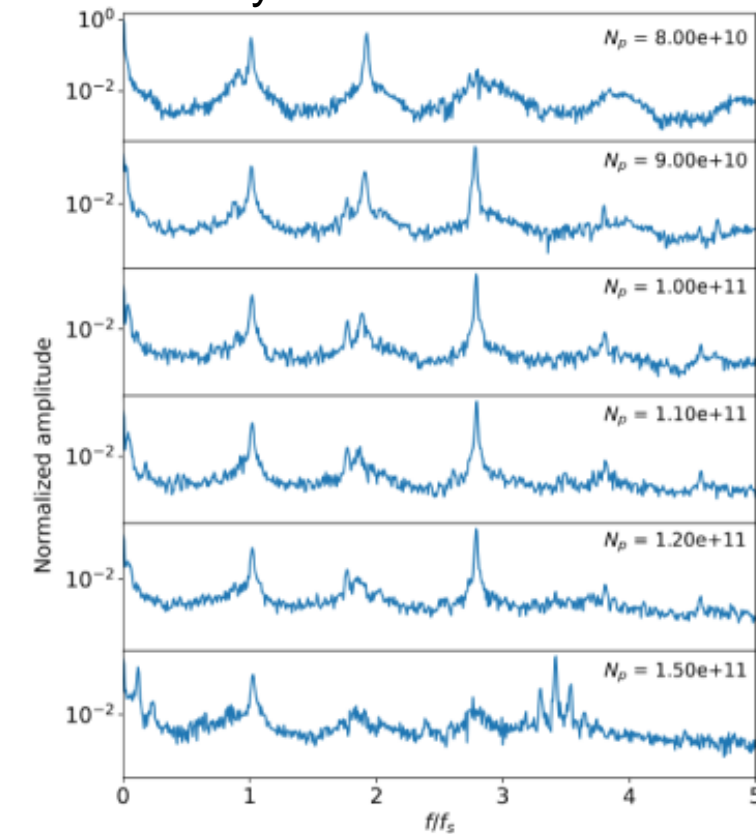


Single Bunch Instability w/ Harmonic Cavity at FCC-ee-Z

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 (Q_x+nQ_s)
- 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.

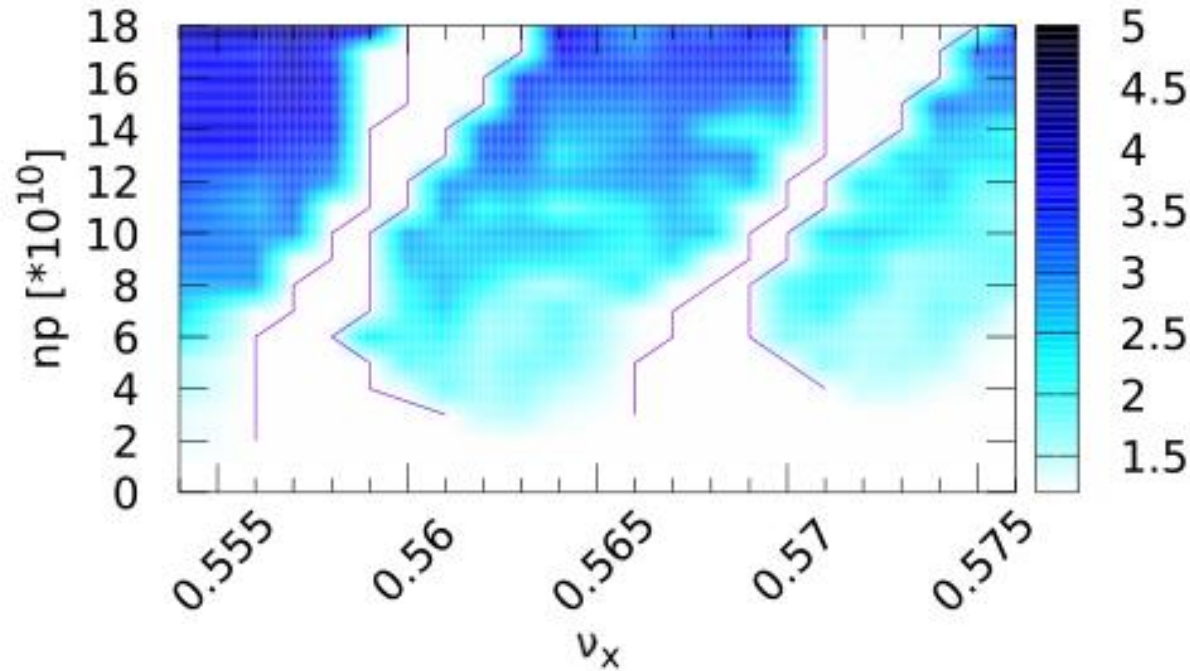
Higher Momentum Compaction

- 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.

