Interplay between beam-beam interaction and collective effects and its impact on the parameters

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Outline

1. Brief introduction
2. Crab waist collision scheme
3. New beam-beam effects in the future colliders
4. Interplay of beam-beam effects and coupling impedances
5. Parameters evolution following the mitigation of the common effects
6. Some latest results

Colliders based on Crab Waist concept

Colliders	Location	Status
DAΦNE	Φ-Factory Frascati, Italy	In operation (SIDDHARTA, KLOE-2, SIDDHARTA-2)
SuperKEKB	B-Factory Tsukuba, Japan	In operation, the world record luminosity has been achieved
SuperC-Tau	C-Tau-Factory Sarov, Russia	Russian mega-science project
FCC-ee	Z,W,H,tt-Factory CERN,Switzerland	91 km, CDR released in December 2018
CEPC	Z,W,H,tt-Factory China	100 km, CDR released in September 2018
HIEPA	2-7 GeV China	Considered base line option

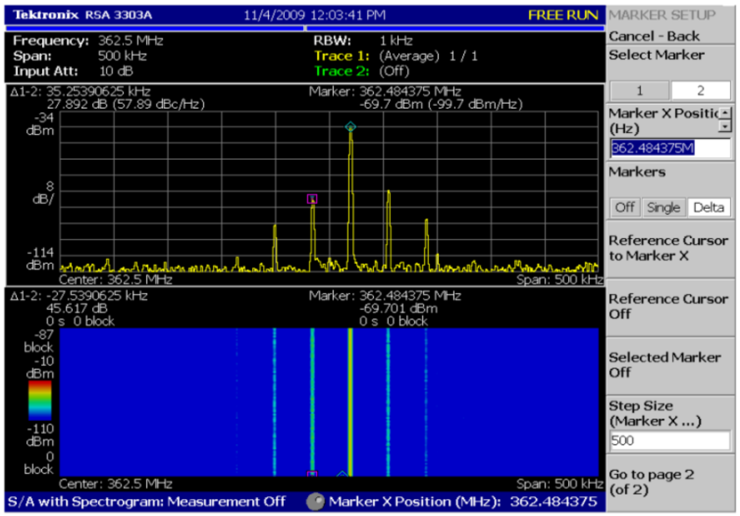
Other Factors Affecting Luminosity

1. Electron cloud (beam size blow up, tune spread)
2. Lattice Nonlinearities
3. Ions of residual gas (incoherent effects, trapped ions)
4. Wake fields (single and multibunch effects)
5. Gap transients (different bunch synchronous phases)
6. Feedback noise (and also in other devices)
7. Low lifetime (not enough time for fine tuning)
8. Space charge effects
9. Touschek scattering
10. Other effects

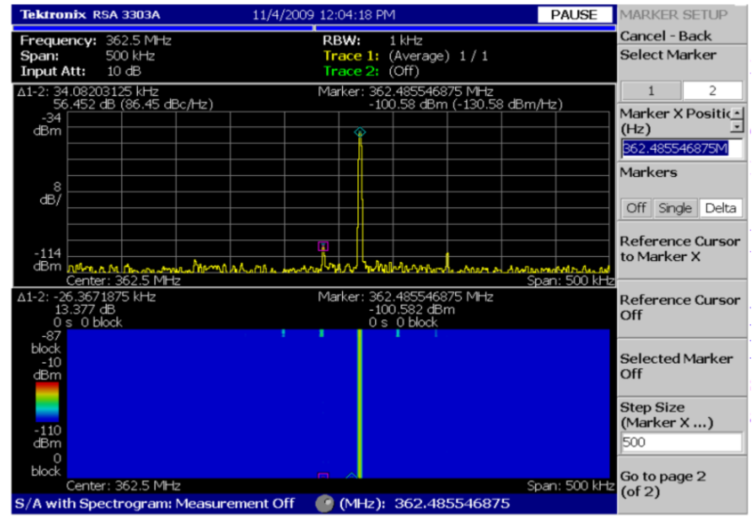
Zobov, see talk at IPAC2010

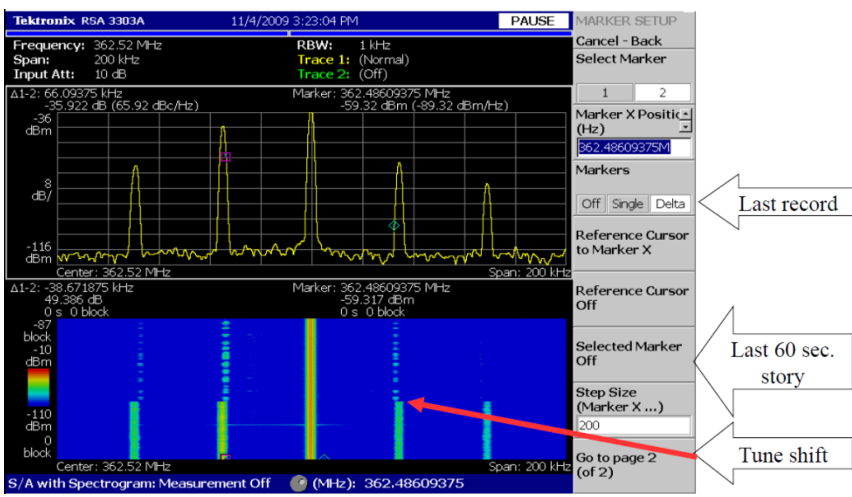
Suppression of longitudinal multi-bunch instabilities in collision with a crossing angle in DAΦNE

No collision



In collision





Collisions with a horizontal angle produce the longitudinal tune shift and tune spread. The synchrotron tune spread results in the instability suppression (Landau damping)

A.Drago, P.Raimondi, D.Shatilov and M.Zobov, *Phys.Rev.ST Accel.Beams* 14 (2011) 092803

Parameters

FCC-ee collider parameters as of June 3, 2023.

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658816			
Bend. radius of arc dipole	[km]	9.936			
Energy loss / turn	[GeV]	0.0394	0.374	1.89	10.42
SR power / beam	[MW]	50			
Beam current	[mA]	1270	137	26.7	4.9
Colliding bunches / beam		15880	1780	440	60
Colliding bunch population	[10^{11}]	1.51	1.45	1.15	1.55
Hor. emittance at collision ε_x	[nm]	0.71	2.17	0.71	1.59
Ver. emittance at collision ε_y	[pm]	1.4	2.2	1.4	1.6
Lattice ver. emittance $\varepsilon_{y,\mathrm{lattice}}$	[pm]	0.75	1.25	0.85	0.9
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	28.6		7.4	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	1000 / 1.6
Transverse tunes $Q_{x/y}$		218.158 / 222.200	218.186 / 222.220	398.192 / 398.358	398.148 / 398.182
Chromaticities $Q'_{x/y}$		0 / +5	0 / +2	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.089	0.070 / 0.109	0.104 / 0.143	0.160 / 0.192
Bunch length (SR/BS) σ_z	[mm]	5.60 / 12.7	3.47 / 5.41	3.40 / 4.70	1.81 / 2.17
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.08 / 0	2.1 / 9.38
Harm. number for 400 MHz		121200			
RF freqeuncy (400 MHz)	MHz	400.786684			
Synchrotron tune Q_s		0.0288	0.081	0.032	0.091
Long. damping time	[turns]	1158	219	64	18.3
RF acceptance	[%]	1.05	1.15	1.8	2.9
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.6	-2.8/+2.5
Beam crossing angle at IP $\pm\theta_x$	[mrad]	±15			
Piwinski angle $(\theta_x \sigma_{z,\mathrm{BS}})/\sigma^*_x$		21.7	3.7	5.4	0.82
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0023 / 0.096	0.013 / 0.128	0.010 / 0.088	0.073 / 0.134
Lifetime (q + BS + lattice)	[sec]	15000	4000	6000	6000
Lifetime (lum) [b]	[sec]	1340	970	840	730
Luminosity / IP	[10^{34}/cm^{2}s]	140	20	5.0	1.25
Luminosity / IP (CDR, 2 IP)	[10^{34}/cm^{2}s]	230	28	8.5	1.8

CDR at Z

97.756

1390

16640

0.27

14.8

150/0.8

0.039/0.132

3.5/12.1

Table from the talk of K.Oide at FCC Week 2023

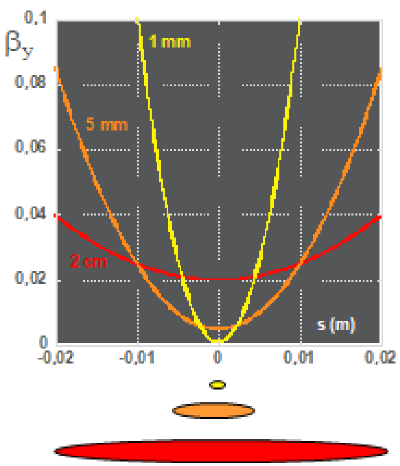
Crab Waist helps

to overcome the hourglass effect

to alleviate the effects of the nonlinear beam-beam interaction

$\sigma_y = \sqrt{\varepsilon_y \beta_y}$ **The "hourglass" effect**

However, β_y^* cannot be shorter than the bunch length, because of the "hourglass effect"



Bunch distribution

How to Increase Luminosity?

Luminosity

$$L = \frac{f_0}{4\pi}\frac{N^2}{\sigma_x\sigma_y}$$

Strength of Nonlinear Beam-Beam Interaction

$$\xi_y = \frac{r_e\beta_y}{2\pi\gamma}\frac{N}{\sigma_y\sigma_x}$$

Nonlinear resonances
Working points' spread
Chaos.........................

