Collective Effects in Lepton Circular Colliders and Synchrotron Light Sources

Mikhail Zobov and Mauro Migliorati

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European network for developing new horizons for RIs

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Beam Current Records at Factories

Parameters	PEP-II		KEKB		DAΦNE	
	LER	HER	LER	HER	e+	e-
Circumference, m	2200	2200	3016	3016	97.69	97.69
Energy, GeV	3.1	9.0	3.5	8.0	0.51	0.51
Damping time, turns	8.000	5.000	4.000	4.000	110.000	110.000
Beam Currents, A	3.21	2.07	1.70*	1.25*	1.40	2.45

Maximum positron beam current

Maximum currents with SC cavities

Maximum electron beam current

* 2.00 A and 1.40 A without crab cavities

$$Brilliance = \frac{Photons}{\sec\cdot mrad^2 \cdot mm^2 0.1\% BW} \propto \frac{I}{\varepsilon_x \varepsilon_y}$$

Parameters	Unit	MAX-IV	ESRF-EBS	SIRIUS	SuperKEKB (LER/HER)		FCC-ee (at Z)	CEPC (at Z)
Energy	GeV	3.0	6.0	3.0	4.0	7.0	45.6	45.5
Circumference	km	0.528	0.844	0.518	3.02	3.02	90.66	100
Beam current	A	0.50	0.20	0.35	3.6	2.6	1.27	0.80
Horizontal emittance	nm rad	0.328	0.133	0.25	3.2	4.6	0.71	0.27

Design values

Operating 4th generation light sources

Biggest future lepton circular colliders

1. Both modern light sources and future lepton colliders based on the crab waist collision concept require smaller emittances
2. The future colliders beam currents should be close to the best values achieved in the factory-class lepton colliders

Topics to be discussed

1. Differences and similarities of collective effects in lepton and hadron synchrotrons
2. New features of beam-beam interaction in modern and future lepton colliders (SuperKEKB, FCC-ee, CEPC..)
3. Interplay of collective effects in the lepton machines

Typical Collective Effects in Lepton Synchrotrons

1.Single bunch instabilities

a) Bunch lengthening
b) Microwave instability
c) TMCI and head-tail instabilities
d) Space charge
e) IBS and Touschek effects

2. Multi-bunch instabilities

a) Transverse resistive wall instability
b) Tune shifts due to the quadrupolar wakes
c) HOM driven instabilities
d) Transient beam loading
e) Electron cloud effects in the positron rings
f) Ion effects in the electron rings

Most of the effects are essentially the same/similar to those in the hadron circular machines. Particular features depend on different particle mass, charge and parameters required to fulfill the accelerator requirements

Synchrotron Radiation

1. Harmful/undesired effects

a) Limits the maximum achievable energy in colliders

b) Heating of the vacuum chamber components

c) High power required to restore the lost energy

2. Useful effects

a) Main product of the dedicated synchrotron light sources

b) Natural mechanism for suppression of instabilities (SR damping)

c) Suitable for beam diagnostics

Synchrotron radiation integrals and accelerator parameters

$$\alpha_c = \frac{I_1}{C} = \frac{1}{C}\oint \frac{D(s)}{\rho} ds$$ → Momentum compaction factor

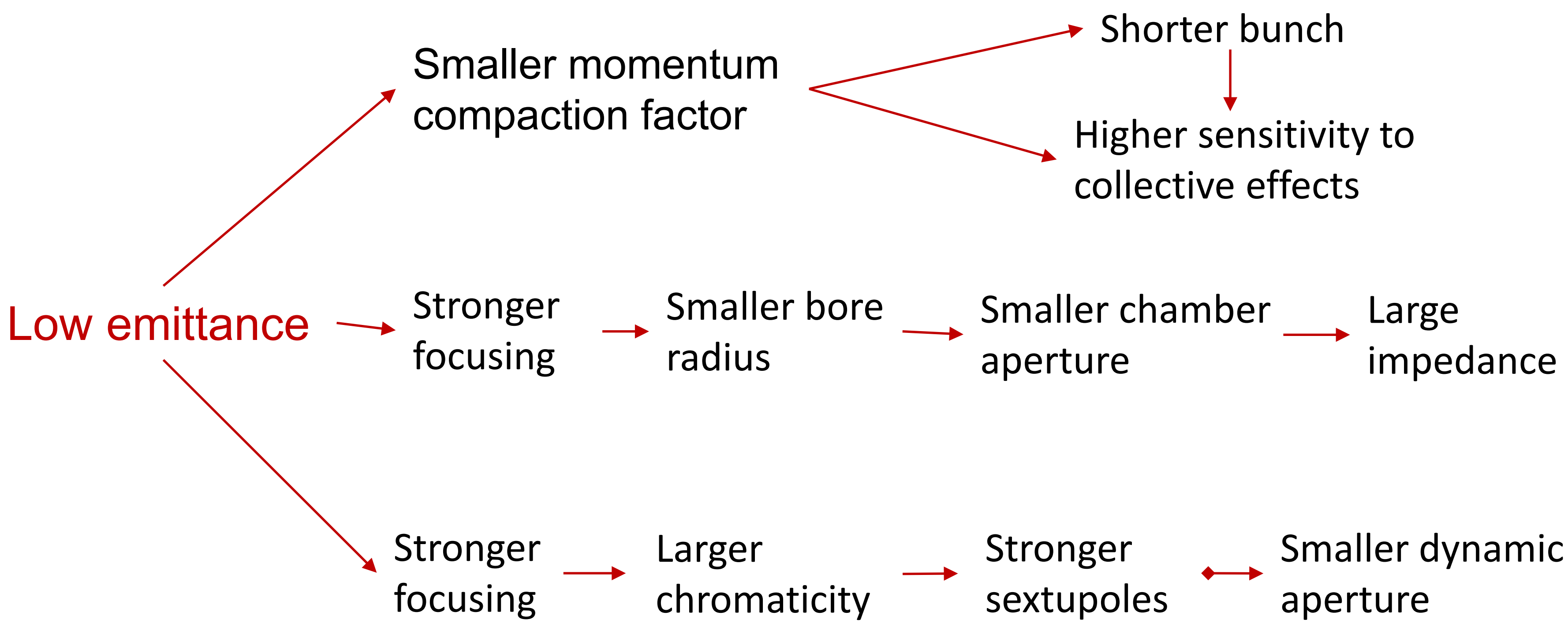
$$U_0 = \frac{C_\gamma}{2\pi} E^4 I_2 = \frac{C_\gamma}{2\pi} E^4 \oint \frac{1}{\rho^2} ds$$ → Energy loss per turn

$$\frac{\sigma_E^2}{E^2} = C_q \gamma^2 \frac{I_3}{J_s I_2} = \frac{C_q \gamma^2}{J_s}\left(\oint \frac{1}{\left|\rho^3\right|} ds / \oint \frac{1}{\rho^2} ds\right)$$ → Equilibrium energy spread

$$\varepsilon_x = C_q \frac{\gamma^2}{J_x} \frac{I_5}{I_2} = C_q \frac{\gamma^2}{J_x}\left(\oint \frac{\beta_x D'^2 + 2\alpha_x D D' + \gamma_x D^2}{\left|\rho\right|^3} ds / \oint \frac{1}{\rho^2} ds\right)$$ → Horizontal emittance

$$J_x = 1 - \frac{I_{4x}}{I_2}, \qquad J_y = 1 - \frac{I_{4y}}{I_2}, \qquad J_s = 2 + \frac{I_{4x} + I_{4y}}{I_2}$$ → Damping partition numbers