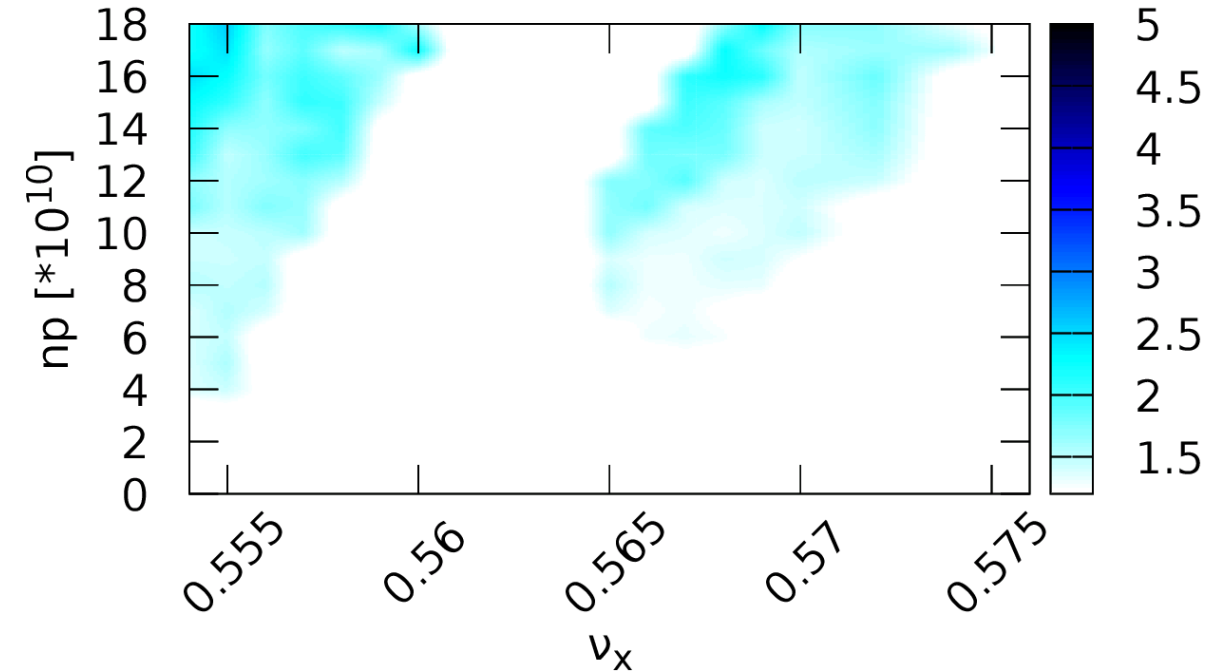
Arc Cell	α_p [10 ⁻⁵]	ϵ_x [nm]	ϵ_y [pm]	ν_s	σ_{z0} [mm]	σ_z [mm]	σ_p [10 ⁻⁴]	L/IP 10 ³⁶	ϕ	ξ_x
45°	2.5	0.6	1.5	0.0163	4.5	11.5	9.7	1.9	18.2	0.004
60°	1.48	0.27	1.0	0.0125	3.5	12	13	2.3	28.5	0.004