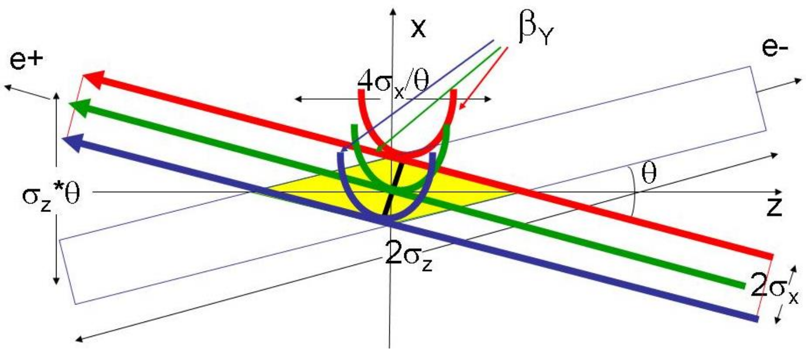
Beam size blow up,
Lifetime reduction,
Instabilities

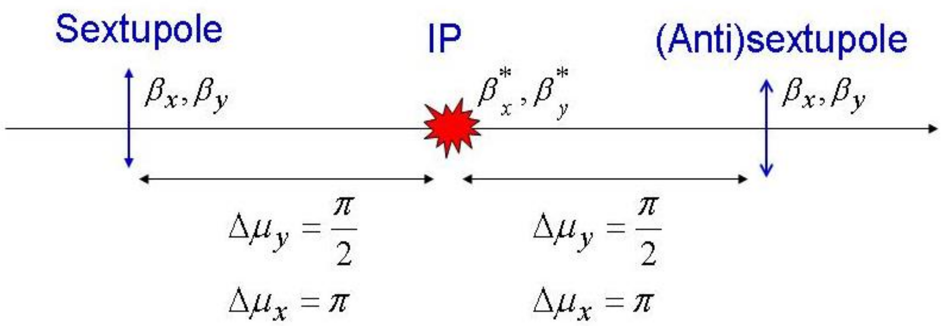
The principal idea is:

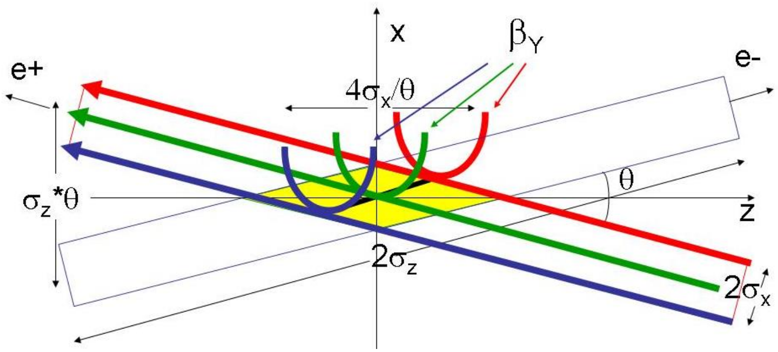
1) To linearize the nonlinear interaction

2) To weaken the effects of the nonlinear interaction

Crab Waist collision scheme







a) Large Piwinski Angle Φ (smaller emittance, large crossing angle, lower horizontal beta)

b) Small vertical beta function at IP

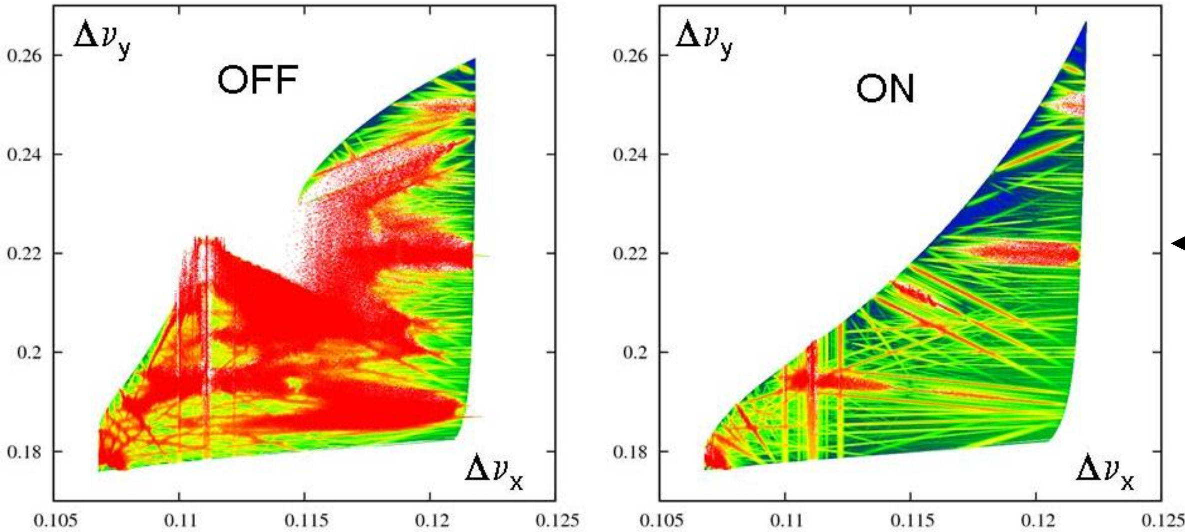
c) Suppression of beam-beam resonances using sextupoles in the interaction region

1. *P.Raimondi, 2° SuperB Workshop, March 2006*
2. *P.Raimondi, D.Shatilov, M.Zobov, physics/0702033*
3. *M.Zobov et al., Phys.Rev.Lett. 104 (2010) 174801*
4. *C.Milardi et al., Int.J.Mod.Phys.A24 (2009) 360*

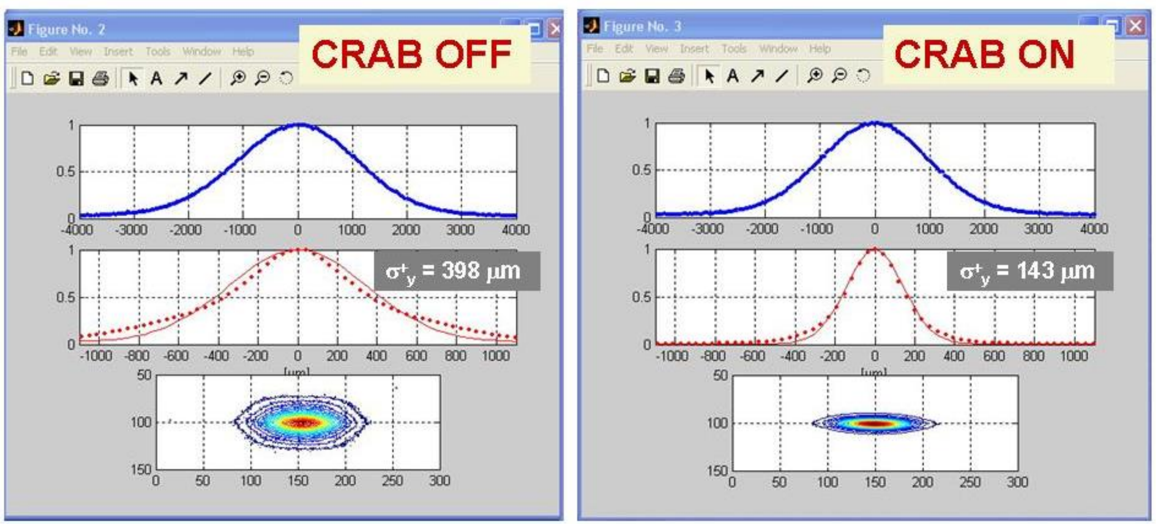
$$\Phi = \frac{\sigma_z}{\sigma_x}\tan\left(\frac{\theta}{2}\right); \quad l_{\text{int}} \approx \frac{\sigma_z}{\Phi}; \quad L \cong n_b f_0 \frac{1}{4\pi\gamma\sigma_x\sigma_y}\left[\frac{N^2}{\sqrt{1+\Phi^2}}\right]$$

$$\xi_y \cong \frac{r_e\beta_y}{2\pi\gamma\sigma_x\sigma_y}\left[\frac{N}{\sqrt{1+\Phi^2}}\right]; \quad \xi_x \cong \frac{r_e\beta_x}{2\pi\gamma\sigma_x^2}\left[\frac{N}{1+\Phi^2}\right]$$

Suppression of beam-beam resonances (DAΦNE example)



← Frequency map analysis



← Images from synchrotron light monitor

D.Shatilov et al., Phys.Rev.Lett. 14 (2011) 014001
M.Zobov, IPAC2010, pp. 3639-3643

Collisions exploiting the crab waist scheme and extreme beam parameters at the interaction point (can) result in additional effects in beam-beam interaction

1. Beamstrahlung
2. Beam-beam head-tail instability (X-Z instability)
3. 3D flip-flop

1. V.I.Telnov, Restriction on the energy and luminosity on e+e- stoage rings due to beamstrahlung, Phys.Rev.Lett. 110 (2013) 114801
2. K.Ohmi et al., Coherent beam-beam instability in collisons with a large crossing angle, Phys.Rev.Lett. 119 (2017) 13, 134801
3. D.Shatilov, FCC-ee parameter optimization, ICFA Beam Dyn.Newslett.72 (2017) 30-41

Beamstrahlung

Bending of particle trajectories during beam-beam interaction produces photon emission, similar to the synchrotron radiation. The effect is called beamstrahlung and its strength is described by beamstrahlung parameter

High energy — High bunch intensity

$$\Upsilon_{\text{ave}} \approx \frac{5}{6} \frac{r_e^2 \gamma N_b}{\alpha \sigma_z (\sigma_x^* + \sigma_y^*)}$$

Short bunch — Small beam sizes

Beamstrahlung is one of the most important effects in the future circular colliders

From FCC-ee CDR	45.6 Gev	80 GeV	120 GeV	175 GeV	182.5 GeV
Energy spread (SR/BS) σ_δ (%)	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.186	0.150/0.192
Bunch length (SR/BS) σ_z (mm)	3.5/12.1	3.0/6.0	3.15/5.3	2.01/2.62	1.97/2.54
Piwinski angle (SR/BS) ϕ	8.2/28.5	3.5/7.0	3.4/5.8	0.8/1.1	0.8/1.0

V. Telnov, Restiction on the energy and luminosity of e+e- storage rings due to beamstrahlung, Phys.Rev.Lett. 110,114801 (2013)

3D Flip-Flop

1) Asymmetry in the bunch currents leads to asymmetry in σ_z due to beamstrahlung (BS).

2) In collision with LPA, asymmetry in σ_z:
   a) Enhances synchrotron modulation of the horizontal kick for a longer (weak) bunch, thus amplifying synchro-betatron resonances.
   b) ξ_x^w grows quadratically and ξ_y^w – linearly with decrease of σ_z^s, so the footprint expands and can cross more resonances.

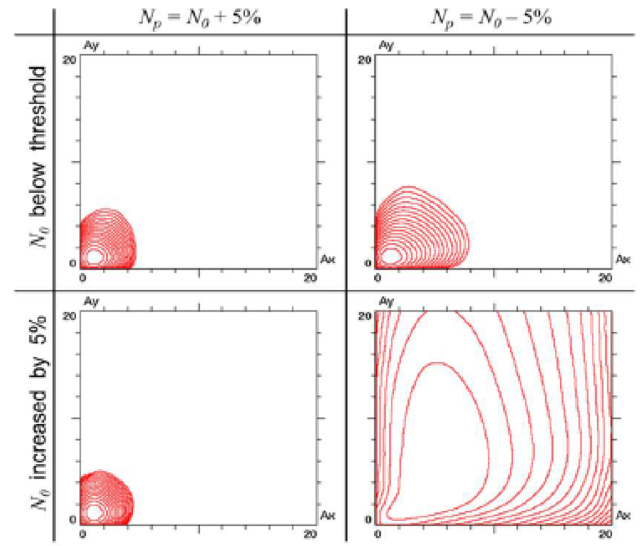
   All this leads to an increase in both emittances of the weak bunch (at the first stage, mainly ε_x^w is affected).

3) An increase in ε_x^w has two consequences:
   1) Weakening of BS for the strong bunch, which makes it shorter and thereby enhances BS for the weak bunch.
   2) Growth of ε_y^w due to betatron coupling, which leads to asymmetry in the vertical beam sizes.