Challenges in achieving low emittances

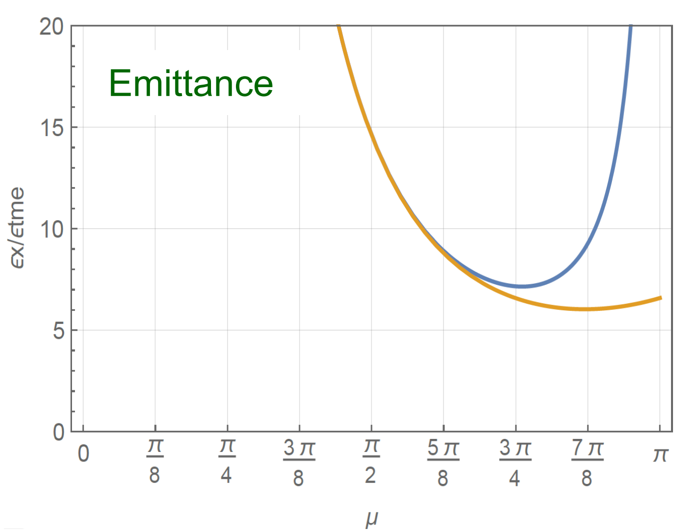


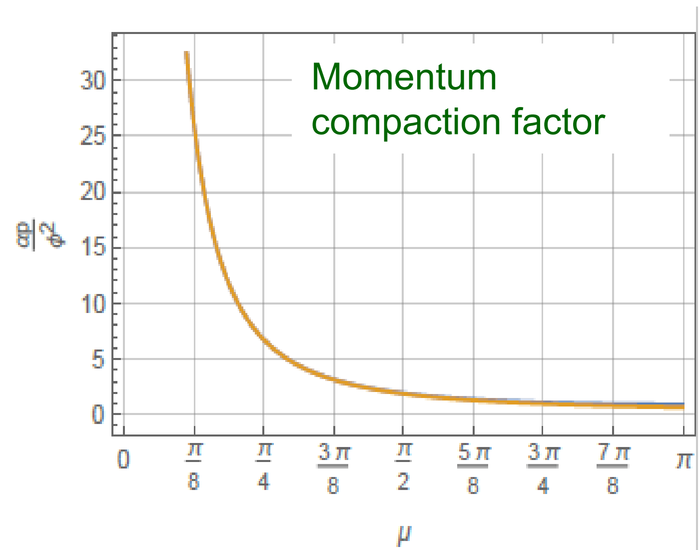
R.Nagaoka and K.Bane, J.Synchrotron Rad 21 (2014) 937-960
R.Nagaoka, ICFA Mini-Workshop, Erice, Italy, 2014

Example of FODO cell

(Courtesy A.Bogomyagkov and E.Levichev)

$$\varepsilon_x = \frac{C_q \gamma^2}{J_x} \phi^3 \frac{1 - \frac{3}{4} u^2 + \frac{1}{60} u^4}{u^3 \sqrt{1 - u^2}}; \quad \alpha_c = \phi^2 \frac{12 - u^2}{12 u^{12}}; \quad u = \sin(\mu/2)$$





By using the series expansion in μ it can be shown that for μ smaller than 100-110 degrees the emittance is well approximated by

$$\varepsilon_x \approx C_q \gamma^2 \frac{\phi}{\mu} 2\alpha_c$$

Bending angle

Momentum compaction factor

Phase advance

The bunches are shorter for the lower momentum compaction factors

$$\sigma_z = \frac{c|\eta_c|}{\omega_s}\left(\frac{\sigma_E}{E}\right) = \frac{\sqrt{2\pi}}{\omega_0}\sqrt{\frac{\alpha_c}{heV_{RF}\cos\phi_s}}\left(\frac{\sigma_E}{E}\right)$$

Typical natural bunch length in these machines is of the order of few millimeters

This can result in

1. Smaller instability thresholds
2. High power losses due to beam coupling impedance
3. Coherent synchrotron radiation
4. The bunch spectrum extends till higher frequencies, beyond the beam pipe cut-off
   a) Bunch «sees» small vacuum chamber objects
   b) A crosstalk between different vacuum chamber components is to be taken into account to create a reliable impedance model

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

Example of single bunch instabilities

1. Microwave instability threshold

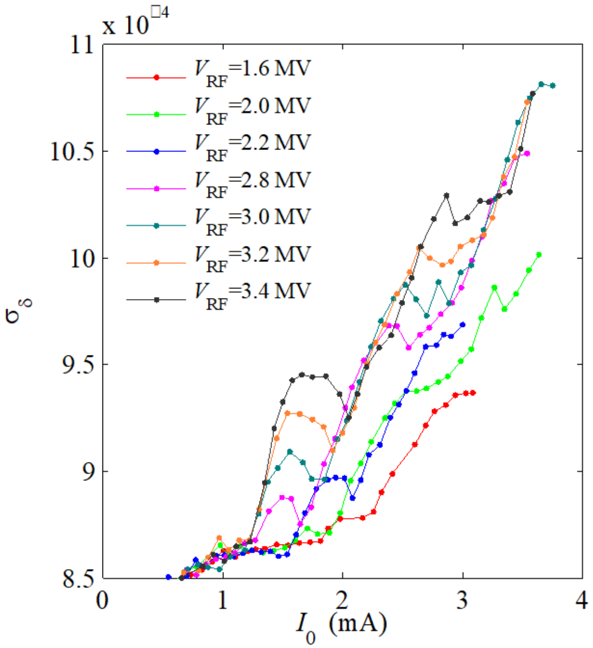
$$I_{th} = \frac{\sqrt{2\pi}\alpha_c (E/e)(\sigma_E/E)^2 \sigma_{z0}}{R(Z_L/n)_{eff}} \propto \alpha_c^{3/2}$$

2. TMCI instability threshold

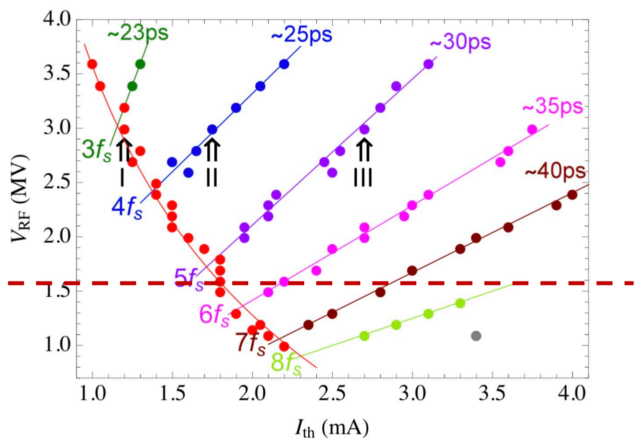
$$I_{th} = \frac{4(E/e)\nu_s}{R\sum([\mathrm{Im}\,Z_T]\beta_{x,y})} \frac{4\sqrt{\pi}}{3} \sigma_z \propto \alpha_c$$

Example of Microwave Instability in NSLS-II
(Courtesy A.Blednykh)