Bootstrapping Injection

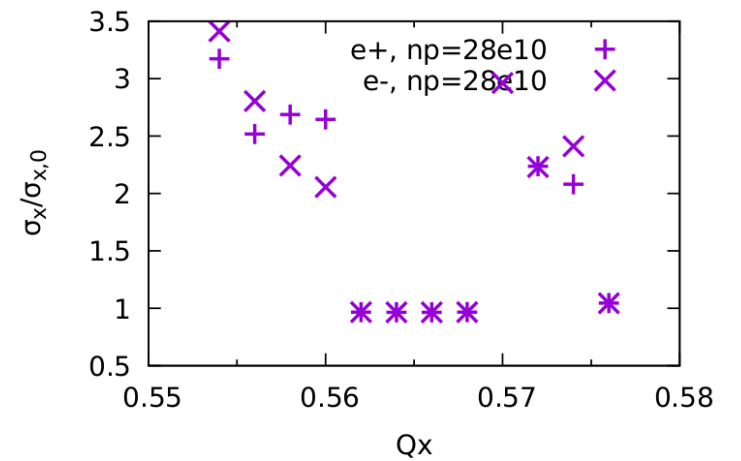
- Horizontal size blowup



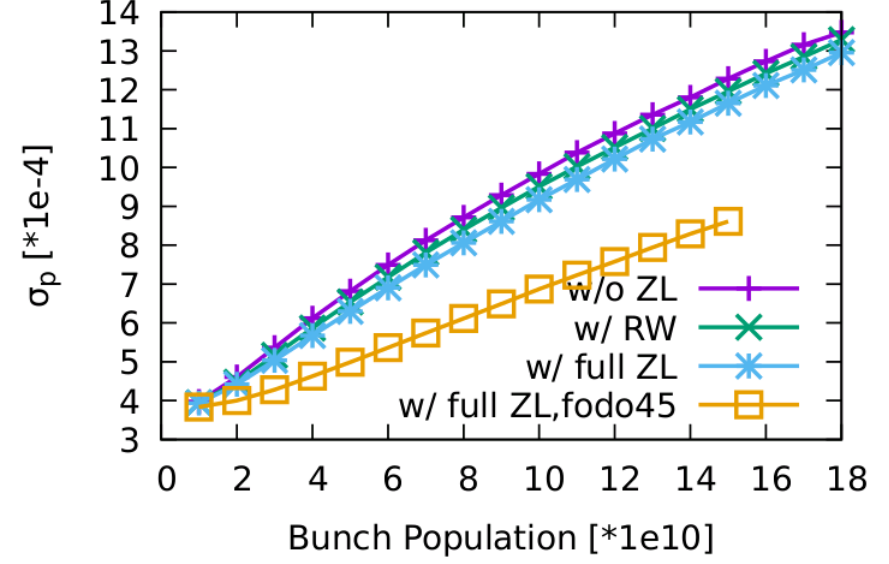
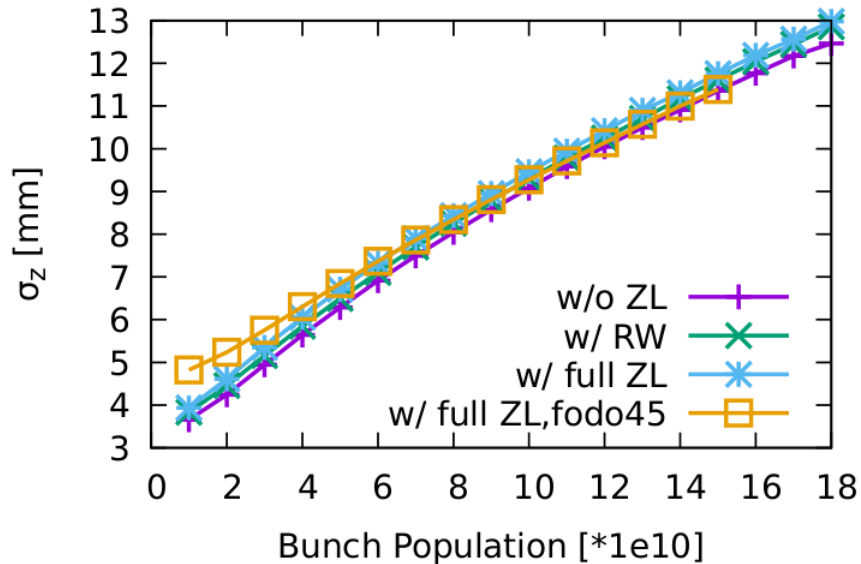
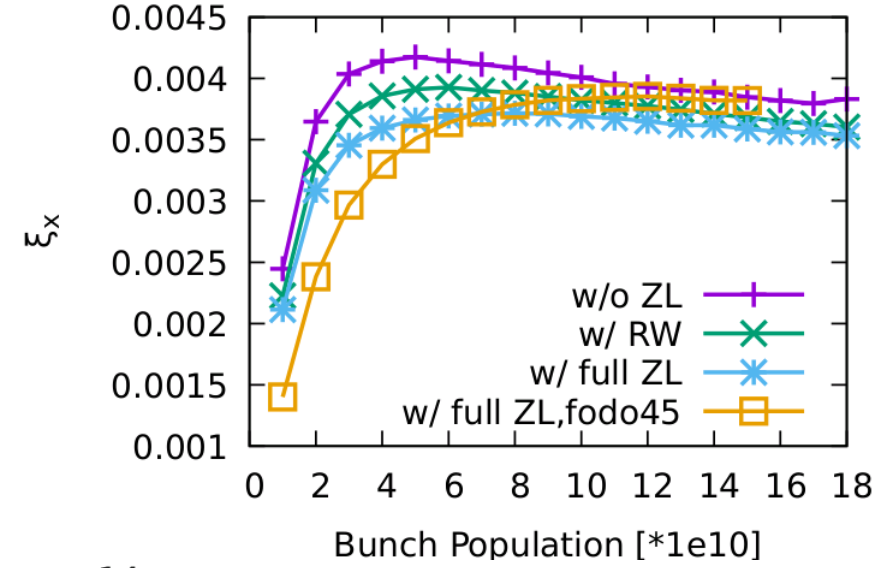
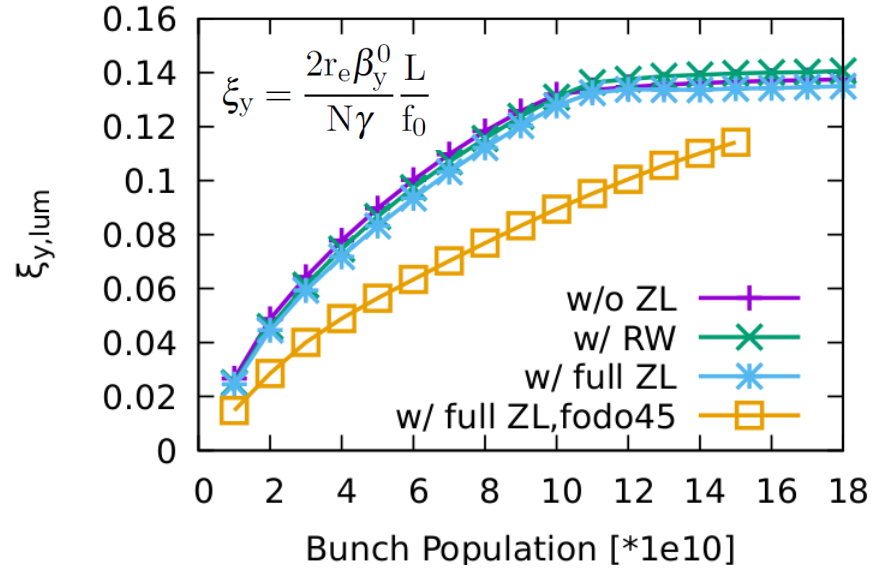
FODO CELL: 60°/60°



