Beam-Beam and Parameter Studies

Dmitry Shatilov

BINP, Novosibirsk

Acknowledgements:

K. Ohmi, K. Oide, F. Zimmermann

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Introduction

The task of maximizing the luminosity is a priority for any collider. From the very beginning of their history, it was realized that one of the main factors limiting luminosity is the beam-beam interaction. And progress in colliders performance was largely determined by *how to increase the beam-beam limit, and how to get the maximum luminosity at a given beam-beam limit*. Here we can distinguish three main stages:

1. Decrease in β^* and, accordingly, decrease in bunch length.
2. Two-ring colliders (factories) with a large number of bunches.
3. Crab Waist collision scheme (implies large Piwinski angle), which makes it possible to significantly reduce β^* and raise the beam-beam limit.

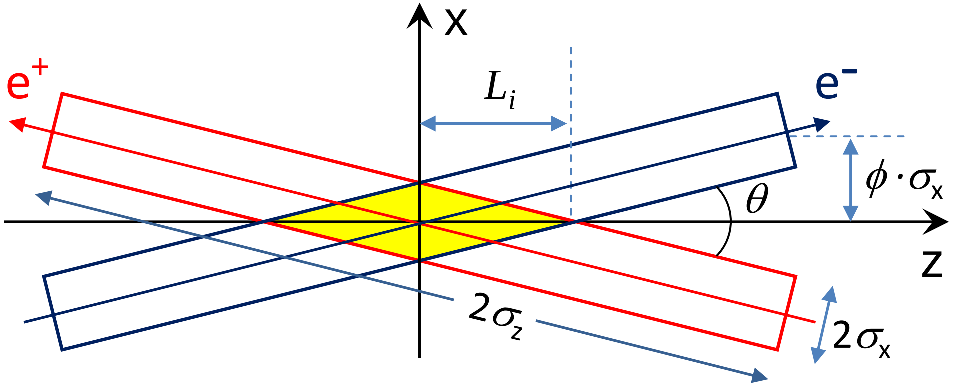
Each of the stages has its own characteristics, so the optimization of parameters is different everywhere. In addition, a *distinctive feature of the FCC-ee is the great influence of beamstrahlung* (radiation in the field of an opposite bunch) on beam dynamics. *In the Crab Waist collision, this is manifested much stronger.*

We will discuss the features of beam-beam interaction for FCC-ee at different energies, optimization of parameters for maximum luminosity, open issues requiring further study and some key points for the next steps.

Collision Scheme

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

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



Sketch of collision with large Piwinski angle

Large Piwinski angle (LPA)

- There are no long-range beam-beam interactions!
- $L_i << \sigma_z$ => small $\beta_y^* << \sigma_z$ without hourglass!
- **Crab waist** => large $\xi_y \sim 0.2$

P. Raimondi, 2006

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

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

- Luminosity and ξ_y are proportional to the linear charge density.
- To achieve large ξ_y, we need small ε_x and small betatron coupling – similar to modern SR light sources. And this greatly enhances beamstrahlung.

Beamstrahlung

The critical energy of emitted photons: $u_c \propto \dfrac{\gamma^2 N_p}{\sigma_x \sigma_z}$

Compared to the previous generation of colliders, linear charge density has not changed much. But σ_x should be very small in CW collision scheme, so the beamstrahlung (BS) is significantly enhanced.

For example, the energy in LEP was high enough, but the charge density was too low, so the influence of BS on the beam dynamics was negligible. In contrast, in FCC-ee BS will be one of the dominant factors at all energies.