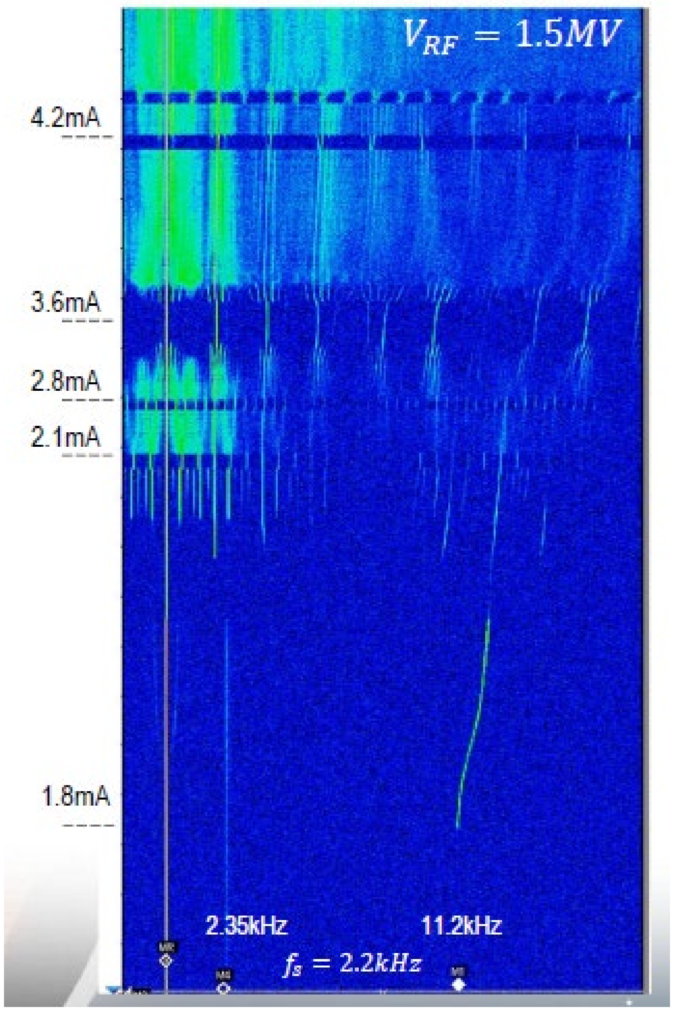
Energy spread versus bunch current



Thresholds at different RF voltages



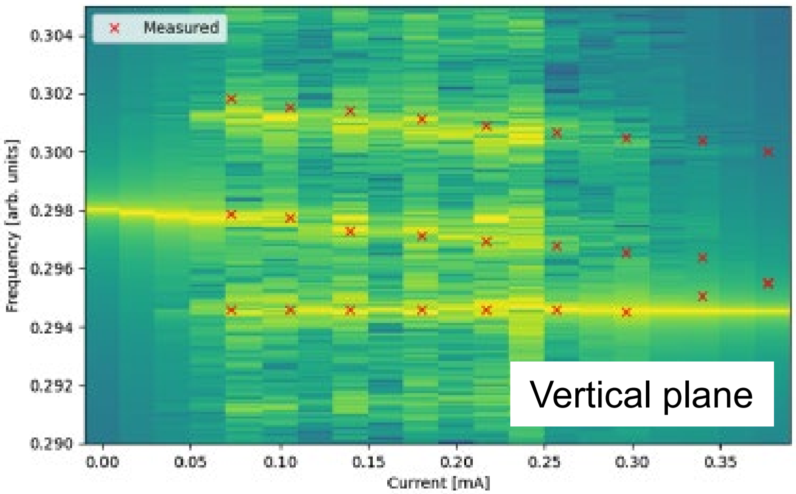
Beam spectra at 1.5 MV

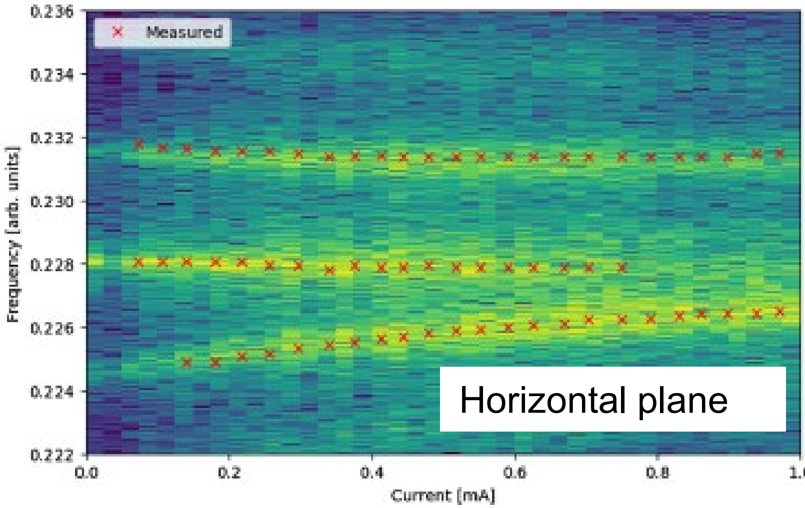


A.Blednykh et al., New aspects of longitudinal instabilities in electron storage rings, Sci.Rep. 8 (2018),1, 11918

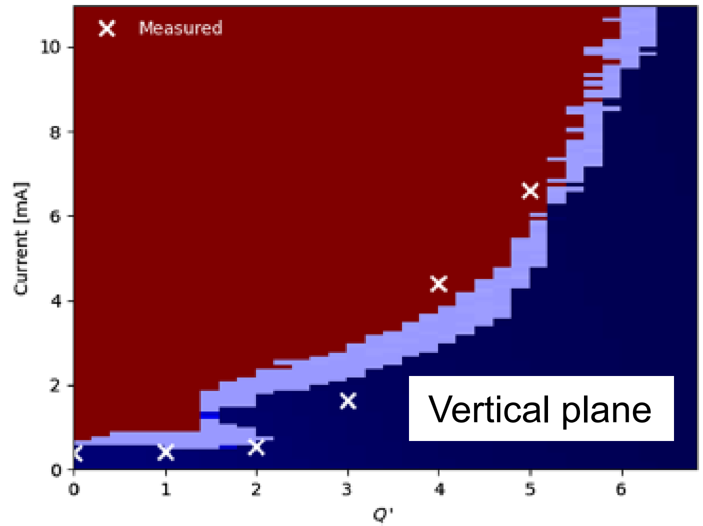
TMCI Instability in ESRF-EBS

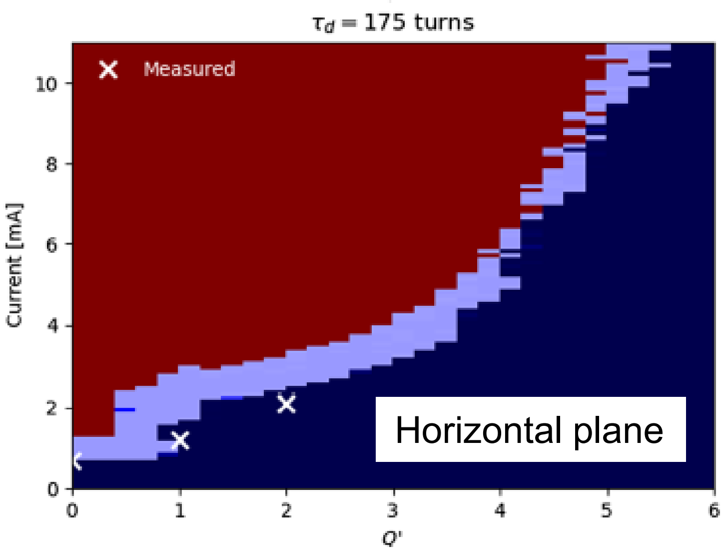
Mode shifts versus bunch current at chromaticity +1.5





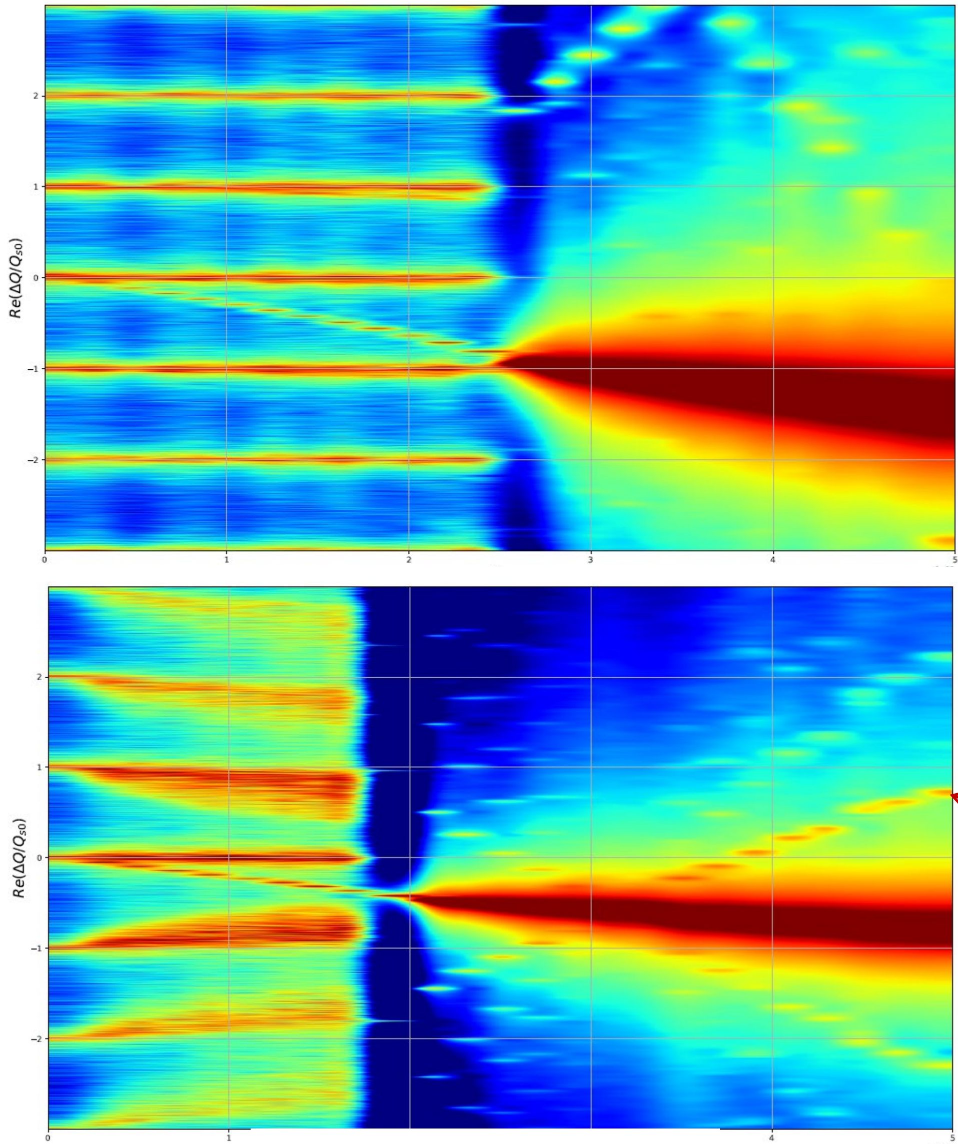
Instability thresholds as a function of chromaticity