FODO CELL: 45°/45°



Evolution of Parameters during Injection



Discussion on High Momentum Compaction

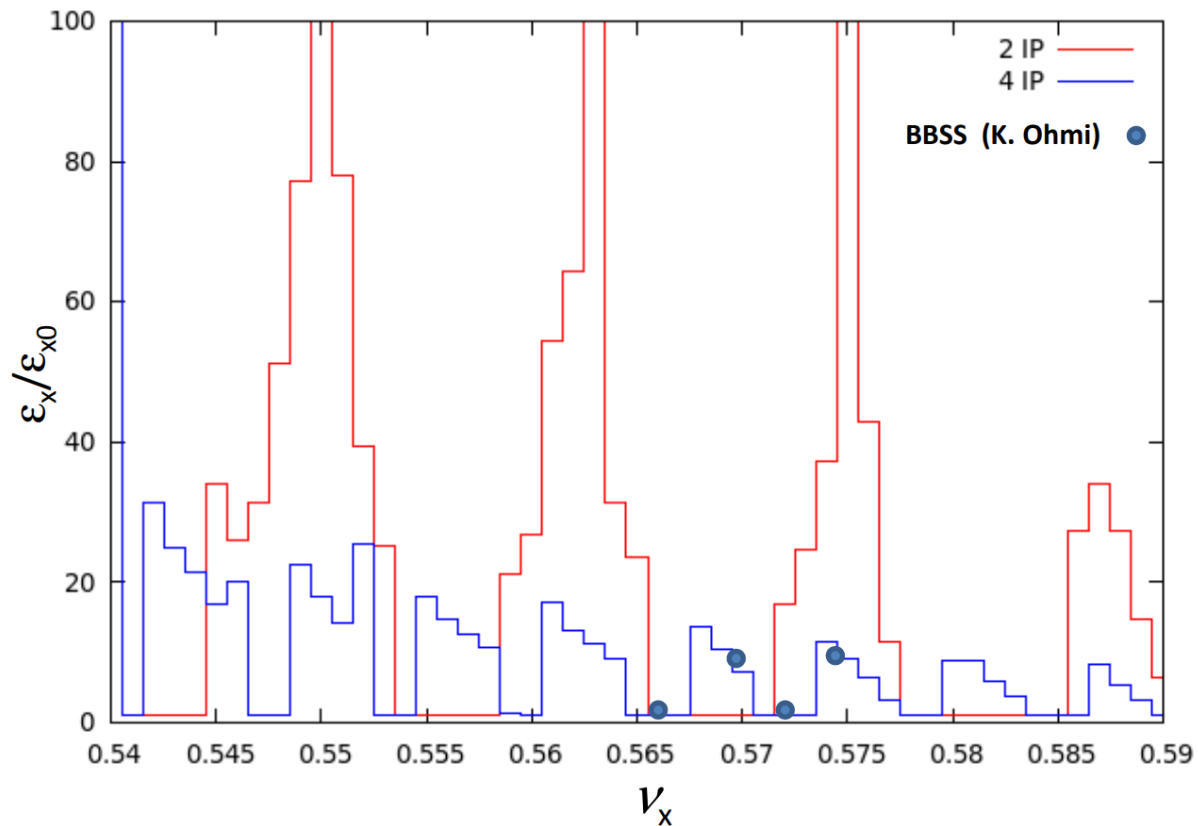
- good tune areas
- less bunches and higher intensity per bunch
- Higher bunch separation and higher bunch intensity
 - e-cloud is much weaker
 - avoiding ion trapping
- Higher synchrotron frequency is better for the energy calibration

4 IP

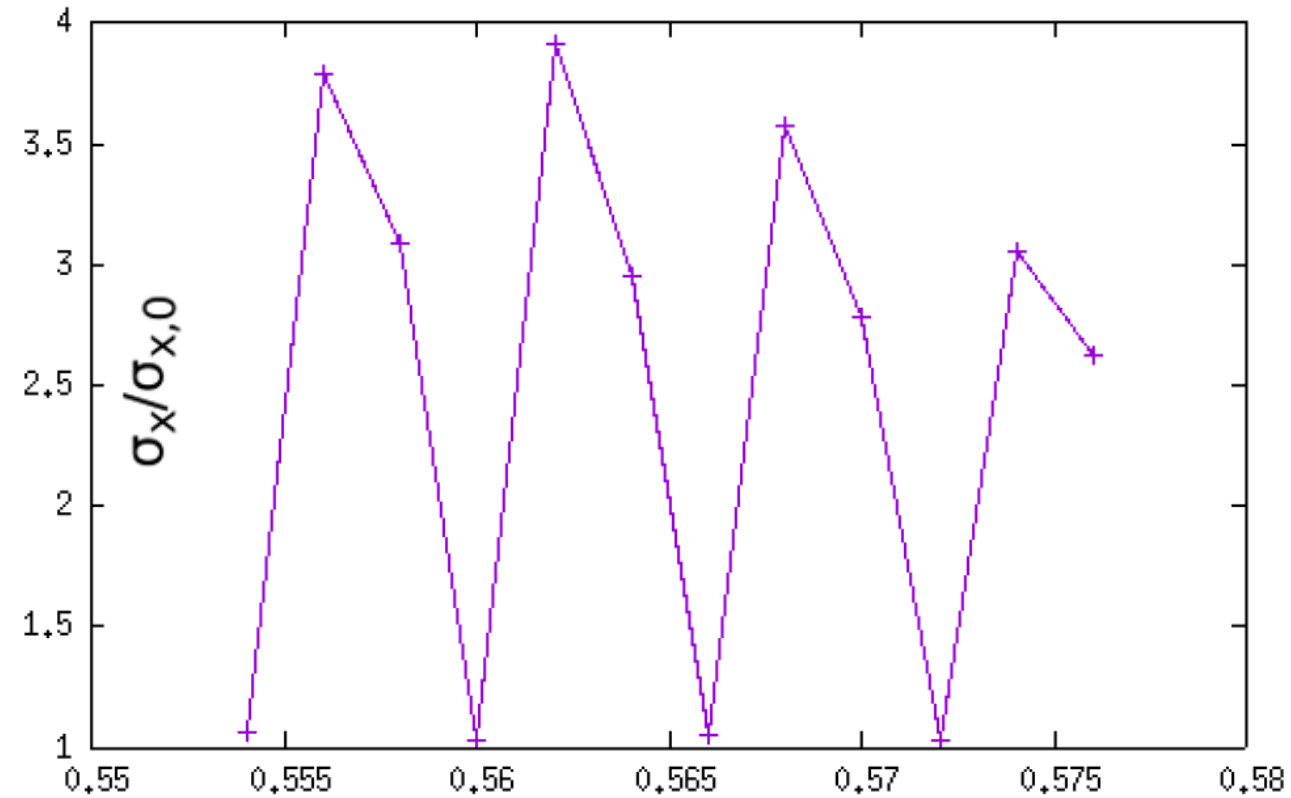
- CDR parameters are used
- The layout is assumed to be **symmetrical**, so that **2×2** bunches collide, and a **quarter** of the ring is a **superperiod**. This means that between each pair of neighboring IPs there is a straight section where the RF cavities and additional intersection without collision are located.
- decrease in the synchrotron tune per superperiod

