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# FCC-ee Pre-Booster Accelerators

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**Abstract**
CERN's ambitious new project, Future Circular Collider-ee, will have four operations as $Z, W, H$, and $tt$ factories covering energies from 45.6 to 175 GeV. The main challenge of $Z$-operation is to achieve currents as high as 1450 mA; this will depend heavily on the injector. For this reason, we conclude that we need a high bunch charge of $3.3 \times 10^{10}$, for both $e^-$ and $e^+$, and fill 91 500 of each of those bunches into the collider. To achieve the goal, we have designed an S-band (2.856 GHz) normal conducting electron linac up to 6 GeV, which we will use to create and accelerate both electrons and positrons. Positrons will be created inside the linac at 4.46 GeV, will be accelerated up to 1.54 GeV at the linac, and will then be transferred to the designed damping ring. In this paper, we present the designed linac, damping ring, and the operational requirements of the 100 km booster.

**Keywords**
Future circular collider; damping ring; linac; filling scheme; injection time schedule; positron injector.

## 1 Introduction

The Future Circular Collider (FCC) is a prospective future project of CERN, and is meant to be the successor of the Large Hadron Collider. The FCC has three different sub-projects for lepton–lepton, hadron–hadron, and hadron–lepton collisions. In this paper, we would like to discuss the FCC-ee which is going to collide positrons and electrons ($e^+e^-$) via four main operations. The FCC-ee is going to serve as a precision machine with high luminosity by colliding leptons with different energy ranges while varying the bunch population and the number of bunches, as demonstrated in Table 1.

The FCC-ee pre-injectors consist of three main parts: a linac, a damping ring, and a pre-booster. These pre-injectors will be followed by a 100 km booster, which would fill the 100 km collider as a top-up injector. Pre-injectors are designed in such a way as to cover all the operations. The linac is crucial to supply the total charge needed. The total charge is the number of bunches per beam multiplied by the bunch population, which is a maximum for the $Z$-operation, whereas the $Z$-operation requires the smallest geometric emittance. Therefore, if the pre-injectors can provide the total charge and smallest geometric emittance required for $Z$-operation, then it can be safely said that the pre-injectors can cover all operations, excluding the final energy, which will be a matter for the pre-booster or booster, which is beyond the scope of this paper.

**Table 1:** FCC-ee baseline parameters

| Operation type | $Z$ | $W$ | $H$ | $tt$ |
|---|---|---|---|---|
| Final energy (GeV) | 45.6 | 80 | 120 | 175 |
| Number of bunches per beam | 91 500 | 5260 | 780 | 81 |
| Bunch population | $3.3 \times 10^{10}$ | $6 \times 10^{10}$ | $8 \times 10^{10}$ | $1.7 \times 10^{11}$ |
| Horizontal emittance (nm) | 0.09 | 0.26 | 0.61 | 1.3 |
| Vertical emittance (pm) | 1 | 1 | 1.2 | 2.5 |

 
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**Table 2:** Emittance evolution for electron flow [1]

| Location | Energy (GeV) | $\epsilon_{\mathrm{geo},x}$ (nm) | $\epsilon_{\mathrm{geo},y}$ (nm) |
|---|---|---|---|
| Collider aims | 45.6 | 0.09 | 0.001 |
| Collider accepts | 45.6 | 27.3 | 2 .0 |
| Booster exit | 45.6 | 0.09 | 0.13 |
| Booster entrance | 6 | 0.7 | 1.0 |
| Linac exit | 6 | 0.7 | 1.0 |
| Linac entrance | 0.012 | 350 | 500 |

Pre-injectors are to operate alternatively to create and accelerate electrons and positrons. An electron linac of 6 GeV has been designed, and positrons will be created at 4.46 GeV of the linac. These positrons will be accelerated in the rest of the linac, 1.54 GeV, and then delivered to the damping ring. The acceleration of the damped positrons is continued at the linac by re-injection at an energy of 1.54 GeV and the positrons are accelerated up to 6 GeV. As a result, the electrons and positrons are at the same energy and emittance when they are transferred directly to the 100 km booster without an intermediate booster in the case of $Z$-operation.