L.R.Carver et al., Phys.Rev.Accel.Beams 26 (2023) 4 044402

TMCI instability in FCC-ee (Z) including both transverse and longitudinal impedances



Only transverse impedance is included

Both transverse and longitudinal impedances are included

Coherent mode relative frequencies

Bunch intensity

E. Carideo, M. Migliorati, M. Zobov et al., "Transverse and Longitudinal Single Bunch Instabilities in FCC-ee", IPAC2021

Combined effect of chromaticity and feedback on transverse head-tail instability

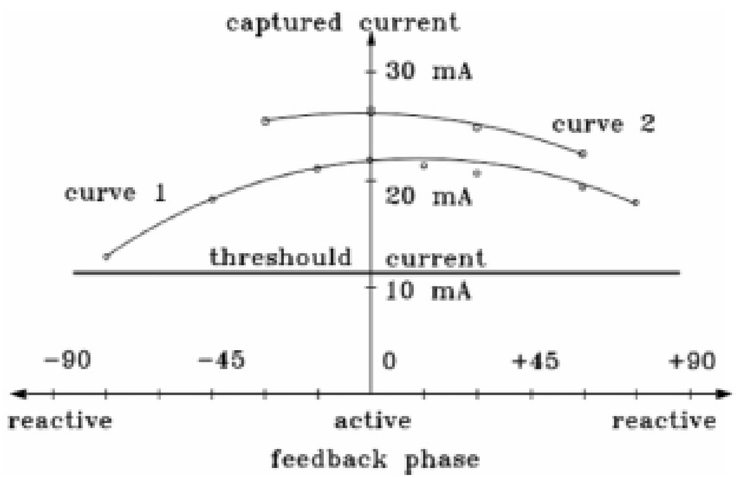


FIG. 1. Single-bunch beam current injected in VEPP-4M as a function of the feedback phase.

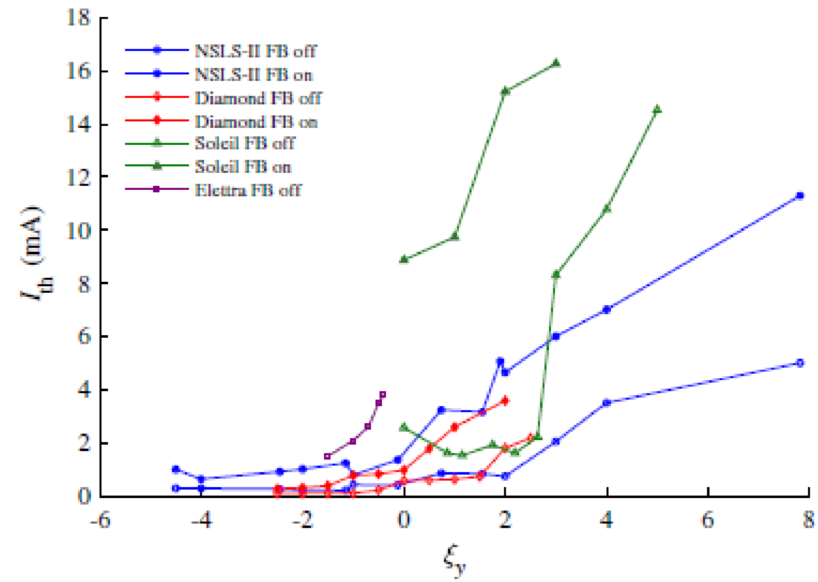


FIG. 2. Measured single-bunch threshold current as a function of chromaticity, with and without feedback.

V.Smaluk et al., Phys.Rev.Accel.Beams 24 (2021) 5, 054401

IBS and Touschek effects

Both effects become important due to low emittances and short bunch length

Intrabeam scattering (IBS) is the multiple Coulomb scattering leading to an increase of all bunch dimensions and enerdy spread

$$\varepsilon_x = \frac{\varepsilon_{x0}}{1-\tau_x/T_x}, \quad \varepsilon_y = \frac{\varepsilon_{y0}}{1-\tau_y/T_y}, \quad \sigma_p^2 = \frac{\sigma_{p0}^2}{1-\tau_p/T_p}$$

K.Bane, EPAC2002, p.1443

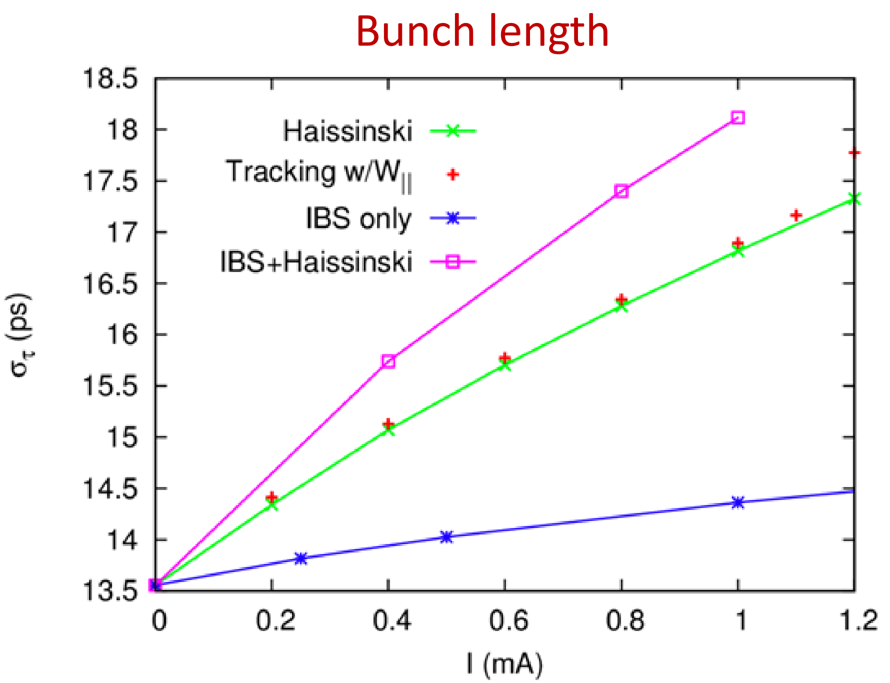
$$\frac{1}{T_p} \approx \frac{r_e^2 cN\ (\log)}{16\gamma^3 \varepsilon_x^{3/4}\varepsilon_y^{3/4}\sigma_z\sigma_p^3}\left\langle \sigma_H g(a/b)\left(\beta_x\beta_y\right)^{-1/4}\right\rangle, \quad \frac{1}{T_x} = \frac{\sigma_p^2}{\varepsilon_x}\left\langle H_x\delta\left(1/T_p\right)\right\rangle$$