Benchmark of simulations for 4IPs

LIFETRACK



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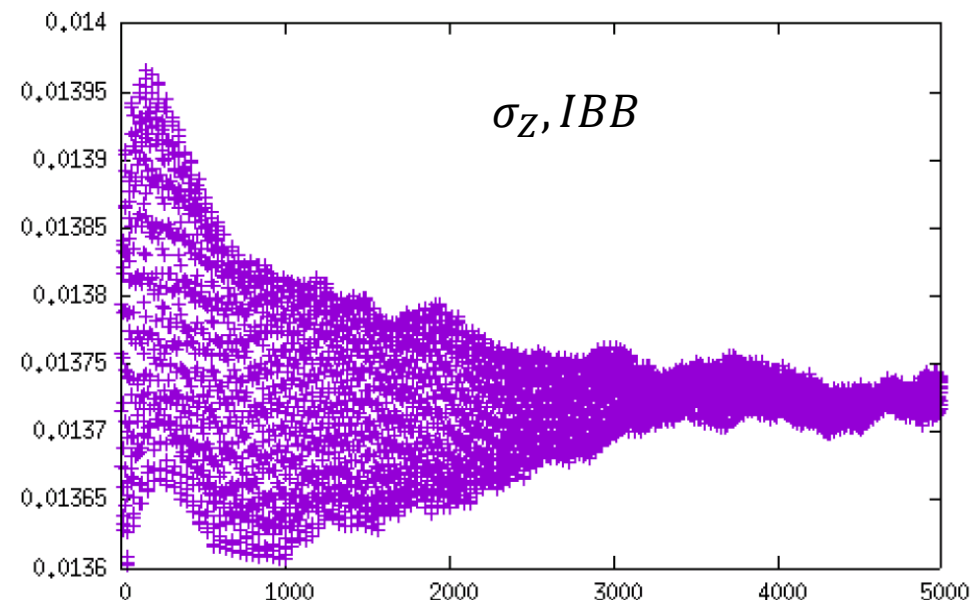
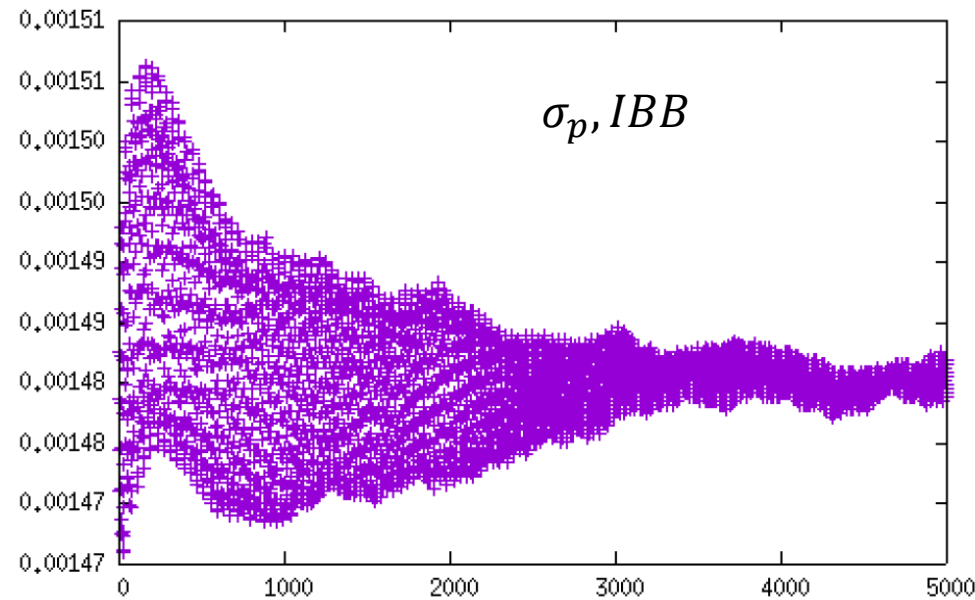


