PRELIMINARY DESIGN OF FCC-ee PRE-INJECTOR COMPLEX*

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Abstract

The design of a 100 km circular e^+e^- collider with extremely high luminosity is an important component of the global Future Circular Collider (FCC) study hosted by CERN. FCC-ee is being designed to serve as Z, W, H and top factory, covering beam energies from 45.6 to 175 GeV. For the injectors, the Z-operation is the most challenging mode, due to the high total charge and low equilibrium emittance in the collider at this energy. Thus, fulfilling the Z-mode will also meet the demands for all other modes of FCC-ee. This goal can be achieved by using a 6 GeV NC linac with an S-band RF frequency of 2.856 GHz and a repetition rate of 100 Hz. This linac will accelerate two bunches per RF pulse, each with a charge of 6.5 nC. Positrons will be generated by sending 4.46 GeV e^- onto a hybrid target so that the e^+ created can still be accelerated to 1.54 GeV in the remaining part of the same linac. The emittance of the e^+ beam will then shrink to the nm level in a 1.54 GeV damping ring. After damping, the e^+ will be reinjected into the linac and accelerated to 6 GeV. The e^- and e^+ will then be accelerated alternately to 45.6 GeV in the booster, before they are injected into the collider.

INTRODUCTION

In a 100 km circular tunnel, the FCC will host a lepton-lepton, a hadron-hadron, and a lepton-hadron colliders, respectively as the project evolves. Among those, the FCC-ee will provide e^+e^- collisions at high luminosity in order to enable precision studies of several fundamental elementary particles, such as the Z and W bosons, the Higgs boson and the top quark. The FCC-ee baseline parameters depend on the particle type to be produced and the associated beam energy [1].

Table 1: FCC-ee Baseline Parameters on the Z Pole

parameter	value
beam energy	45.6 GeV
luminosity	0.9×10^{36} cm^{-2}s^{-1}
no. bunches / beam	91500
bunch population	3.3×10^{10}
horiz., vert. emittance	90, 1 pm

The injector design has focused on supplying the beam required for operation on the Z pole, where the luminosity and beam current are the highest, and the emittance the lowest. These parameters are shown in Table 1. Producing the heavier particles (W, H and $t\bar{t}$) requires a higher extraction energy of the booster, but lower beam intensity from the injector.

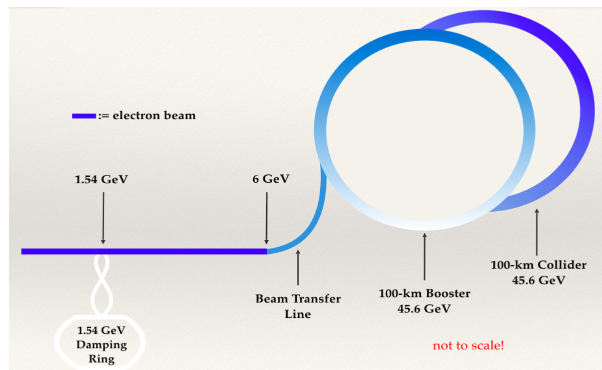

Figure 1: FCC-ee electron flow scheme for Z-pole operation. Electrons, accelerated in the linac up to 6 GeV, will be directly injected into the top-up booster, which will further raise their energy to 45.6 GeV, suitable for transfer to the collider. If the electron emittance is acceptable without DR, the latter may stay idle during the e^- beam delivery.

