Beam-Beam Effects at High Energy e+e- Colliders

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eeFACT2018, Hong Kong
24 – 27 September 2018

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Introduction

- One of the main requirements for future colliders is high luminosity. If the energy per beam does not exceed 200 GeV, the optimal choice will be a circular collider with “crab waist” collision scheme.

- To achieve maximum luminosity, the beams should have a very high density at the IP. For this reason, radiation in the field of a counter bunch (BS – beamstrahlung) becomes an appreciable factor affecting the dynamics of particles.

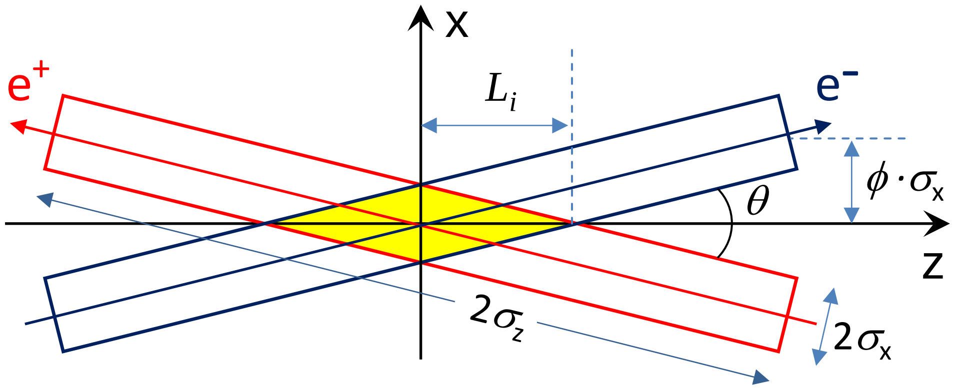
- In the simulations for FCC-ee, new phenomena were discovered: 3D flip-flop and coherent X-Z instability. The first is directly related to BS. The second can manifest itself at low energy (where BS is negligible), but at high energies BS substantially changes the picture.

- In the example of FCC-ee, we consider the features of beam-beam interaction at high-energy crab waist colliders, and optimization of parameters for high luminosity.

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, θ << 1 and ϕ >> 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

- 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.

- Two new phenomena were recently discovered in simulations:

  1) 3D flip-flop (occurs only in the presence of beamstrahlung, when $\sigma_z >> \sigma_{z0}$)
  2) Coherent X-Z instability

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

  Most strongly manifested at low energies.

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

  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.

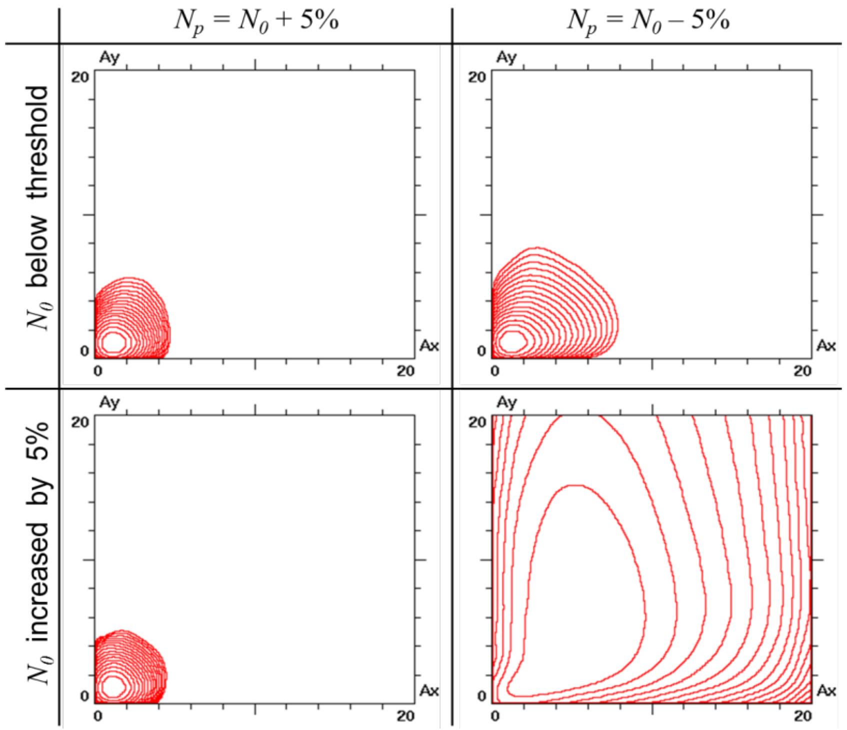
   All this leads to an increase in both emittances of the weak bunch (at the first stage, mainly ε_x^w is affected).

