COMBINED OPERATION AND STAGING FOR THE FCC-ee COLLIDER

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Abstract

FCC-ee is a proposed high-energy electron positron circular collider that might initially occupy the 100-km FCC tunnel which would eventually house the 100 TeV FCC-hh hadron collider. The parameter range for the $e^+e^-$ collider is large, operating at c.m. energies from 90 GeV (Z-pole) to 350 GeV ($\bar{t}\bar{t}$ production) with beam currents ranging between 1.5 A and 7 mA, at fixed synchrotron radiation power of 50 MW per beam, and the radiative energy loss varying from about 30 MeV/turn to 7500 MeV/turn. This presents challenges for the radiofrequency (rf) system due to the varying rf voltage requirements and beam loading conditions. In this paper we present a possible gradual evolution of the FCC-ee complex by step-wise expansion, and possibly reconfiguration, of the superconducting rf system and of the optics. The performance attainable at each step is discussed, along with possible advantages and drawbacks.

PHYSICS GOALS AND ENERGIES

The highest priority of a potential future $e^+e^-$ collider in the 100-km FCC tunnel is Higgs production at a centre-of-mass energy of about 240 GeV corresponding to the peak rate of $e^+e^- \rightarrow ZH$ events. The second FCC-ee priority is running on the $Z$ pole (91 GeV c.m.) with exceptionally high luminosity in order to generate $10^{12}-10^{13} Z$‘s over a couple of years. Further FCC-ee collision energies will be at the $\bar{t}\bar{t}$ threshold ($\sim 350$ GeV c.m.), at the $WW$ threshold, and possibly, with energy monochromatization, on the $e^+e^- \rightarrow H$ resonance ($\sim 125$ GeV). The baseline physics program assumes no longitudinal polarization. However, scaling from LEP experience, some transverse polarization of non-colliding bunches is expected at the $Z$ and up to the $WW$ threshold, which can be used for precise calibration of the beam energy.

PARAMETERS AND OPERATION MODES

The number of FCC-ee interaction points (IPs) could be 2 or 4. A model used to describe the performance of LEP [1] suggests that with two collision points the maximum beam-beam tune shift and the luminosity per IP could be about 40% higher than with four collision points. However, the collision conditions for many of the FCC-ee scenarios are rather different from those at LEP. Preliminary weak-strong simulations for FCC-ee indicate a weaker dependence on the number of IPs, i.e. only a 10–20% gain in the maximum beam-beam tune shift at 240 GeV c.m. with 2 instead of 4 IPs [2] and even less (or no) gain at 91 GeV c.m. However, our further discussion assumes two IPs.

For constant synchrotron radiation power, e.g. 50 MW per beam, at lower beam energy the beam current increases as the inverse fourth power of energy. The much higher beam current at lower energy implies a correspondingly increased number of bunches.

Indeed, the requirements on the rf system differ substantially at low and high energies. On the $Z$ pole the beam current is about 1.5 A, but the energy loss per turn only some 30 MeV and the rf voltage required is moderate. The cavity impedance is a concern for this mode of operation [3]. In consequence, the smallest number of cavities which can still provide $2 \times 50$ MW to the beams would be desired. Conversely, when running at the $ZH$ peak or at the $\bar{t}\bar{t}$ threshold the beam current is much lower, 30 or 7 mA, but the energy loss per turn amounts to 1.7 or 7.6 GeV, respectively, calling for a total rf voltage of up to 11 GV. Because of the lower beam current and higher beam energy, the cavity impedance is less of a concern here. Therefore, a staging where cavity modules are installed in steps appears natural.

The geometric emittance from the arcs scales as $\theta_b^2 \gamma^2$ [4], where $\theta_b$ denotes the bending angle per arc cell and $\gamma$ the Lorentz factor. The natural emittance decrease at lower energy can be counteracted by choosing longer optical cells in the arcs. The baseline parameter set of FCC-ee [5] assumes a 50-m arc FODO cell length, required for $ZH$ and $tt$ running, a 100 m cell length for the $WW$ threshold and a 300-m cell length at the $Z$ pole [6]. The increased cell length at lower energies allows for the geometric emittance to stay roughly constant or even to increase, at similar bunch charge, in order for the beam-beam tune shift to remain at, or below, the expected energy-dependent limit [1].