All the designs and simulations are made using SAD (Strategical Accelerator Design) [2], which has proven successful in the design and commissioning of many linear and circular accelerators. However, before the designs can be prepared, a discussion of the evolution of the emittance throughout the accelerators is of great importance in determining the initial parameters. The values in Table 2 have been calculated by assuming that the normalized emittances are to be conserved at approximately 8/12 µm (hor/vert) throughout the electron acceleration at the pre-boosters.

### 1.1 The first fill of accelerators

A well-planned time schedule is necessary for the pre-injection complex, owing to the multi-use of accelerators. The booster fill time is suggested as 4 s, plus 6 s for the acceleration of the available bunches. The electrons are injected within a frequency $f = 100$ Hz from the linac as two bunches per RF pulse; the repetition is chosen to be easily feasible in current technology. Therefore, the booster will accumulate and accelerate 800 bunches to the designated energy in each 10 s period. Firstly, the electron bunches are accumulated in the collider, which is filled with 92 000 bunches in about 19 min. Secondly, the positrons would arrive late because they follow a different path, owing to their creation and re-transfer to the linac; in addition, they have to go through the damping ring. The time schedule also determines the available time to reach the designated emittance for the positrons, therefore we have decided to follow the schedule outlined in Table 3.

This scheme continues with a periodicity of $T = 20$ ms, finally reaching 400 bunches in 4050 ms. What is important is that each pair of bunches of positrons spends 50 ms inside the damping ring.

## 2 Linac

An S-band normal conducting linac operating at 2855.98 MHz will work with a repetition of 100 Hz. The RF frequency was chosen based on previous experience using that famous frequency. Some parameters of the linac are shown in Table 4.

The cavities and their wakes are taken from KEK-ATF [3], with a length of 2.97 m (27 $1/3$ wavelengths), having an aperture size of 11 mm at the entrance and 9 mm at the exit to keep the field uniformity inside the cavity. The linac will accelerate $4 \times 10^{10}$ particles per bunch, which is intentionally more particles than the full charge for $Z$-operation presented in Table 1, leaving margin for probable transmission loss throughout the linac. The initial emittance of the electrons is taken from Table 2, and we assume a

**Table 3:** Time schedule of the positrons in FCC-ee pre-injectors

| RF time (ms) | Linac | Damping ring | Booster |
|---|---|---|---|
| 0–20 | 2 bunches of $e^-$ | 2 bunches of $e^+$ | Empty |
| 20–40 | 2 bunches of $e^-$ | 4 bunches of $e^+$ | Empty |
| 40–50 | 2 bunches of $e^-$ | 6 bunches of $e^+$ | Empty |
| 50–60 | 2 bunches of $e^+$ | 4 bunches of $e^+$ | 2 bunches of $e^+$ |
| 60–70 | 2 bunches of $e^-$ | 6 bunches of $e^+$ | 2 bunches of $e^+$ |
| 70–80 | 2 bunches of $e^+$ | 4 bunches of $e^+$ | 4 bunches of $e^+$ |
| 80–90 | 2 bunches of $e^-$ | 6 bunches of $e^+$ | 4 bunches of $e^+$ |
| 90–100 | 2 bunches of $e^+$ | 4 bunches of $e^+$ | 6 bunches of $e^+$ |
| 100–110 | 2 bunches of $e^-$ | 6 bunches of $e^+$ | 6 bunches of $e^+$ |

**Table 4:** Linac design parameters

| Parameter | Value |
|---|---|
| Initial energy (MeV) | 12 |
| Final energy (GeV) | 6 |
| Length (m) | 257.3 |
| Initial geometric emittance (h/v) (μm) | 0.35/0.5 |
| Final geometric emittance (h/v) (nm) | 0.7/1.0 |
| Number of cavities | 80 |
| Gradient (MV/m) | 25 |
| Gradient through accelerator (MV/m) | 23 |

Gaussian beam for the simulation of the beam envelope; the resulting optics are presented in Fig. 1.

The beam profile of the designed linac has a two-horn distribution in the energy dispersion graph, as shown in Fig. 2, because of the wakefields and because the RF phase is chosen as $-94°$. In addition, the acceleration gradient has been kept low, such that the SLED [4] scheme can be applied and the energy difference between the two bunches in the same RF pulse is also low. The linac elements are tightly allocated for the time being. Some errors are to be introduced in cavity, quadrupole and injection alignments to study robustness of the linac. Therefore, as some beam diagnostic elements are introduced and the orbit correction study continues to keep the transmission high, the designed linac will extend and evolve.

