Beam-Beam Effects and Parameter Optimization for FCC-ee

Dmitry Shatilov
BINP, Novosibirsk

Acknowledgements:
K. Ohmi, K. Oide, F. Zimmermann

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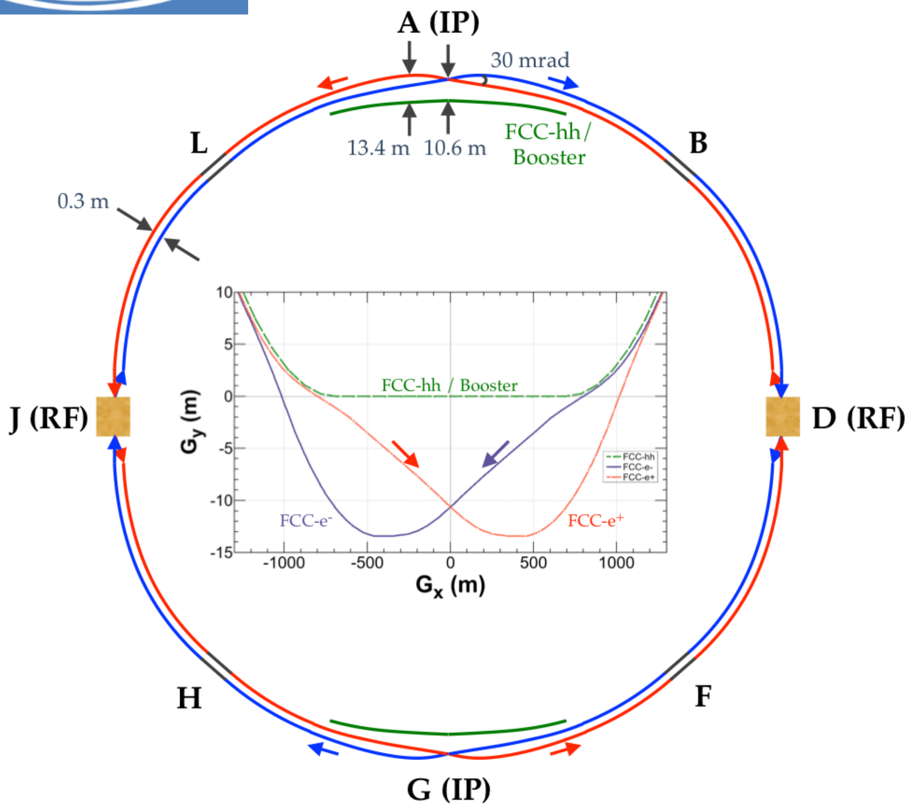
What is FCC-ee?



https://fcc.web.cern.ch/

FCC-ee: Your Questions Answered
https://arxiv.org/abs/1906.02693

FCC-ee is the first stage of the integrated **Future Circular Colliders (FCC)** programme

double ring e^+e^- collider ~100 km perimeter

follows footprint of FCC-hh, except around IPs

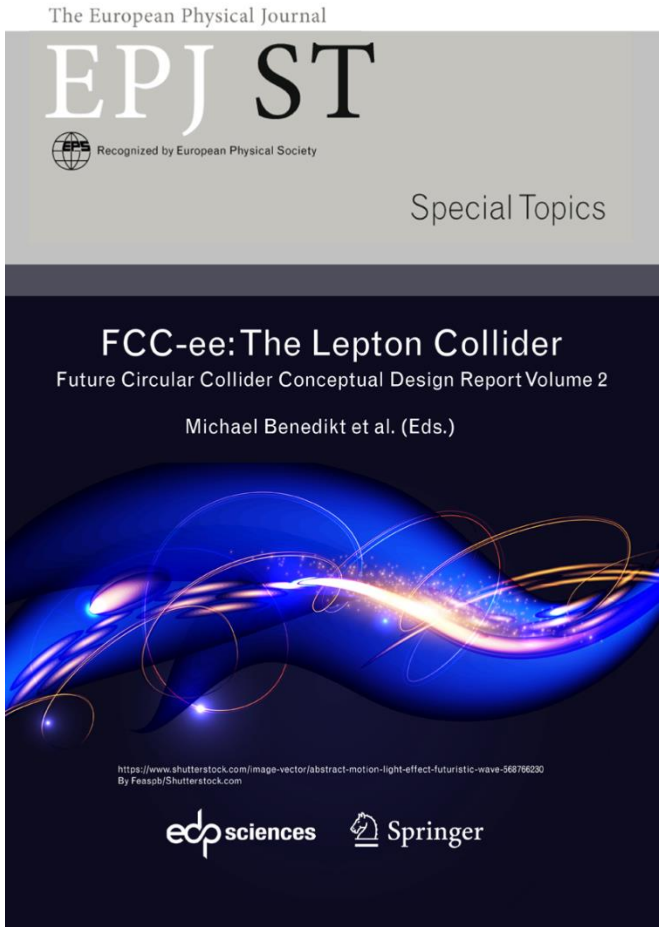
asymmetric IR layout & optics to limit synchrotron radiation towards the detector

presently 2 IPs (alternative layouts with 3 or 4 IPs under study), horizontal crossing angle **30 mrad, crab-waist optics**

beam energies [GeV]**:** 45.6 (**Z**), 80 (**WW**), 120 (**ZH**), 175÷182.5 (**ttbar**)

synchrotron radiation power 50 MW/beam at all beam energies; tapering of arc magnet strengths to match local energy

top-up injection scheme; requires **booster synchrotron in collider tunnel**



1364 contributors from 351 institutes

Introduction

To achieve high luminosity it is necessary to fulfill many conditions:

- Small horizontal emittance: $\varepsilon_x < 1$ nm.
- Small betatron coupling: $\varepsilon_y / \varepsilon_x \sim 0.002$.
- Small beta-functions at the IP: $\beta_y^* \sim 1$ mm.
- Large enough dynamic aperture.
- Large momentum acceptance: > 2% at high energies.

Other important issues:

- RF systems: high beam current & low voltage at Z, low beam current & high voltage at ttbar.
- Collective and multi-bunch instabilities, electron cloud (esp. at low energy).
- Misalignments, lattice errors, corrections.
- MDI, injection, energy calibration, etc, etc.
- And finally, beam-beam effects.

In this presentation, we discuss beam-beam effects assuming that beams with the required parameters can be obtained.

The question is, what limitations does beam-beam impose and how can the other parameters be optimized to increase the luminosity.

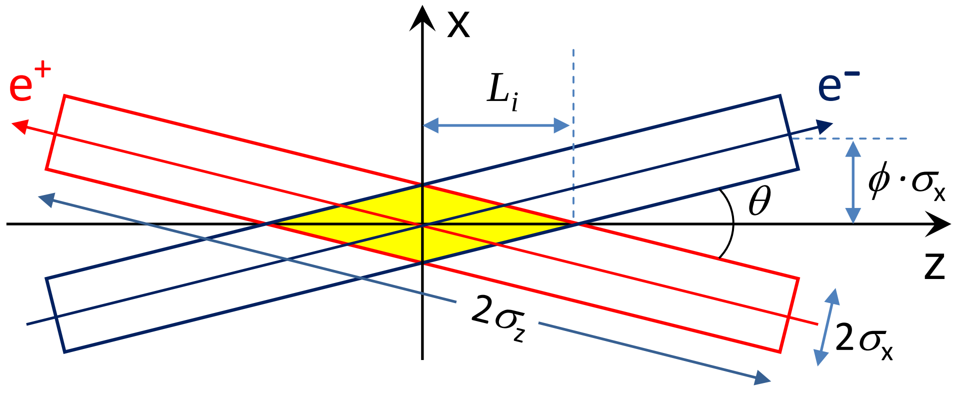
FCC-ee has unique features (large Piwinski angle and beamstrahlung) that significantly affect the beam dynamics.

New types of beam-beam instability were found in simulations, and then mitigated by proper selection of parameters.

Basic Equations

Luminosity: $L = \frac{\gamma}{2er_e} \cdot \frac{I_{tot}\xi_y}{\beta_y^*} \cdot R_H$

Piwinski angle: $\phi = \frac{\sigma_z}{\sigma_x} tg\left(\frac{\theta}{2}\right)$



Collision scheme with large Piwinski angle

Large Piwinski angle (LPA)

- $L_i << \sigma_z$ => small $\beta_y^* << \sigma_z$ without hourglass!
- Crab waist => large $\xi_y \sim 0.2$

P. Raimondi, 2006

Beam-beam parameters for flat beams, $\theta << 1$ and $\phi >> 1$:

$$\xi_x = \frac{N_p r_e}{2\pi\gamma} \cdot \frac{\beta_x^*}{\sigma_x^2(1+\phi^2)} \rightarrow \frac{2r_e}{\pi\gamma\theta^2} \cdot \frac{N_p \beta_x^*}{\sigma_z^2}$$

Proportional to β_x, does not depend on ε_x

Increase in N_p and σ_z in the same proportion: L_i, ξ_y and L remain unchanged, ξ_x drops.

$$\xi_y = \frac{N_p r_e}{2\pi\gamma} \cdot \frac{\beta_y^*}{\sigma_y \sigma_x \sqrt{1+\phi^2}} \rightarrow \frac{r_e}{\pi\gamma\theta} \cdot \frac{N_p}{\sigma_z} \cdot \sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$

Does not depend on β_x, ε_x

Small ε_y is needed to achieve high ξ_y. This implies small betatron coupling and small ε_x.

Main Limitations Associated with Beam-Beam

- Two new phenomena were recently discovered in simulations:

  1) 3D flip-flop (occurs only in the presence of beamstrahlung).
  2) Coherent beam-beam instability.

  Both instabilities are bound with LPA and horizontal synchro-betatron resonances – satellites of half-integer.

  Most strongly manifested at low energies.

- Beamstrahlung leads to an increase in the energy spread (several times at low energies) and creates long non-Gaussian tails (mainly at high energies).

  This requires obtaining a large momentum acceptance (especially at high energies) to ensure the necessary beam lifetime.

