IP Beam Parameter Optimization for FCC-ee

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Outline

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- ☐ Main limitations
- ☐ Parameter optimization at low energies
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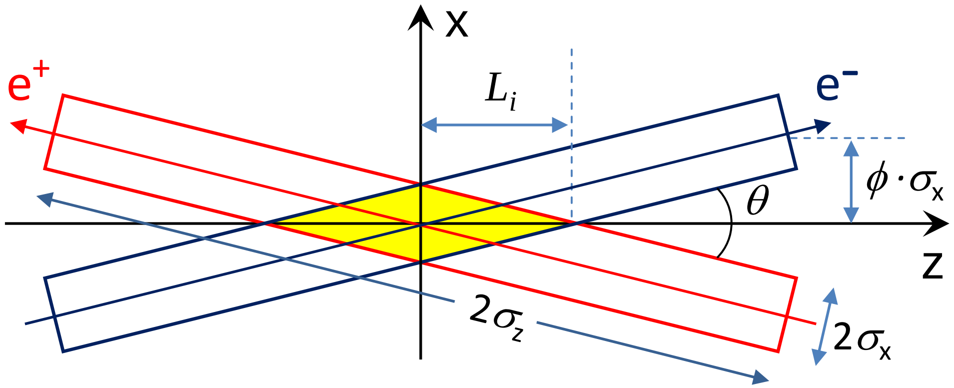
- ☐ Table of parameters
- ☐ Summary

Basic Equations

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

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 $\xi_y \sim 0.2$

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

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

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.

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

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

- Two new phenomena were recently discovered in simulations:

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

- 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.

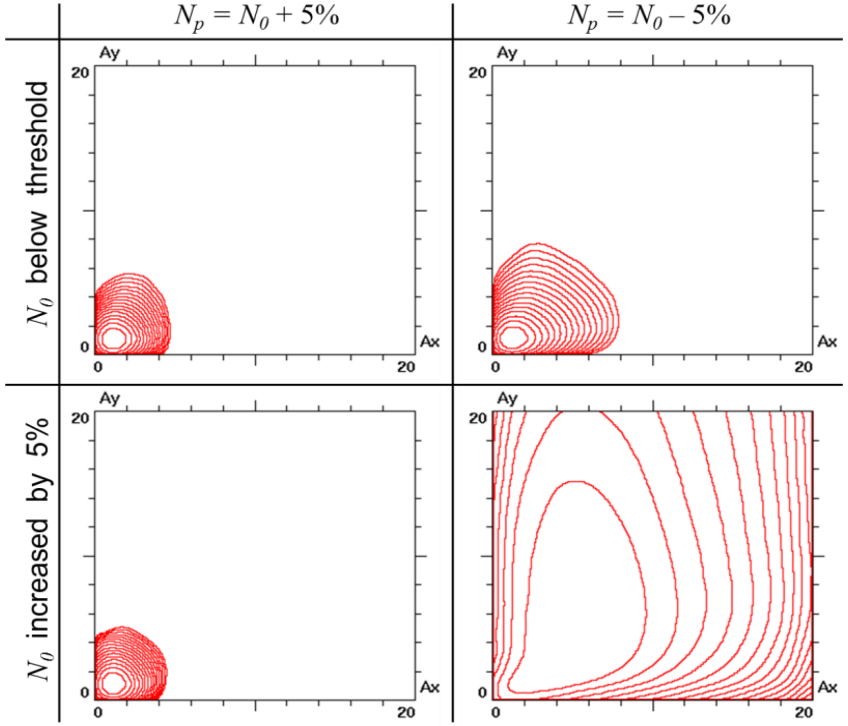
  This imposes strict requirements on the injector and the scheme of its operation.

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.