## 3 Damping ring

The positrons will be created by colliding 4.46 GeV electrons with crystalline and amorphous targets. The positrons' emittance and energy spread would be high as a result of this statistical process; therefore, a damping ring is needed to match the conditions of the electrons for the collisions. After an adiabatic matching section and an energy compressor, we assume that we will produce an emittance compatible with KEKB [5] at the entrance of the damping ring. To produce an initial kick, we adopt the parameters for the SuperKEKB, provided by Iida and Miyahara (KEK), to our bunch charge and energy; the damping necessity of the FCC-ee pre-injection system will then evolve as in Table 5.

The damping ring must have a very low natural emittance, down to 1 nm; meanwhile, the damping time should be small, such that damping from the micrometre to the nanometre level can occur in less than 50 ms. However, a very large dynamic aperture is a fundamental necessity, since there are orders of magnitude difference in the emittance values of the incoming and outgoing beams. Another issue is the bunch spacing, which is again chosen to be easily feasible; the bunch separation is determined to be

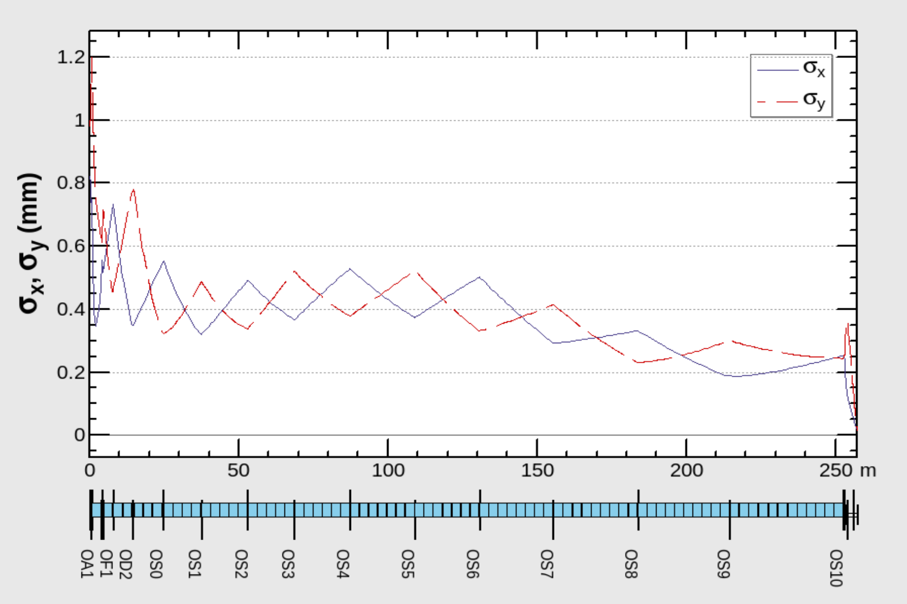



**Fig. 1:** Linac optics

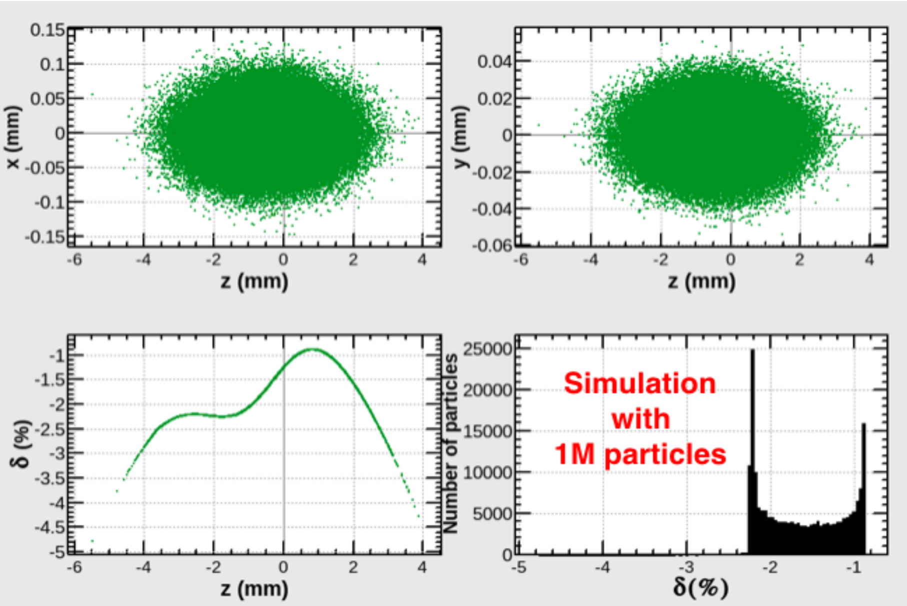


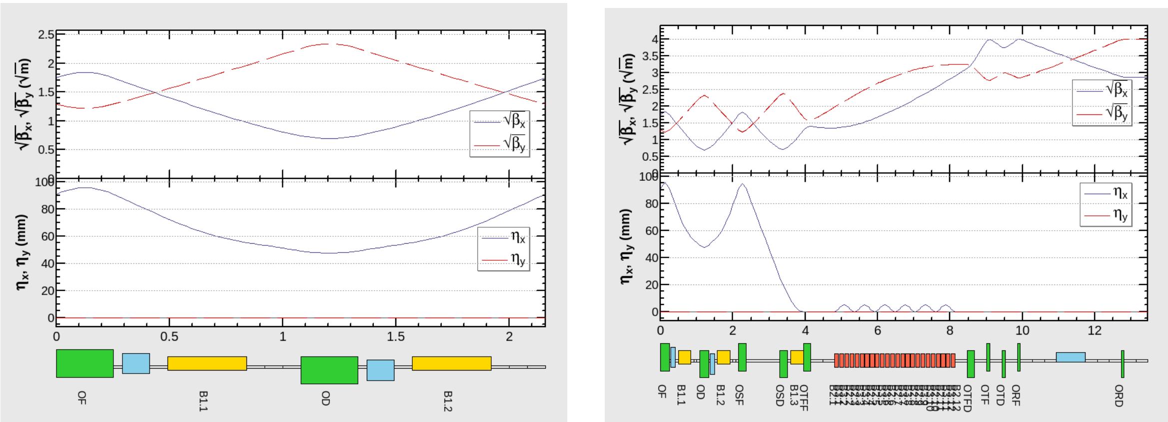

**Fig. 2:** Linac beam profile

**Table 5:** Emittance evolution for positron flow

| $e^+$ accelerators | Energy (GeV) | $\epsilon_{\mathrm{geo},x}$ | $\epsilon_{\mathrm{geo},y}$ |
|---|---|---|---|
| Damping ring entrance | 1.54 | 0.76 µm | 0.71 µm |
| Damping ring exit | 1.54 | 2.66 nm | 3.9 nm |
| Booster exit | 45.6 | 0.09 nm | 0.13 nm |
| Collider aims | 45.6 | 0.09 nm | 1 pm |

**Table 6:** Damping ring design parameters

| Parameter | Value |
|---|---|
| Energy (GeV) | 1.54 |
| Number of trains | 3 |
| Bunches per train | 2 |
| Circumference (m) | 178.6 |
| Number of cells | 60 |
| Dipole field (T) | 0.74 |
| Bending radius (m) | 6.96 |
| Kicker time (ns) | <300 |
| Bunch spacing (ns) | 99 |
| $\tau_x$ (ms) | 10.6 |
| $\tau_y$ (ms) | 11.2 |
| Horizontal natural emittance (nm) | 1.7 |
| Vertical natural emittance | – |




(a) FODO lattice unit cell

(b) Dispersion suppressor

**Fig. 3:** Damping ring sections (horizontal axis in m)

around 100 ns for any two consecutive bunches in the damping ring. Some parameters of the damping ring are shown in Table 6.

