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DESIGN OF THE FCC-ee INJECTOR LINACS UP TO 20 GeV BEAM ENERGY*

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Abstract

The FCC-ee injector complex aims to deliver tunable, high-charge electrons and positron bunches for injection into a collider operating at center-of-mass energies from 90 to 365 GeV. The injector complex includes multiple linacs that sequentially boost the energy of the bunches to the booster injection energy of 20 GeV. This work addresses the significant challenges posed by the required beam parameters. We designed the electron (up to about 3 GeV) and the high energy (up to 20 GeV) linacs to provide very limited emittance growth caused by static imperfections, maximum acceleration efficiency, excellent stability of the beam transverse jitter, and to match the requirements on the bunch length and single- and multi-bunch energy spread as well. An energy compressor system has been foreseen, to provide flexibility to scan beam charges across a wide range without significantly altering the final energy spread. This paper summarizes the comprehensive design and optimization studies conducted, demonstrating that the proposed linac system meets all current requirements for efficient injection into the booster ring, paving the way for the ambitious operational goals of the FCC-ee accelerator complex.

THE FUTURE CIRCULAR COLLIDER AND ITS LINACS DESIGN

The Future Circular Collider (FCC) is a proposed research infrastructure located near CERN, spanning Switzerland and France. It aims to push the energy and precision frontiers beyond the LHC through two phases: FCC-ee and FCC-hh. The first accelerator will be an electron-positron collider with a 91 km circumference and will operate at several center-of-mass energies from 45 GeV up to about 350 GeV to study the Z, W, Higgs bosons, and top quark. FCC-hh, a proton-proton collider, targets beam energies up to 100 TeV. Construction of FCC-ee may begin in the late 2030s, with operations in the 2040s; FCC-hh is planned for the 2070s.

The FCC-ee injector complex includes a photo-injector, linacs, a damping ring (DR) [1], a bunch compressor (BC) [2], an energy compressor (EC), and a booster [3], preparing beams for injection into the collider ring. A schematic of the current layout is shown in Fig. 1.

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After the photo-injector, the electron beam is accelerated from 200 MeV to 2.86 GeV in the electron linac (e-linac). At this point the beam can be used to generate positrons or proceed to the next acceleration stages. Both electrons and positrons are sent to a shared damping ring. The bunch length at the DR equilibrium is much longer than the optimal one for the transport through the downstream linacs, so the beams undergo a bunch compression before being finally accelerated. In the last linac (HE linac) the beams are then accelerated to 20 GeV for booster injection. Both linacs are optimized for performance, cost, and reliabilityand is made of a succession of RF modules. Each RF module consist of klystrons, pulse compressors, and accelerating structures. A configuration with four structures per module balances hardware and ten-year operational costs, assuming 80 MW klystrons with 42% efficiency and 20% power margin, yielding about 20 MV/m gradients.

The beam reaching the end of the HE linac must fulfill several constraints on the final bunch length and the energy spread, which must be large enough to mitigate the instability in the booster, and the emittances, which must be kept small enough for an efficient transport through the different sections. Table 1 shows the parameters and the most relevant constraints for this manuscript for the highest charge mode.

A challenging requirement for the linac design is the ability to vary the bunch charge over a wide range — from nearly zero up to 5 nC — while maintaining the final beam parameters within acceptable limits. In particular, for low-charge operation, relaxed constraints on the minimum energy spread and bunch length are permissible. If not otherwise specified, the high charge mode is considered in this work.

The linac design addresses both transverse and longitudinal dynamics to meet the collider injection requirements.

Table 1: Design parameters and constraints for the e- and HE linacs.