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).



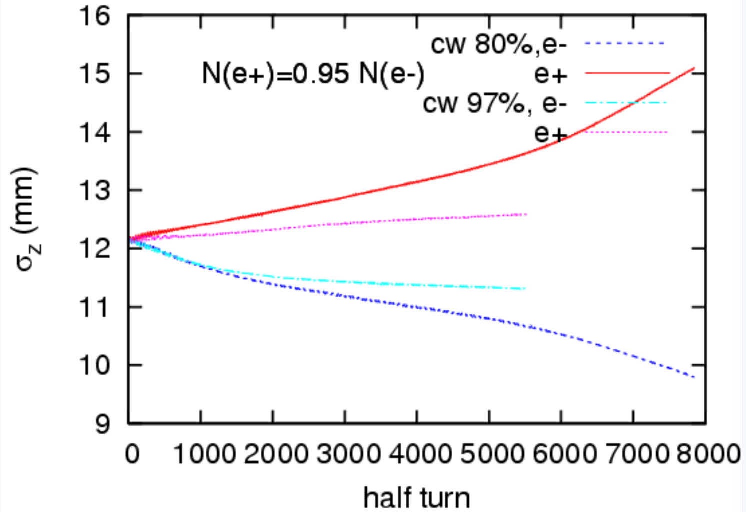
Density contour plots ($\sqrt{e}$ between successive lines) in the space of normalized betatron amplitudes.

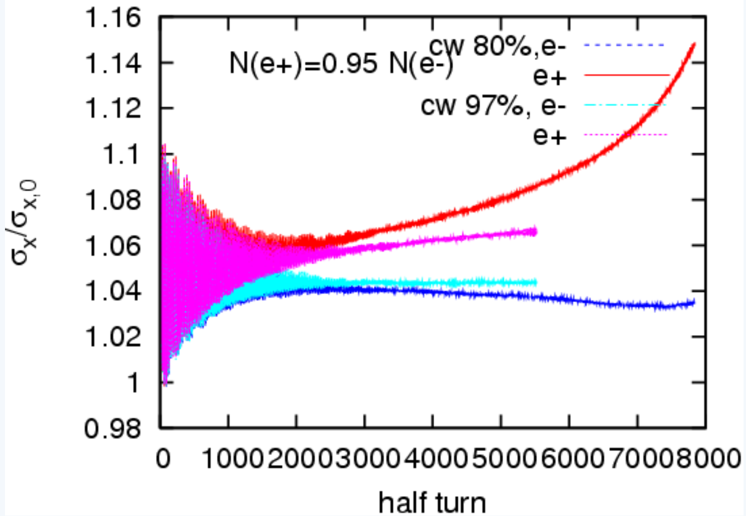
All three beam sizes grow slowly, until the footprint touches strong resonance, then the "weak" bunch blows up.

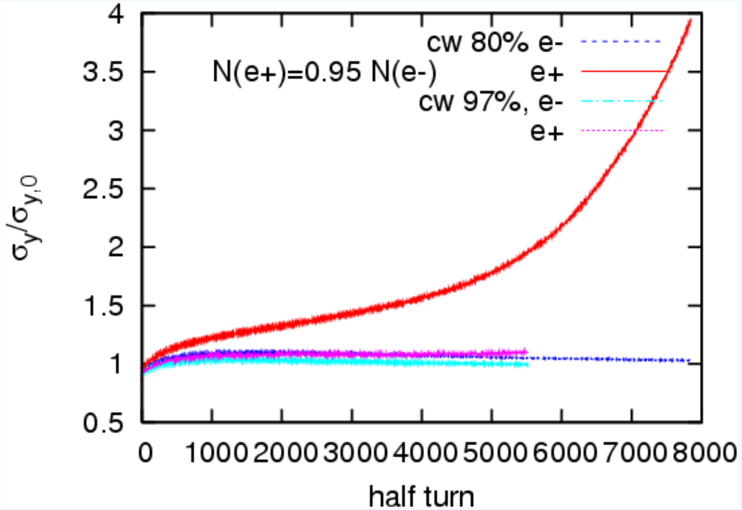
3D Flip-Flop, Another Example

Crab waist 80% and 97% (FCC-ee at Z)

K. Ohmi, Jan. 2018







In this model there is no explicit betatron coupling, but the strength of CW sextupoles (80% of the “nominal”) is not optimal.

