FUTURE CIRCULAR COLLIDER
Innovation Study

FCC-ee Parameter Choice for Luminosity Optimization

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Outline

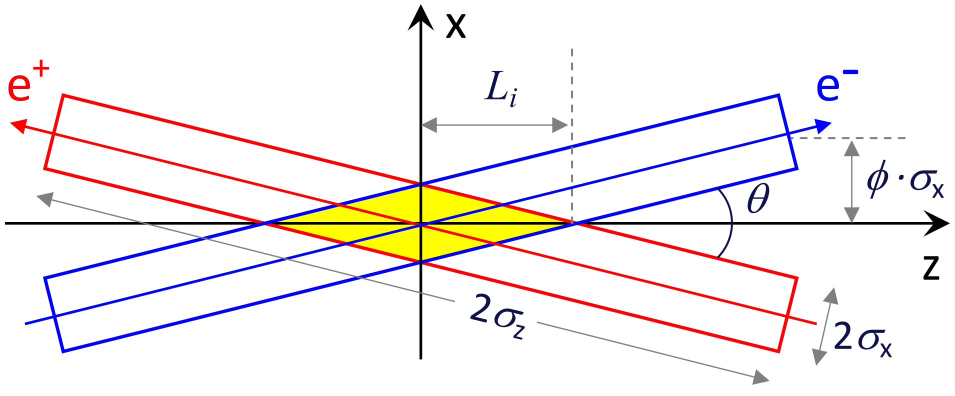
- The main points on which the choice of parameters and their optimization was based
- Parameter changes after CDR
- Problems: lattice errors and misalignments
- 2 IPs vs. 4 IPs
- Next steps

Basic Equations

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

Length of overlap: $L_i = \frac{\sigma_z}{\sqrt{1+\phi^2}} \xrightarrow[\theta\ll 1,\ \phi\gg 1]{} \frac{2\sigma_x}{\theta} \approx \beta_y^*$

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



Collision scheme with large Piwinski angle

$$\xi_y = \frac{N_p r_e}{2\pi\gamma}\cdot\frac{\beta_y^*}{\sigma_y\sigma_x\sqrt{1+\phi^2}} \xrightarrow[\theta\ll 1,\ \phi\gg 1]{} \frac{r_e}{\pi\gamma\theta}\cdot\overset{\text{linear density}}{\boxed{\frac{N_p}{\sigma_z}}}\cdot\sqrt{\frac{\beta_y^*}{\boxed{\varepsilon_y}}}$$

The beam-beam limit in the Crab Waist collision scheme can be high, but to obtain it, a small vertical emittance and a sufficiently high bunch linear density are required. The latter is an important parameter for collective instabilities and impedance-related issues, so this is another limitation.

- There is no sense to optimize the luminosity *per bunch* (or *per collision*). Attention should only be paid to ξ_y.
- σ_z is one of the most variable parameters: it depends on many factors, including the bunch population N_p. Accordingly, N_p should be adjusted to obtain the desired ξ_y.
- The number of bunches $n_b \propto 1/N_p$. We don't need to worry about this (except for Z) since the range of valid values is quite wide.

