Parameter Optimization for Smaller Betatron Coupling

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Introduction & Motivation

When we started our study of the FCC-ee project 6 years ago, two conditions for vertical emittance were defined by common agreement, after discussion:

$$\frac{\varepsilon_y}{\varepsilon_x} \geq 0.002 \quad \text{and} \quad \varepsilon_y \geq 1pm$$

CDR meets these requirements, parameters were also optimized taking them into account. But modern synchrotron light sources have shown that better results can be achieved, and modeling of misalignments and corrections for the FCC-ee also confirms this.

Maybe we should rethink the limits on ε_y and try to do better?

In resuming this discussion, there are several important issues to consider:

- How does this affect other parameters? What are the benefits?
- What are the disadvantages and how critical are they?
- How realistic is it to get and constantly maintain a smaller betatron coupling?
- Do we need to be more flexible and support several sets of parameters?

How ε_y affects the other parameters?

For flat beams:

$$L = \frac{\gamma}{2er_e} \cdot \frac{I_{tot}\xi_y}{\beta_y^*} \cdot R_{hg} \qquad \xi_y = \frac{r_e}{2\pi\gamma} \cdot \frac{N_p}{\sigma_x\sqrt{(1+\phi^2)}}\sqrt{\frac{\beta_y^*}{\varepsilon_y}} \xrightarrow{\phi \gg 1} \frac{r_e}{\pi\gamma\theta} \cdot \frac{N_p}{\sigma_z} \cdot \sqrt{\frac{\beta_y^*}{\varepsilon_y}}$$

Maximum critical energy of emitted BS photons: $u_c \propto \frac{\gamma^2 N_p}{\sigma_x \sigma_z}$

With a smaller ε_y, we can increase ξ_y (and L) for the same N_p and σ_z. The question is, what is the beam-beam limit and how close we are to it. The answer is not clear yet and depends on the number of IPs (2 or 4), betatron tunes, symmetry breaking degree (misalignments, errors, corrections).

Let us assume for now that ξ_y cannot be increased. Then is there any benefit from reducing the vertical emittance?

YES !

Benefits from reducing ε_y
(for example, twice)

- ✓ Increase in the vertical aperture (in units of σ_y) by $\sqrt{2}$ times
- ✓ Decrease in the linear charge density by $\sqrt{2}$ times
  (at low energy, N_p will be halved and σ_z will decrease by $\sqrt{2}$ times, number of bunches doubled, ξ_x is not affected)
- ✓ Problems associated with impedance and coherent instabilities weaken
- ✓ Beamstrahlung will decrease significantly. As a consequence:
- ✓ Reducing energy spread by $\sqrt{2}$ times (at low energies)
- ✓ Momentum acceptance can be reduced
- ✓ The 3D flip-flop instability threshold will rise. Consequently:
- ✓ The requirements on the symmetry of the intensities of colliding bunches can be relaxed.
- ✓ Bootstrapping will be easier (fewer steps required)
- ✓ Problems associated with high energy BS photons at the IR weaken

Some features at different energies

Z

With 2 IPs, the detector solenoids contribute about 0.3 pm to ε_y, and betatron coupling 0.1% allows to achieve $\varepsilon_y \approx 0.6$ pm. With 4 IPs, the main contribution is made by solenoids and $\varepsilon_y \approx 1$ pm is a good estimate – no benefits…

H (s-channel)

Luminosity is limited by an increase in emittances due to BS. The rest of the problems are not so significant, ξ_y is well below the limit. Therefore, decrease in ε_y completely transforms into an increase in luminosity.

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One more advantage: by decreasing N_p, we reduce ξ_x, which is not small here. This can be useful, especially with 4 IPs.

Possible problems and side effects

- Control of vertical offset of colliding beams at the IP.
- The vertical emittance must be the same for both rings with high accuracy. This can be controlled by asymmetry in σ_z for colliding bunches with equal populations.
- The X-Y tilt at the IP must be << σ_y / σ_x, otherwise we lose luminosity.
- The vertical size of the SR area will be smaller. Does this pose a problem for SR absorbers?
- Injection patterns will be affected.
- It is necessary to consult with other groups, which depend on the number of bunches (RF, collective effects, feedback systems, etc.)
- …..

Feasibility

Can we base our expectations on the results obtained on light sources?

- We have several IP with solenoids, complicated IR optics, very sensitive lattice. Is our case more complicated?
- Does ring size matter?

Experience of SuperKEKB will be very important.

- After upgrade of the IR, will it be similar to our case? Can we extrapolate these results to FCC-ee?
- Again, does ring size matter? Number of IPs?
- Touschek lifetime can limit the optimum ε_y in SuperKEKB. Can they perform a special run with reduced bunch population and the lowest possible coupling?

Concluding remarks

- If the beam-beam limit allows, a decrease in ε_y will be converted to the maximum possible increase in luminosity. In this case, decrease in the bunch population will be smaller.
- If we cannot get a very small ε_y, then to increase the luminosity it will be necessary to increase N_p, which means a stronger BS with all the consequences.
- Should we consider preparing two sets of parameters?
- What will be our "optimistic" coupling? 0.1%? Or even smaller?
- If we decide to move in this direction, then we need to somehow formalize it and officially approve.