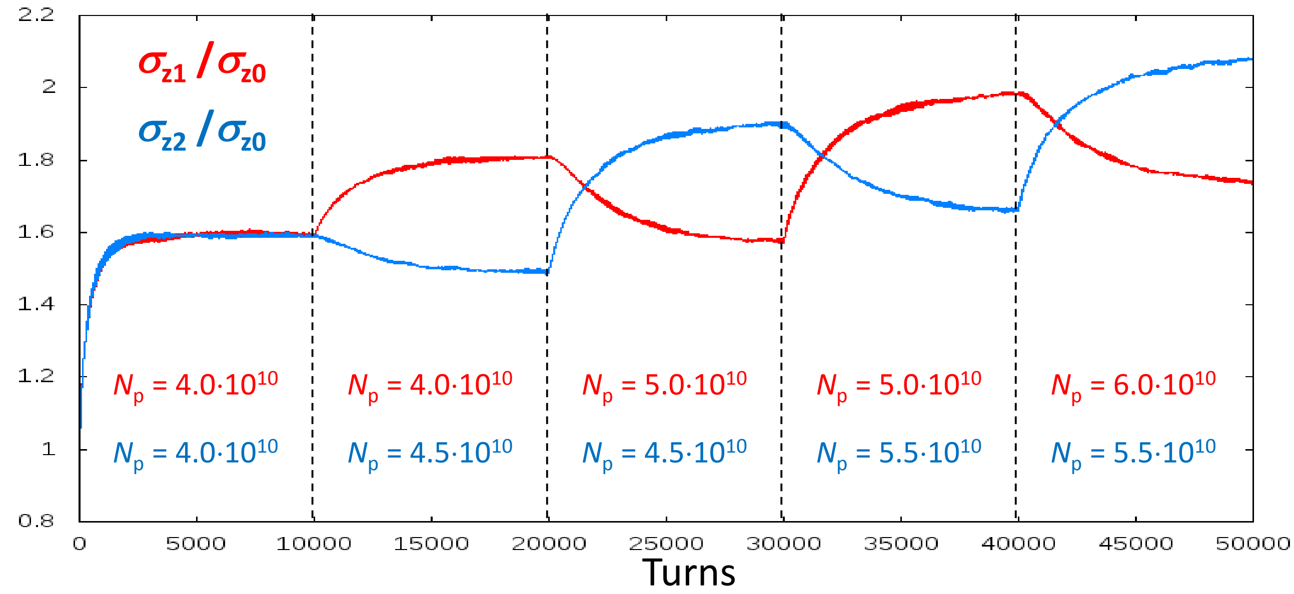
The bending radius of trajectories at the IP is less than 8 m at Z-pole and increases with energy. Energy losses at IP are negligible compared to arcs, but BS photon energies are much higher.

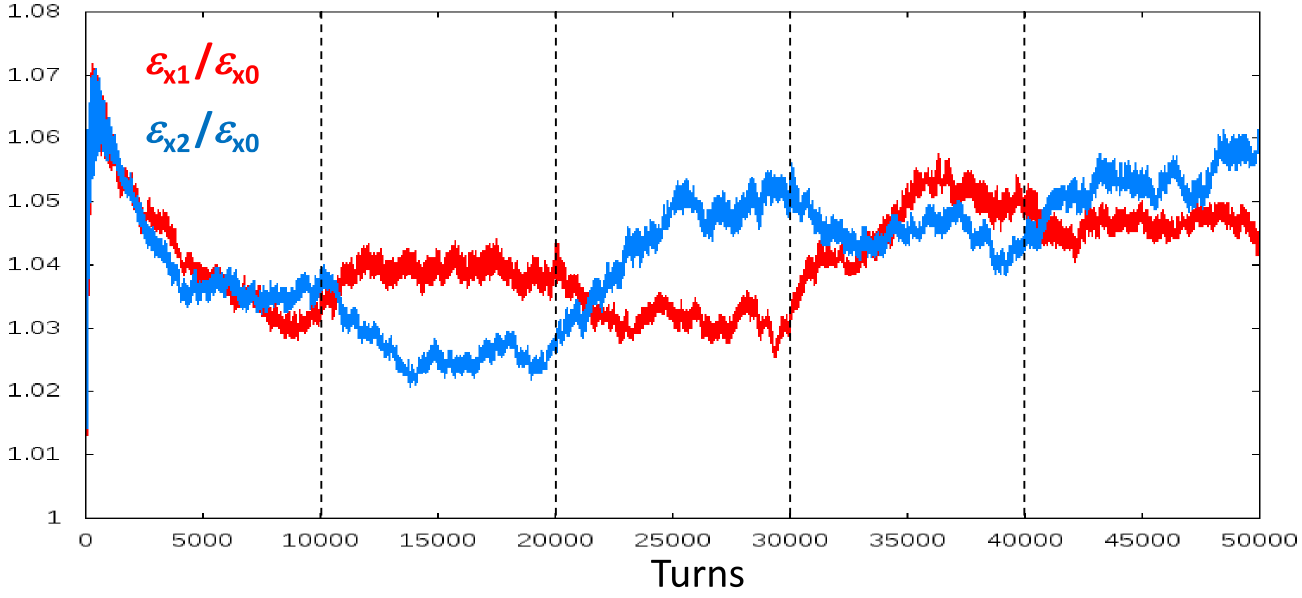
At high energies, BS manifests itself in a limitation of the beam lifetime, at low energies – in a significant increase in the energy spread and the bunch length.

