# BEAM DYNAMICS OPTIMIZATION OF THE HIGH ENERGY LINAC OF THE FCC-ee INJECTOR

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### *Abstract*

The FCC-ee injector complex is designed to deliver tunable, high-charge electron and positron bunches for injection into the collider over a center-of-mass energy range of 90–365 GeV. A key element is the high-energy (HE) linac, which accelerates the beam from about 3 to 20 GeV before injection into the booster. In this work, we present beam-dynamics studies aimed at minimizing emittance growth and improving transverse stability along the HE linac. Different lattice configurations, phase advances, and RF layouts were investigated to identify an optimized design. The selected configuration satisfies the present performance requirements for efficient booster injection and supports the operational goals of the FCC-ee injector complex.

## TRANSVERSE DYNAMIC: STATIC EFFECTS

The normalized emittances at the damping ring exit were assumed to be 10 mm mrad and 1 mm mrad in the horizontal and vertical planes, respectively. The corresponding maximum tolerated values at the booster injection are 20 mm mrad and 2 mm mrad. Since the vertical plane is more critical, the optimization was primarily focused on the normalized vertical emittance, while the horizontal plane was evaluated only after the final lattice had been selected.

A campaign of detailed simulation was performed using RF-Track [1]. Gaussian-distributed random lattice misalignments with rms values of 100 µm were assumed for quadrupoles and RF structures, and 30 µm for BPMs in both transverse planes, consistent with operational experience at SwissFEL, were included in the simulations to assess the impact of static imperfections. A conservative BPM resolution of 30 µm was also included.

For each configuration, 200 seeds were simulated. The final emittance was defined as the value below which 90% of the seeds fall. For each seed, the orbit was corrected using three steering algorithms applied in cascade: response-matrix-based correction, dispersion-free steering (DFS), and wakefield-free steering (WFS). Although WFS has been experimentally validated [2], in this study only response-matrix correction and DFS were used to provide a conservative estimate based on well-established techniques. The potential improvement from WFS is discussed separately.

An example of the emittance distribution at the HE linac exit is shown in Fig. 1. The threshold used to define the final emittance was changed from 98% to 90%, in order to reduce sensitivity to the tails of the distribution and ensure consistency with other projects.

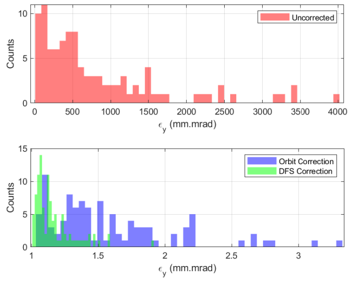

Figure 1: Emittance distribution at the end of the HE linac. Top plot: before any correction is applied. Lower plot: after the RM-based correction before and the DFS after have been applied.

The main optimization parameters were the RF aperture, expressed as $a/\lambda$ (where $a$ is the iris radius and $\lambda$ the RF periodicity), the RF structure length, the phase advance per cell, and the number of quadrupoles per RF structure. The aperture mainly affects the transverse wakefields, while the other parameters determine the focusing strength and the beam optics.

As already pointed out in previous studies [3], the number of subsections (bins) used in the simulations is an important parameter. Also the change in the emittance threshold affects the optimum number of bins and has an impact of about 0.2 mm mrad on the final emittance, whereas doubling the quadrupole rms misalignment has only a marginal effect, as shown in Table 1.

The final selection was made in conjunction with the dynamic effects discussed in the next section.

### *Dynamic Effects*

Dynamic effects were quantified through the jitter amplification (JA), defined as the square root of the ratio between the area transverse phase-space and defined by N bunches launched with different initial positions and angles and traveling through the HE linac. A complete description of the method can be found in Ref. [4]. Since no tolerances have yet been defined for the transfer line to the booster, a maximum acceptable JA of 2 was adopted based on the booster injection specifications. The design goal was not only to remain below this limit, but also to minimize the JA at the end of the HE linac at the first phase of the design and along it in the final stage of the study.