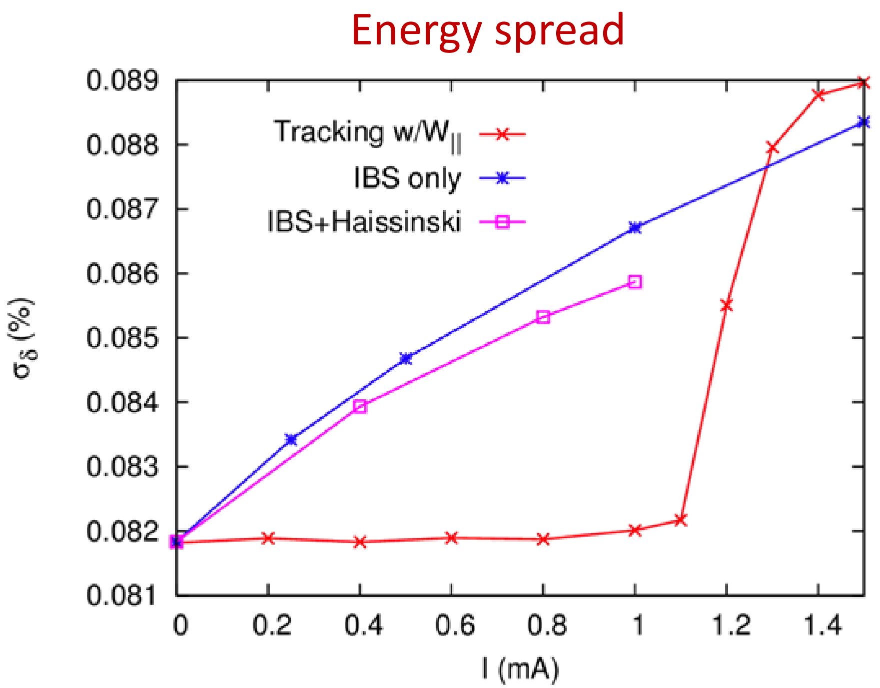
Touschek effect is the large single Coulomb scattering leading to energy transfer from transverse to longitudinal plane resulting in immediate particle loss

$$N = \frac{N_0}{1+t/T}, \quad \frac{1}{T} = \frac{r_e^2 cN}{8\sqrt{\pi}\beta^2\gamma^4\sigma_z\sigma_p\varepsilon_x\varepsilon_y}\left\langle \sigma_H F(\delta_m)\right\rangle$$

The most popular mitigation technique is bunch lengthening by using harmonic cavities. The harmonic cavities can have also beneficial effect increasing the single bunch instability thresholds, but it typically magnifies the transient beam loading

Combined effect of IBS and longitudinal impedance
(NSLS-II example)





1. The bunch becomes longer when both effects are considered
2. The energy spread growth due to IBS somewhat reduces since the bunch gets longer due to the impedance related bunch lengthening
3. Experimentally it was found that the microwave instability threshold is higher with IBS (presumably due to higher energy spread)

1. *A.Blednykh et al., 8th Low Emittance Rings Workshop, Frascati, 2020*
2. *A.Blednykh et al, IPAC2021, pp.4274-4277*

Typical multibunch effects

Source	Beam effects	Cures/Remedies
Longitudinal narrow-band impedance	Longitudinal coupled bunch instabilities. Transient beam loading. Vacuum chamber heating.	Low impedance vacuum chamber design. HOM dampers. Feedback. Synchrotron radiation. Landau damping. Other.
Transverse narrow-band impedance (including RW impedance)	Transverse coupled bunch instabilities	Low impedance vacuum chamber design. HOM dampers. Feedback. Synchrotron radiation. Chromaticity. Nonlinear decoherence. Other.
Ion related effects	Transverse coupled bunch instabilities. Emittance growth.	Better vacuum. Feedback. Bunch train shaping/gaps. Other.
e-Cloud	Beam instabilities. Anomalous pressure rise. Vacuum pipe heating. Tune and synchronous phase spread along bunch train. Other	See the next slide

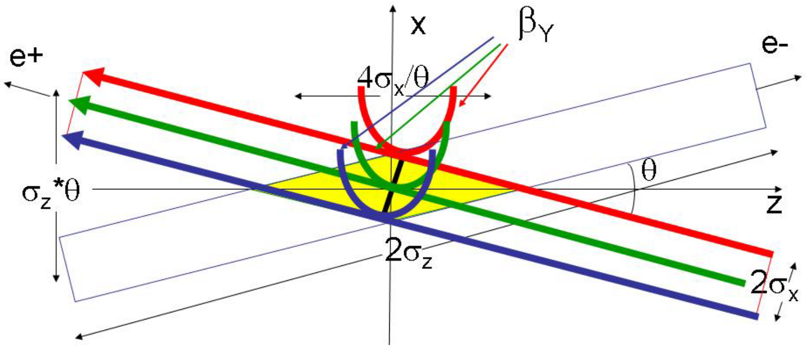
e-cloud mitigation techniques used in the collider positron rings

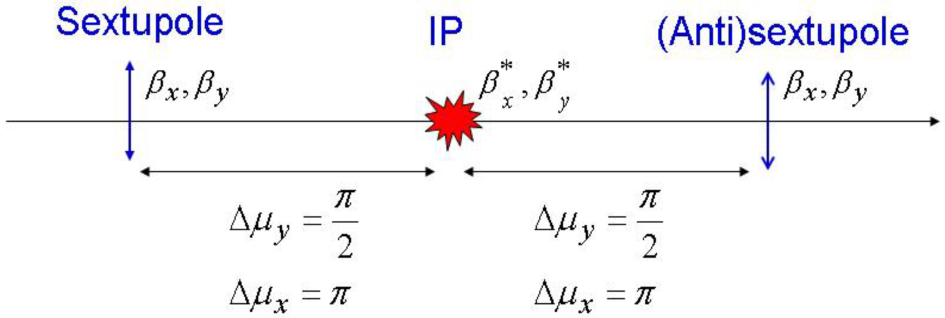
Technique	DAΦNE	PEP-II	KEKB	SuperKEKB
Empty gaps	No	Yes	Yes	Yes
Feedback Systems	Yes	Yes	Yes	Yes
Solenoids	Yes	Yes	Yes	Yes
Coatings	No	Yes	No	Yes
Antechamber	Yes	Yes	No	Yes
Grooved Surface	No	No	No	Yes
Clearing Electrodes	Yes	No	No	Yes
Permanent magnets	No	No	No	Yes

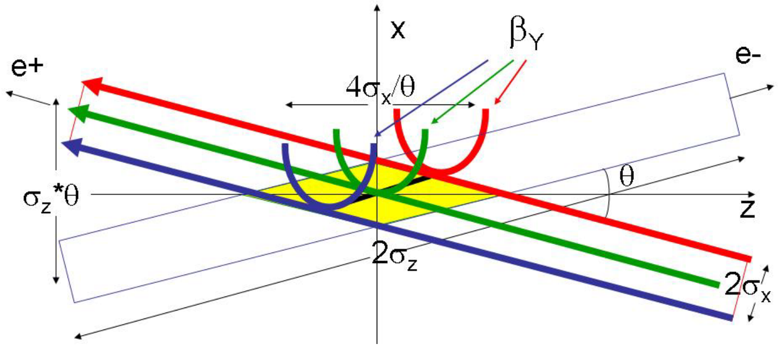
Colliders based on Crab Waist concept

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	100 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

Crab Waist collision scheme







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

b) Small vertical beta function at IP

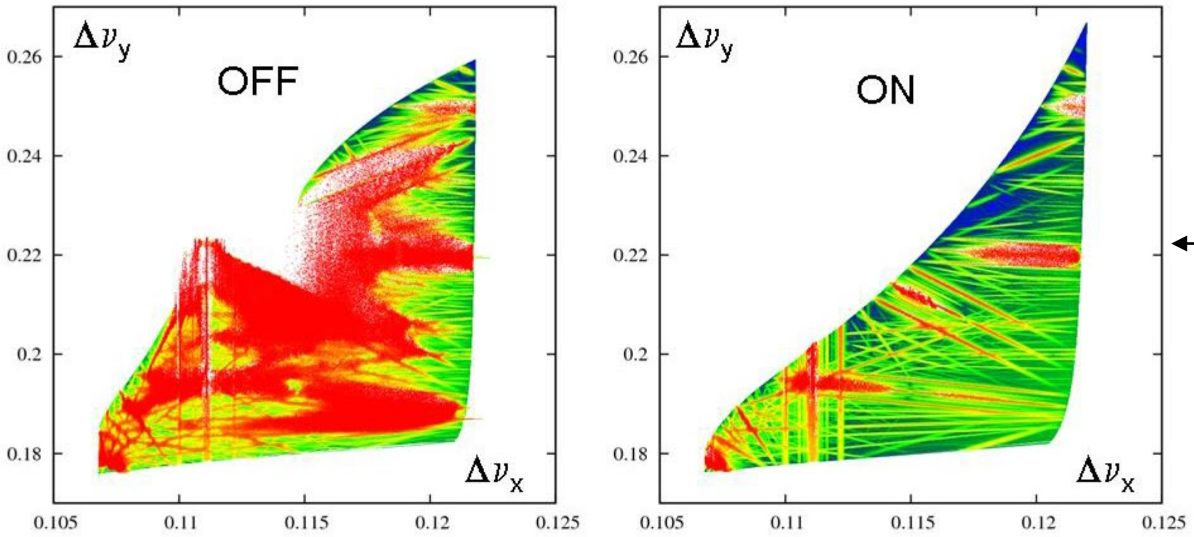
c) Suppression of beam-beam resonances using sextupoles in the interaction region