4) Asymmetry in σ_y enhances BS for the weak bunch and its lengthening, while BS for the opposite bunch weakens and σ_z^s shrinks. Thus the asymmetry in σ_z increases even more.

5) Go back to point 2, and the loop is closed.

The threshold depends on the asymmetry of the colliding bunches. But even in symmetrical case the instability arises (with higher N_p).

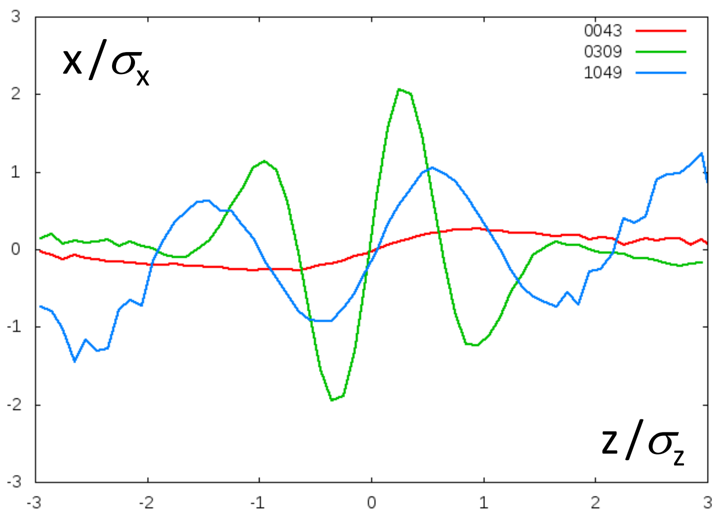


Density contour plots ($\sqrt{e}$ between successive lines) in the space of normalized betatron amplitudes.

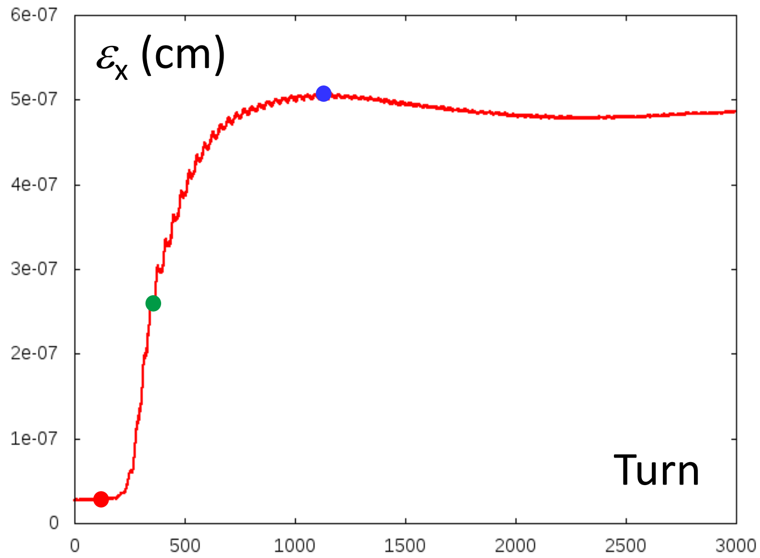
All three beam sizes grow slowly, until the footprint touches strong resonance, then the week bunch blows up.

Coherent beam-beam head-tail instability (X-Z instability)

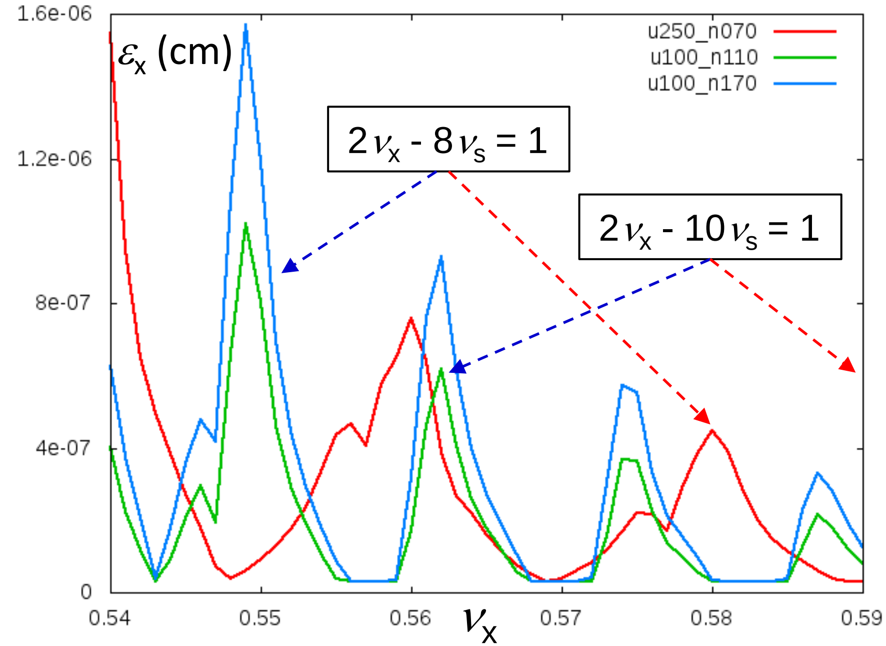
Bunch shape at different turns



Evolution of the horizontal emittance



Coherent instability: ε_x dependence on ν_x and ν_z.
U_{RF} = 250 MV (red) and 100 MV (green, blue).



Semi-analytical scaling law

$$N_{th} \propto \frac{\alpha_c \sigma_\delta \sigma_z}{\beta_x^*} \propto \frac{\nu_s}{\xi_x}$$

1. *K.Ohmi et al., Phys.Rev.Lett. 119 (2017) 13, 134801*
2. *K.Ohmi et al., Phys.Rev.Accel.Beams 21 (2018) 3, 031002*
3. *D.Shatilov, ICFA Beam Dyn.Newslett. 72 (2017) 30-41*

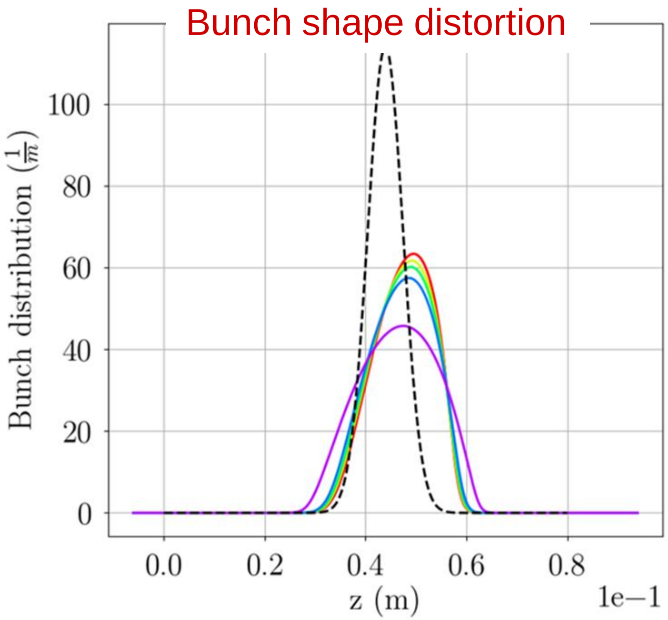
Why have we started with the longitudinal impedance?

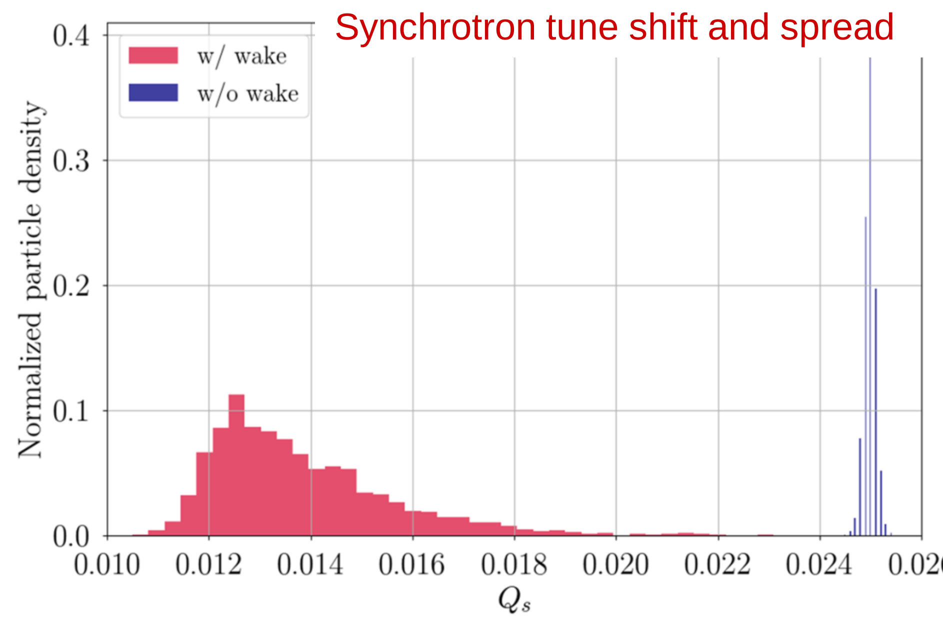
1. In the collision scheme with Crab Waist and Large Piwinski Angle the luminosity and tune shifts strongly depend on the bunch length

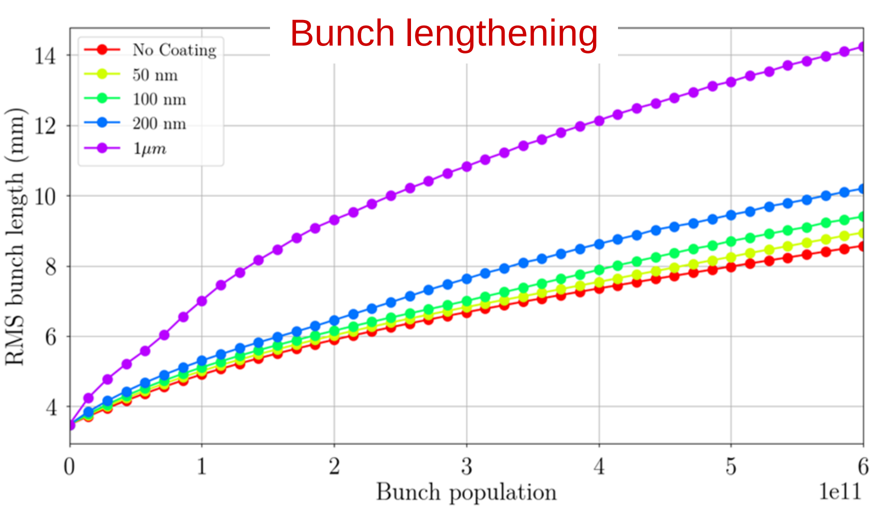
$$L \propto \frac{N\xi_y}{\beta_y^*}, \quad \xi_y \propto \frac{N\sqrt{\beta_y / \varepsilon_y}}{\sigma_z \theta}, \quad \xi_x \propto \frac{N}{(\sigma_z \theta)^2}$$