If the cell length is held constant, equal to 50 m, at the lower beam energies the emittance shrinks substantially. In this case the beam-beam tune shifts can still be kept under control, however, with the help of a large crossing angle, complemented by crab-waist sextupoles. In such a crab-waist scenario, the luminosity at the $Z$ pole is about an order of magnitude higher than for the baseline [7]. The low-emittance crab-waist running implies extremely small vertical emittance values. Table 1 compares some example parameters (based on analytical calculations, and not fully optimized) for the proposed schemes at two beam energies.

It may be possible to further reduce the rf voltage, much
below the values shown in the table, in order to lengthen
the bunches. E.g., by choosing 200 or 80 MV instead
of 400 MV at the Z pole, the rms bunch length for the
crab-waist scheme without beamstrahlung (non-colliding
beams) would exceed 1.6 or 2.5 mm, respectively. Longer
bunches would reduce the excitation of higher-order modes
and the energy-loss factor for the rf cavities.

Table 1: Parameters for FCC-ee running at 91 GeV (Z)
and 240 GeV (ZH) centre-of-mass energy, considering
two IPs, a ring circumference of 100 km, and an rf fre-
quency of 400 MHz. ‘CW’ refers to crab waist, ‘SR’ to
synchrotron radiation, ‘BS’ to beamstrahlung. The bunch
length with beamstrahlung is calculated by solving an ap-
proximate self-consistent analytical equation [13]. The
baseline and crab-waist parameters roughly correspond
to those proposed in Refs. [5] and [7] [modified so as to
correspond to the 120/175-GeV arc optics parameters of Ref. [5]], respectively.

<table>
<thead>
<tr>
<th>beam energy [GeV]</th>
<th>base</th>
<th>CW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>beam current [A]</td>
<td>1.45</td>
<td>1.45</td>
</tr>
<tr>
<td>energy loss / turn [GeV]</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>rf voltage [GV]</td>
<td>2.5</td>
<td>0.4</td>
</tr>
<tr>
<td>mom. comp. [10⁻⁵]</td>
<td>18</td>
<td>0.5</td>
</tr>
<tr>
<td># bunches / beam</td>
<td>13k</td>
<td>60k</td>
</tr>
<tr>
<td>βₙₓ [m]</td>
<td>2.4</td>
<td>0.5</td>
</tr>
<tr>
<td>βₙᵧ [mm]</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>εₓ [mm]</td>
<td>29</td>
<td>0.13</td>
</tr>
<tr>
<td>εᵧ [pm]</td>
<td>60</td>
<td>1</td>
</tr>
<tr>
<td>σₓ (SR only) [mm]</td>
<td>3.3</td>
<td>1.0</td>
</tr>
<tr>
<td>σᵧ (with BS) [mm]</td>
<td>3.8</td>
<td>2.8</td>
</tr>
<tr>
<td>θₓ [mrad]</td>
<td>11</td>
<td>30</td>
</tr>
<tr>
<td>b.-b. param. ξₓ/ IP</td>
<td>0.04</td>
<td>0.07</td>
</tr>
<tr>
<td>b.-b. param. ξᵧ/ IP</td>
<td>0.07</td>
<td>0.18</td>
</tr>
<tr>
<td>Piwinski angle</td>
<td>0.17</td>
<td>5.3</td>
</tr>
<tr>
<td>lum./IP [10³⁴ cm⁻² s⁻¹]</td>
<td>27</td>
<td>247</td>
</tr>
</tbody>
</table>

Figure 1: Luminosity per IP vs. full crossing angle. The stars indicate the operation points of Table 1.

Achieving the target emittance values may be chal-
lenging, given the size of the ring (with misalignments),
the presence of beam-beam collisions, the effects of syn-
chrotron radiation etc. In particular, for the crab waist
scheme the 30-mrad crossing angle can lead to signif-

Figure 2: Beam-beam parameter per IP vs. full crossing angle. Solid lines: ξₓ, dashed: ξᵧ. The stars indicate the operation points of Table 1.