⇒ The beam-beam parameter ξ_y becomes too large for imperfect CW, amplifying the vertical blowup for the “weak” bunch.

⇒ Asymmetry in the vertical beam sizes enhances the asymmetry in the bunch lengths (due to BS).

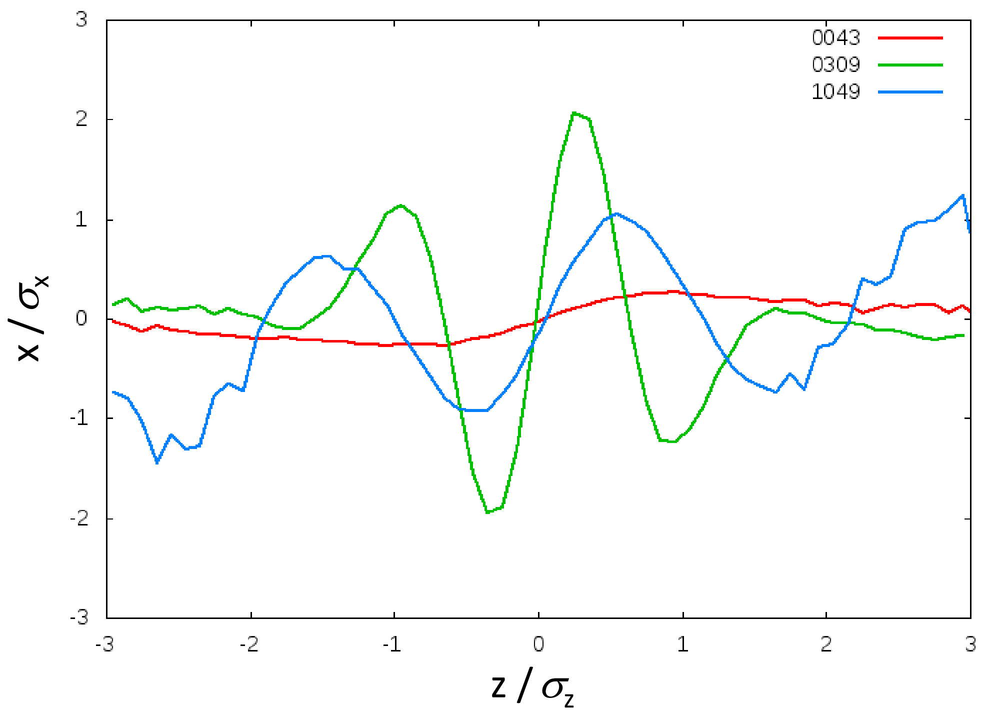
⇒ 3D Flip-flop

Coherent X-Z Instability

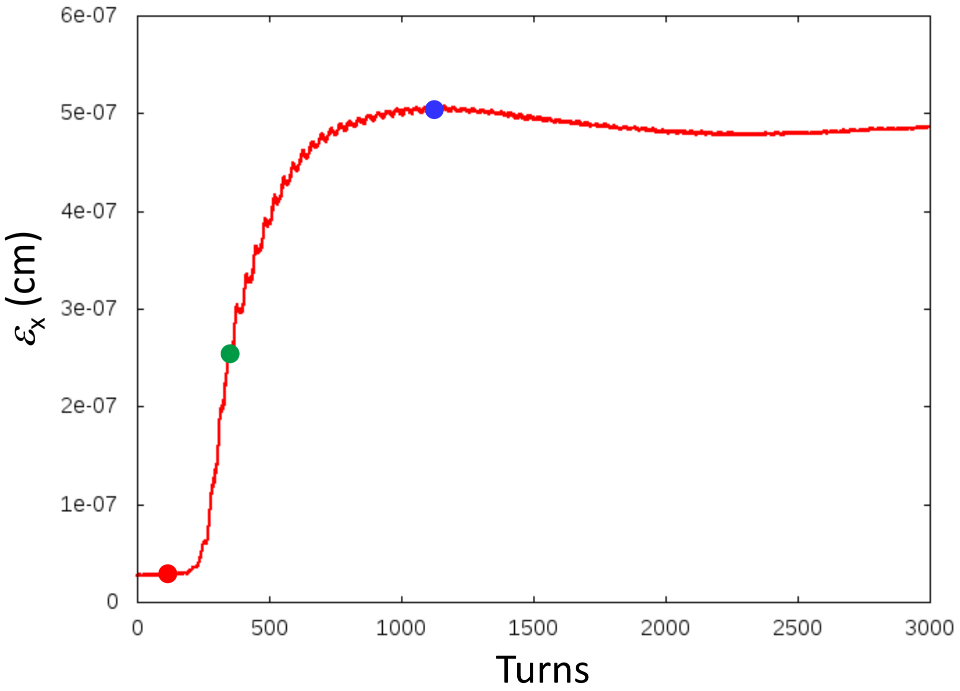
Discovered by K. Ohmi in strong-strong simulations (BBSS).
Reproduced in quasi-strong-strong simulations (Lifetrac).
Good agreement between the two codes.

