PARAMETERS – UPDATE AND PLAN

D. Shatilov (BINP)

Many thanks to T. Charles, K. Oide, F. Yaman, Y. Zhang, F. Zimmermann, M. Zobov

FUTURE CIRCULAR COLLIDER
Innovation Study

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 95175.

Horizon 2020
European Union Funding
for Research & Innovation

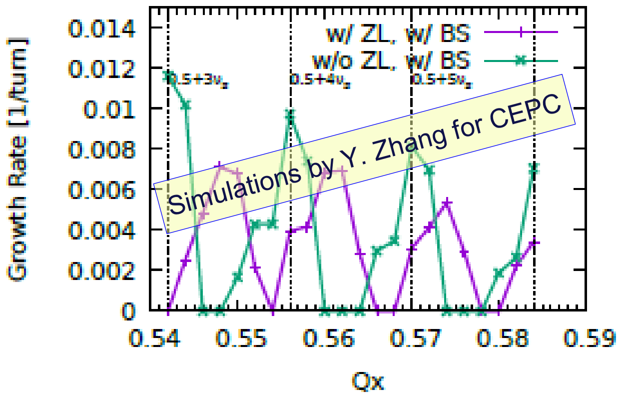
Introduction

The main parameters of the FCC-ee collider are fixed in the CDR, but this does not mean that they will not change anymore. Further and deeper consideration of this project reveals new problems, both physical and technical, and new ideas appear.

This mainly concerns the operation at low energy, where a large total beam current can lead to various collective instabilities. We will discuss some of the problems that have emerged recently and possible solutions.

In addition, the parameters of the RF system can be revised. And this will require changing some other parameters of the collider.

Impedance at Low Energy



→ more in talk by Y. Zhang on Thursday

Longitudinal impedance leads to a spread of synchrotron tunes. As a result, the good regions for Q_x shrink.

If Q_z is decreased, the order of resonances near the working point will increase and they will become weaker. This is an old recipe, we have already applied it for basic parameters and now we have Q_z=0.025. Further reduction of Q_z is not possible due to limitations associated with energy calibration by resonant depolarization.

⇒

Larger momentum compaction

Arc Cell	60° / 60°	45° / 45°
α_p [10^{-5}]	1.48	2.5
ε_x [nm]	0.27	0.6
ε_y [pm]	1.0	1.5
Q_z	0.025	0.032
N_p [10^{11}]	1.7	2.8
N_b	16640	10100
σ_z [mm]	12.	15.2
σ_δ [10^{-4}]	13.	12.7
L / IP [10^{36} cm^{-2}c^{-1}]	2.3	2.3

- Mitigation of coherent beam-beam instability.
- Larger Q_z → better conditions for energy calibration.
- Increasing the microwave instability threshold.
- Increase in the bunch spacing → mitigation of electron cloud instability.
- Mitigation of other coherent instabilities (e.g. ion instability).

RF 600-650 MHz at Z

Parameters for 45° / 45° arc cell

RF frequency [MHz]	400	650
RF voltage [MV]	100	120
RF acceptance [%]	1.46	1.35
Momentum accept. [%]	±1.3	
Synchrotron tune [ν_z]	0.032	0.046
Bunch length (BS) [mm]	15.2	10.9
Bunch population [10^{11}]	2.8	2.0
Number of bunches [N_b]	10100	14140
L / IP [10^{36} cm^{-2}c^{-1}]	2.3	2.3

Consequences of increasing RF frequency:

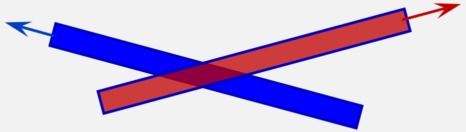
- Decrease in RF acceptance → larger U_{RF} is required.
- Larger Q_z → not optimal for coherent beam-beam instability.
- Shorter bunches → larger number of bunches → not optimal for electron clouds.

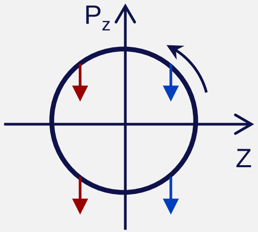
3rd Harmonic Cavities?

- If we want to control the number of bunches at a given luminosity and in a given magnetic lattice, then this can be done only by changing the bunch length, i.e. the synchrotron tune.
- To reduce Q_z without affecting the RF acceptance, it is necessary to use the 3rd harmonic cavities.
- For example, 22 MV at the 3rd harmonic decreases Q_z from 0.046 to 0.03.
- 3rd harmonic cavities with moderate voltage and no energy transfer to the beam add flexibility in parameter selection. It is like another degree of freedom.
- One of the main disadvantages is associated with the enhancement of transient beam loading. This issue becomes especially acute in the presence of beamstrahlung.

Transient Beam Loading

LPA collision + beamstrahlung





- Geometrical loss of luminosity (small).
- Amplification of synchro-betatron resonances.
- Asymmetry in the energy loss due to BS $\rightarrow$ asymmetry in the bunch lengths and energy spreads. This can lead to a 3D flip-flop.

dZ [mm]	σ_z [mm]	σ_δ [10^{-3}]
0	12 / 12	1.3 / 1.3
5	11.3 / 12.4	1.24 / 1.33
10	8.7 / 14.5	0.97 / 1.55

For dZ = 5 mm, requirements for the permissible asymmetry of the bunch currents are tightened from $\pm$5% to $\pm$3%.