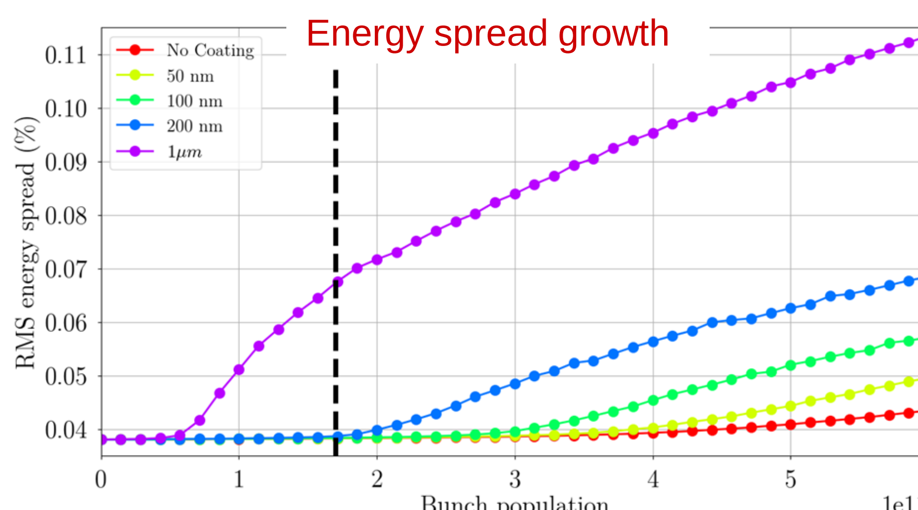
2. For the future circular colliders with extreme beam parameters in collision several new effects become important such as beamstrahlung, coherent X-Z instability and 3D flip-flop. The longitudinal beam dynamics plays an essential role for these effects.

Single bunch longitudinal dynamics









M.Migliorati, E.Belli and M.Zobov,
Phys.Rev.Accel.Beams 21 (2018) 041001

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

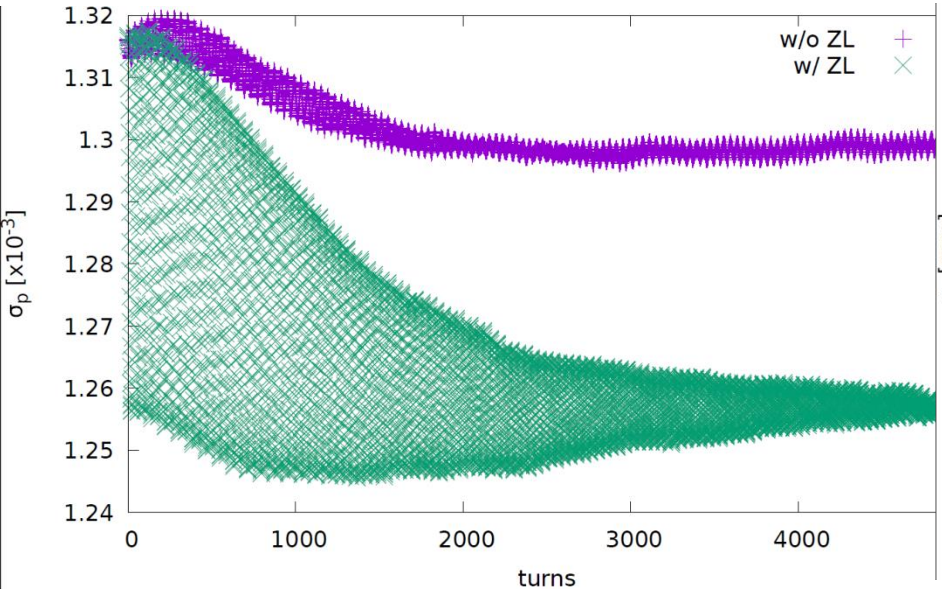
In Stable Areas

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

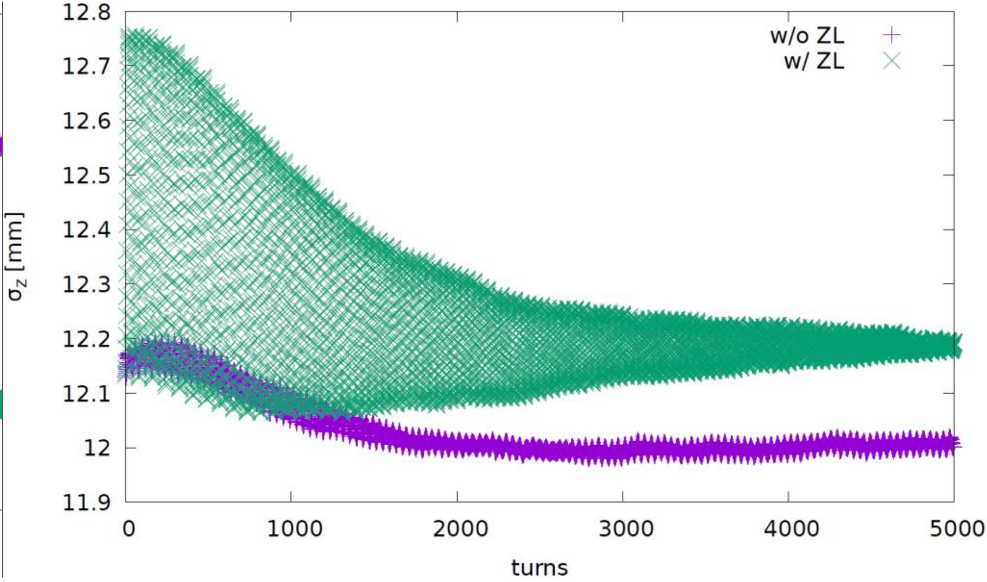
1. *D.Leshenok et al., Phys.Rev.Accel.Beams 23 (2020) 10, 101003*
2. *Y.Zhang et al., Phys.Rev.Accel.Beams 23 (2020) 104402*
3. *M.Migliorati et al., Eur.Phys.J.Plus 136, (2021), 11, 1190.*
4. *C.Lin et al., Phys.Rev.Accel.Beams 25 (2022), 1, 011001*

Combined effect of beamstrahlung and longitudinal impedance in stable tune areas

Energy spread

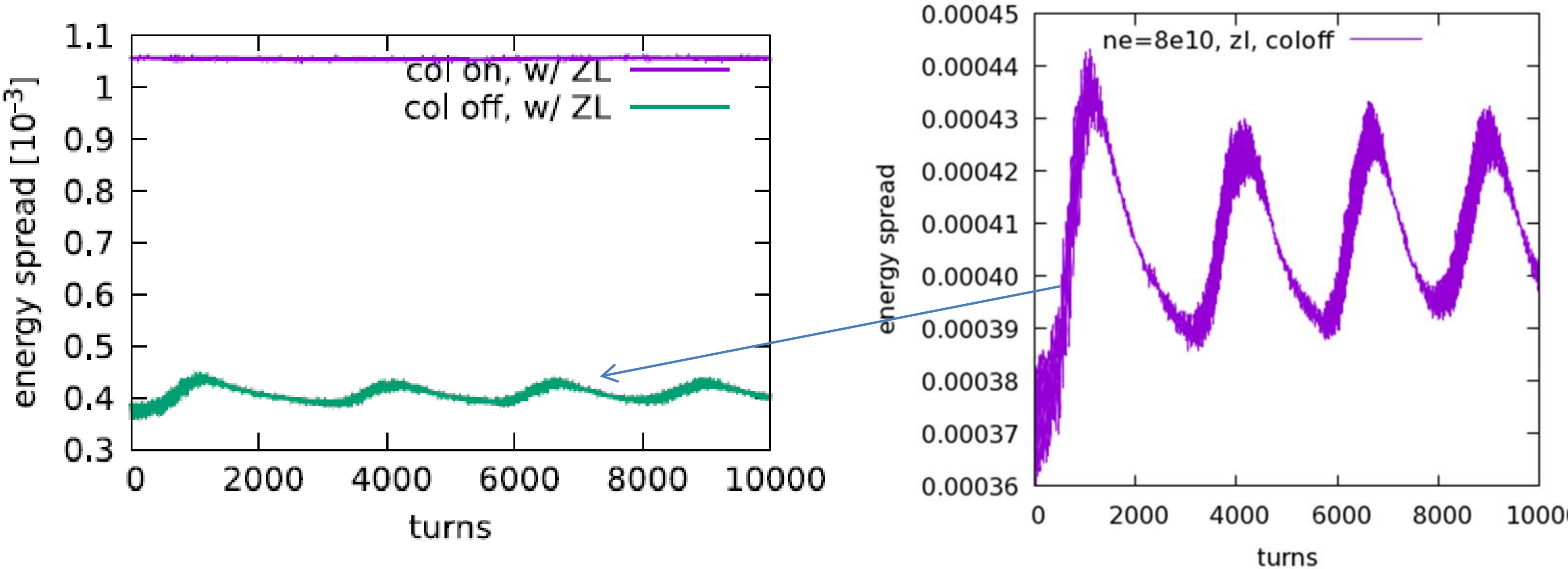


Bunch length

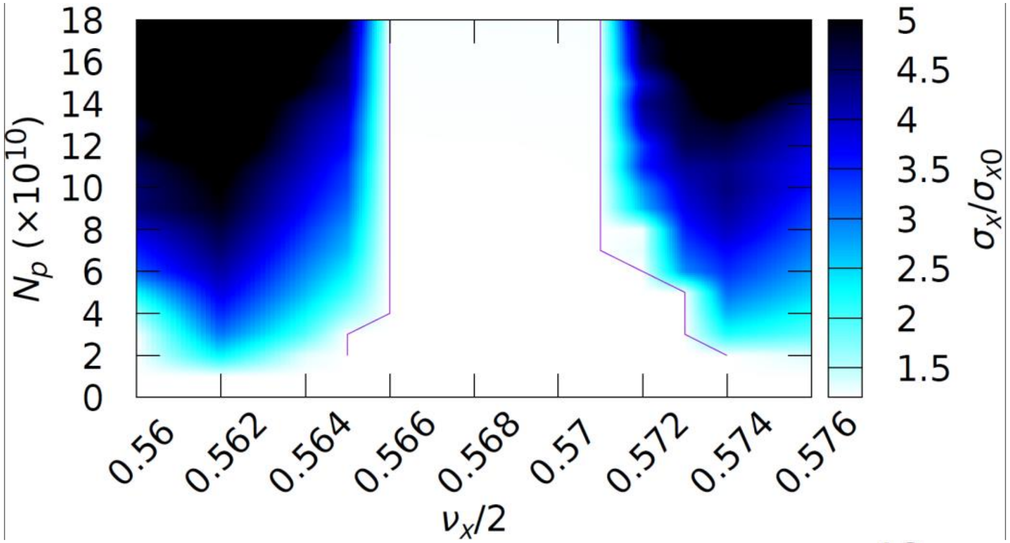


D.Leshenok, S.Nikitin, Y.Zhang and M. Zobov,
Phys.Rev.Accel. Beams 23 (2020) 10, 101003