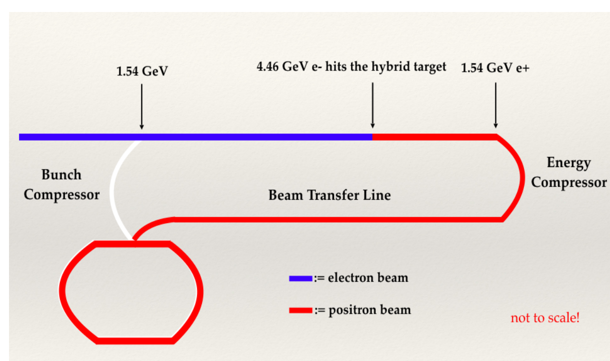

Figure 2: FCC-ee positron flow scheme for the Z-pole operation. The same linac and the same DR (if employed) as for e^- are used for e^+. Hence, electrons at 4.46 GeV in the linac hit a hybrid e^+ target [2], generating positrons. The remaining portion of the 6 GeV linac will accelerate the captured e^+ to 1.54 GeV. These positrons are then sent through an energy compressor and transferred to the 1.54 GeV DR. After radiation damping, the positrons will be sent back to the linac, via a bunch compressor section, so as to finally also reach 6 GeV, when they can be injected into the top-up booster.

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In this paper we do not discuss the detailed design of the booster [3] or of a possible pre-booster [4], but we focus on the upstream linac and damping ring (DR), whose energies will stay fixed for all modes of operation. The performance of linac and DR has been simulated and optimized using the code SAD [5].

The design of the FCC-ee pre-injector is based on available accelerator technology and aims at achieving target performance with minimum cost. Alternatively, CLIC injector parameters can also be considered [6]. A normal-conducting linac operating up to 6 GeV can meet the objectives. An S-band frequency of 2.856 GHz has been chosen for the linac radiofrequency cavities, in line with existing large S-band linacs (such as SLAC, Pohang, KEK), so as to profit from the available infrastructure and experience.

Recent design effort has considered direct injection of 6 GeV e^+ and e^- into the 100 km top-up booster; the latter would further accelerate these particles to the collider energy (45.6 GeV for Z operation). The corresponding electron flow scheme is depicted in Fig. 1. Alternative options would be extending the linac to 10 GeV or adding a pre-booster [4] covering an intermediate range from 6 to 20 GeV. This paper will consider the option of 6 GeV linac, the creation of positrons at 4.46 GeV inside the same linac, and a damping ring of 1.54 GeV, as shown in Fig. 2.

FCC-ee will accumulate up to about 90,000 e^- and e^+ bunches in less than 1 hour [7]. Using the same accelerators alternately for e^+ and e^- results in a tight time schedule for the injector. Still, for the schedule developed, each positron would spend 50 milliseconds inside the DR.

6 GeV S-BAND LINAC

We have designed the optics of a normal conducting linac as shown in Fig. 3 and listed the design parameters in Table 2. This linac comprises two types of accelerating structures: 1) large aperture cavities (diameter 40 mm) with a module length of 1.50 meter; 2) narrow aperture cavities (20 mm) with a module length of 2.97 meter.

Table 2: Linac Design Parameters

Parameter	Value
injection-extraction energy	12 MeV-6 GeV
initial emittance (x/y)	0.35/0.5 μm
final emittance w/o blowup (x/y)	0.7/1.0 nm
linac repetition	100 Hz
bunch charge, bunches/RF pulse	6.5 nC, 2
unloaded cavity gradient	≤ 26 MV

Tracking simulations were set up including both transverse and longitudinal wakefields [8]. Quadrupoles and cavities are randomly displaced according to a Gaussian distribution with an rms misalignment of 0.1 mm. Also a random injection error of 0.1 mm and 1 mrad rms is considered. Beam position monitors are taken to be attached to the entrances and the exits of the accelerating structures. Simulations were performed for 10^6 macro-particles with

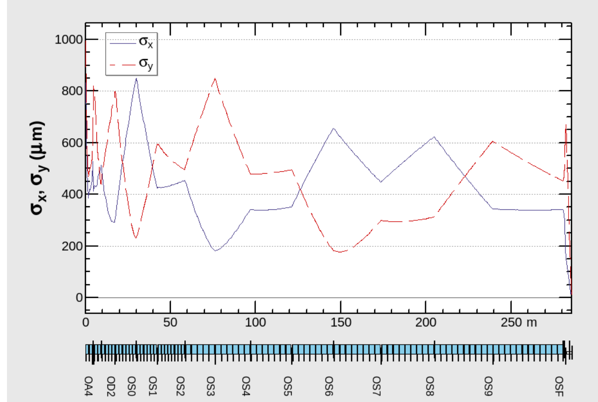

Figure 3: Linac optics including pairs of steerers for correcting the wakefield effects due to random misalignments. Up to 1.1 GeV 28 larger-aperture cavities are deployed to reduce the impact of the wakefields. These are followed by 64 smaller-iris 3 m long accelerating structures.