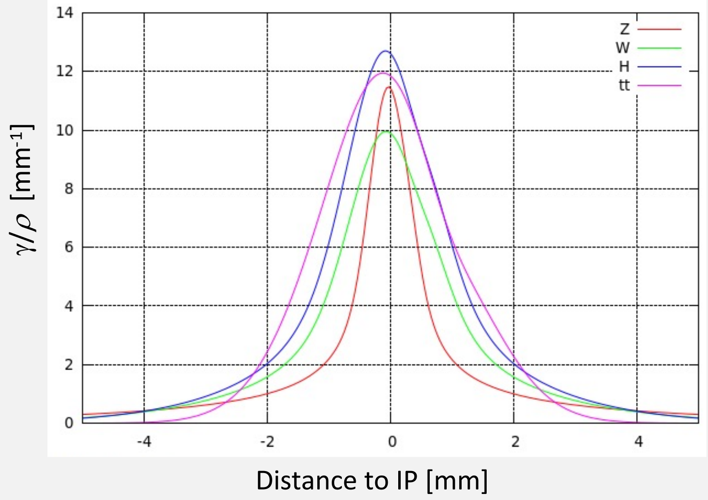
Beamstrahlung

Bending radius in the field of the opposite bunch

surface density

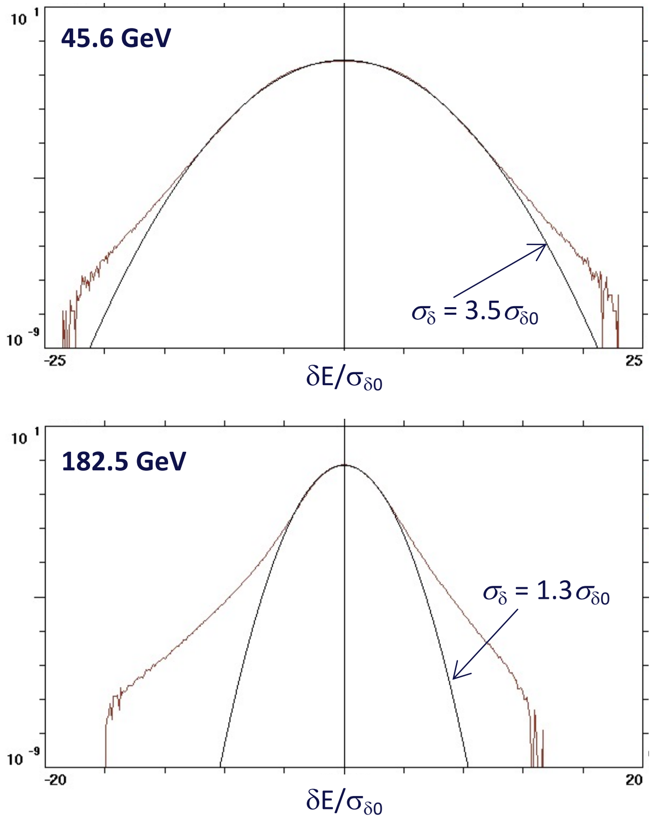
$$\frac{1}{\rho_{\min}} \propto \boxed{\frac{N_p}{\gamma\sigma_x\sigma_z}} \propto \frac{\xi_y}{\sqrt{\beta_x^*\beta_y^*}}\sqrt{\boxed{\frac{\varepsilon_y}{\varepsilon_x}}} \approx 0.002$$

- With increasing energy, beta functions at IP should grow while ξ_y almost does not change => ρ increases.
- Bending radius is not constant along the trajectory, and it depends on the particle coordinates.



Critical energy of BS photons: $u_c \propto \gamma^3/\rho \propto \xi_y \propto L$

Equilibrium energy distribution



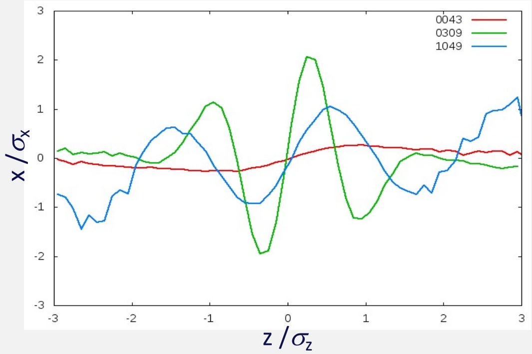
- The factor of increasing the energy spread is higher at low energies. The explanation is that it depends on the ratio of the bending radii in the arcs (SR) and in the IPs (BS).
- For low-energy colliders, $\rho_{\min}$ at the IP can be even smaller, but the effect of BS is negligible there, since the arc radius is <u>much</u> smaller than in the FCC.
- At 45.6 GeV, the energy loss due to BS is ~0.31 MeV per IP, compared to ~37 MeV in the arcs due to SR.
- Long tails at ttbar are produced by single emitted BS photons. Here the ratio u_c/σ_δ is important, which grows with γ.
- For asymmetry of the tails, an important parameter is the damping factor during the period of synchrotron oscillations. Therefore, asymmetry grows with γ.

Momentum acceptance determines the maximum allowable critical energy of BS photons, which in turn is proportional to ξ_y (and hence luminosity).