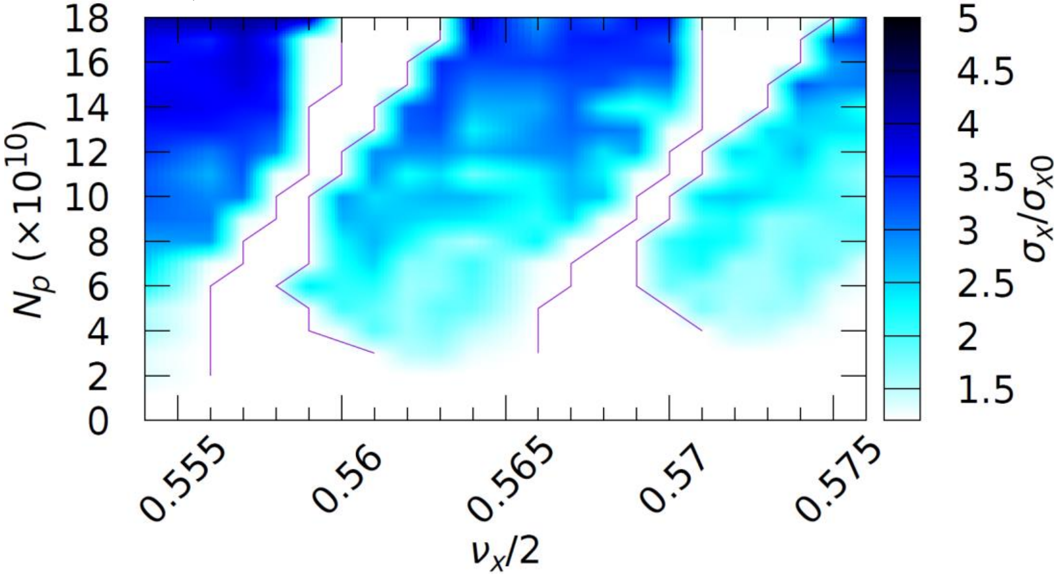
Microwave instability suppression in collision (CEPC example)



Horizontal beam size blowup due to beam-beam interaction in FCC-ee Z (CDR parameters)



Without longitudinal impedance



Including longitudinal impedance

M.Migliorati, E.Carideo, D.De Arcangelis, Y.Zhang and M.Zobov, Eur. Phys. J. Plus 136, 1190 (2021)

The lower momentum compaction factor results in higher sensitivity to collective effects

Examples of bunch instabilities

1. Microwave instability threshold

$$I_{th} = \frac{\sqrt{2\pi}\alpha_c(\ E/e)(\frac{\sigma_E}{E})^2\sigma_{z0}}{R(\frac{Z_L}{n})_{eff}} \propto \alpha_c{}^{3/2}$$

2. TMCI instability threshold

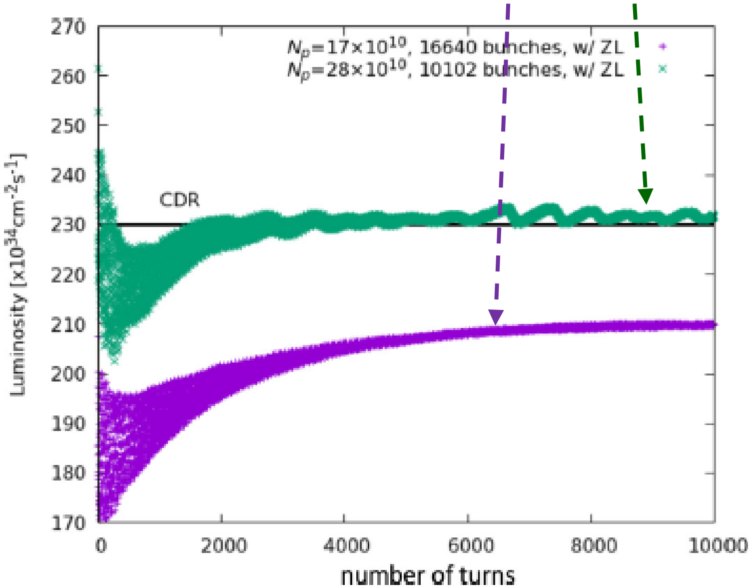
$$I_{th} = \frac{4(\ E/e)\nu_s}{R\Sigma(ImZ_T\ \beta_{x,y})}\frac{4\sqrt{\pi}}{3}\sigma_z \propto \alpha_c$$

3. Beam-beam X-Z instability

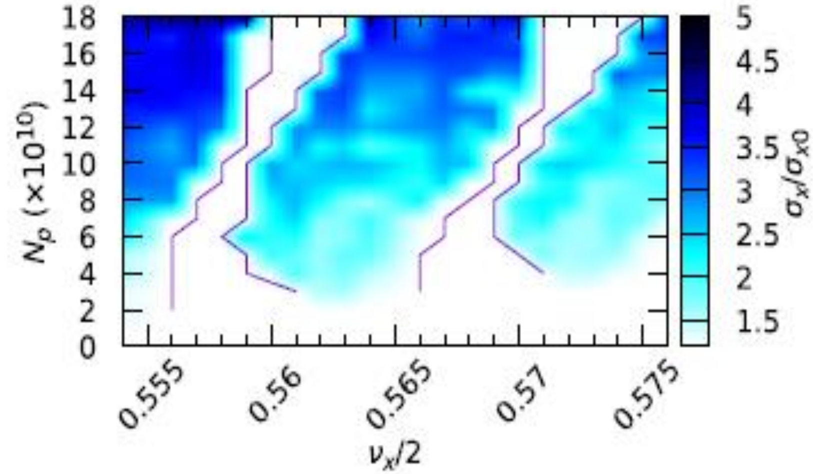
$$I_{th} \sim \frac{\nu_s}{\xi_x} \sim \frac{\alpha_c(\sigma_E/E)\sigma_z}{\beta_x^*}$$

Lattice with a higher momentum compaction factor

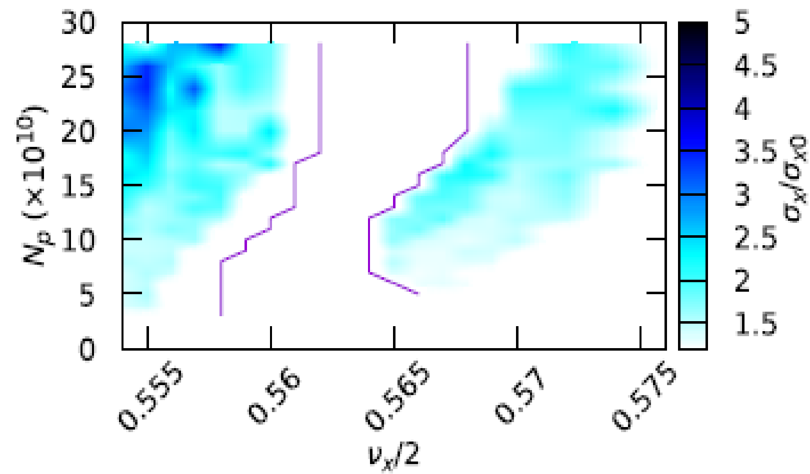
Arc Cell	60° / 60°		45° / 45°		
α_p [10^{-5}]	1.48		2.5 -?		
ε_x [nm]	0.27		0.6 -?		
ε_y [pm]	1.0		1.5		
RF voltage [MV]	100		100		66
ν_z / superperiod	0.0125		0.0163		0.0125
RF acceptance [%]	1.9		1.46		0.91
σ_{z0} [mm]	3.5		4.5		5.8
Beamstrahlung	OFF	ON	ON		
N_p [10^{11}]	0.5	1.7	1.7	2.8	3.6
N_b	56580	16640	16640	10100	7860
σ_z [mm]	3.5	12.	11.5	15.2	19.8
σ_δ [10^{-4}]	3.8	13.	9.7	12.7	12.7
ϕ	8.2	28.5	18.2	24	31.3
ξ_x	0.013	0.004	0.004	0.004	0.003
L/IP [10^{36} cm^{-2}c^{-1}]	2.3	2.3	1.9	2.3	2.3



αc=1.48e-5



αc=2.50e-5



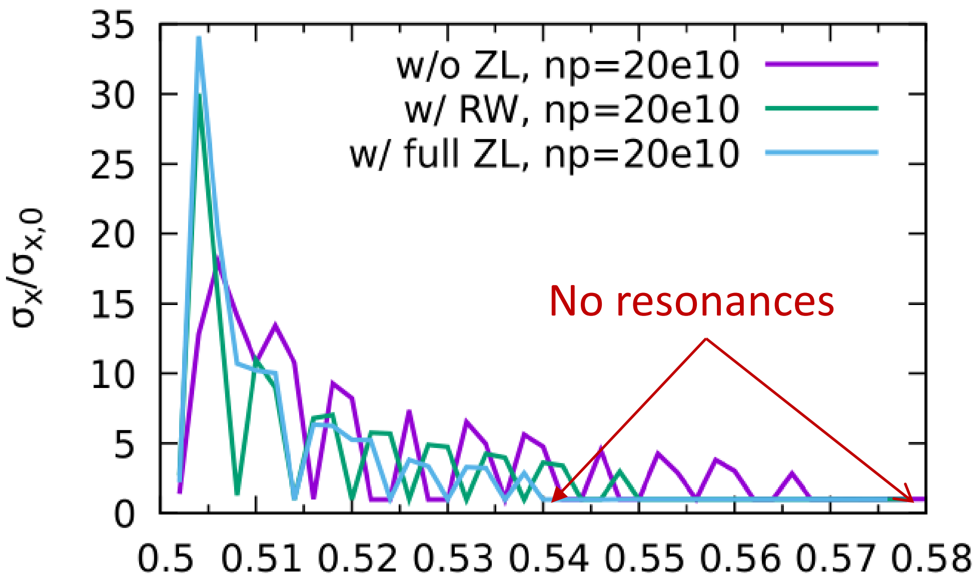
D.Shatilov, talk at 133th Optics Design Meeting