a Gaussian distribution in all planes, and an rms length of σ_z =1 mm. Although at most 3.3×10^{10} e^+ and e^- per bunch are required if a full collider bunch is to be injected in a single shot, the initial bunch population is taken to be even higher, namely 4.0×10^{10} (i.e. 6.5 nC) per bunch, to introduce a margin for downstream losses.

Introducing misalignment and injection errors dramatically changes the optics and the transmission [9]. Emittance blow up and beam loss are mitigated by steering magnets and by the larger-aperture cavities. Pairs of adjacent steering correctors are used to execute an automatic orbit correction, so as to steer the beam to the cavity center, controlling both position and angle. The tracking was carried out for many random seeds. The emittance blow up is always smaller than a factor of ten, and the transmission above 95%. As an illustration, the beam profile for one random seed is displayed in Fig. 4. In this example, the transmission is 100% at 6 GeV, the transverse (x/y) emittances are 2.3/5.0 nm, i.e. a few times higher than the emittances expected without any blow up, see Table 2. However, this blow up can be damped in the booster in 1 sec or, possibly, in the DR in few ms.

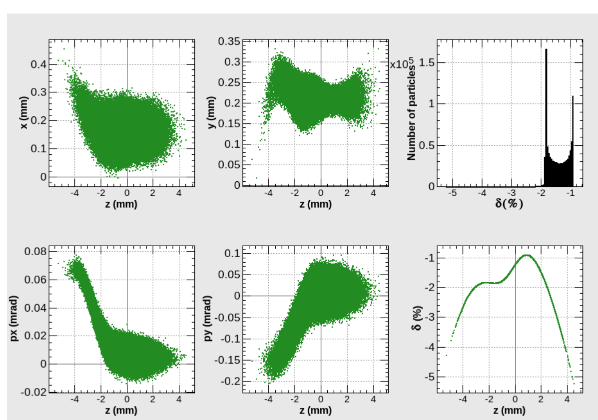

Figure 4: Linac beam profile at 6 GeV, after orbit steering.

1.54 GeV DAMPING RING

The positron creation by high-energy electrons hitting a target inevitably results in a huge energy spread and large transverse emittance. A damping ring is required to reduce the e^+ emittance by about 3 orders of magnitude.

The positron production and positron transport from the target up to the damping ring has been modelled using KEK e^+ software [10], and assuming the relevant FCC-ee parameters.

Table 3 shows the main DR parameters. The design goal was to minimize natural emittance and damping time. The DR can host up to 6 bunches, or 3 trains of 2 bunches, with 121 nanoseconds of separation between any two bunches. This bunch separation enables a kicker to ramp up, flatten and ramp down, with a total duration of less than 363 ns. The kicker pulse should have a plateau lasting more than 121 ns such that trains consisting of two bunches can be injected or extracted. The injection and extraction will happen in the same straight section of the DR, possibly sharing a kicker. Each positron bunch experiences 50 ms of damping [7].

Table 3: Damping Ring Design Parameters

parameter	value
energy	1.54 GeV
circumference	217.6 m
no. trains, bunches/train	3, 2
bunch charge, spacing	6.5 nC, 121 ns
no. of cells in arc, cell length	49, 1.56 m
FODO cell phase advance (x/y)	69.5/66.1 deg
betatron tune (x/y)	21.19/20.14
natural emittance (x/y)	1.00/- nm
damping time (x/y)	10.4/10.7 ms
bending radius, wiggler field	7.1 m , 1.66 T
RF voltage, frequency	5 MV, 400 MHz

The DR consists of 2 straight sections housing in total 4 wigglers of 6.64 m length each. One of the straight sections also contains a 8.56 m of drift space reserved for injection/extraction and the opposite section hosts two LHC-type 400 MHz superconducting cavities of 1.5 meter length (3.5 m with cryostat). The DR optics is displayed in Fig. 5.