- For high luminosity, an allowable asymmetry in the population of colliding bunches should be small.

  This imposes strict requirements on the injector and the scheme of its operation.

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.

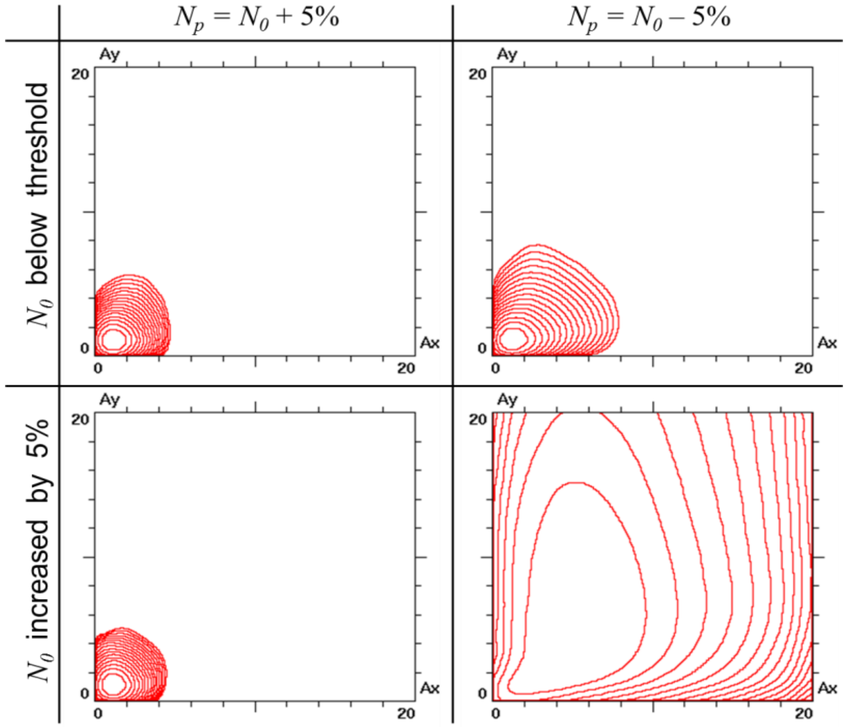
   All this leads to an increase in both emittances of the weak bunch (at the first stage, mainly ε_x^w is affected).

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).

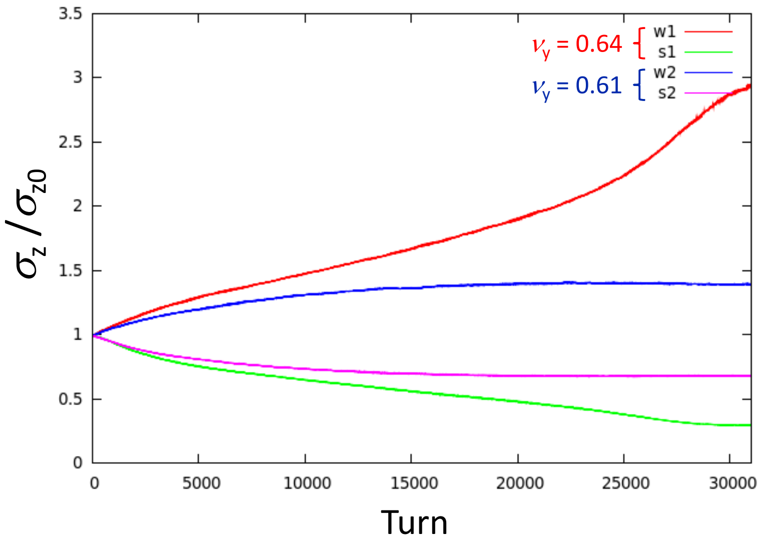


Density contour plots ($\sqrt{e}$ between successive lines) in the space of normalized betatron amplitudes.

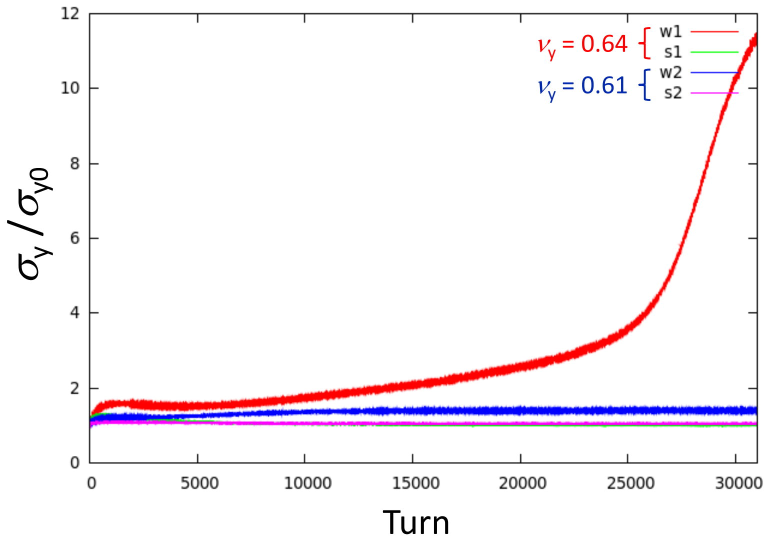
All three beam sizes grow slowly, until the footprint touches strong resonance, then the week bunch blows up.