M.Migliorati et al., Eur.Phys.J.Plus, 136 (2021) 1190

Idea of using harmonic cavities

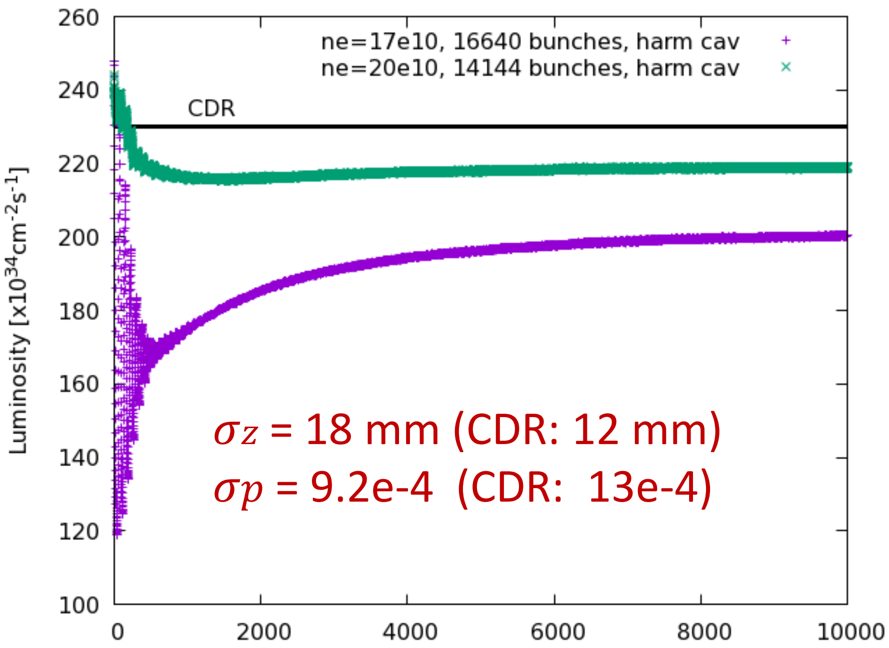
Eur. Phys. J. Plus (2021) 136:1190
doi:10.18429/JACoW-IPAC2021-MOXC01

1. Lower synchrotron tune
2. Higher order X-Z resonances
3. Landau damping due to higher synchrotron frequency spread
4. Longer bunches reduce the horizontal tune shift, which helps in suppressing the X-Z instability.
5. Longer bunches in collision result in a smaller energy spread due to beamstrahlung.



Issues to be solved/studied

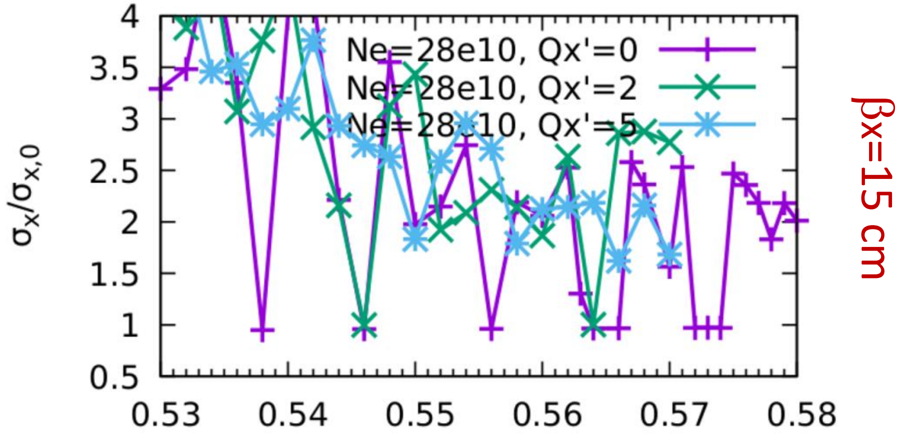
1. Transient beam loading
2. TMCI should be investigated
3. Some luminosity loss due to longer bunches
4. Additional impedance contribution
5. Energy calibration

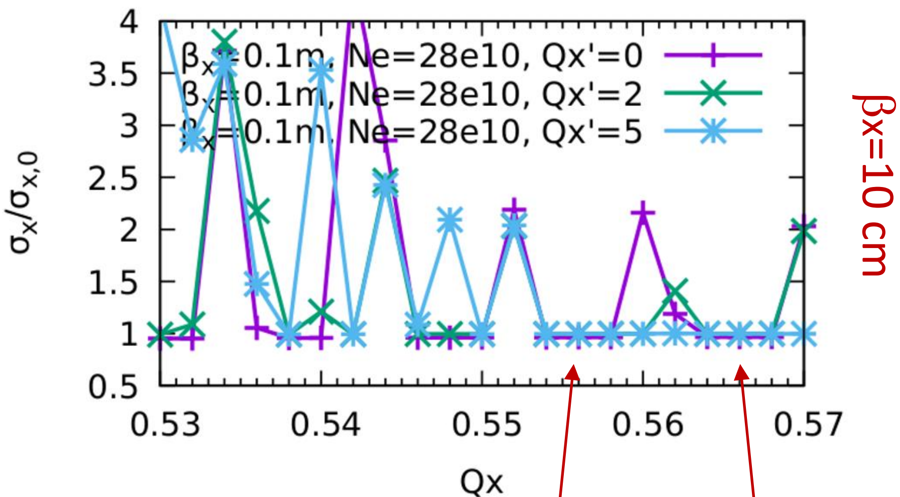


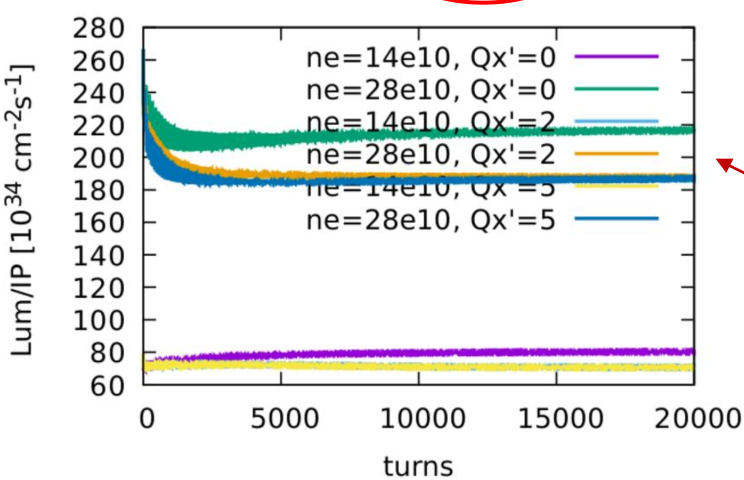
Collisions with 4 IPs

Table 1 Parameter list used in simulations

Layout	PA31-1.0	
	Z	WW
Circumference (km)	91.174117	
Beam energy (GeV)	45.6	80
Bunch population (10^{11})	2.53	2.91
Bunches per beam	9600	880
RF frequency (MHz)	400	
RF Voltage (GV)	0.12	1.0
Energy loss per turn (GeV)	0.0391	.37
Longitudinal damping time (turns)	1167	217
Momentum compaction factor 10^{-6}	28.5	
Horizontal tune/IP	55.563	
Vertical tune/IP	55.600	
Synchrotron tune	0.0370	0.0801
Horizontal emittance (nm)	0.71	2.17
Verical emittance (pm)	1.42	4.34
IP number	4	
Nominal bunch length (mm) (SR/BS)*	4.37/14.5	3.55/8.01
Nominal energy spread (%) (SR/BS)*	0.039/0.130	0.069/0.154
Piwinski angle (SR/BS)*	6.35/21.1	2.56/5.78
ξ_x/ξ_y	0.004/0.152	0.011/0.125
Horizontal β^* (m)	0.15	0.2
Vertical β^* (mm)	0.8	1.0
Luminosity/IP (10^{34}/cm^{2}s)	181	17.4







The reduction of the horizontal beta at IP is obligatory to get good tune areas larger than the horizontal tune shift and to obtain the required luminosity

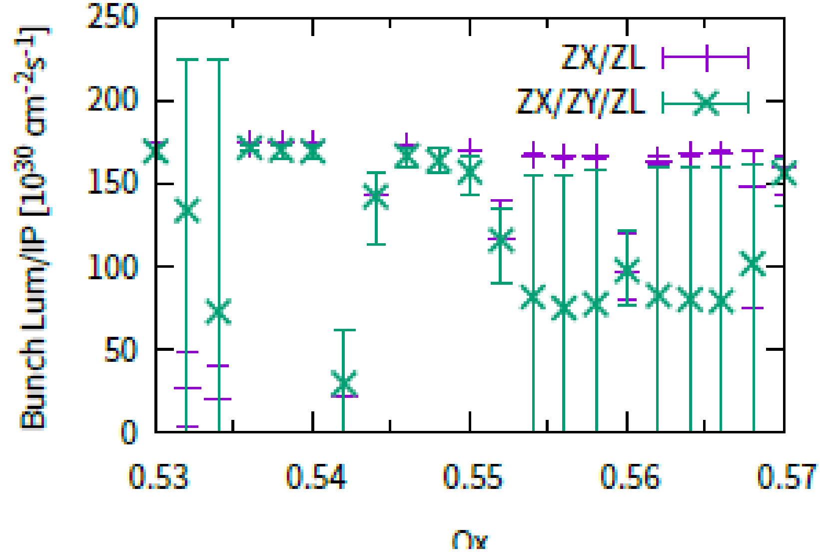
M.Migliorati et al., EPJ Tech.Instrum. 9 (2022) 1, 10

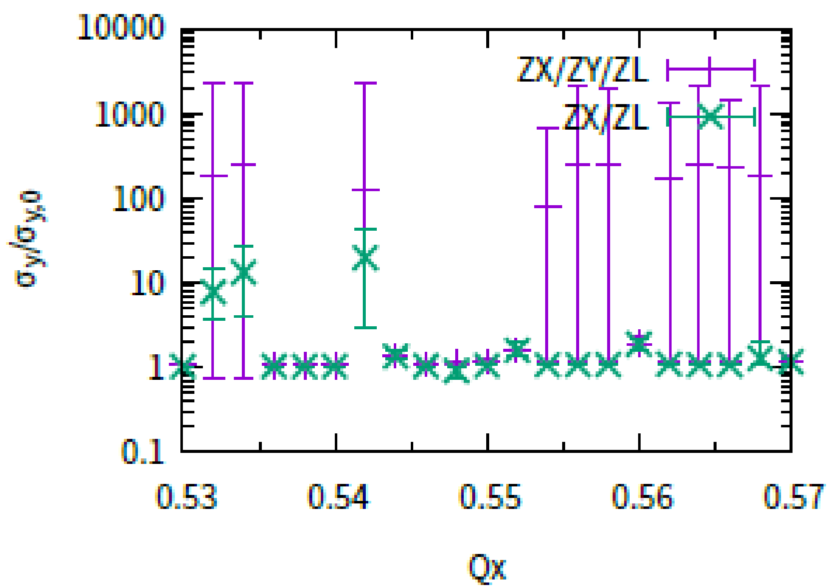
Beam-beam interaction including both longitudinal and transverse impedances

IPAC2023

Table 1: Main Parameters (FCCee-Z)