Parameter Optimization at Z, WW and ZH

Coherent beam-beam instability (TMCI)

Bunch shape at some turns



Excited coherent modes are associated with synchro-betatron resonances:

$$2\nu_x - 2m\nu_z = n, \qquad m \le \phi$$

If ϕ is not too large, we can solve the problem by choosing

$$\nu_x > 0.5 + \phi\nu_z$$

We are close to this requirement at ZH and are fulfilling it at ttbar.

An important parameter for this instability is the ratio ξ_x / ν_z, which needs to be minimized.

$$\xi_x = \frac{N_p r_e}{2\pi\gamma}\cdot\frac{\beta_x^*}{\sigma_x^2\left(1+\phi^2\right)} \xrightarrow[\theta\ll1,\ \phi\gg1]{} \frac{2r_e}{\pi\gamma\theta^2}\cdot\frac{N_p\beta_x^*}{\sigma_z^2}$$

Mitigation of instability:

1) Decrease in β_x^*
2) Increase in the momentum compaction factor (but there is a side effect: increased emittances) – only at Z and WW
3) Decrease in RF voltage – only at Z
4) Proper choice of the working point

Changes after CDR

- Arc optics at Z and WW: 60°/60° => 90°/90°, long cell. This is needed to increase the momentum compaction factor and mitigate the coherent instabilities.
- The baseline scenario now assumes 4 IPs. In this case, at Z energy, it will be necessary to reduce β_x^* from 15 to 10 cm. *And it will affect the DA and momentum acceptance*… But, most likely, we will have to reduce the bunch population due to other problems, and then it will be possible to keep $\beta_x^* = 15$ cm.
- The RF voltage at WW increased to 1 GV. This increases the synchrotron tune to 0.08, which is necessary for precise energy calibration by the resonant depolarization.
- At ZH energy – no significant changes.

Parameter Optimization at ttbar

Luminosity is limited by BS lifetime (single photon):

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

α – fine structure constant

η – momentum acceptance

ρ – bending radius of trajectories at the IP

L_i – length of interaction area

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 $L_i \approx \beta_y^*$)

(this works for any ϕ)

- We need to increase ρ with large luminosity => small emittances (90°/90° short arc cell optics) and ***increase*** L_i (i.e. σ_x) and β_y^*.
- Since ε_x should be small, σ_x is controlled by β_x^* which was increased to 1 m. *This is the main difference in parameter optimization*: at lower energies, β_x^* must be minimized to mitigate coherent beam-beam instability. There is no such problem at ttbar, so β_x^* becomes a free parameter.
- Asymmetrical momentum acceptance to match the actual energy distribution (K. Oide).
- Recent change: increasing ν_y from 0.59 to 0.64 to move away from the main coupling resonance.

Lattice Errors and Misalignments

- Misalignments and errors can lead to a significant decrease in the DA and momentum acceptance. This limits the luminosity per IP even in the case of ideal super-periodicity.
- The full beam-beam footprint from 2 or 4 IPs can cross a number of strong resonances, e.g. 1/2, 1/3, etc. The width of these resonances depends on the level of symmetry breaking, which depends on the magnitude of misalignments and the quality of corrections.
- Ways to solve the problem: improve the quality of corrections, and reduce the magnitude of misalignments (can be expensive!). Perhaps the increased accuracy of the alignment will be required only for some sections, and not for the entire ring – this needs to be clarified.
- Error correction should consist of several stages: obtain a stable orbit and designed emittances, then enlarge the DA and momentum acceptance, and special attention must be paid to obtaining designed lattice parameters at the IPs and crab sextupoles (dedicated knobs at the IR). This work is ongoing and notable progress has been made recently.
- A realistic assessment of the beam dynamics, luminosity and lifetime is possible only in simulations, taking into account all errors, corrections and beam-beam effects.

Footprint Size

(machine resonances w/o beam-beam)

Ideal lattice (4-fold symmetry)

Only the quarter ring footprint matters. For the whole ring, the footprint will be 4 times larger, but most of the resonances it crosses will be forbidden.

Seed 2, 1/4 of the ring

A quarter of the ring is artificially repeated 4 times. New resonances appeared due to errors, but many remained forbidden due to symmetry.