If N_p corresponds to the beam-beam limit with the nominal σ_z, then *in collision* σ_z increases due to BS, resulting in ξ_y and luminosity drop. To achieve the designed ξ_y *in collision*, N_p should be increased about 3.5 times at low energy!

Bootstrapping

- If we bring into collision such high populated bunches with the *initial* σ_z, $\xi_{x,y}$ will be far above the limits.
- The beams will be blown up and killed before they are stabilized by BS.
- To avoid this, we have to gradually increase the bunch population during collision, so we come to *bootstrapping*.





3D Flip-Flop

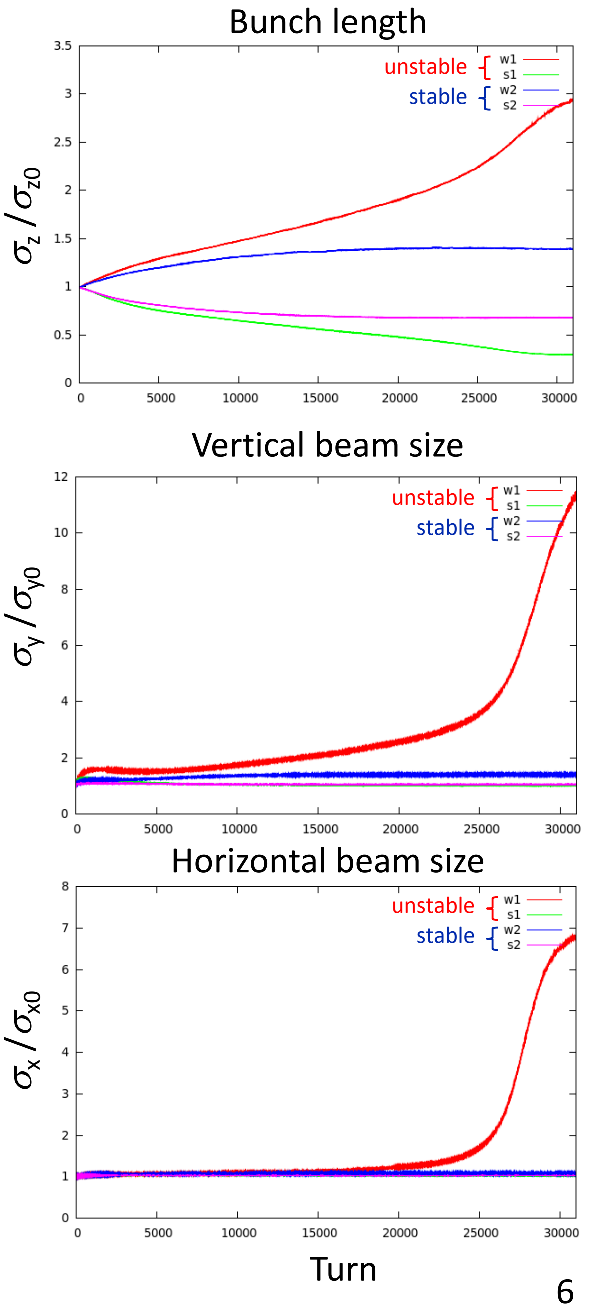
In collision with LPA: $\xi_x \propto \dfrac{1}{\sigma_z^2}, \quad \xi_y \propto \dfrac{1}{\sigma_z}$

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.

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, 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.