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



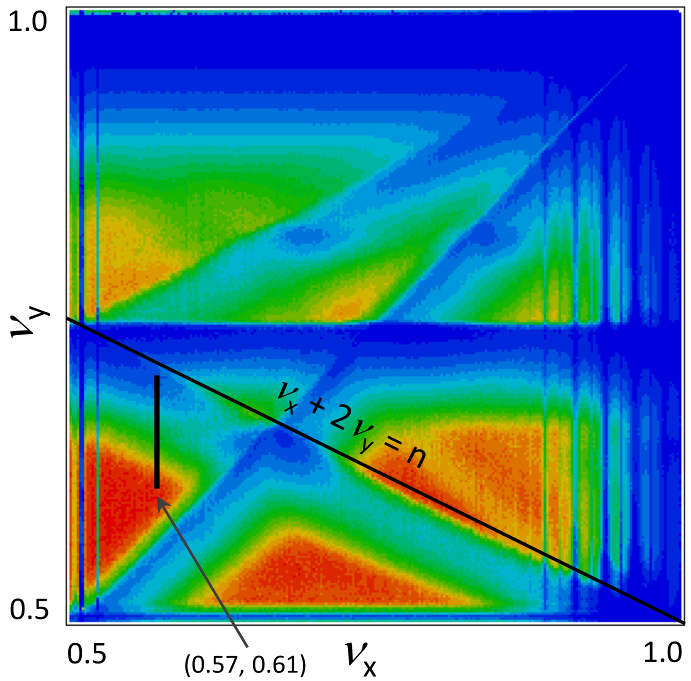
Evolution of the horizontal emittance



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

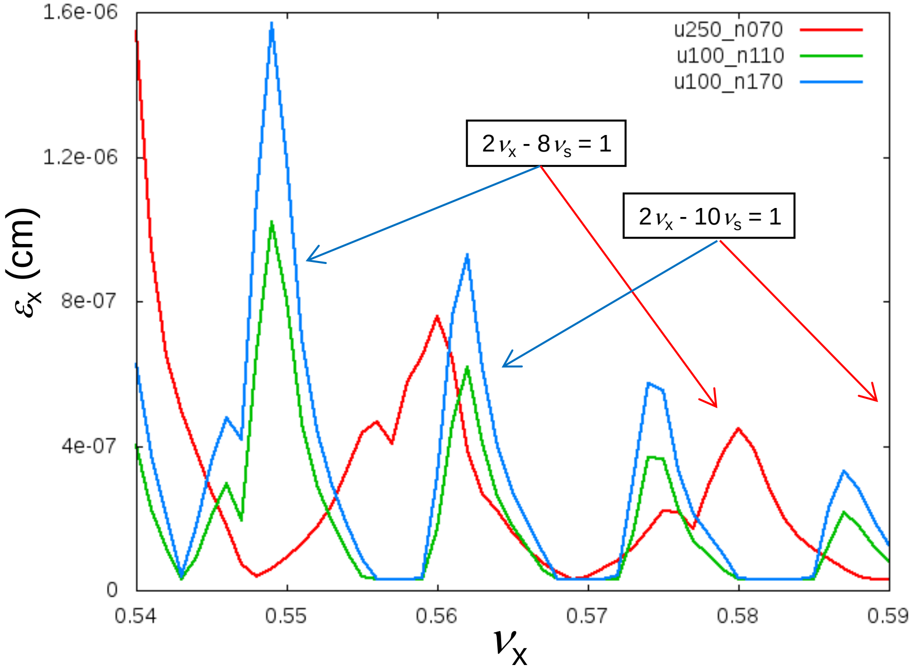
FCC-ee at Z (45.6 GeV)

Luminosity vs. betatron tunes, simplified model, weak-strong simulations. Colors from zero (blue) to $2.3\cdot10^{36}$ 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_s. Quasi-strong-strong simulations. U_{RF} = 250 MV (red) and 100 MV (green, blue).