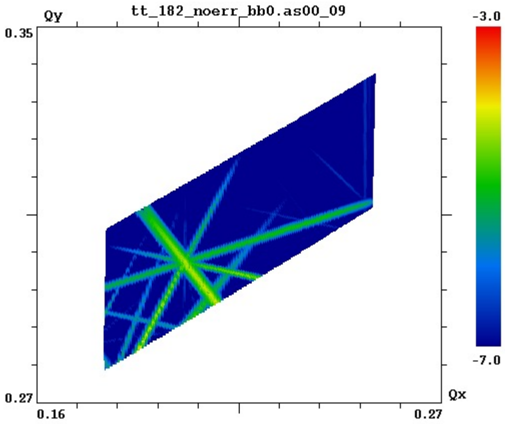
Seed 2, 1/2 of the ring

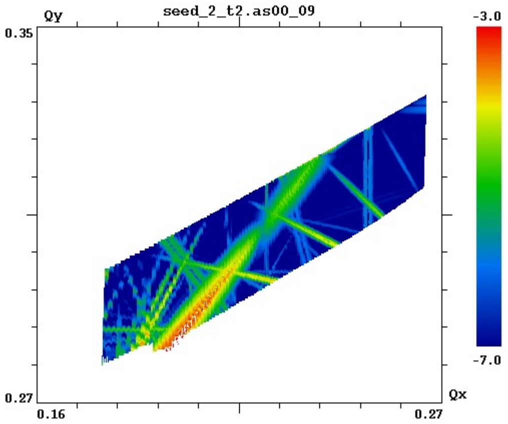
The half ring is artificially repeated 2 times. Two different quarters form a super period, which corresponds to a doubled footprint. And new resonances appeared.

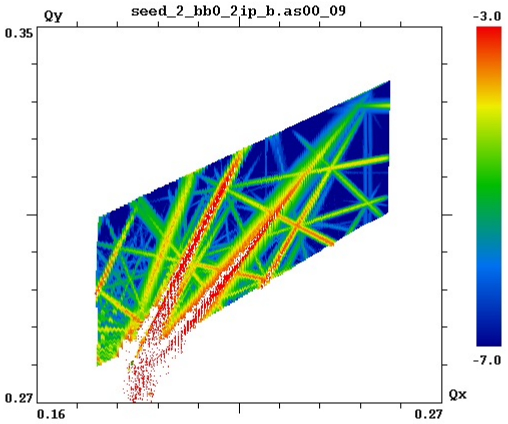
Seed 2, full ring

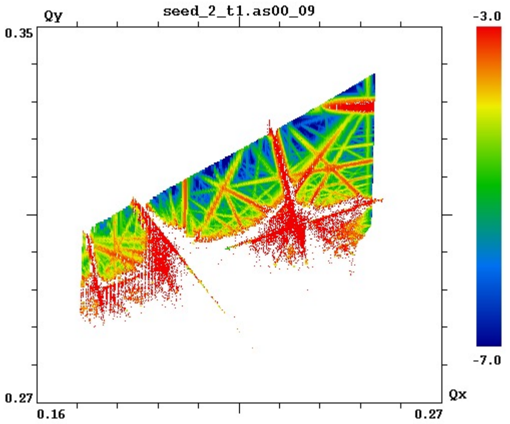
A realistic situation where there is no symmetry between quarters, and accordingly all resonances are allowed.

Betatron tunes (footprint)