Bunch length

Vertical beam size

Horizontal beam size

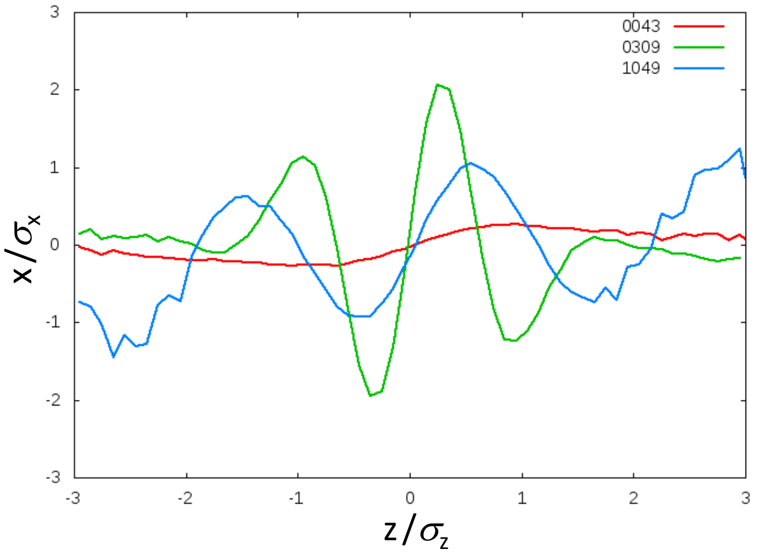
Turn

Coherent Beam-Beam Instability

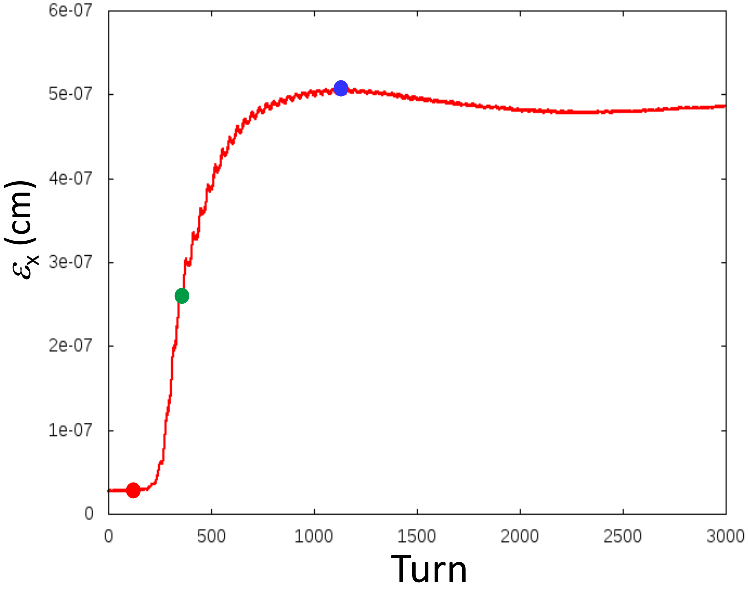
Discovered by K. Ohmi in strong-strong simulations in 2016. **Recently it was observed at SuperKEKB.**

- This is TMCI induced by beam-beam interaction with LPA. It develops in the horizontal plane and is manifested by wriggle of the bunch shape.
- The effect is 2D, ε_x increases 5 ÷ 15 times. Then the betatron coupling leads to ε_y increase in the same proportion, and luminosity falls several times.
- Synchro-betatron resonances $2\cdot(\nu_x - m\cdot\nu_z) = 1$ play a key role.
- This instability cannot be mitigated by feedback. The only solution: find conditions under which it does not arise.

Bunch shape at some turns

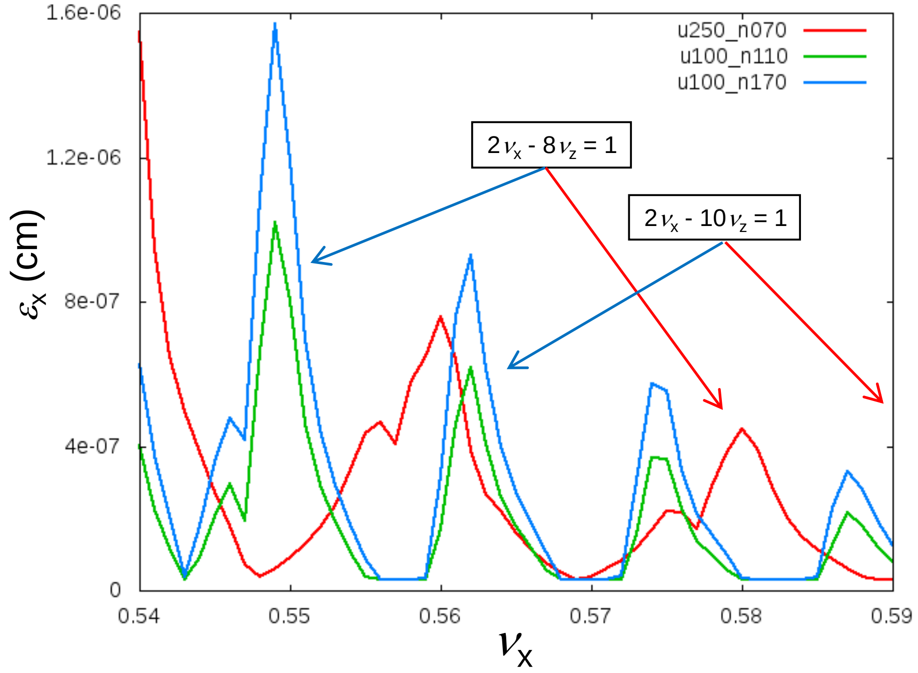


Evolution of the horizontal emittance



Parameter Optimization at Low Energy

Coherent instability: ε_x dependence on ν_x and ν_z.
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 resonance.