Parameter	e^- Linac	HE Linac
Initial energy (GeV)	0.2	2.86
Final energy (GeV)	2.86	20
Bunch species	e^-	e^-, e^+
Maximum bunch charge	5	5
Number of bunches/specie	4	4
Maximum $\epsilon_{x,y}$ (mm.mrad)	(4,4)	(20,2)
Target δE (%)	<few %	0.1
Target rms bunch length (mm)	–	4

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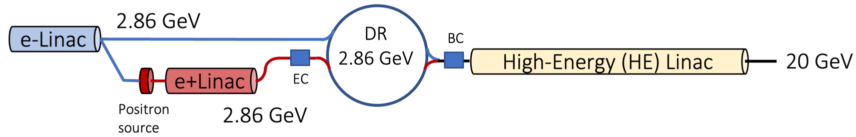

Figure 1: Schematic of the present injector layout. After the e-linac and the e+linac both the species are injected to the DR and undergo to a bunch compression before being accelerated to an energy of 20 GeV by the HE linac.

Transversely, the focus is on minimizing emittance growth and jitter amplification, whereas, longitudinally, it is on controlling energy spread and bunch length. Short- and long-range wakefields were considered for single- and multi-bunch effects, respectively.

We explored the impact of RF frequency, gradient, and bunch length on energy spread for all these three linacs. S-band RF cavities at 2.8 GHz offers a good compromise between the gradient, the optimal bunch length (1 mm rms) and the corresponding off-crest operation (10 degrees off-crest) necessary to reach the target energy spread. A higher frequency leads to a shorter bunch length and consequently a more pronounced off-crest operation, whereas a smaller frequency is limited by the availability of RF sources and leads to reduced gradients.

However, off-crest operation reduces acceleration efficiency and degrades the beam transverse quality. We studied then an approach that uses on-crest RF phases, maximizing acceleration while preserving beam quality. The energy spread is controlled throughout the injector to avoid chromatic aberrations and matched only at the end of the HE linac to the booster requirement via an energy compressor. Another important advantage of the energy compressor is that it also enables charge tunability from 0 to 5 nC per bunch without the necessity of altering any of the linac settings, requiring only adjustments to the photo-injector laser intensity.

A major revision in late 2023 reduced the linac repetition rate from 400 to 100 Hz, improving RF system compatibility. The updated layout features a shared DR for both species, enhancing emittance control and beam stability, and allowing future polarization. The following sections present simulation results and performance comparisons between the updated and previous layouts.

We used several tracking codes to perform the simulations: Elegant [4] for the longitudinal dynamics, and RF-Track [5] for the transverse dynamics, including the single- and multi-bunch mode.

TRANSVERSE DYNAMICS

The preservation of transverse beam emittance is a critical requirement in the design of linacs, particularly for beams such as those required by the FCC-ee injector, high charge and multi-bunch. Several mechanisms can lead to emittance degradation, with wakefields, both short- and long-range, playing a major role.

Short-range wakefields are excited when the bunch travels off-axis through wakefield-generating structures such as RF cavities or beam pipe discontinuities. Even for an initially centered beam, misalignments of beamline elements, such as quadrupoles, higher-order magnets, or RF structures, can induce trajectory deviations, producing similar effects. In the multi-bunch regime, long-range wakefields become relevant. Here, the first bunches traveling off-axis excite wakefields that persist long enough to impart a kick on the subsequent bunches. These effects are enhanced at higher bunch charges, necessitating detailed analysis and appropriate mitigation strategies in the linac design.

To assess emittance preservation under realistic conditions, we performed several hundred simulation seeds, each incorporating Gaussian randomly distributed misalignments of all lattice elements. We computed the corresponding cumulative distribution function and we defined the emittance growth as the value exceeded by no more than 2% of the seeds, a conservative metric compared to the 90th percentile criterion often adopted in other designs.

The assumed rms misalignments were 50 μm for RF structures, 100 μm for quadrupoles, and 30 μm for beam position monitors (BPMs). A BPM resolution of 10 μm was also included in the simulations. The tracking simulations used an initial transverse emittance of 3.2 mm·mrad in both planes [6], a 5 nC single bunch with an rms bunch length of 1 mm and a beam energy of 200 MeV at the photo-injector exit.