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*

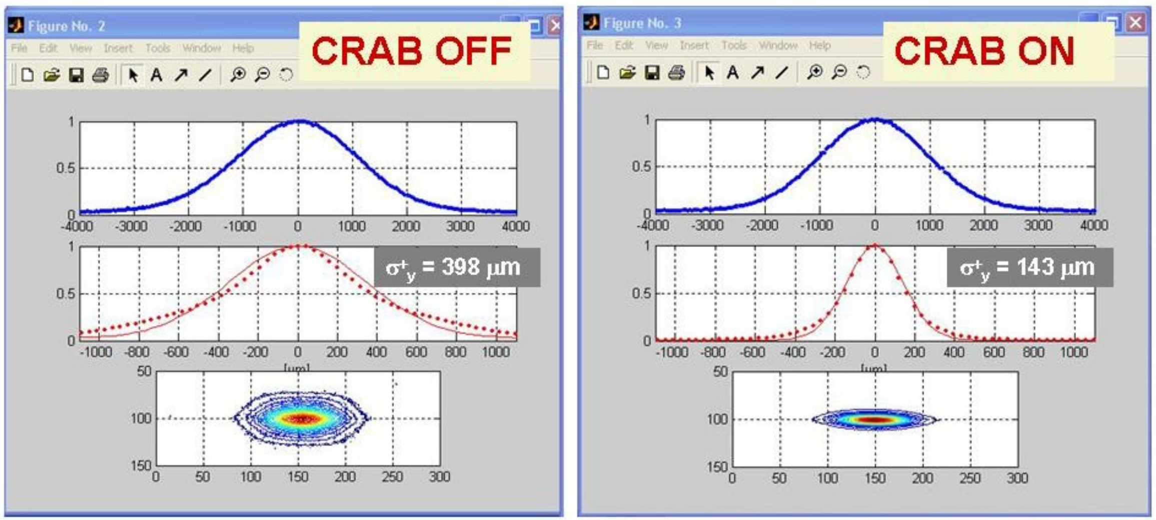
$$\Phi = \frac{\sigma_z}{\sigma_x}\tan\left(\frac{\theta}{2}\right); \quad l_{\rm int} \approx \frac{\sigma_z}{\Phi}; \quad L \cong n_b f_0 \frac{1}{4\pi\gamma\sigma_x\sigma_y}\left[\frac{N^2}{\sqrt{1+\Phi^2}}\right]$$

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

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.

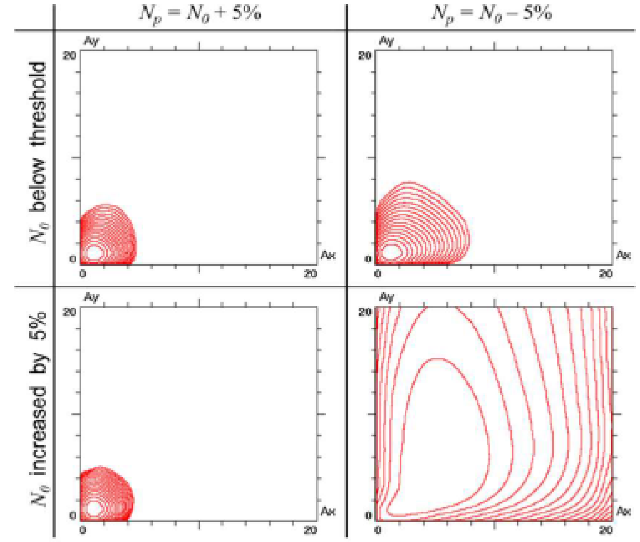
   All this leads to an increase in both emittances of the weak bunch (at the first stage, mainly ε_x^w is affected).

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 ($1/\sqrt{e}$ 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.

3D Flip-Flop

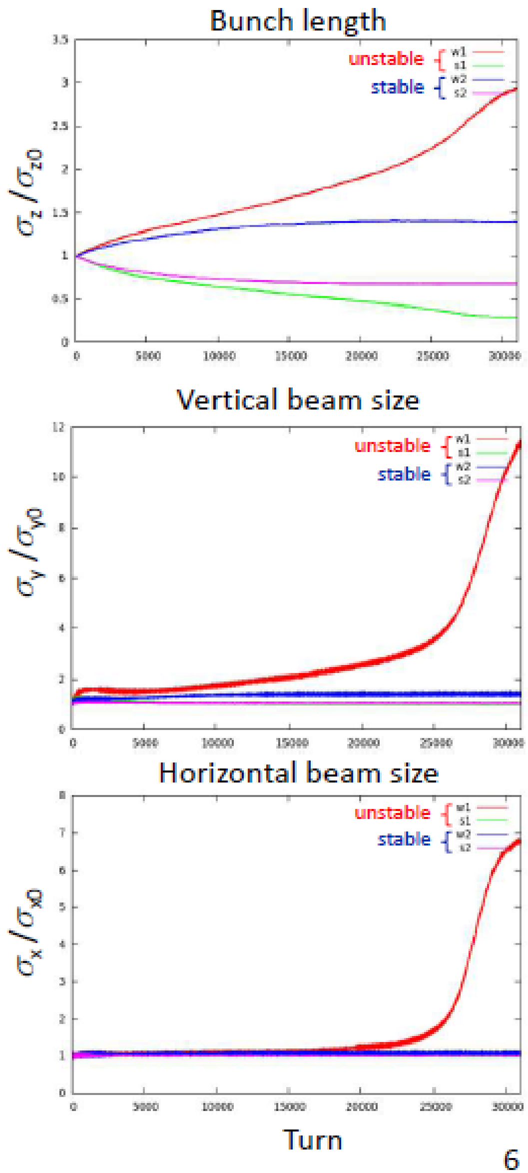
In collision with LPA: $\xi_x \propto \frac{1}{\sigma_z^2}, \quad \xi_y \propto \frac{1}{\sigma_z}$

BS affects σ_z and is affected by asymmetry in N_p and all three beam sizes, $\sigma_{x,y}$ are affected by $\xi_{x,y}$, σ_y also depends on σ_x due to betatron coupling. So, everything is interconnected and can become unstable.

Triggers can be different and we have to take care of many parameters.

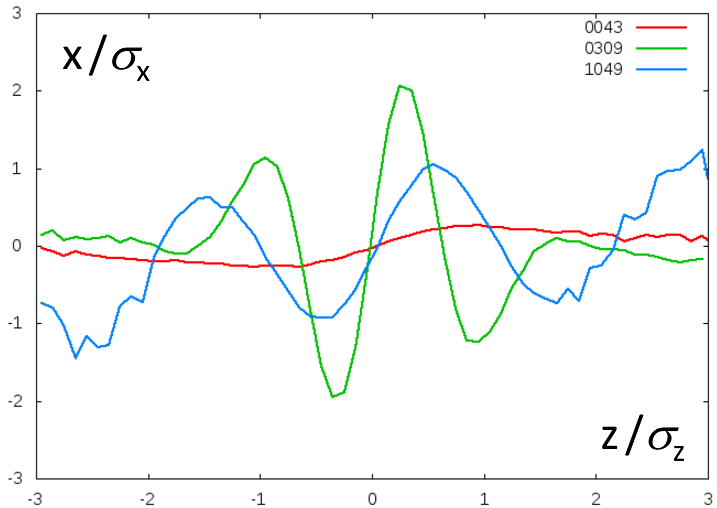
<u>To avoid 3D flip-flop</u>:

- Mitigation of synchro-betatron resonances, satellites of half-integer. This is also very important for coherent beam-beam instability (see the next slides).
- Avoid the vertical blowup: good choice of the working point, strength of crab sextupoles. We need enough room for the footprint.
- Minimize asymmetry in the population of colliding bunches. This sets the requirements for the injector.
- Minimize asymmetry in the vertical beam sizes: keep the same betatron coupling for both rings.