The distance between resonances is ν_s. The width depends on ξ_x and the order of resonances.

We need to reduce ξ_x / ν_s ratio and increase the order of resonances near the working point.

- Decrease β_x^* (and thus ξ_x).

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

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

  This is done by changing FODO arc cell (K. Oide), 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.

- Reduce the RF voltage.

  This decreases ν_s 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

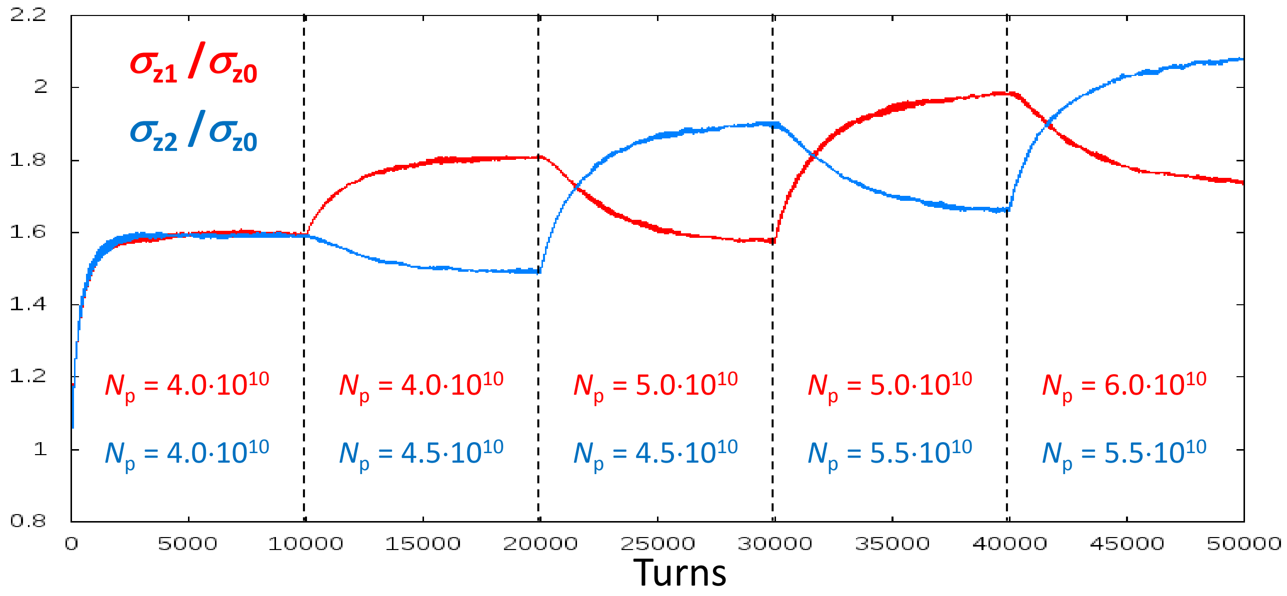
- When the energy spread is defined mainly by beamstrahlung, the dependence on N_p (bunch population) becomes:

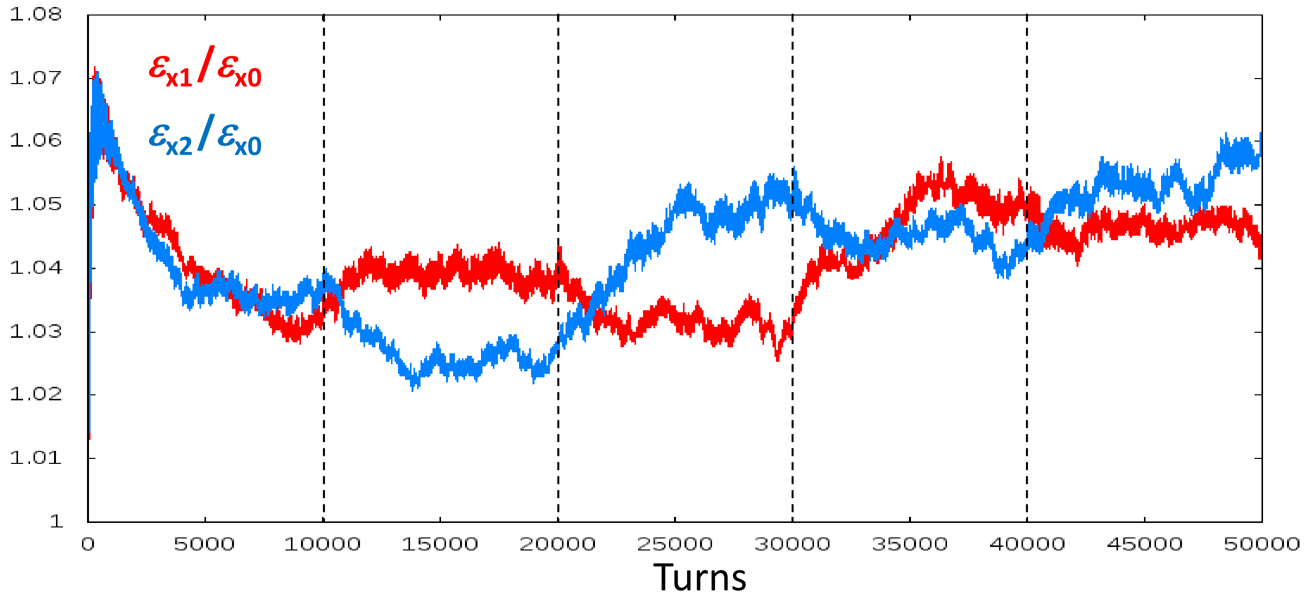
$$\xi_x = \text{const}, \quad \sigma_E\,,\ \sigma_z\,,\ \xi_y\,,\ L \propto \sqrt{N_p}$$

- With the nominal $N_p = 1.7 \cdot 10^{11}$ 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.

⇩

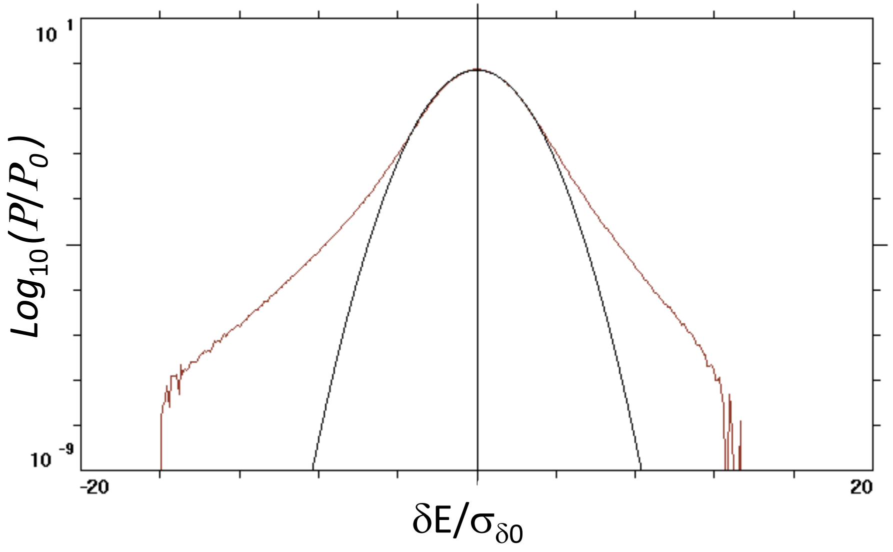
- The beams will be blown up and killed on the transverse aperture, before they are stabilized by the beamstrahlung.
- To avoid this, we have to gradually increase the bunch population during collision, so we come to *bootstrapping*.





FCC-ee at $t\bar{t}$ (175÷182.5 GeV)

Energy distribution in the logarithmic scale, black line: Gauss with σ_δ = 1.3 $\sigma_{\delta 0}$



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

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

- 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 distribution with beamstrahlung (K. Oide).

Parameter Optimization Issues

"Low" energies (e.g. FCC-ee at Z and W)

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

"High" energies (e.g. FCC-ee at tt)

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

=> $\alpha_{\mathrm{p}}\downarrow$

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

"Medium" energies (e.g. FCC-ee at HZ)

- Coherent instabilities are weak, but still exist => $\beta_x^*\downarrow$
- There is no polarization, small emittances are better => $\alpha_{\mathrm{p}}\downarrow$

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.

Summary

- The main factors limiting the FCC-ee luminosity at high and low energies were recognized and understood.
- Mitigation methods have been found and implemented in the new lattice design.
- Parameters of FCC-ee were optimized at each energy separately, taking into account various requirements and limitations.
- Requirements for the injection system were developed.