D. Shatilov, FCC week 2019, Beam-Beam Effects for 4 IP

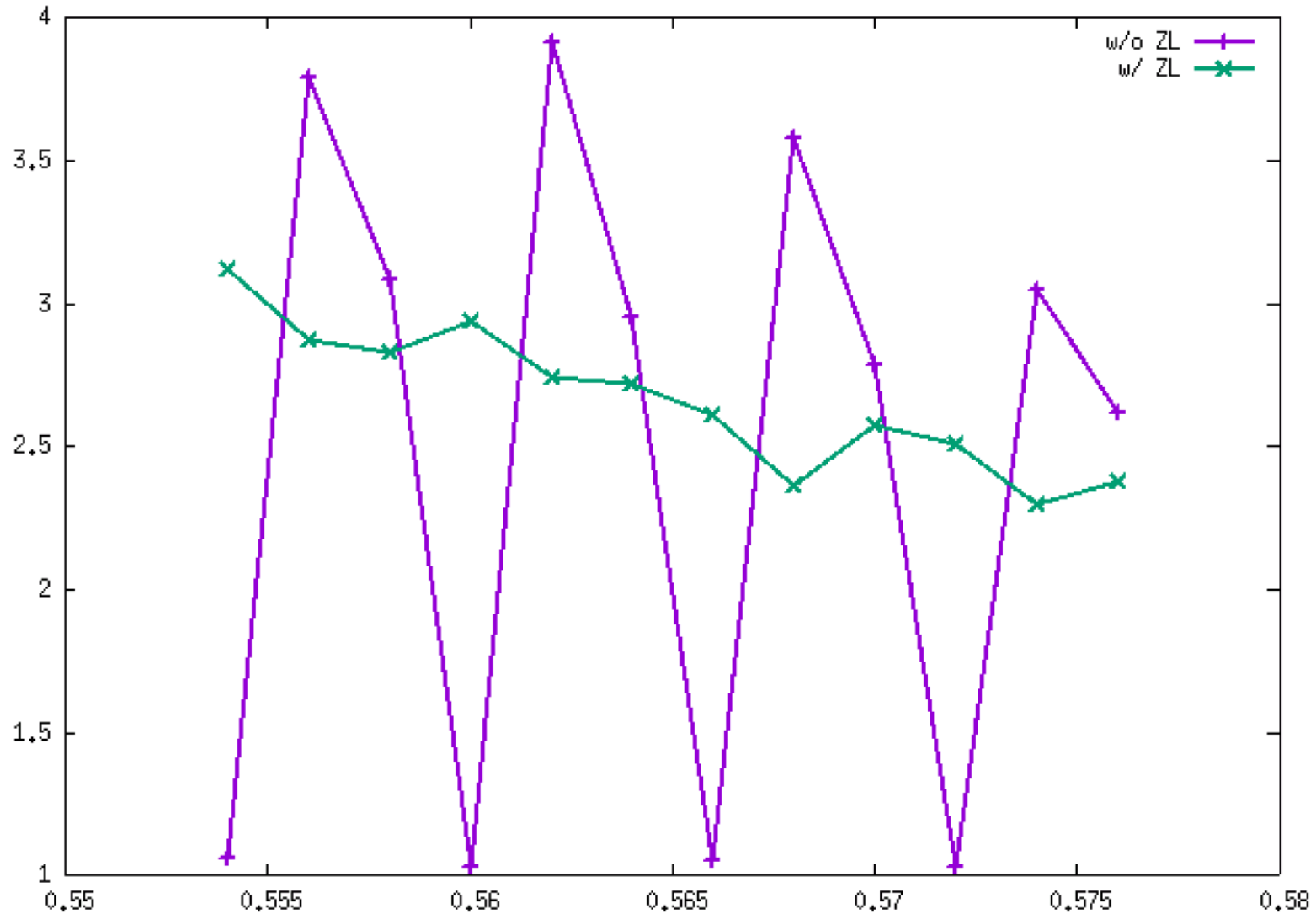
Benchmark of simulations for 4IPs

D. Shatilov, FCC week 2019, Beam-Beam Effects for 4 IP

	$\sigma_\delta(\text{SR})$	$\sigma_\delta(\text{SR+BS})$	$\sigma_z(\text{SR})$	$\sigma_z(\text{SR+BS})$	N_p	ξ_x	L / IP
2 IP	3.8E-4	1.32E-3	3.5 mm	12.1 mm	1.7E+11	0.0038	2.3E+36
4 IP	3.8E-4	1.48E-3	3.5 mm	13.7 mm	1.7E+11	0.0030	2.0E+36