3D Flip-Flop (continued)

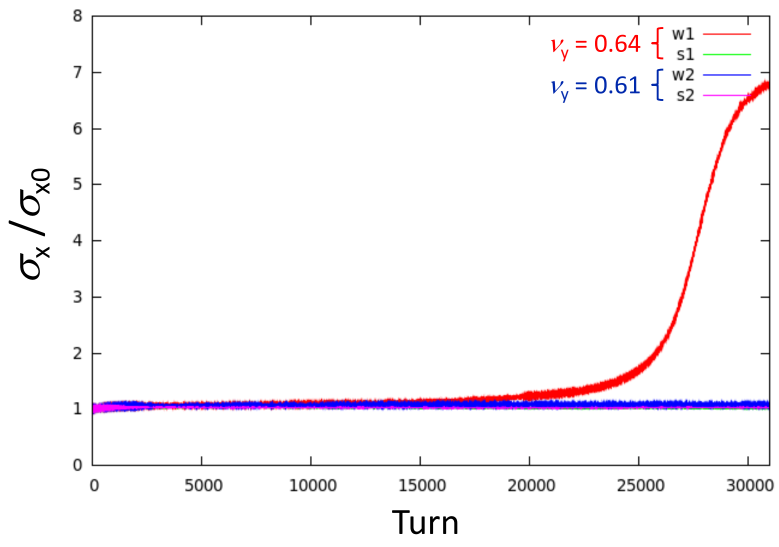
Bunch length



Vertical beam size



Horizontal beam size



There are two possible scenarios for 3D flip-flop:

1) Starts from ε_x^w growth (e.g. synchro-betatron resonances $2\nu_x - k\nu_z = 1$), then ε_y^w increases due to betatron coupling.
2) Starts from ε_y^w growth (e.g. non-optimal ν_y or strength of crab sextupoles). After σ_z^s is sufficiently reduced, and ξ_x^w increased, the resonances $2\nu_x - k\nu_z = 1$ lead to ε_x^w blowup.

In all cases, beamstrahlung plays a key role: σ_z dependence on emittances, and $\xi_{x,y}$ dependence on σ_z .

To avoid 3D flip-flop:

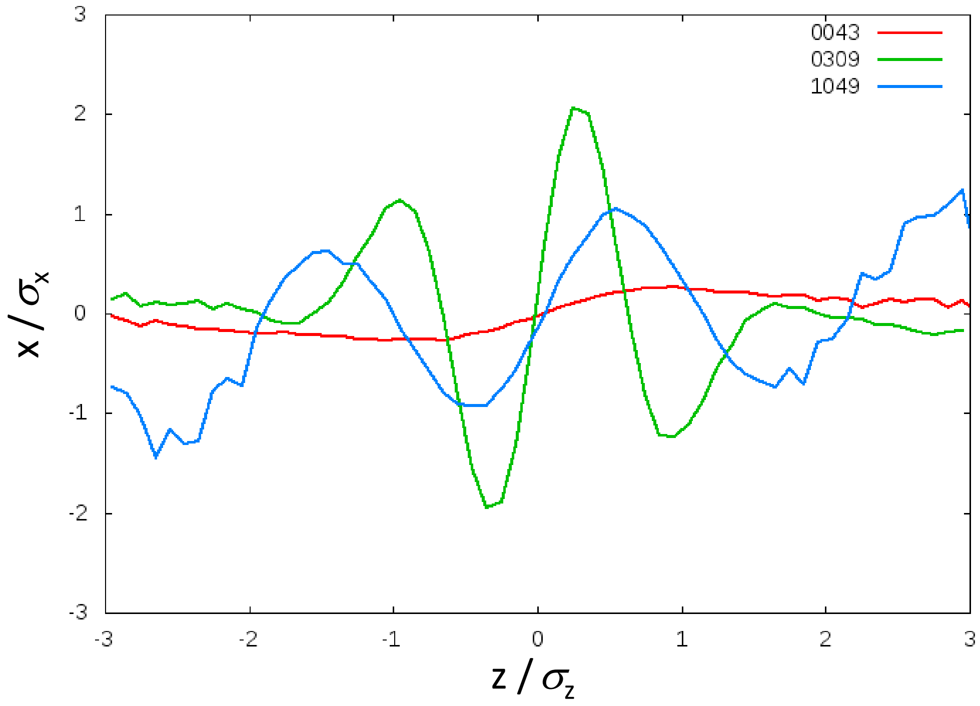
- Mitigation of synchro-betatron resonances, satellites of half-integer. This is also very important for coherent beam-beam instability (see the next slides).
- Avoid the vertical blowup: good choice of the working point, CW strength, etc. We need enough room for the footprint.
- Minimize asymmetry in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