Some remarks:

- If two colliding bunches have the same longitudinal displacement, then there will be no effect.
- If the displacements are regular (not random) and depend on the filling scheme, which should be the same for the two rings, the effect will be suppressed by this symmetry.
- Electron clouds will make the difference for electrons and positrons. But basically it will be a regular offset and can be corrected by adjusting the RF phase (it is independent for the two rings).
- If one of the two colliding bunches is lost (e.g. due to 3D flip-flop), the counter bunch will create asymmetry in the filling schemes for two beams. What will be the effect on the asymmetry of longitudinal displacements?

Different Options at Low Energy

- Larger momentum compaction factor.
  1) Short arc cell 45° / 45°
  2) Long arc cell 90° / 90° (concatenation of two short cells)

  We need to choose an option that will simplify the transition from one lattice to another.

- Increase in the RF frequency.

  Can we use 3rd harmonic cavities to lower the synchrotron tune?

- What is the optimal synchrotron tune (i.e. the number of bunches)?

In favor of reducing Q_z
1) Coherent beam-beam instability
2) Electron cloud instability (→ F. Yaman)
3) Ion instability
4) …..?

In favor of increasing Q_z
1) Energy calibration (depolarization)
2) Detectors (to avoid pileup)
3) …..?

We need to find a compromise, because there are different requirements on different sides.

Larger Momentum Compaction at W ?

A side effect of increasing the momentum compaction is an increase in the emittances. We assume that $\beta^*_{x,y}$ and momentum acceptance remain the same as in the CDR, and estimate the impact of increased emittances on luminosity.

Luminosity: $$L \propto R_h \xi_y = R_h \frac{r_e}{\pi\gamma\theta} \cdot \frac{N_p}{\sigma_z} \cdot \sqrt{\frac{\beta_y^*}{\varepsilon_y}} \propto R_h \frac{N_p}{\sigma_z \sqrt{\varepsilon_x}}$$

Maximal critical energy of BS photons: $$u_c \propto \frac{\gamma^2 N_p}{\sigma_x \sigma_z} \propto \frac{N_p}{\sigma_z \sqrt{\varepsilon_x}}$$

Length of interaction area: $$L_i \propto \sigma_x \propto \sqrt{\varepsilon_x}$$

Increase in ε_x can be compensated by increase in the linear bunch density N_p / σ_z

How this affects the beamstrahlung, which is the main limitation?

Increase in L_i => decrease in the hour-glass factor R_h and increase in the number of BS photons. The balance between luminosity and BS shifts towards BS. Since the luminosity is limited by BS lifetime, this leads to a decrease in the luminosity by 15-20%.

The optimum arc cell at W is 60° / 60°

RF 600-650 MHz at W, H, ttbar

W

RF frequency [MHz]	400	650
RF voltage [MV]	750	530
RF acceptance [%]	3.5	1.66
Momentum acc. [%]	±1.3	
Synchrotron tune [Q_z]	0.05	0.05

All other parameters are the same.

Important: $Q_z \geq 0.05$ is required for the energy calibration.

650 MHz is even better than 400.

H

RF frequency [MHz]	400	650
RF voltage [GV]	2	2
RF acceptance [%]	2.3	1.84
Momentum accept. [%]	±1.7	
Synchrotron tune [Q_z]	0.036	0.046
Bunch length [mm]	5.3	4.1
Bunch population [10^{11}]	1.8	1.4
Number of bunches	328	422

Q_x needs to be adjusted slightly, since Q_z has changed. No problems are expected.

ttbar

RF frequency [MHz]	400 + 800	650
RF voltage [GV]	4 + 6.9	10.75
RF acceptance [%]	3.36	3.55
Momentum accept. [%]	+2.4 / -2.8	
Synchrotron tune [Q_z]	0.087	0.087

All other parameters are the same.

4 IPs: Problems and Questions

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 and 1/3.
- 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 will lead to a decrease in $\xi_{x,y}$ and luminosity.
- We need to constantly perform the lattice corrections to minimize asymmetry. What is the acceptable margin of error? To answer, we need simulations in a realistic model with errors and their correction.

The lattice of FCC-ee is very sensitive to small orbit errors. Even a deviation of 0.1 mm leads to a noticeable beat of the beta functions.

Algorithms for global correction and emittance tuning were developed ($\rightarrow$ T. Charles). But correcting while maintaining 4-fold symmetry is more challenging. Work continues.

The next step: beam-beam simulations in such a lattice. Until that is done, it is difficult to make predictions about what luminosity can be expected with 4 IPs. We hope there will be some results by the end of this year.

Summary

- Potential problems associated with high currents, impedances, and collective instabilities have been found at low energy. To solve them, it was proposed to increase the momentum compaction factor.
- A new effect was discovered: transient beam loading + beamstrahlung lead to asymmetry in the colliding bunches and potential 3D flip-flop instability. This puts a limit on the permissible transient beam loading.
- The influence of changes in the RF frequency on the main parameters is estimated. Switching to 600-650 MHz should not cause problems at W, H and ttbar. Some problems are possible at low energy, but they can be solved by using 3rd harmonic cavities.
- We must take into account more and more factors and potential problems that were previously considered in less detail. So far, this has not led to a decrease in the declared luminosity, and we hope that it will remain so.

Thank you
for your attention.