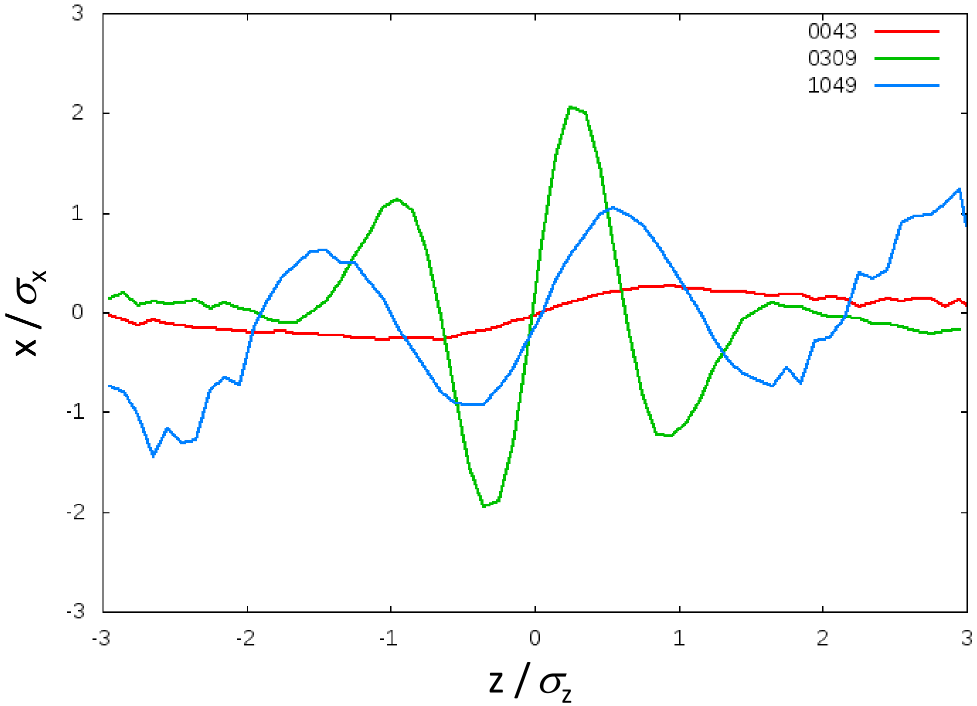
All three beam sizes grow slowly, until the footprint touches strong resonance, then the week bunch blows up.

Coherent X-Z Instability

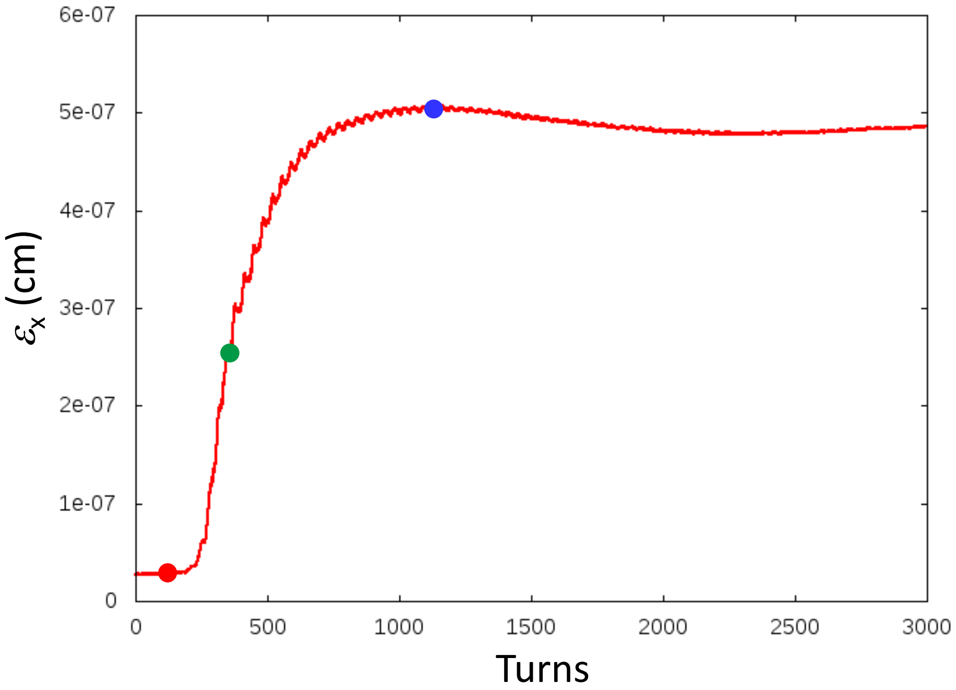
Discovered by K. Ohmi in strong-strong simulations (`BBSS`).
Reproduced in quasi-strong-strong simulations (`Lifetrac`).
Good agreement between the two codes.