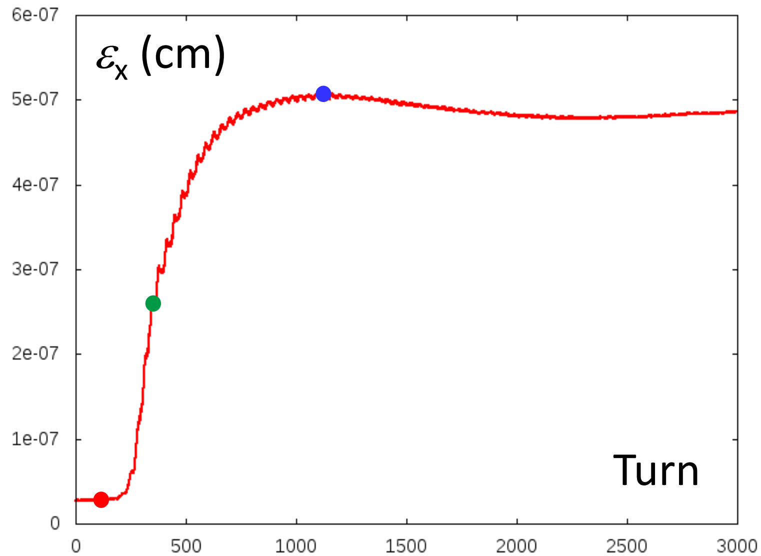


Coherent beam-beam head-tail instability (X-Z instability)

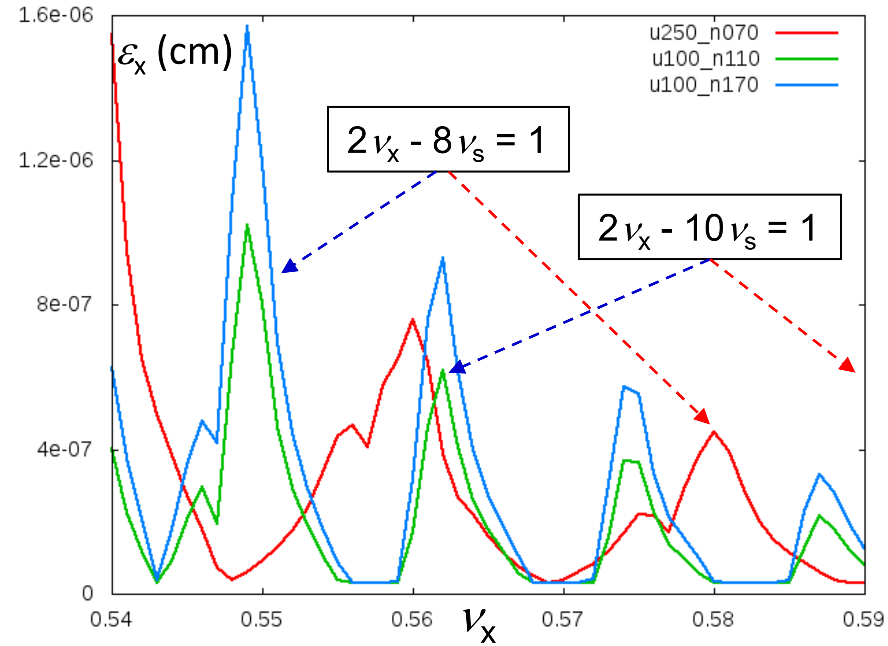
Bunch shape at different turns



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*

Interplay between beam-beam interaction, beamstrahlung and longitudinal impedance

X-Z Instability

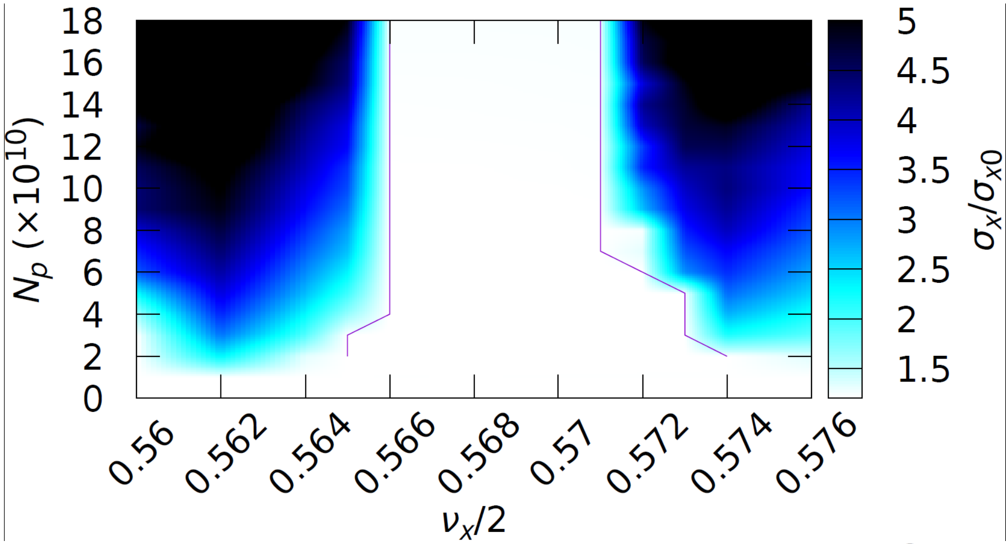
1. Tune shift of stable tune areas due to the impedance related synchrotron frequency reduction
2. Reduction of sizes of the stable tune areas
3. Smaller beam blowup presumably due to the synchrotron frequency spread induced by the impedance

In Stable Areas

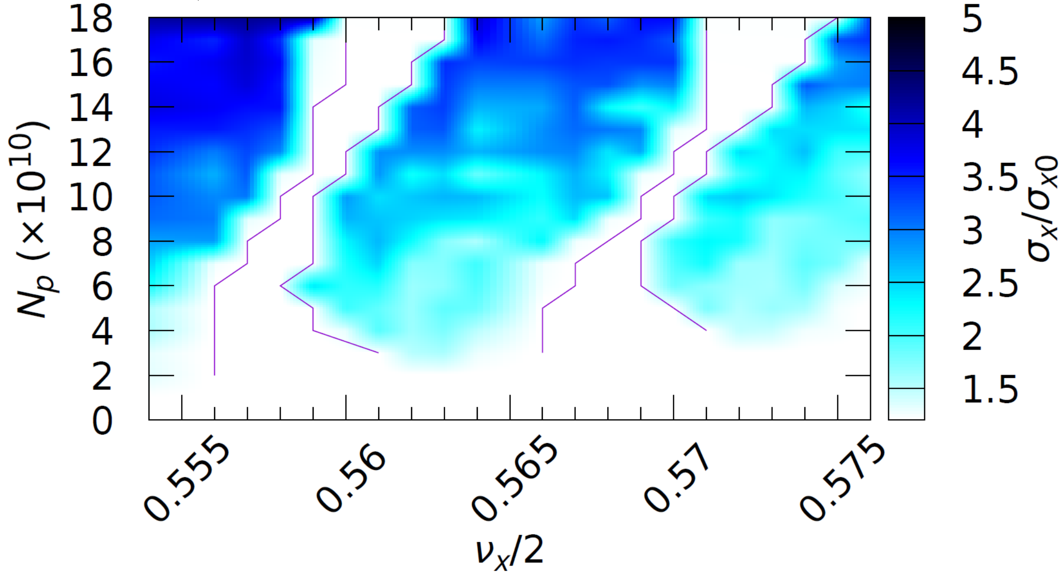
1. Longer bunch length
2. Smaller energy spread than that due to beamstrahlung alone
3. Eventual damping of the microwave instability due to longer bunches and overall higher energy spread