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Table 1: Final normalized emittance as a function of the number of subsections for different rms quadrupole alignment errors and evaluation thresholds in percentage. The minimum value in each row is highlighted in bold.

| **Bins** ⟶ | 4 | 6 | 8 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|
| $\varepsilon_n$, $\sigma_Q$ =50 µm, 98% | 64.9923 | – | 1.8049 | 1.4944 | – | **1.3774** | – | 1.4102 |
| $\varepsilon_n$, $\sigma_Q$ =100 µm, 98% | 245.1132 | 7.9218 | 2.5621 | 1.9607 | 1.5114 | 1.4519 | 1.4238 | **1.4080** |
| $\varepsilon_n$ , $\sigma_Q$ =100 µm, 90% | 147.0510 | 6.0931 | 2.2694 | 1.4798 | 1.2847 | **1.2152** | 1.2403 | 1.3001 |

For all configurations considered, the final JA at the linac exit is lower than the incoming value, indicating intrinsic damping of orbit errors. In the selected operating conditions, the HE linac reduces incoming position and angle jitter by approximately one third, as shown in Fig. 2.

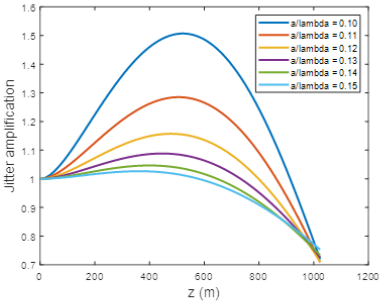

Figure 2: JA along the HE linac at different apertures of the RF structures.

In addition to the baseline lattice with one quadrupole per RF structure (2Q2RF), an alternative lattice with one quadrupole every two RF structures (1Q2RF) was also investigated. The 2Q2RF lattice provides smaller beam size and shorter betatron wavelength, at the cost of higher quadrupole strength, whereas the 1Q2RF lattice features larger beam size and weaker focusing.

The 1Q2RF option was found to be less favorable in terms of JA over the parameter range considered. A systematic scan of RF structure length, RF aperture, and phase advance per cell showed that shorter RF structures and larger phase advances generally improve JA performance. Shorter RF structures reduce the FODO cell length and increase the focusing, leading to lower final JA. Similarly, increasing the phase advance per cell reduces the beam size and results in improved JA. Figure 3 shows the dependence of JA on all the parameters combined. The lowest final JA was obtained for configurations with short RF structures and large phase advance. However the final selection was therefore based on a compromise between transverse stability, emittance growth, RF performance, and cost, as discussed in the next section.

## SELECTED HE LINAC CONFIGURATIONS

We summarize the most promising HE linac configurations, reporting the final emittance assuming an initial normalized vertical emittance of 1 mm mrad at the damping ring exit. For each case, the number of subsections (bins) was scanned and the configuration yielding the minimum emittance was selected. Only response-matrix-based orbit

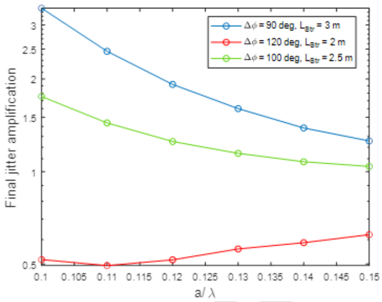

Figure 3: JA at the end of the HE linac assuming different phase advance per cell and RF structure lengths varying the Rf structure aperture.

correction and DFS were considered, in order to provide a conservative estimate based on well-established techniques. Wakefield-free steering (WFS) is expected to further reduce the emittance by about 0.1–0.15 mm mrad, depending on the specific configuration. Table 2 summarizes the most promising configurations. A compromise between beam dynamics performance, RF efficiency, and overall system complexity was selected. The present baseline corresponds to the cases indicated in bold in the Table 2.

The sensitivity to the initial emittance was investigated, showing that the emittance growth is approximately additive within a 20% accuracy. The final emittance can therefore be estimated by adding the computed growth to any updated initial value within this uncertainty. The analysis focuses on the vertical emittance, which has a tighter budget, while additional simulations with asymmetric initial emittances confirm similar relative growth in the horizontal plane with sufficient margin.

Overall, the proposed HE linac design fulfills all static and dynamic beam dynamics requirements with significant margin, allowing tolerance to possible variations in the initial beam parameters. This design was used to drive the RF design of the structures [5].