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.

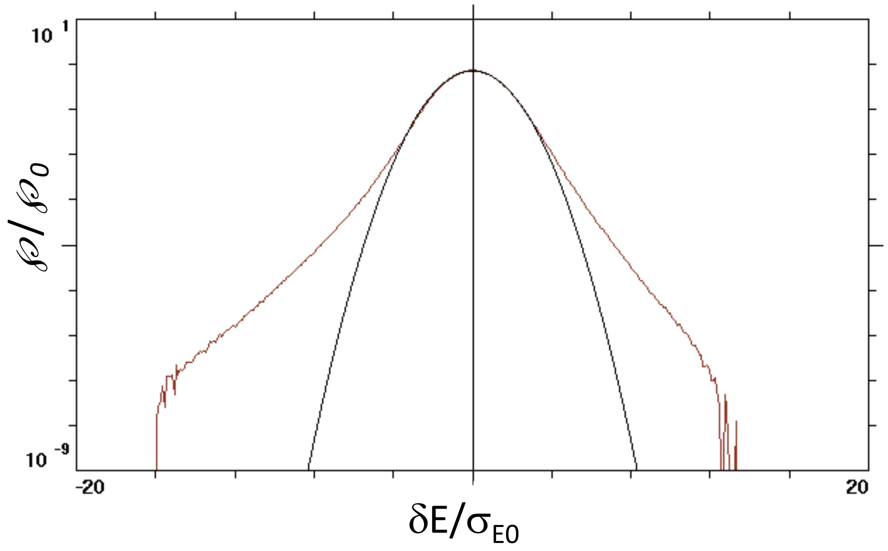
- Reduce the RF voltage.

  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.

Parameter Optimization at High Energy

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



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 BS 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 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 1 m.
- Asymmetrical momentum acceptance to match the actual energy distribution (K. Oide).

4 IP vs. 2 IP: Problems

- Decrease in the synchrotron tune *per superperiod*.
- Intensified beamstrahlung: increase in the energy spread and bunch length.

Even in the case of perfect 4-fold symmetry, the luminosity per IP decreases by 10÷20 %, depending on the energy.

The main problems are related to lattice errors that break symmetry and super-periodicity.

- The full beam-beam footprint from 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 4-fold symmetry breaking. The beams will survive, but they may swell and the luminosity will drop.
- Possible solution: shift the working point to avoid harmful resonances. But this can lead to a decrease in $\xi_{x,y}$ and luminosity.
- Another solution: perform lattice corrections to minimize asymmetry. What is the acceptable margin of error?

Work continues...

4 IP vs. 2 IP: Questions

- What correction accuracy do we need in order for 4 IP to give a noticeable increase in luminosity?
- What correction accuracy can be achieved? At what cost?
- We are strictly limited in time. If 4 IP would potentially allow higher luminosity, but the commissioning time is longer, will we get a higher integrated luminosity?
- Which is better: a simpler and more reliable machine, or a more complex and risky one, but with a potentially higher luminosity?
- Is there any benefit from increasing the number of detectors, if the integrated luminosity will not increase?

Other Issues

- Control of orbit, lattice, betatron coupling. Tolerances.
- Synchrotron radiation in the quadrupoles.
    - Dynamic aperture
    - Damping decrements
    - High energy photons from the FF quads
- Top-up injection with beam-beam interaction.
- Interplay of impedances and beamstrahlung.
- Beam lifetime versus collimation aperture.
- Potential questions/issues from MDI side.
- And more…

Modeling Tools

- The FCC-ee has a very intensive program that needs to be completed within a limited time frame. Consequently, the time for commissioning and reaching the design luminosity should be minimized.
- We need to anticipate potential problems and be prepared.
- The experience of DAFNE, SuperKEKB, other colliders and light sources will be very useful, but…
- For studying beam dynamics *with beamstrahlung*, we cannot create prototypes and test facilities, because BS can only be observed in the FCC-ee when it is built.

We can only rely on analytical estimates and modeling

It is necessary to develop simulation programs with the following in mind:

- Strive for more complete models, take into account more effects and their mutual influence, errors and imperfections.
- We need different tools for different tasks, as well as several tools for the same task – to be able to cross-validate the results.

Summary

- The main factors limiting the FCC-ee luminosity at high and low energies were recognized and understood. Mitigation techniques have been found.
- The ability to increase the number of IPs from 2 to 4 depends on how well we can maintain 4-fold symmetry of the lattice. The answer is still unclear, work is underway.
- Many other issues also require attention for the further development of the project. Modeling tools will play an important role here.

Thank you!