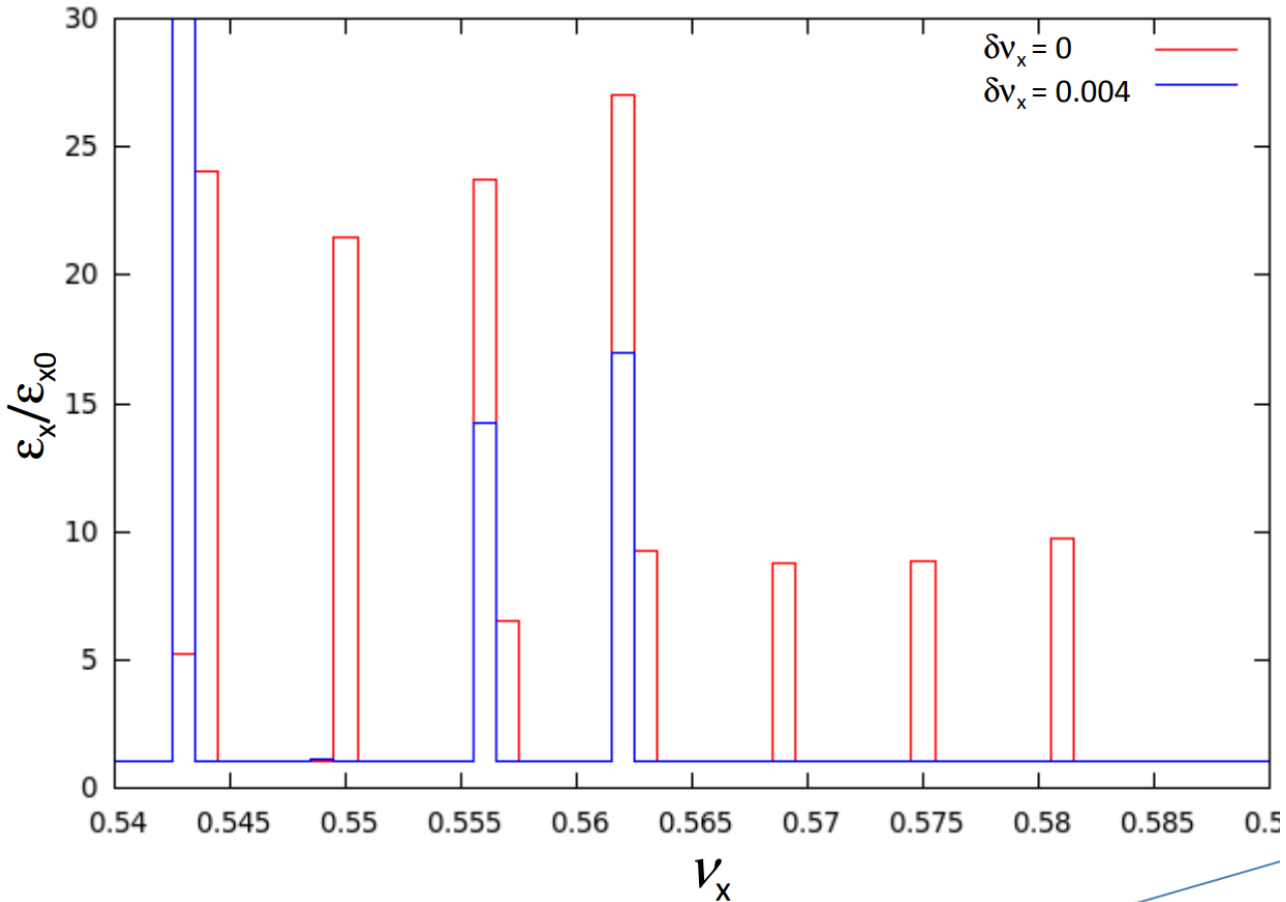


Impact of Impedance, 4 IP, BetaX=0.15m

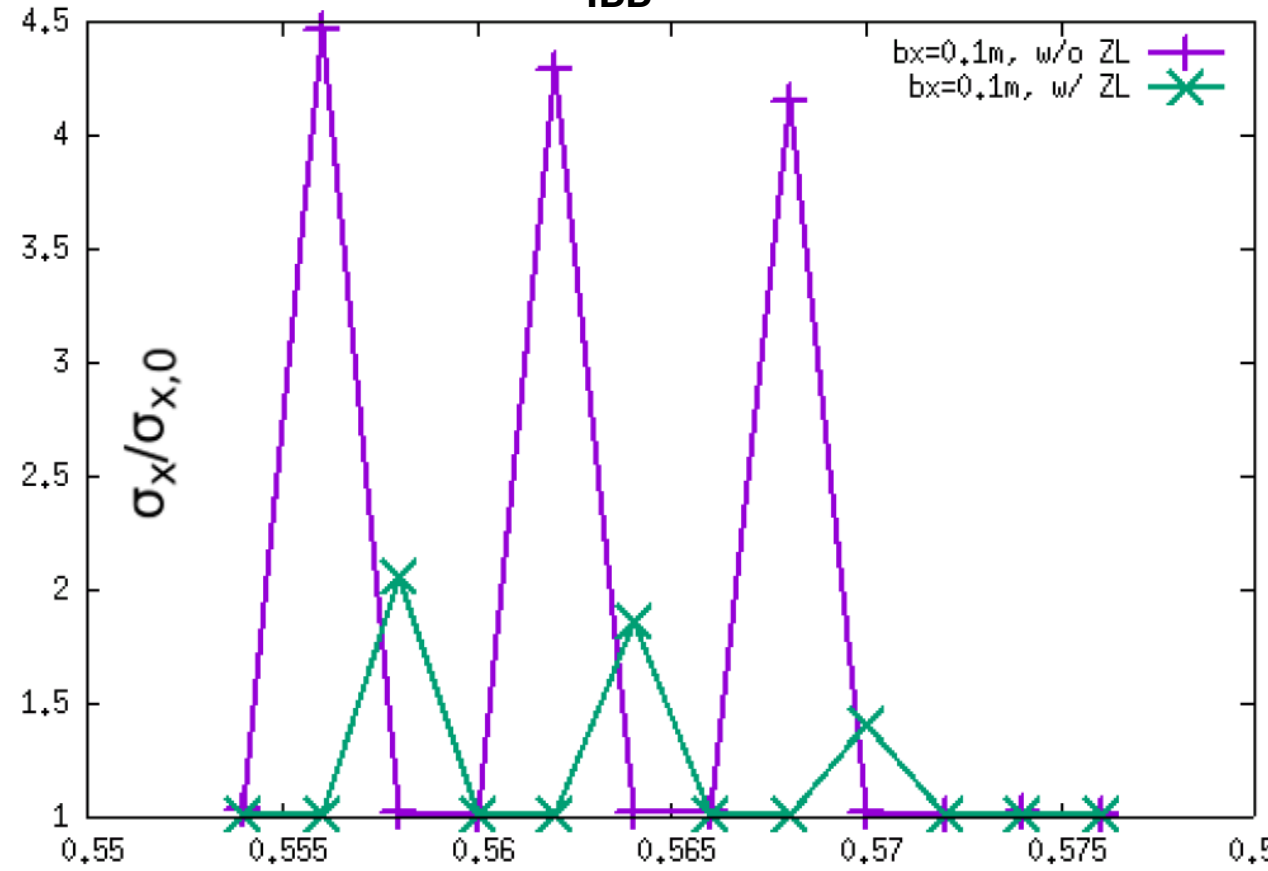


4IP, betaX=0.1m

LIFETRACK



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Summary

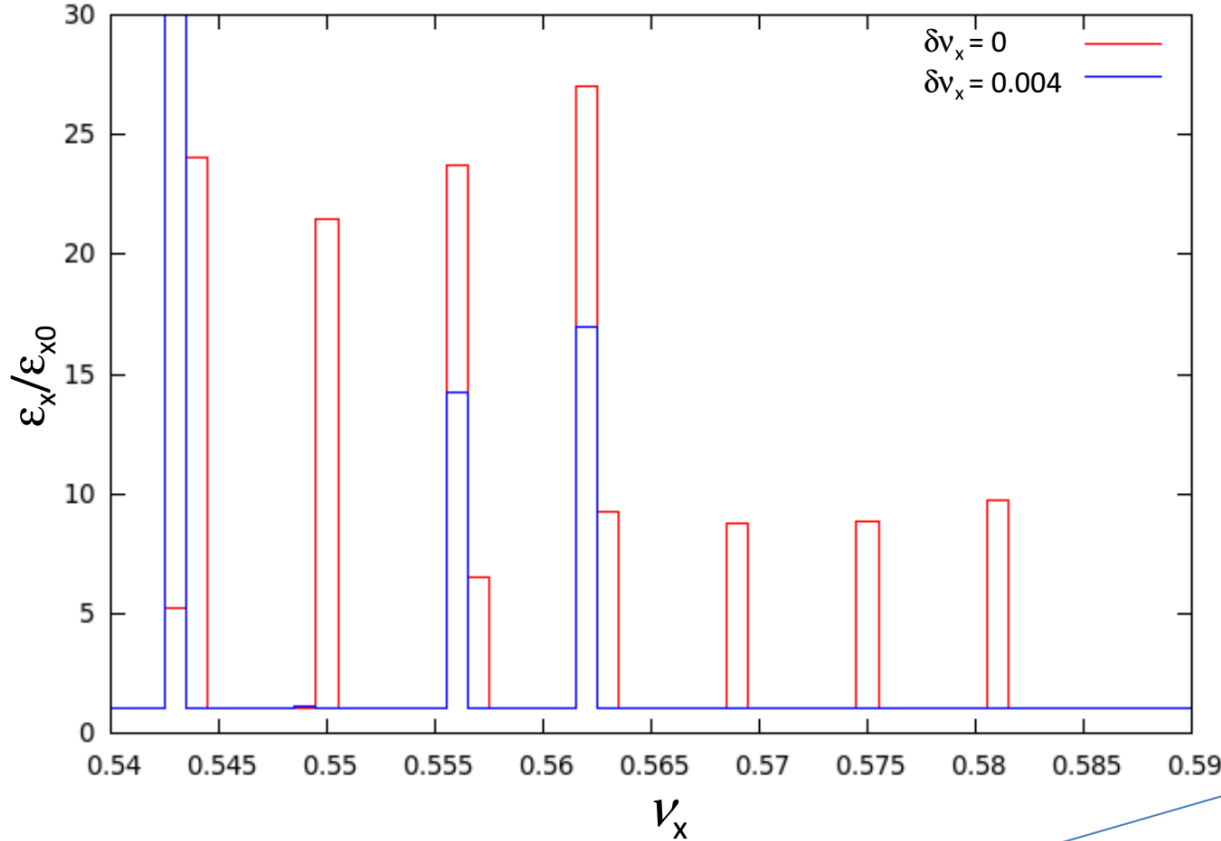
- The beam coupling impedance can have a substantial impact on the choice of beam parameters and the final collider performance.
- The principal effects are summarized:
 - Tune shift of stable tune areas
 - Smaller safe tune area
 - Smaller beam blowup
- Possible Mitigation Options:
 - Smaller β_x^*
 - Higher Harmonic Cavity (energy calibration?)
 - Higher Momentum compaction
- The effect for 4IP scheme is evaluated roughly
- 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.

- backup

Machine Parameter (CDR version)

	FCCee-Z
Beam Energy	45.6 GeV
Bunch Population	17e10