Various mitigation strategies were explored to preserve emittance under misalignment-induced wakefield effects. These include beam-based alignment procedures, such as steering and dispersion-free steering (DFS), and hardware choices uch as RF structures with larger aperture to reduce wakefield amplitudes.

In our simulations for each random seed, we first computed the distribution of the final transverse emittance without applying any orbit correction. Then, using the same lattice configuration, we computed the emittance growth after applying a two-step correction procedure: response matrix-based one-to-one orbit correction followed by dispersion-free steering (DFS). The combination of the two resulted to be the most efficient way to mitigate the emittance growth.

A key finding from our study is the strong dependence of emittance growth on the RF operating phase. In the previous linac design corresponding to an energy boost from 0.2 GeV to 6 GeV we determined an emittance growth a factor 2 larger for the case corresponding to 8 degrees off-crest compared to the on-crest operating phase. This is one of the major motivation which convinced us to adopt an on-crest RF phase configuration throughout the linacs, as anticipated before. Another important finding was that a splitting of the linacs in several sections to correct the orbit is beneficial for the

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emittance growth mitigation. Table 2 shows the simulated emittance growth for the selected RF structure geometry and one corresponding to a smaller aperture. Following the same approach we computed the emittance growth along the HE linac. After a careful optimization of the bunch length, RF aperture and number of sub-sections, we obtained a configuration corresponding to an emittance growth of only 0.6 mm.mrad. Figure 2 shows the evolution of the expected emittance along the full injector chain assuming the emittance growths stated by the other expert groups in the DR and BC [2].

Table 2: Emittance growth expected at the exit of the e-linac assuming RF structure aperture characterized by a/λ = 0.15 and a/λ = 0.12 in parenthesis.

Sub-section	$\Delta\epsilon$ (mm.mrad)	ϵ (mm.mrad)
3	0.5 (1.8)	3.7 (5.0)
4	0.4 (1.5)	3.6 (4.7)
5	0.3 (1.2)	3.5 (4.4)
7	0.3 (1.2)	3.5 (4.4)
10	0.3 (1.2)	3.5 (4.4)

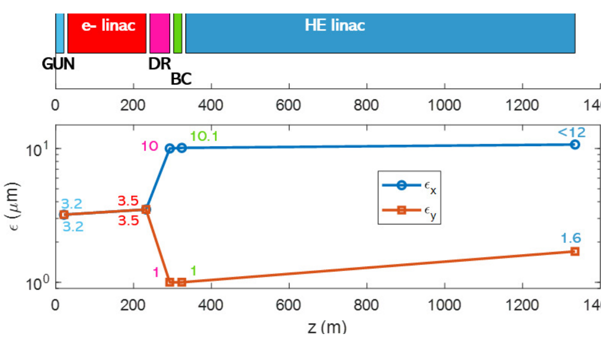

Figure 2: Expected emittance growth along the injector chain.

With the present design we fulfill the requirements on the final emittances in both transverse planes required for an efficient injection and transport to the booster.

We performed extensive studies on the amplification of any incoming transverse jitter (angle and/or position). We report them in a dedicated proceeding/article.

LONGITUDINAL DYNAMICS

Transverse and longitudinal beam dynamics are strongly coupled. Therefore, many of the considerations that induced the choice of design parameters have already been discussed in the previous sections. This system allows independent control of bunch length and energy spread. It enables the upstream linacs to operate on-crest for maximum acceleration efficiency, while bunch lengthening is performed only at the end of the high-energy (HE) linac to match the requirements of the booster ring. Moreover, the EC reduces the dependence of energy spread on bunch charge and stabilizes energy jitter at the cost of increased timing jitter, which is more tolerable in the transfer line and within the booster.