The damping ring consists of two arcs and two straight sections linking these arcs; each arc consists of 30 FODO cells. The tune values per unit cell are 0.311 rad horizontally and 0.125 rad vertically. The spacing between the elements in the unit cell is optimized individually, as shown in Fig. 3(a). The straight sections are dispersion suppressors and have 3.36 m long normal conducting 1.74 T wigglers. The dispersion suppressor is shown in Fig. 3(b). Finally, the damping ring, shown in Fig. 4, has around 1 nm of natural emittance horizontally and about 11 ms of damping time in both planes. According to Eq. 1, the damping necessities stated in Table 5 can be reached well below 50 ms:

$$\epsilon(t) = \epsilon_{\mathrm{inj}} \mathrm{e}^{-2t/\tau} + \epsilon_{\mathrm{nat}} (1 - \mathrm{e}^{-2t/\tau}) \,. \tag{1}$$

## Conclusions

The linac is normal conducting with a length of 257.3 m, deploying 80 cavities and 22 quadrupoles, with modest and achievable requirements. Furthermore, some dipoles and beam diagnostic elements will be included in the next phase of the study.

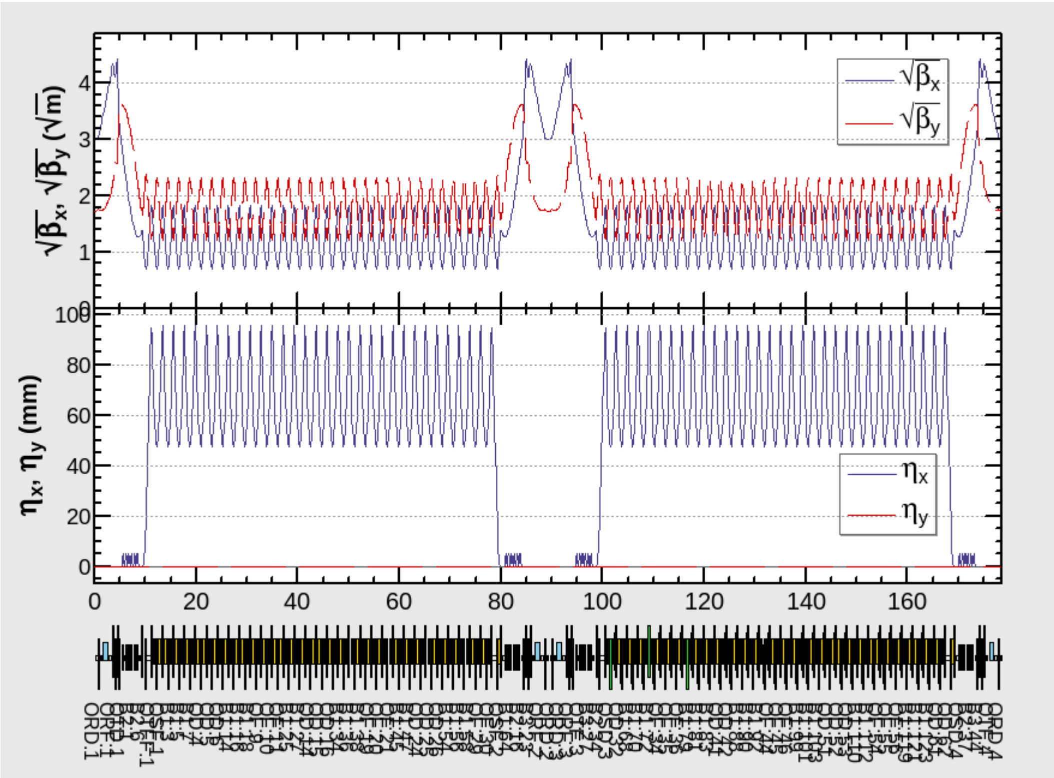



**Fig. 4:** Damping ring optics

The dynamic aperture of the damping ring is continuously being enhanced, even though we have already surpassed 60 sigmas in the transverse axis, which is sufficient to accept 99% of the positrons, based on experience with KEK positron data [5]. However, additional work is still required to enlarge the dynamic aperture to outstretch the expected shrink in dynamic aperture, owing to probable misalignment errors.

Accelerating more than two bunches per RF pulse is also under consideration, since it is intended to reduce the fill time from the beginning. Conclusively, the scheme presented would enable the collider to be filled with 91 500 bunches of electrons in 19 min, and 91 500 bunches of positrons in 27 min.

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