The dynamic acceptance of the DR simulated over two damping times, $2 \times \tau_x = 20.8$ ms (i.e. 28900 turns), and including synchrotron radiation, is presented in Fig. 6.

The DR performance is summarized in Table 4. The positron emittance can be damped from about 1 μm down to approximately 1 nm in 50 ms (i.e. about 5 damping times), that is indeed better than required. In other words, even if the emittance of the e^+ injected into the DR were a few times larger, one could still obtain the target emittance; see Table 4.

CONCLUSIONS

The 6 GeV S-band linac promises a nearly perfect transmission. Transverse wakefields increase the normalized emittance by a factor of a few, which seems acceptable. The linac is 285.5 meters long; the cavity gradient ≤26 MV/m, for all cavities. Positrons must be cooled in the 1.54 GeV damping ring. Optionally, the electron beam can also be passed through this DR. Without errors the DR as designed has a dynamic aperture of ≥ 100σ in both transverse and longitudinal directions.

Near-term plans include acceleration of more bunches per RF pulse to reduce the first fill time, linac simulations with BPM errors, optics models of all transfer lines and compressors, a baseline configuration for the e^+ source [11] and the design of an e^- RF gun with 0.35/0.50 μm (x/y) emittance at 12 MeV [12].

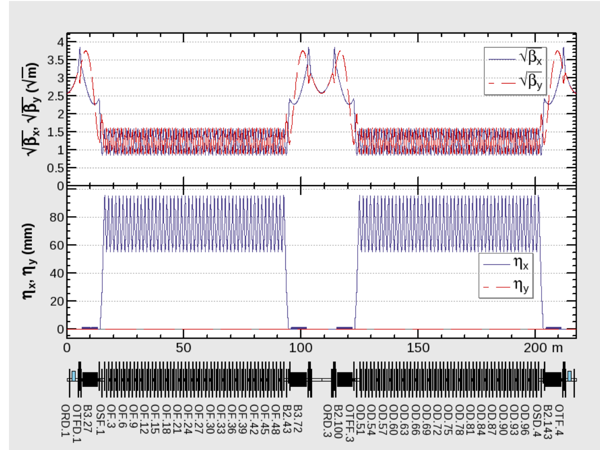

Figure 5: Damping ring optics.

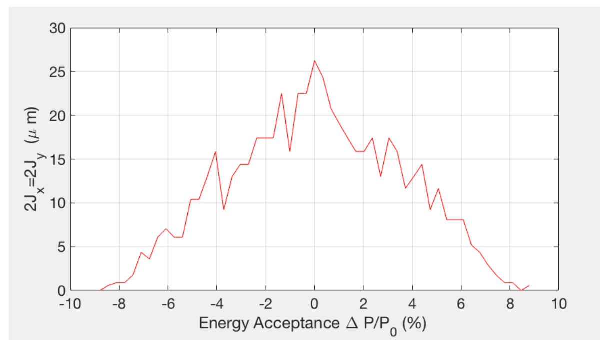

Figure 6: Simulated dynamic acceptance of the damping ring calculated over two damping times.

Table 4: Damping Ring Performance Without Errors

parameter	value
natural emittance (x)	1.00 nm
dynamic aperture	162 σ_x
longitudinal natural emittance	1.29 μm
longitudinal dynamic aperture	± 125 σ
energy acceptance	±8.1 %
bucket height	8.3 %
energy spread	6.76 $\times 10^{-4}$
injected emittance (x/y)	0.76/0.72 μm
extracted emittance (x/y)	1.07/0.07 nm
target emittance (x/y)	2.66/3.90 nm

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[11] Collaboration with I. Chaikovska and R. Chehab (LAL) and P. Martyshkin (BINP).

[12] One RF gun design study for FCC-ee is being performed by A. Levichev, D. Nikiforov and colleagues at BINP. Another study was done by S. Polozov and colleagues at MEPhI.