Here, we briefly describe the key system that enables on-crest operation of the RF structures maximizing linac performance: the energy compressor. This system consists of a magnetic chicane, which introduces a correlation between particle energy and arrival time via the transport matrix element R_{56}, and a series of RF structures that impart an energy kick based on the particles' arrival time (seen as phase difference by the particles). For short bunches, where the induced longitudinal displacement Δz remains small compared to the RF wavelength λ, the required voltage V from the RF cavities is given by:

$$V = \frac{\lambda P}{2\pi e R_{56}} \quad (1)$$

where λ is the RF wavelength, P is the mean particle momentum, and e is the elementary charge. The selection of λ reflects a trade-off between longitudinal acceptance—favoring larger values and RF system compactness and efficiency, which benefit from shorter wavelengths. We considered the X-band (11.2 GHz), C-band (5.6 GHz), and S-band (2.8 GHz) options for the RF frequency, and here we present the results for the S-band case, where the structures are he same as those used in the HE linac. Table 3 summarizes the optimized EC configuration.

Table 3: Beam and EC parameters at the HE linac exit for FCC-ee, assuming R_{56} = 0.55 m and a total RF voltage of 450 MV. More than a factor 3 smaller energy spread can be reached keeping the same bunch length.

Parameter	Q = 5 nC	Q = 5 pC
Initial $\Delta E/E$ (%)	0.60	0.14
Initial bunch length (mm)	0.80	0.80
Final $\Delta E/E$ (%)	0.09	0.11
Final bunch length (mm)	4.05	1.04
Final Δt from 5 nC B_1 (ps)	0	–29

The EC adds flexibility to the injector design, and it allows to fulfill all requirements for final energy spread and bunch length at maximum charge. In the low-charge regime, the final minimum energy spread and bunch length—relevant for mitigating instabilities in the booster—remain within acceptable limits. The shorter bunch length in this regime is permissible due to the significant reduction of collective effects at low intensity.

CONCLUSION

We have presented the design of the FCC-ee injector linacs, optimized with respect to emittance preservation, transverse jitter suppression (detailed elsewhere), acceleration efficiency, and overall cost-effectiveness. While further refinements are currently under investigation, the present design satisfies all requirements for injection into the booster at nominal high bunch charge. Moreover, it supports up to a 100% bunch-to-bunch charge variation without compromising final beam parameters.

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REFERENCES

[1] A. Abada *et al.*, in Future Circular Collider Feasibility Study Report Volume 2: Accelerators, Technical Infrastructure and Safety, M. Benedikt *et al.*, Eds. CERN, Geneva, Switzerland, Mar. 2025, pp. 308-310. doi:10.17181/CERN.EBAY.7W4X

[2] S. Spampinati, C. Milardi, A. De Santis, and O. Etiksen, "Positron bunch and energy compressor (to/from damping ring)", presented at the 10th Future Circular Collider Conference (FCC Week'24), San Francisco, USA, Jun. 2024, https://indico.cern.ch/event/1298458/contributions/5978155/

[3] A. Abada *et al.*, in Future Circular Collider Feasibility Study Report Volume 2: Accelerators, Technical Infrastructure and Safety, M. Benedikt *et al.*, Eds. CERN, Geneva, Switzerland, Mar. 2025, pp. 221-289. doi:10.17181/CERN.EBAY.7W4X

[4] M. Borland, "elegant: A flexible sdds-compliant code for accelerator simulation", Argonne National Lab., Argonne, IL, USA, 2000. doi:10.2172/761286

[5] A. Latina, "RF-Track Reference Manual", v.2.0.24, CERN, Geneva, Switzerland. doi:10.5281/zenodo.4580369

[6] Z. Vostrel and S. Doebert, "Design of an electron source for the FCC-ee with top-up injection capability", *Nucl. Instrum. Methods Phys. Res. A*, vol. 1063, p. 169261, 2024. doi:10.1016/j.nima.2024.169261.

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