Coherent Beam-Beam Instability

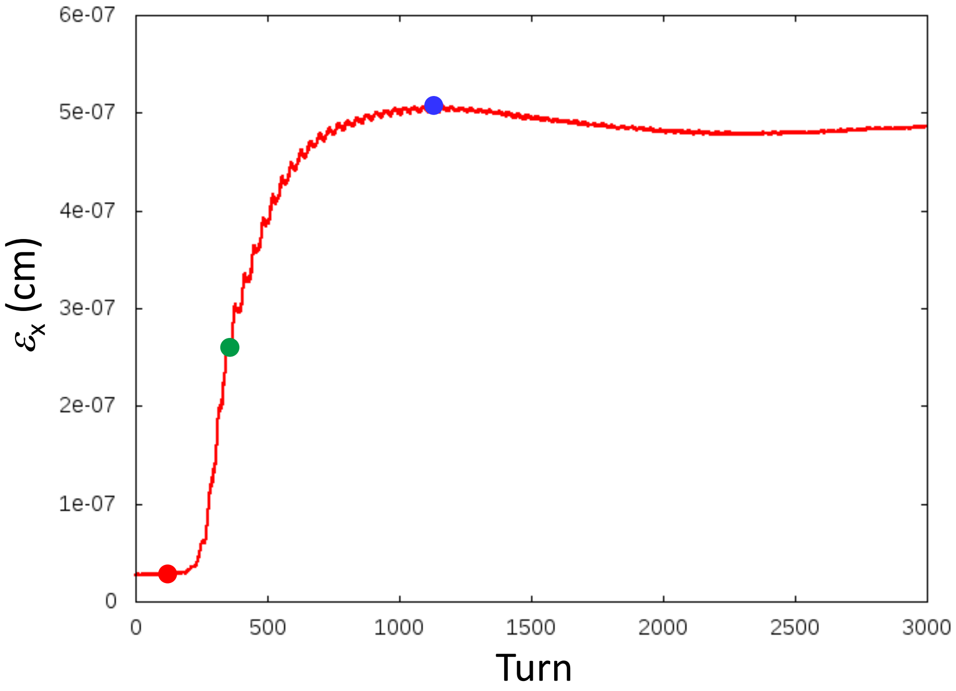
Discovered by K. Ohmi in strong-strong simulations (`BBSS`).
Reproduced in quasi-strong-strong simulations (`Lifetrac`).
Good agreement between the two codes.
Recently it was observed at SuperKEKB (K. Ohmi).

The effect is 2D, ε_x increases 5÷15 times. Then betatron coupling leads to ε_y growth in the same proportion, and luminosity falls several times.

Bunch shape in the horizontal plane at some turns



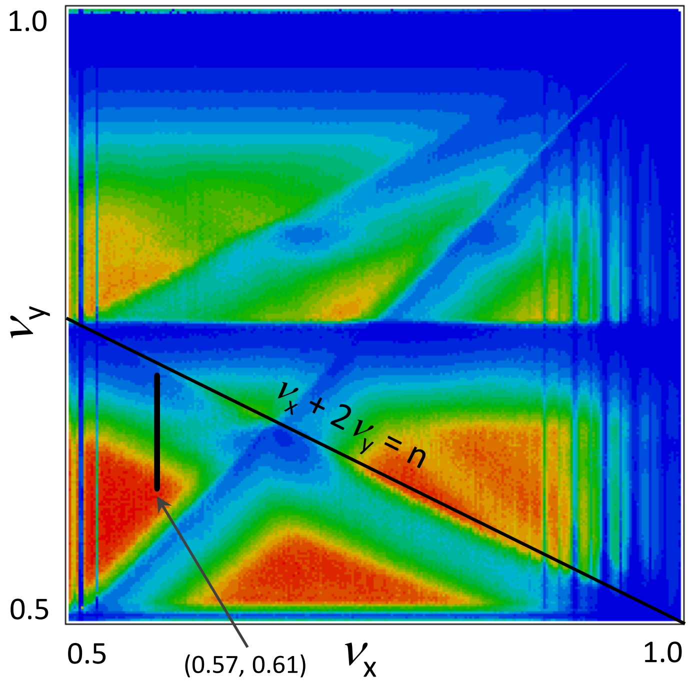
Evolution of the horizontal emittance



This instability cannot be mitigated by feedback. The only solution: find conditions under which it does not arise.