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



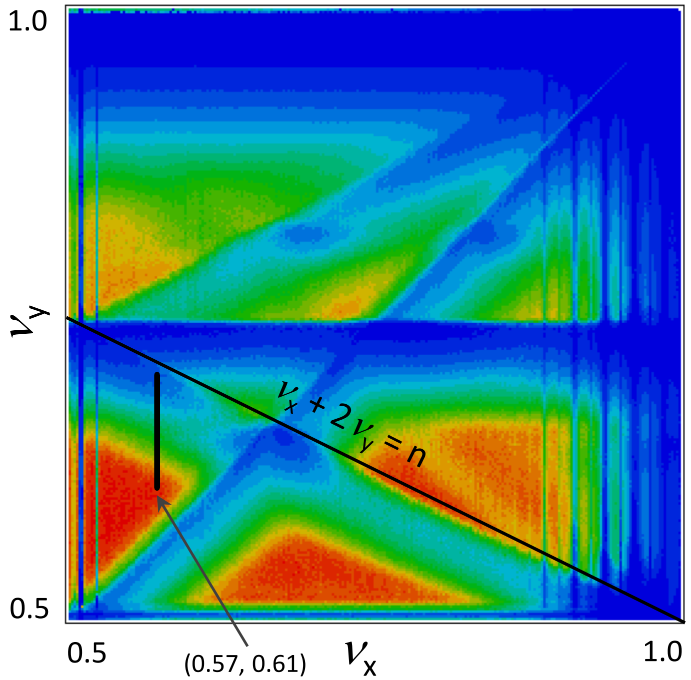
Evolution of the horizontal emittance



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

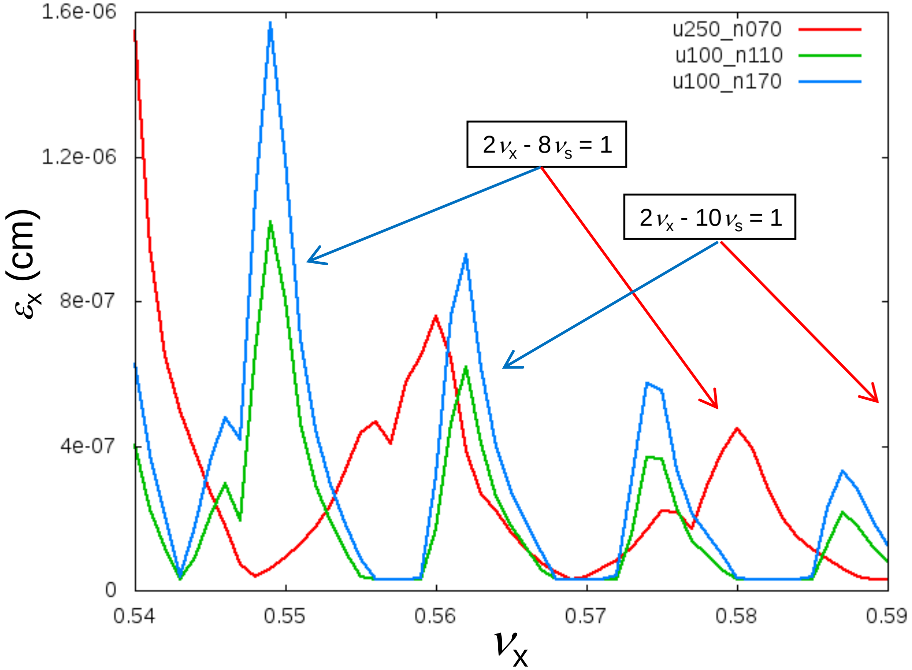
Parameter Optimization at Z

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