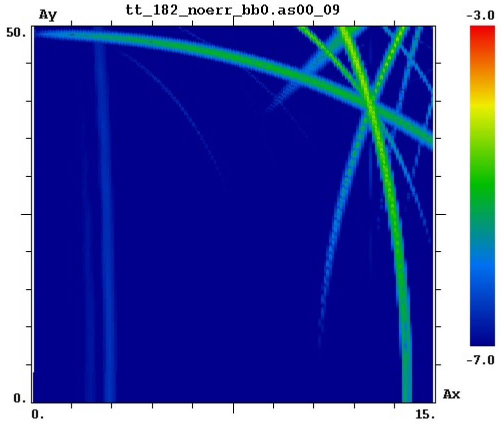


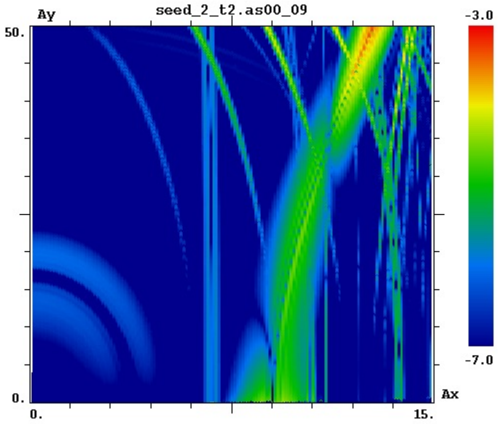


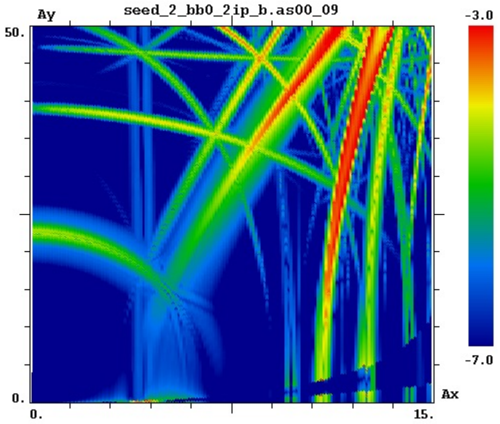


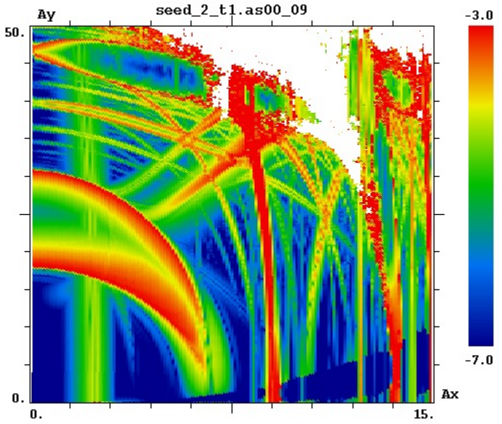


Normalized betatron amplitudes









2 IPs vs. 4 IPs

- A layout designed for just 2 IPs is much simpler. Only two additional crossings in the straight sections are required, and such insertions in the arcs (in each quarter) will not be needed. Much more space will be available in the straight sections.
- Horizontal beta-function at Z-pole can be relaxed, since ν_s per superperiod will be twice as much.
- Two-fold lattice symmetry is easier to achieve than four-fold. The 2 IPs option is more stable for fine tuning, the commissioning time will be shorter.

But

- With the same total luminosity, the increase in energy spread due to BS will be less at 4 IPs. Since the luminosity will be limited mainly by the energy spread, it will be higher at 4 IPs. How much higher depends on what footprint size is achievable, taking into account the symmetry breaking between superperiods.

For more reasonable estimates and comparison (2 vs. 4), modeling is needed taking into account all the details. Work in progress…

Next Steps

- ☐ We should try to improve the situation with misalignments and imperfections
  - More sophisticated correction algorithms to mitigate DA reduction.
  - Mechanical movers for all sextupoles to reduce the orbit offsets relative to the center of sextupoles to several microns. High resolution BPMs are required. What will be the cost?
  - Some new ideas…
- ☐ Perform simulations to understand how much luminosity can be achieved with different levels of misalignments and errors, and at what cost.
  - To do this, it is necessary to have knobs for controlling the lattice and orbit at all IPs, betatron phase advances between IPs, etc. Some progress has been made here recently.
  - These simulations must be performed for all energies, 2 and 4 IPs. Only after that it will be possible to give reasonable recommendations about the optimal number of IPs and the achievable luminosity.

Conclusion

- The main parameters of FCC-ee (lattice, RF, beta-functions at the IP, etc.) are more or less defined. Further optimization is mainly related to misalignments and errors, and it will affect only the bunch population N_p (and, accordingly, the number of bunches n_b and luminosity).
- There are many other things that depend on N_p and n_b. For some of them (i.e. electron clouds and ion instabilities, mainly at Z), an increase in N_p and, consequently, a decrease in n_b are beneficial. For impedance-related phenomena, the opposite is true. In any case, we need to have large flexibility in these parameters.
- Perhaps as we resolve the current issues, new ones will be discovered. Parameter optimization is a very interesting and exciting (and maybe endless) process, the work continues...