Parameter	
Beam Energy	45.6 GeV
Bunch Population (10^{10})	24
Emittance ($\epsilon_{x,y}$)	0.71 nm / 1.42 pm
β_x^* / β_y^*	0.1 m / 0.8 mm
Bunch Length [natural/bs]	4.38/16.6 mm
Energy Spread [natural/bs] (10^{-4})	3.8/13.8
Synchrotron Tune	0.00925
Damping Rate (x/y/z) (10^{-4})	1.07/1.07/2.14
Half Crossing Angle	15 mrad
Piwinski Angle	29.5
Beam-Beam Parameter (x/y)	0.0019/0.11



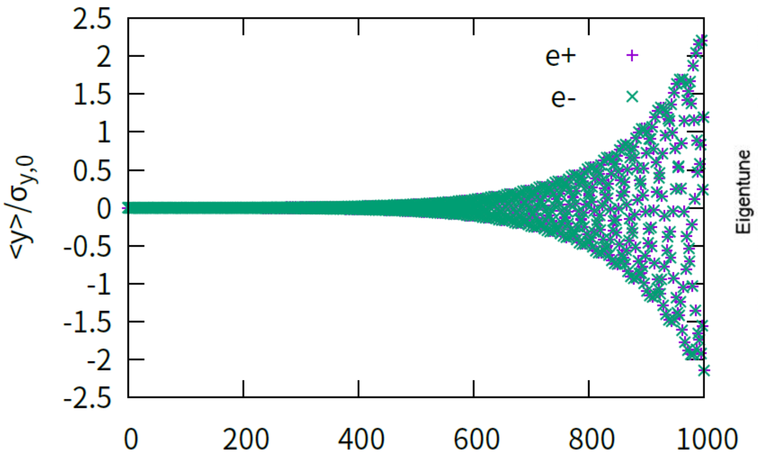


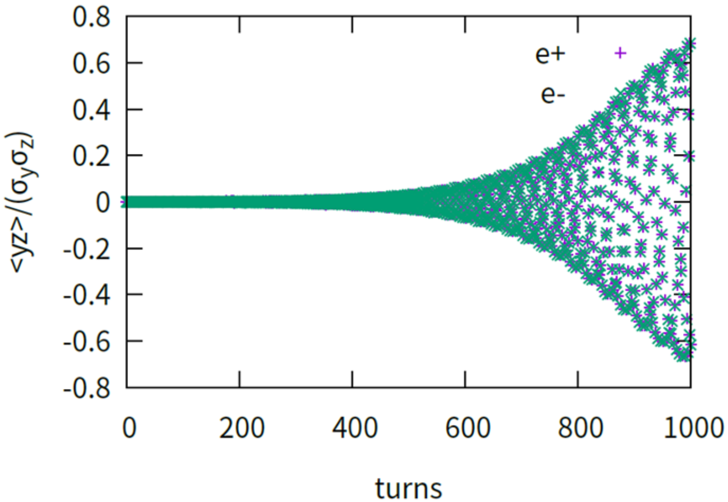
1. The X-Z instability gets somewhat stronger when the horizontal impedance is included

2. A strong vertical instability can arise when the vertical impedance is included that can limit the working point choice

3. The vertical chromaticity is an effective tool to suppress the instability

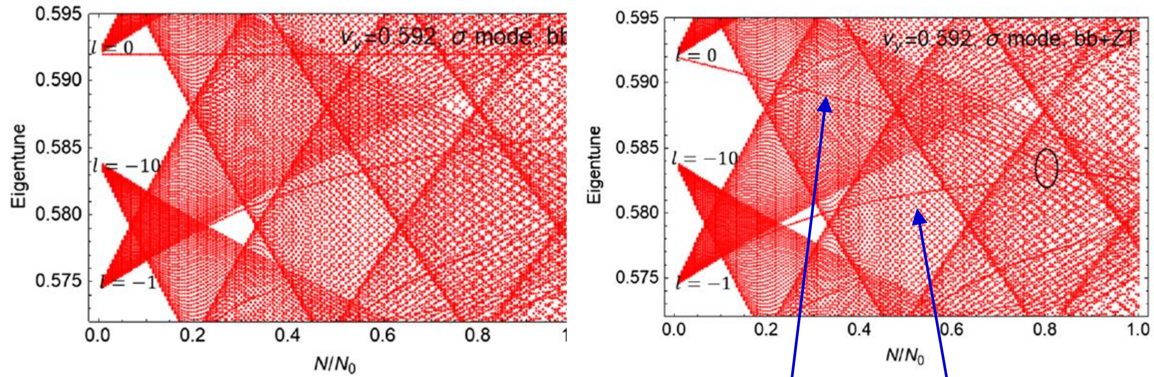
Mode coupling due to beam-beam interaction and the vertical impedance (CEPC example)





No Zy

Zy included



Observations

1. Mode 0 decreases due to the ring impedance
2. Mode –1 increases due to beam-beam cross wake impedance
3. The threshold is reduced from 2.1e11 to 1.1e11

Possible mitigation

1. Chromaticity
2. Asymmetric tunes
3. Feedback

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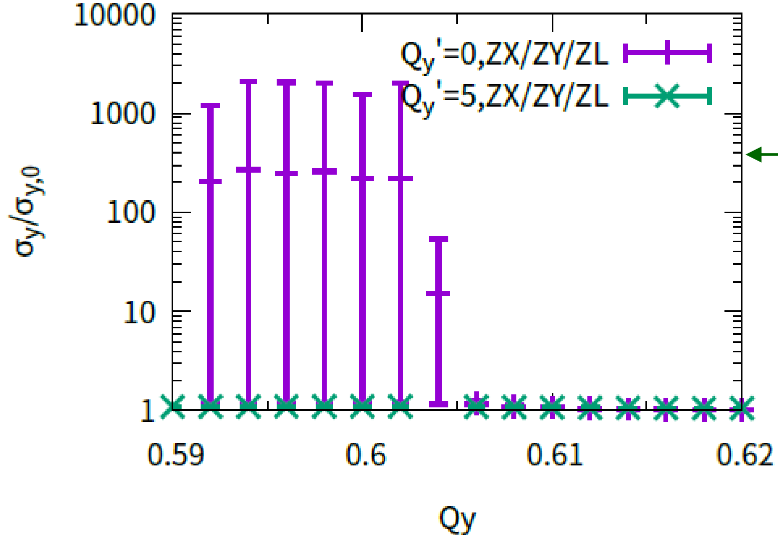
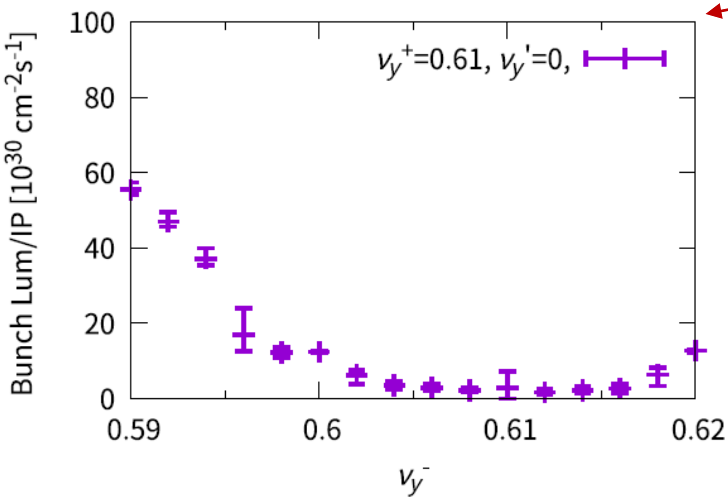
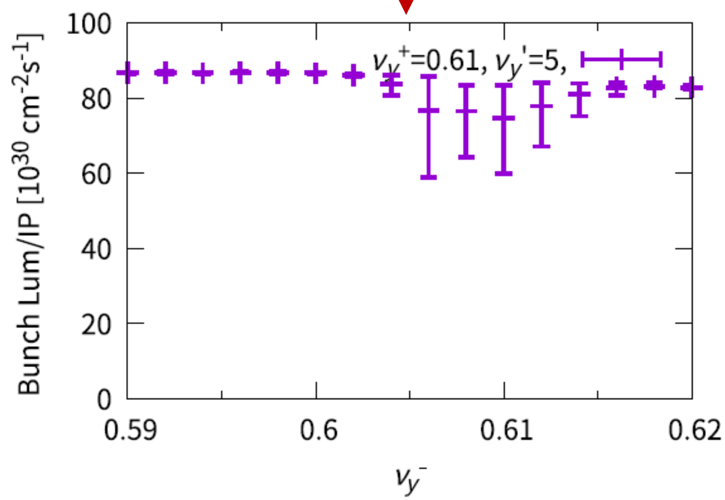
Mitigation of TMCI in beam-beam collisions



Suppression of TMCI instability in FCC-ee by using the vertical chromaticity of +5.

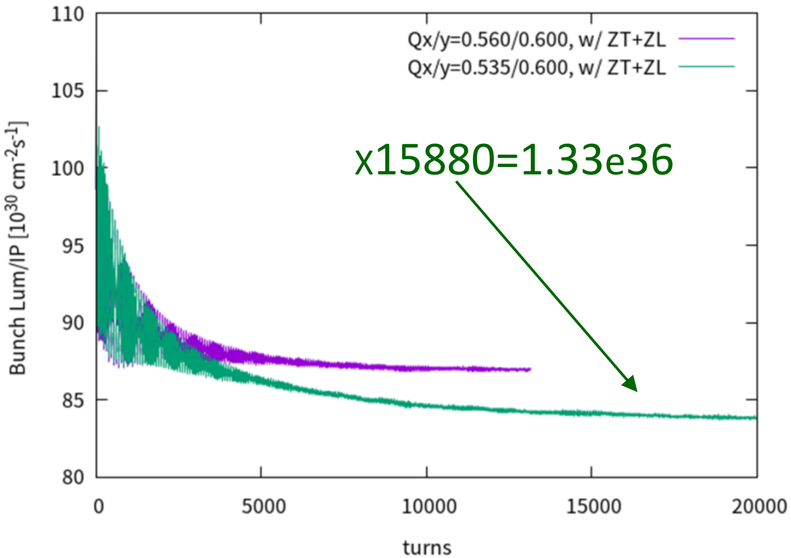
Suppression of TMCI instability in CEPC by using the asymmetric tunes and reduced chromaticity of +5 (instead of +10)