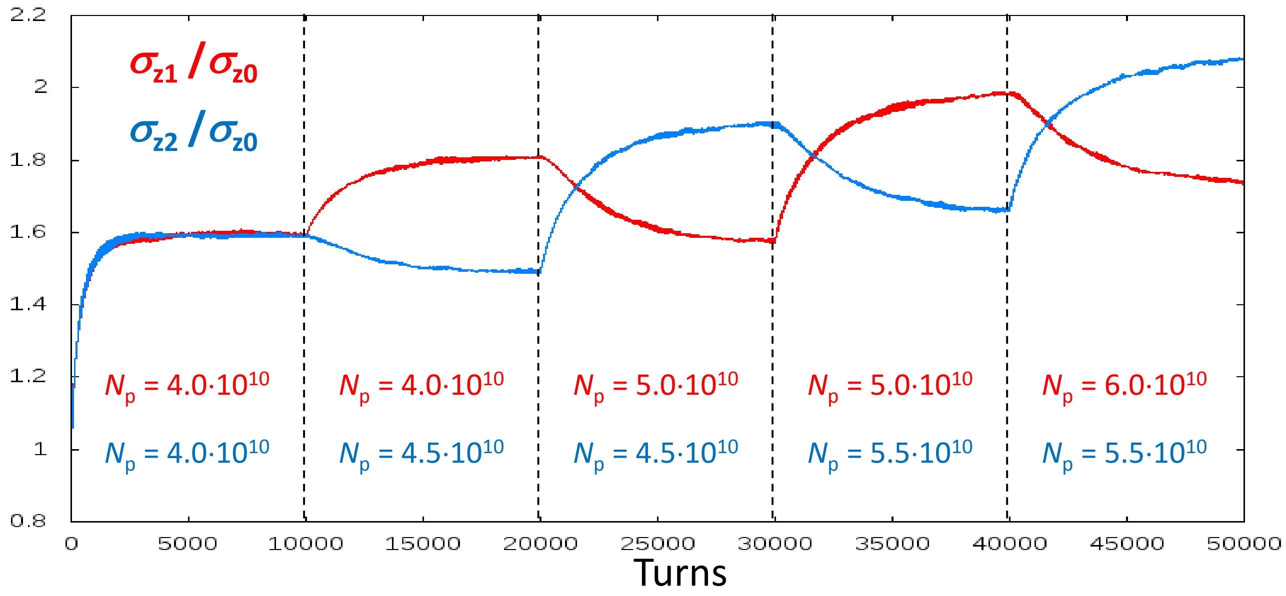
- When the energy spread is defined mainly by beamstrahlung, the dependence on N_p (bunch population) becomes:

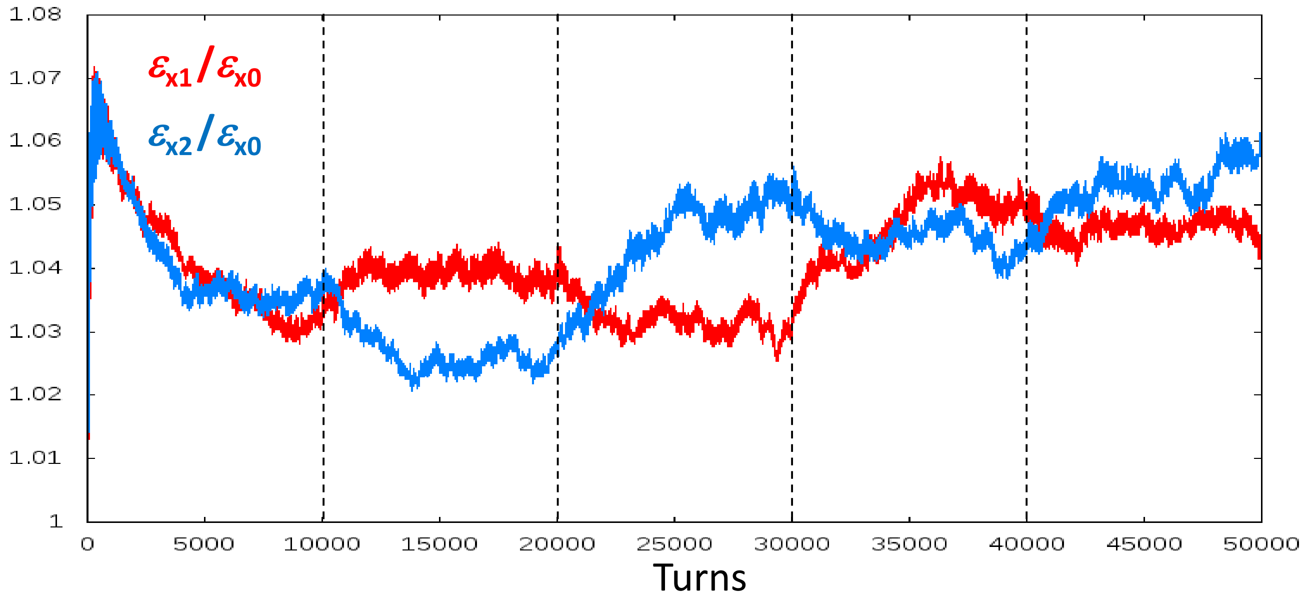
$$\xi_x = \text{const}, \quad \sigma_E, \sigma_z, \xi_y, L \propto \sqrt{N_p}$$

- 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*.