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*

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



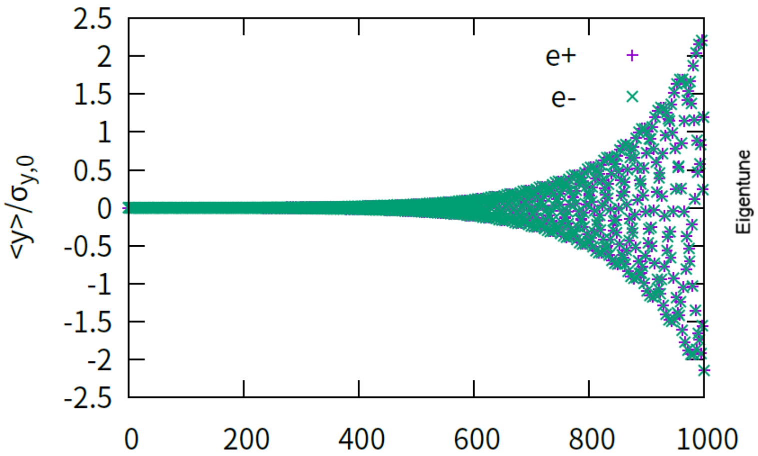
Without longitudinal impedance



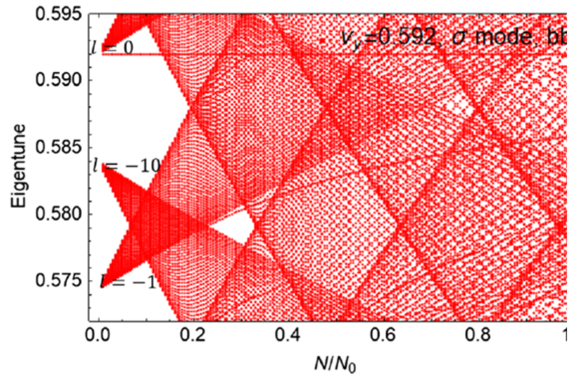
Including longitudinal impedance

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

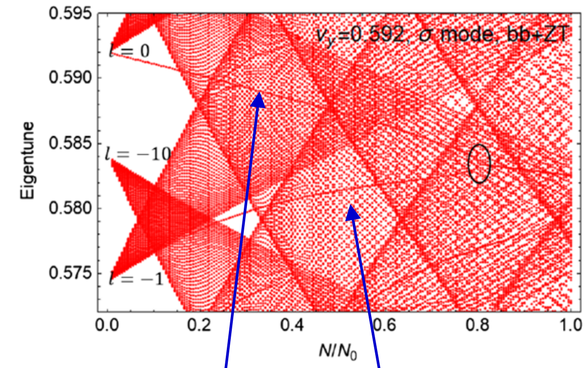
Mode coupling due to beam-beam interaction and the vertical impedance (CEPC example)

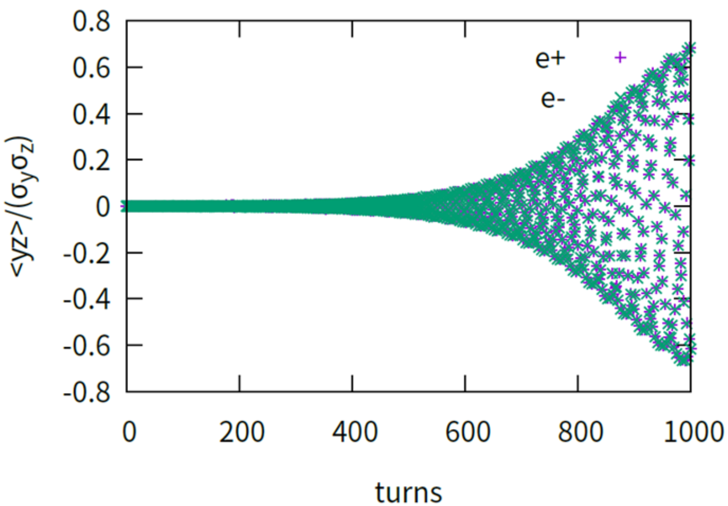


No Zy



Zy included





Observations

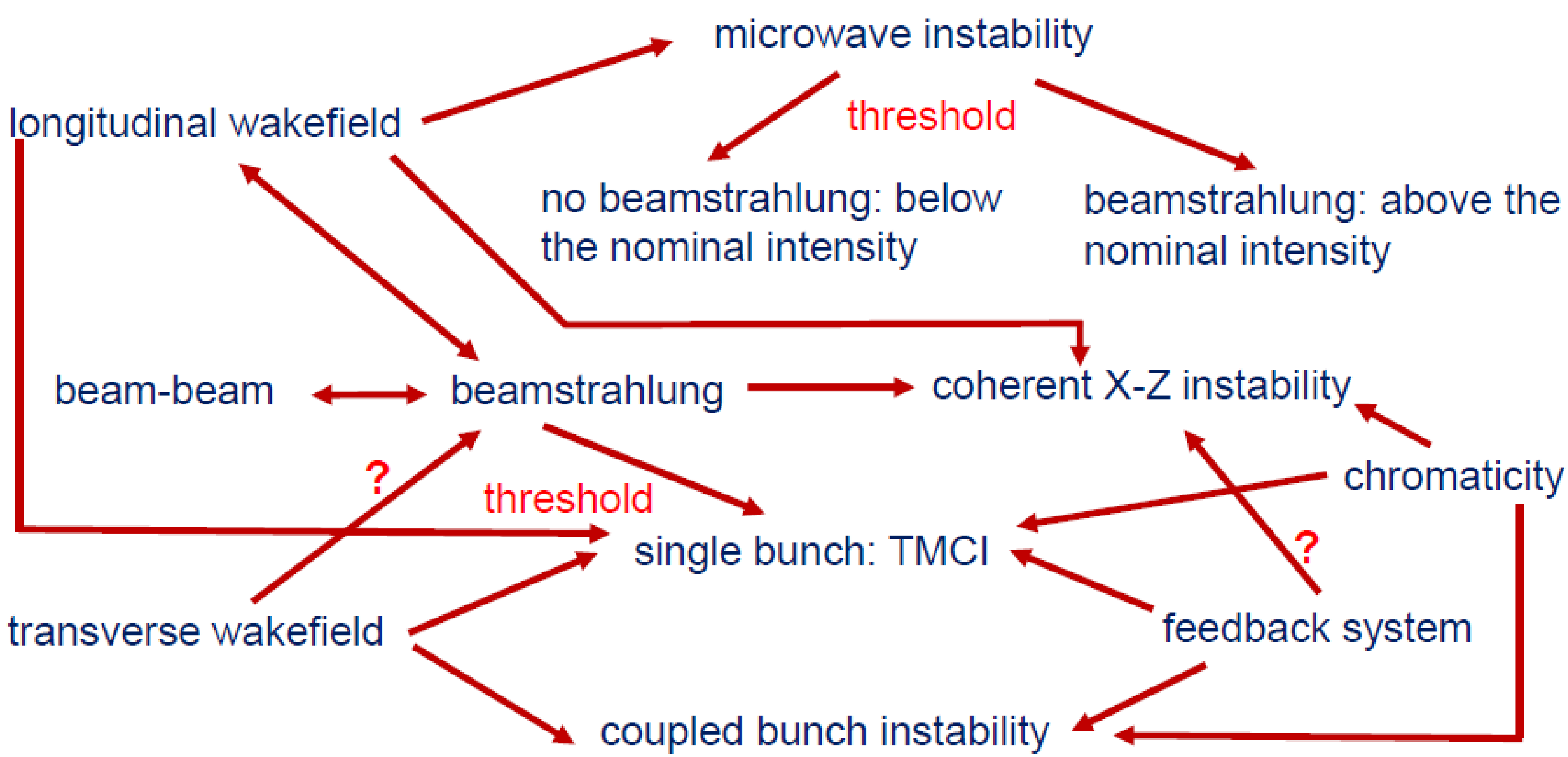
1. Mode 0 decreases due to the ring impedance
2. Mode –1 increases due to beam-beam cross wake impedance
3. The threshold is reduced from 2.1e11 to 1.1e11

Possible mitigation

1. Chromaticity
2. Asymmetric tunes
3. Feedback

Y. Zhang et al., Phys.Rev.Accel.Beams 26 (2023) 6, 064401

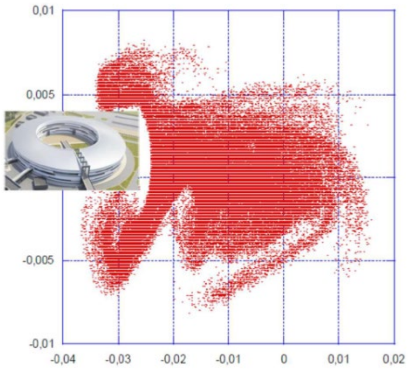
Interplay between different collective effects for FCC-ee (mainly single bunch) that we have analysed so far



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

Slide from my IPAC2010 talk



Concluding comment

Collective effects become more and more important in the modern/future synchrotron light sources and lepton colliders making challenging their parameter choice and achieving the final design goals.

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