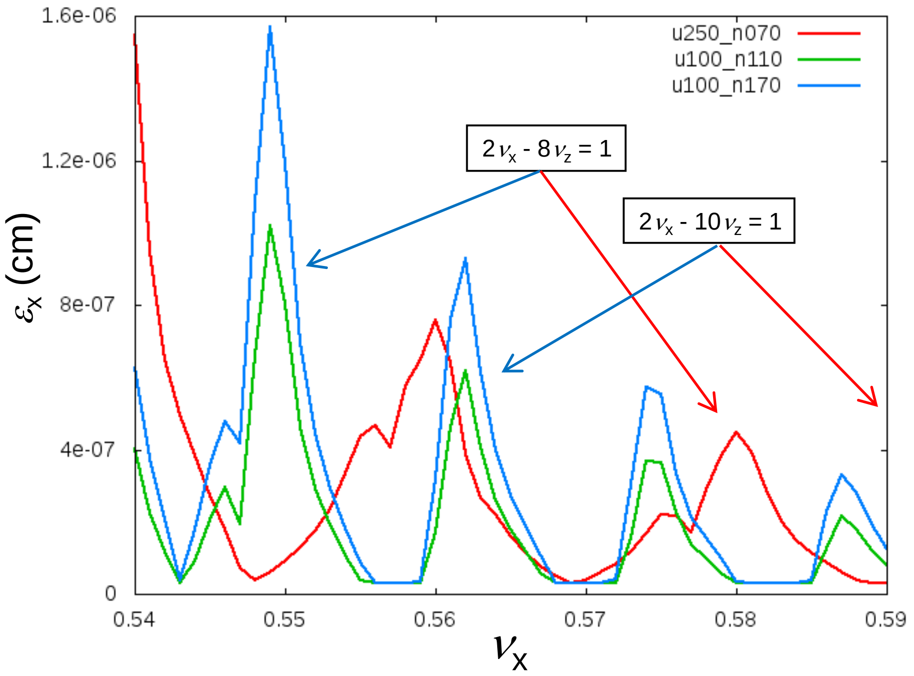
Parameter Optimization at Z (45.6 GeV)

Luminosity vs. betatron tunes, simplified model, weak-strong simulations. Colors from zero (blue) to 2.3·10^{36} cm^{-2}c^{-1} (red).



The range of permissible ν_x for large ξ_y is bounded on the right by 0.57÷0.58.

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



The distance between resonances is ν_z. The width depends on ξ_x and the order of resonances.
We need to reduce ξ_x / ν_z ratio and increase the order of resonances near the working point.

- Increase the momentum compaction factor: ν_z and σ_z grow, ξ_x decreases.

  This is done by changing FODO arc cell, which also leads to an increase in ε_x. However, ε_y = 1 pm can be achieved. Besides, the threshold of microwave instability is raised.

- Decrease β_x^* (and thus ξ_x).

  This leads to a decrease in the energy acceptance. Eventually it can be reduced to 15 cm.

- Reduce the RF voltage.

  This decreases ν_z and ξ_x in the same proportion, but increases the order of resonances near the w.p.

- Neat choice of ν_x between synchro-betatron resonances.

Bootstrapping

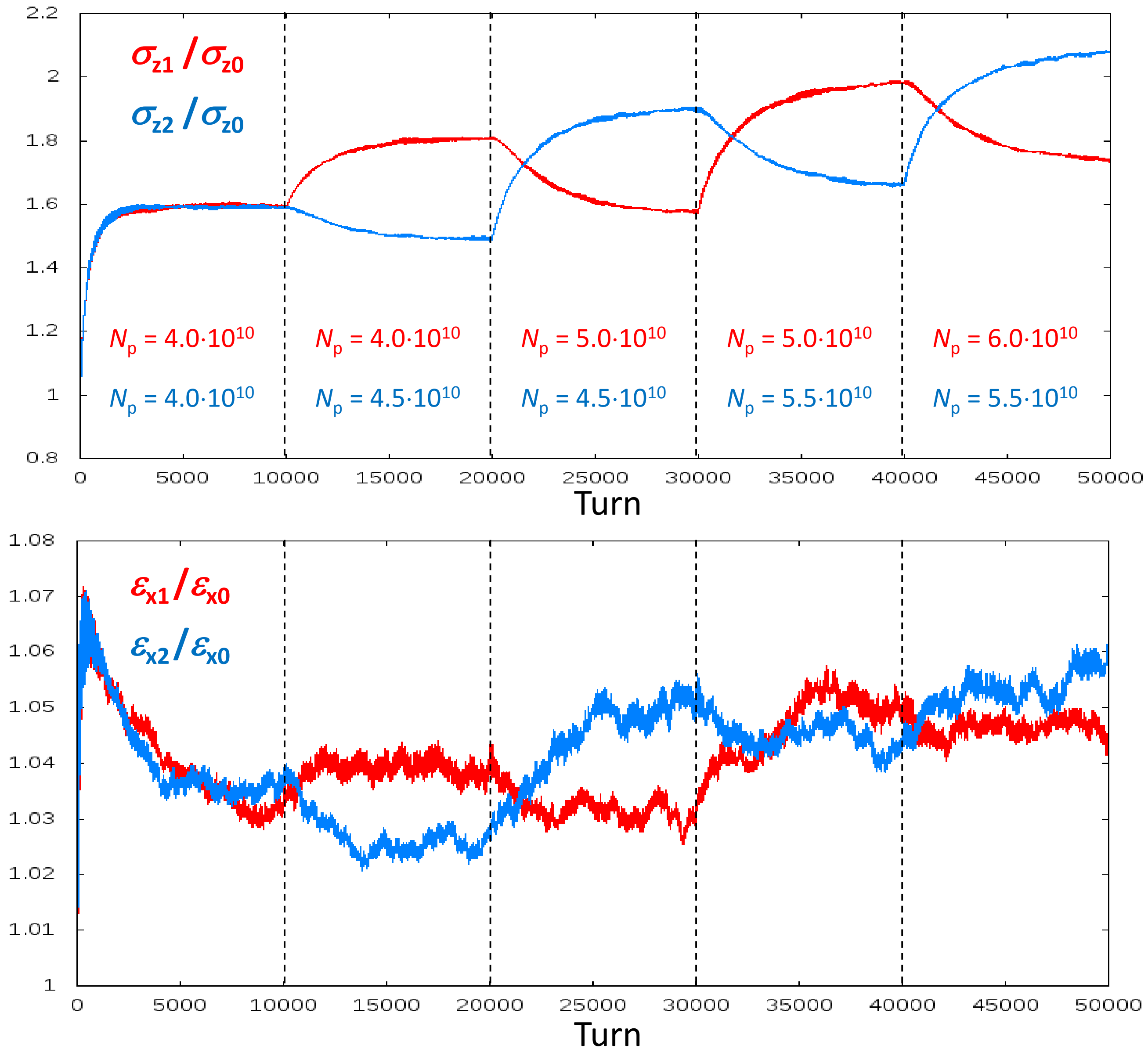
- When the energy spread is defined mainly by beamstrahlung, the dependence on N_p (bunch population) becomes:

$$\xi_x = \text{const}, \quad \sigma_E\,,\ \sigma_z\,,\ \xi_y\,,\ L \propto \sqrt{N_p}$$

- With the nominal N_p = 1.7 ·10^{11} required for high luminosity, σ_z increases ~3.5 times.
- If we bring into collision such bunches with the "initial" σ_z (energy spread created only by SR), the beam-beam parameters will be far above the limits.

⇩

- The beams will be blown up and killed on the transverse aperture, before they are stabilized by the beamstrahlung.
- To avoid this, we have to gradually increase the bunch population during collision, so we come to *bootstrapping*.



Parameter Optimization at 80 and 120 GeV

WW (80 GeV)

- In order to obtain a resonant depolarization, we need $\nu_z \geq 0.05$ => momentum compaction factor should be large – same as at low energy. The RF voltage also is determined by ν_z => U_{RF} increased to 750 MV.
- Another limitation is the HOM power. This sets the upper limit on N_p which corresponds to ~2000 bunches.
- Perform steps 3 – 6 as described below (except that β_x^* should be 20 cm).

ZH (120 GeV)

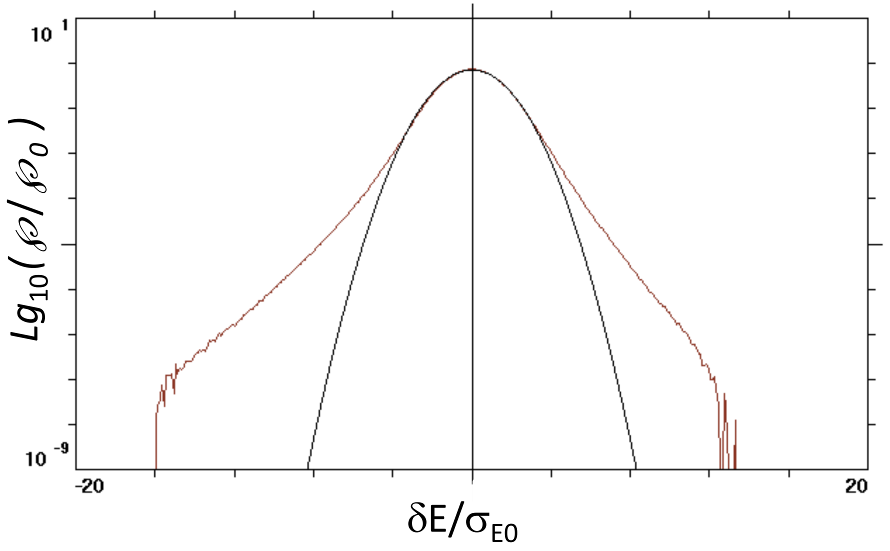
Here we do not care about polarization and select the parameters as follows:

1) Lattice with small momentum compaction and small emittances.
2) U_{RF} is made "small", but so that RF acceptance still exceeds the energy acceptance, and this determines ν_z.
3) Then ν_x is selected in the range of 0.56÷0.58, between synchro-betatron resonances.
4) Look for β_x^* at which the coherent instabilities disappear; in our case 30 cm is enough.
5) With the given ε_x and β_x^*, the length of interaction area defines the optimal β_y^*.
6) The lattice optimization for the selected $\beta_{x,y}^*$, to maximize the dynamic aperture and energy acceptance.
7) The bunch population is scanned, while the restriction is the lifetime. Thus we determine the maximum N_p and luminosity.

Single high-energy beamstrahlung photons become important and they impose a limit on N_p.