Parameter Optimization at W

Major recent changes: increase in ν_s

- In order to obtain a resonant depolarization, we need $\nu_s \geq 0.05$. Therefore, momentum compaction should be large – same as at Z. The RF voltage also is determined by ν_s.
- Another limitation is the HOM power. This sets the upper limit on N_p which corresponds to ~2000 bunches.
- We also considered the possibility of further increase ν_s to 0.075, to make the conditions for resonant depolarization even better. But this means doubling U_{RF} which will require a revision of RF staging scenario.
- At the moment, the main option is $\nu_s = 0.05$, 2000 bunches (middle column in the Table), and luminosity is limited by HOM.

Parameter	Old (Dec. 2017)	Low HOM	High ν_s
vertical beta* [mm]	1		1
horizontal beta* [cm]	20		15
synchrotron tune	**0.0506**		**0.075**
total RF voltage [GV]	0.75		1.5
energy acceptance [%]	1.3		1.2
number of bunches / beam	1300	2000	2500
bunch intensity [10^{11}]	2.3	1.5	1.2
bunch length (SR / BS) [mm]	3.0 / 7.5	3.0 / 6.0	2.0 / 4.6
energy spread (SR / BS) [%]	0.066 / 0.165	0.066 / 0.131	0.066 / 0.150
Piwinski angle (SR / BS)	3.5 / 8.7	3.5 / 7.0	2.7 / 6.15
luminosity [10^{34} cm^{-2}s^{-1}]	**34**	**28**	**30**
beam-beam parameter (x / y)	0.010 / 0.141	0.010 / 0.113	0.011 / 0.119
required lifetime by BS [min]	16	15	15
actual lifetime by BS [min]	24	> 200	27

Parameter Optimization at H (ZH)

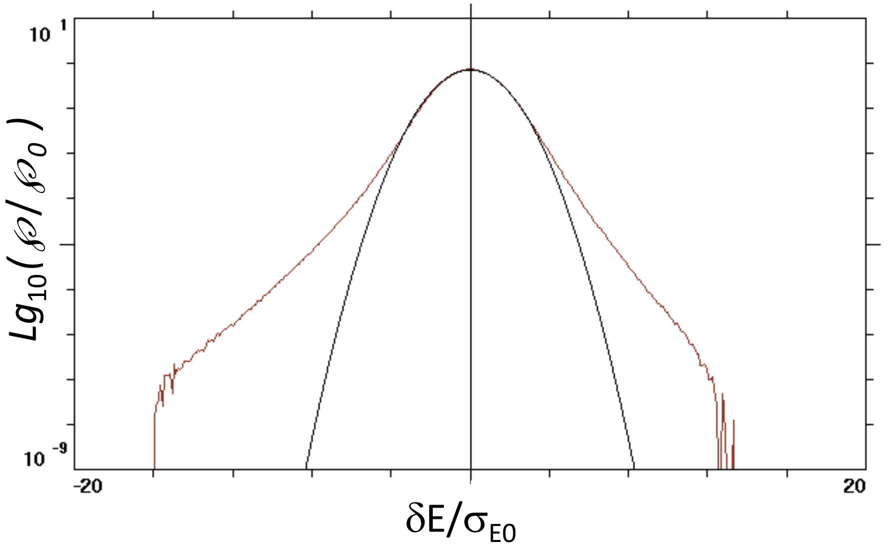
At 120 GeV we do not care about polarization and select the optimal parameters as follows:

1) The 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_{s}.
3) Then ν_{x} (for half ring) is selected in the range of $0.56 \div 0.58$, 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

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 distribution with beamstrahlung.

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
RF acceptance [%]	1.9	3.5	2.3	3.36	3.36
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
luminosity [10^{34} cm^{-2}s^{-1}]	**230**	**28**	**8.5**	**1.8**	**1.55**
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
rad. Bhabha lifetime [min]	68	59	38	40	39
allowable asymmetry [%]	±5	±3	±3	±3	±3
required lifetime by BS [min]	29	15	11	12	12
actual lifetime (w) by BS [min]	> 200	> 200	18	30	18

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 were optimized at each energy separately, taking into account various requirements and limitations (e.g. high synchrotron tune and HOM power at W, two RF systems at ttbar, etc.).
- ❑ Requirements for the injection system were developed, which include minimizing the asymmetry in population of colliding bunches, a special procedure of filling the collider at low energies (bootstrapping).
- ❑ The next steps towards the full version of CDR: beam-beam simulations with a realistic nonlinear lattice, misalignments, explicit betatron coupling, radiation in the quads, etc.