The rf system naturally lends itself to staging, i.e., it can

GRADUAL EVOLUTION AND STAGING

The low-emittance crab-waist scheme is most interest-
ing at the Z pole, where the luminosity gain is maximum
[7]. Table 2 shows three possible stages at this energy, il-
lustrating the transition from less challenging parameters
to a crab-waist scheme. The transition is characterized by de-
creasing emittances (corresponding to FODO cell lengths
of 300 m, 100 m and 50 m, respectively), reduced βᵧ∗, in-
creasing number of bunches, and growing luminosity. The constant crossing angle of 20 mrad was chosen as an inter-
mEDIATE value between the two scenarios of Table 1, where
the Piwinski angle is still larger than 2 at the smallest hor-
izontal emittance considered. The RF voltage of only 0.2
GV may allow for a total cavity impedance compatible with
the desired high beam current. The table illustrates that
by reducing the arc emittance and simultaneously changing
the bunch filling pattern the luminosity can be increased by
an order of magnitude. Therefore, as the orbit control and
emittance tuning of FCC-ee improve, operational stages on
the Z pole could, or should, proceed towards shorter arc
cell lengths.

The rf system naturally lends itself to staging, i.e., it can

1: Circular and Linear Colliders

A02 - Lepton Colliders
Table 2: Example stages at 91 GeV c.m., with a constant crossing angle of 20 mrad and varying emittance. The luminosity numbers are still to be confirmed by simulations.

<table>
<thead>
<tr>
<th>beam energy [GeV]</th>
<th>45.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam current [A]</td>
<td>0.7  (1.45) 1.45 1.45</td>
</tr>
<tr>
<td>rf voltage [GV]</td>
<td>0.2  0.2 0.2</td>
</tr>
<tr>
<td>arc cell length [m]</td>
<td>300 100 50</td>
</tr>
<tr>
<td>mom. comp. [10^{-5}]</td>
<td>18 2 0.5</td>
</tr>
<tr>
<td>(\beta^*_x) [mm]</td>
<td>3 1 1</td>
</tr>
</tbody>
</table>

The possibility of a special run with mono-chromatic collisions [15] on the \(e^+e^- \rightarrow H\) resonance is also indicated in Table 3. A large horizontal IP dispersion (e.g. \(D^*_x \approx 2 \text{ m}\)) would yield a relative c.m. energy spread of \(\sim 10^{-5}\), i.e. 3 times smaller than the standard-model width of the Higgs boson. The luminosity value quoted with a question mark in Table 3 accounts for the dispersive contribution to the horizontal IP beam size, but does not consider any horizontal emittance growth due to the combined effect of IP dispersion and beamstrahlung beyond a factor \(\sim 2\) margin included in the FCC-ee optics design. The generation of the large IP dispersion (in a dedicated IP?) as well as the possibly large emittance growth caused by beamstrahlung with \(D^*_x \neq 0\) [16] requires further investigation.

Table 3: Example operational stages of FCC-ee. The total crossing angle is held constant, equal to \(\theta_c = 20\) mrad.

<table>
<thead>
<tr>
<th>stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(V_{rf,\text{max}}) / beam [GV]</td>
<td>2.7</td>
<td>5.5</td>
<td>5.5</td>
<td>11</td>
</tr>
<tr>
<td>(P_{rf}) / beam [MW]</td>
<td>25</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>(\beta^*_y) [mm]</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>arc cell length [m]</td>
<td>300</td>
<td>100</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>(L/\text{IP} [10^{34} \text{ cm}^{-2}s^{-1}])</td>
<td>8</td>
<td>68</td>
<td>134</td>
<td>—</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Staging the FCC-ee could save time or money. A staged construction could also improve the performance, e.g. by minimizing the impedance at low energy. Staging might as well profit from growing operational experience. Many types of staging are possible, e.g. a stage could be equal to the operation at a single beam energy — an obvious option, which we have not considered in this paper.

As an illustration of a more complex scheme, we have presented a combined staging scenario for the collider-ring optics and rf systems, which allows for interesting physics in each stage, and which renders the machine operation and optics tuning gradually more challenging. In this example, the crossing angle is held constant for all stages and energies. Between stages 1 and 2 additional rf units are installed, e.g. during an annual winter shutdown. If helpful also arc quadrupoles could be added in the stops between stages, since, e.g. the first stage requires 6 times fewer quadrupoles in the arc than the final stage. The step from stage 3 to stage 4 requires a reconfiguration of the rf system, e.g. transverse movements of the rf cavities by tens of centimetres, plus, probably, the installation of electrostatic combiners and separators at the entrance and exit of each rf straight section.
REFERENCES