Parameter Optimization at ttbar (175÷182.5 GeV)

Energy distribution in the logarithmic scale, black line: Gauss with $\sigma_E = 1.3\ \sigma_{E0}$



Luminosity is limited by the beamstrahlung lifetime:

$$\tau_{bs} \propto \exp\left(\frac{2\alpha\eta\rho}{3r_e\gamma^2}\right)\cdot\frac{\rho\sqrt{\eta\rho}}{L_i\cdot\gamma^2}$$

α – fine structure constant

η – energy acceptance

ρ – bending radius of a particle's trajectory at the IP

The major tool for increasing the lifetime is making ρ larger. For flat beams, ρ is inversely proportional to the surface charge density:

$$\frac{1}{\rho} \propto \frac{N_p}{\gamma\sigma_x\sigma_z} \propto \frac{\xi_y}{L_i}\sqrt{\frac{\varepsilon_y}{\beta_y^*}} \propto L\sqrt{\frac{\varepsilon_y}{\beta_y^*}}$$

(assuming $L_i \approx \beta_y^*$)

Length of interaction area

Luminosity

- To reduce beamstrahlung, σ_x should be increased. As a result, L_i grows and we have to increase β_y^* as well.
- We also need to keep ε_y small. Thus σ_x is controlled by β_x^* which was increased to 100 cm.
- At such high energies, the coherent instabilities are suppressed by very strong damping and not so large Piwinski angle, so we can allow increase in β_x^*.
- Momentum acceptance is made asymmetrical to match the actual distribution with beamstrahlung.

Parameter Optimization Summary

"Low" energies (Z and WW)

- 3D flip-flop and coherent X-Z instability are dangerous => $\alpha_p\uparrow$ $U_{RF}\downarrow$ $\beta_x^*\downarrow$
- Resonant depolarization requires large synchrotron tune => $\alpha_p\uparrow$ $U_{RF}\uparrow$
- Small emittances are required for high luminosity => $\alpha_p\downarrow$
- Dynamic aperture, momentum acceptance => $\beta_x^*\uparrow$

There are contradictions between the requirements. The optimum was found taking into account the possibility of changing various parameters.

"High" energy (ttbar)

- Coherent instabilities are suppressed by strong damping
- There is no polarization
- Small emittances are required for high luminosity

(the three items above) => $\alpha_p\downarrow$

- Lifetime limitation due to beamstrahlung => $\beta_x^*\uparrow$

"Medium" energy (ZH)

- Coherent instabilities are weaker, but still exist => $\beta_x^*\downarrow$
- There is no polarization, small emittances are better => $\alpha_p\downarrow$

U_{RF} is determined by the energy loss per turn. There is no much freedom for optimization.

Optimal β_y^* should be comparable with L_i => increase with energy.

Basic FCC-ee Parameters from CDR

parameter	Z	W	H (ZH)	ttbar	
beam energy [GeV]	45.6	80	120	175	182.5
arc cell optics	60 / 60	60 / 60	90 / 90	90 / 90	
momentum compaction [10^{-5}]	1.48	1.48	0.73	0.73	
horizontal emittance [nm]	0.27	0.84	0.63	1.34	1.46
vertical emittance [pm]	1.0	1.7	1.3	2.7	2.9
horizontal beta* [m]	0.15	0.2	0.3	1	
vertical beta* [mm]	0.8	1	1	1.6	
length of interaction area [mm]	0.42	0.85	0.9	1.8	1.8
RF frequency [MHz]	400	400	400	400 + 800	
tunes, half-ring (x, y, s)	(0.57, 0.61, 0.0125)	(0.562, 0.60, 0.0253)	(0.565, 0.60, 0.0179)	(0.554, 0.59, 0.0409)	(0.554, 0.59, 0.0436)
longitudinal damping time [ms]	415	77	23	7.5	6.6
SR energy loss / turn [GeV]	0.036	0.34	1.72	7.8	9.2
total RF voltage [GV]	0.10	0.75	2.0	4.0 + 5.4 = 9.4	4.0 + 6.9 = 10.9
energy acceptance [%]	±1.3	±1.3	±1.7	+2.4 / -2.8	+2.4 / -2.8
energy spread (SR / BS) [%]	0.038 / 0.132	0.066 / 0.131	0.099 / 0.165	0.144 / 0.186	0.150 / 0.192
bunch length (SR / BS) [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)	8.2 / 28.5	3.5 / 7.0	3.4 / 5.8	0.8 / 1.1	0.8 / 1.0
crab sextupoles [%]	97	87	80	40	40
bunch intensity [10^{11}]	1.7	1.5	1.8	2.2	2.3
number of bunches / beam	16640	2000	328	59	48
beam current [mA]	1390	147	29	6.4	5.4
beam-beam parameter (x / y)	0.004 / 0.133	0.010 / 0.113	0.016 / 0.118	0.097 / 0.128	0.099 / 0.126
allowable asymmetry [%]	±5	±3	±3	±3	±3
Luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	**230**	**28**	**8.5**	**1.8**	**1.55**

Summary

- The main factors limiting the FCC-ee luminosity at high and low energies were recognized and understood. Mitigation techniques have been found.
- The parameters have been optimized at each energy separately, taking into account various requirements and limitations.
- The injection scheme requirements have been developed.