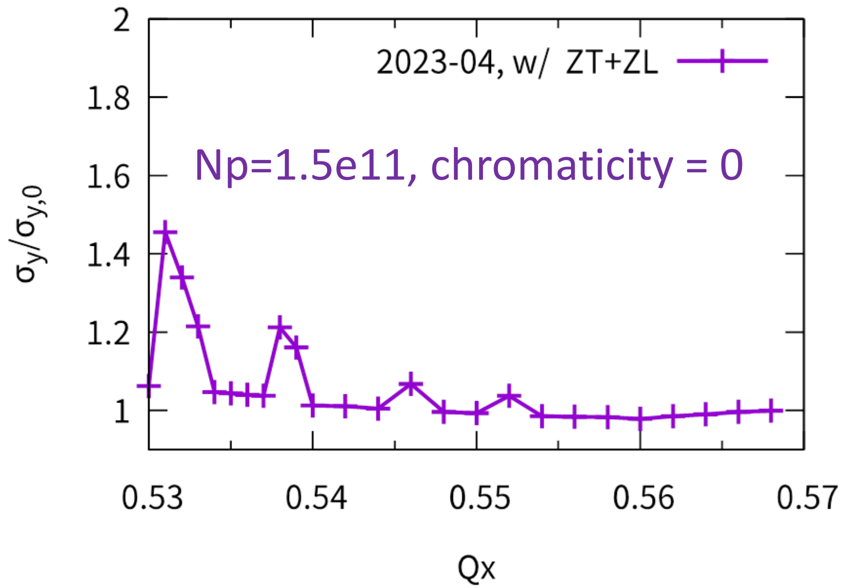


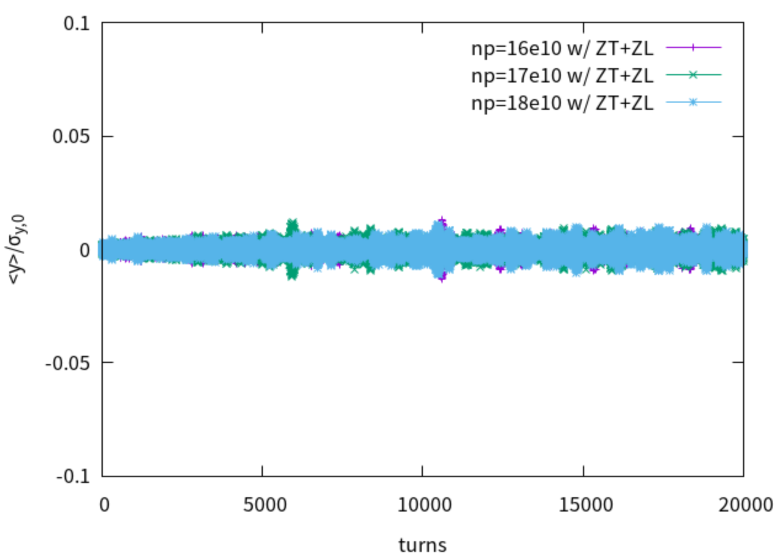


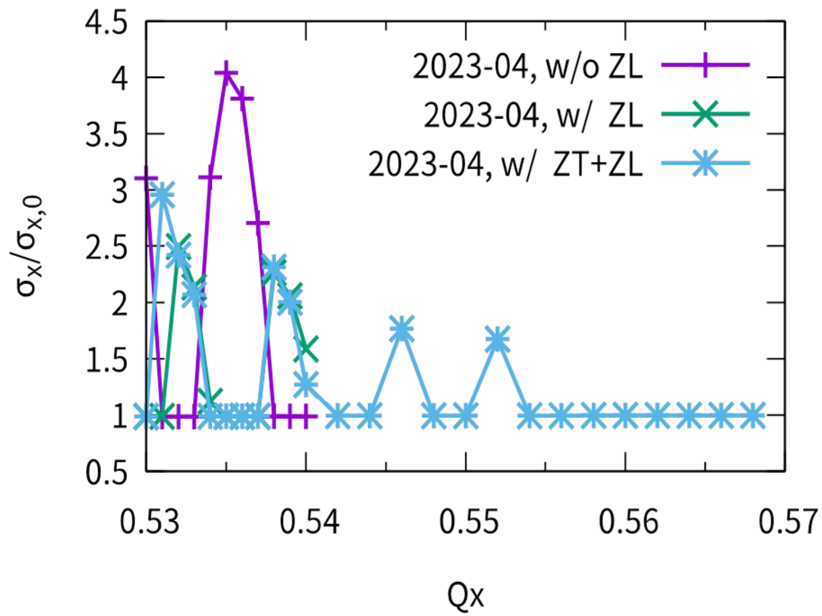
1. Y.Zhang, M.Migliorati and M.Zobov, Proceedings of IPAC2023, pp. 3510-3513
2. Y.Zhang et al., Phys.Rev.Accel.Beams, 26 (2023) 064401

Simulations before the mid-term review





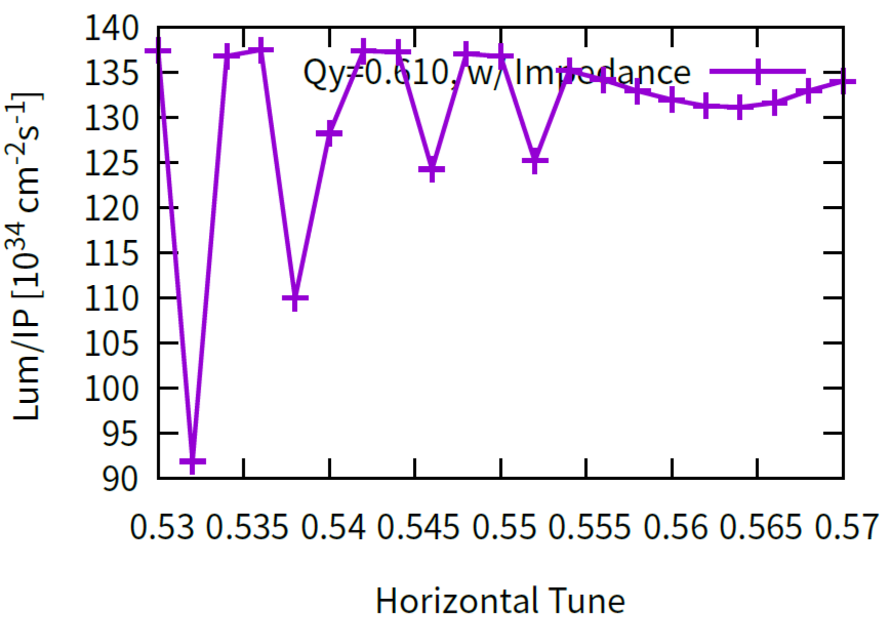


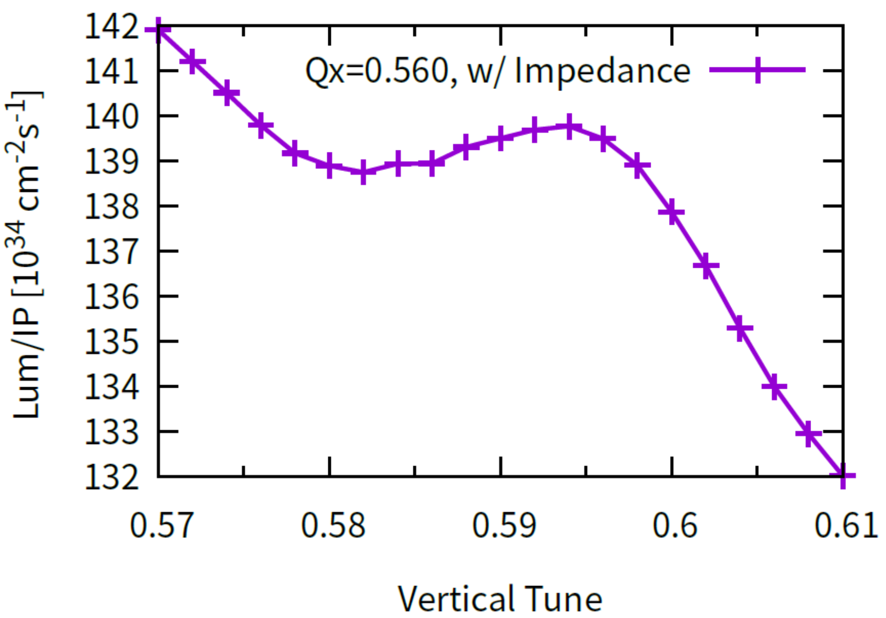


Simulations for the case with the reduced beam pipe radius of 30 mm

1. Reduced beam pipe radius (30 cm)
2. Beam pipe RW impedance (150 nm coating)
3. RW contribution of collimators
4. No geometric impedance of collimators
5. 10000 bellows (SuperKEKB model)
6. 4000 BPMs
7. 52 single-cell cavities (400 MHz)
8. 13 double tapers for cryo-modules

1. *The luminosity of 1.4e36/IP can be achieved in the vicinity of the proposed betatron tunes (218.158, 222.20) for the collisions with 4IPs*
2. *The respective bunch length is equal to 14 mm and the energy spread is 9.0e-4*





Hopefully more combined effects can be studied soon with the modern software tools

Xsuite: An Integrated Beam Physics Simulation Framework

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Presented at HB2023

Xsuite is a newly developed modular simulation package combining in a single flexible and modern framework the capabilities of different tools developed at CERN in the past decades, notably Sixtrack, Sixtracklib, COMBI and PyHEADTAIL. The suite is made of a set of python modules (Xobjects, Xparts, Xtrack, Xcoll, Xfields, Xdpes) that can be flexibly combined together and with other accelerator-specific and general-purpose python tools to study complex simulation scenarios. The code allows for symplectic modeling of the particle dynamics, combined with the effect of synchrotron radiation, impedances, feedbacks, space charge, electron cloud, beam-beam, beamstrahlung, electron lenses. For collimation studies, beam-matter interaction is simulated using the K2 scattering model or interfacing Xsuite with the BDSIM/Geant4 library. Tools are available to compute the accelerator optics functions from the tracking model and to generate particl
ing platforms are supported, including conventional CPUs,

GOAT: a simulation code for high-intensity beams

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Abstract

A simulation code, GOAT, is developed to simulate single-bunch intensity-dependent effects and their interplay in the proton ring of the Electron-Ion Collider in China (EicC) project. GOAT is a scalable and portable macroparticle tracking code written in Python and coded by object-oriented programming technology. It allows for transverse and longitudinal tracking, including impedance, space charge effect, electron cloud effect, and beam-beam interaction. In this paper, physical models and numerical approaches for the four types of high-intensity effects, together with the benchmark results obtained through other simulation codes or theories, are presented and discussed. In addition, a numerical application of the cross-talk simulation between the beam-beam interaction and transverse impedance is shown, and a dipole instability is observed below the respective instability threshold. Different mitigation measures implemented in the code are used to suppress the instability. The flexibility, completeness, and advancement demonstrate that GOAT is a powerful tool for beam dynamics studies in the EicC project or other high-intensity accelerators.

Conclusions

1. Interplay of beam-beam collisions and collective effects makes achievement of the collider design goals (even more) challenging

2. Several techniques have been found to mitigate the harmful combined effects of the beam-beam interaction and the beam coupling impedances such as the use of higher momentum compaction factors, lower horizontal beta functions, positive chromaticity, asymmetric tunes, harmonic cavities etc.

3. The future efforts should be aimed at the collider impedance minimization, at including other collective effects in these studies and at elaboration of the new means and techniques to cope with the collective effects which can deteriorate the collider performance

We thank Dmitry Shatilov for providing useful material and many fruitful discussions