Arc Cell	60°/60°
$\beta_{x/y}^*$	0.15 m/0.8 mm
ϵ_x/ϵ_y	0.27 nm/1.0 pm
ν_s /superperiod	0.0125
σ_z [SR/BS]	3.5 / 12.1 mm
σ_p [SR/BS]	3.8 / 13.2×10^{-4}
ξ_x [BS]	0.004
ξ_y [BS]	0.133
Piwinski Angle [SR/BS]	8.2 / 28.5

β_x^* reduced from 15 to 10 cm [45.6 GeV]



- Beamstrahlung becomes stronger, since σ_x drops. As a result, σ_z increases and ξ_x drops even more:

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

- The resonances become very narrow. If we apply some asymmetry, e.g. slightly different ν_x , their widths decrease even more.
- Now the width of stable areas is sufficient.
- Luminosity is *almost* limited by increased σ_δ .

	σ_δ (SR)	σ_δ (SR+BS)	σ_z (SR)	σ_z (SR+BS)	N_p	ξ_x	L / IP
2 IP	3.8E-4	1.32E-3	3.5 mm	12.1 mm	1.7E+11	0.0038	2.3E+36
4 IP	3.8E-4	1.63E-3	3.5 mm	15.0 mm	1.7E+11	0.0017	1.9E+36

-18%