## LONGITUDINAL DYNAMIC

The longitudinal requirements at booster injection are an rms energy spread of 0.1% and an rms bunch length of 4 mm. Considering that this bunch length in incompatible with the propagation along the HE linac, and that the on-crest operation provides the preserve emittance preservation, we designed an energy compressor (EC) at the end of the HE linac. The main advantages of the EC are the modularity of the injector design, decoupling the HE linac from booster constraints, the reduction of the final energy spread

Table 2: Configurations Simulated for the HE Linac. Colors indicate performance ranges: green (emittance < 1.5 mm·mrad, $JA_{max} < 1.2$, $JA_{Final} < 1.0$), yellow (emittance < 1.6 mm·mrad, $JA_{max} < 1.5$, $JA_{Final} < 1.2$), and orange (emittance > 1.8 mm·mrad, $JA_{max} > 1.8$). For space reasons we excluded from the table all the configurations giving results outside of any of the listed cases. Configurations with summed $L_{str}$ correspond to the 1Q2RF scheme; all others correspond to 2Q2RF.

| $a/\lambda$ | $L_{str}$ (m) | $\Delta\phi$ (deg) | $\epsilon$ (mm mrad) | $N_{quad}$ | $N_{struct}$ | $N_{bpm}$ | Linac length (m) | Max JA | Final JA | $R_{eff}$ (ohm) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.13 | 2.5 | 90 | 1.20 | 337 | 336 | 339 | 1111.5 | 1.03 | 0.25 | 93.1 |
| 0.13 | 3 | 90 | 1.22 | 281 | 280 | 283 | 1049.5 | <1.10 | 0.73 | 97.1 |
| **0.13** | **3** | **80** | **1.19** | **281** | **280** | **283** | **1049.5** | **1.10** | **0.91** | **97.1** |
| 0.13 | 3 | 70 | 1.20 | 281 | 280 | 283 | 1049.5 | 1.13 | 1.08 | 97.1 |
| **0.12** | **3** | **90** | **1.46** | **283** | **282** | **285** | **1077.0** | **1.15** | **0.71** | **108** |
| 0.12 | 3 | 80 | 1.36 | 283 | 282 | 285 | 1077.0 | 1.20 | 0.95 | 108 |
| 0.12 | 3 | 70 | 1.35 | 283 | 282 | 285 | 1077.0 | 1.26 | 1.17 | 108 |
| 0.13 | 4 | 90 | 1.48 | 211 | 210 | 213 | 1017.0 | 1.22 | 1.19 | 103.3 |
| 0.13 | 2+2 | 90 | 1.20 | 211 | 420 | 633 | 1069.5 | 1.21 | 1.12 | 103.3 |
| 0.13 | 2+2 | 100 | 1.17 | 211 | 420 | 633 | 1069.5 | 1.17 | 0.97 | 103.3 |
| 0.13 | 2+2 | 120 | 1.16 | 211 | 420 | 633 | 1069.5 | 1.13 | 0.56 | 103.3 |
| 0.12 | 2+2 | 100 | 1.28 | 212 | 422 | 636 | 1074.5 | 1.29 | 1.03 | 110.4 |
| 0.12 | 2+2 | 120 | 1.43 | 212 | 422 | 636 | 1074.5 | 1.22 | 0.52 | 110.4 |
| 0.13 | 2.5+2.5 | 120 | 1.26 | 169 | 336 | 505 | 1017.5 | 1.26 | 0.98 | 93.1 |
| 0.12 | 2.5+2.5 | 120 | 1.44 | 170 | 338 | 508 | 1023.5 | 1.42 | 1.06 | 104 |
| 0.13 | 3+3 | 90 | 1.34 | – | – | – | – | 1.60 | 1.60 | 97.1 |

from the moderate intrinsic linac value (~0.7%) down to the required 0.1%, the bunch decompression to the 4 mm rms value required by the booster, the stabilization of the energy jitter, beneficial for transport through the transfer line in the presence of dispersion, the longer bunch length along the transfer line, reducing CSR effects, and the fact that the 3 GHz RF doesn't need to be underground. We discussed in details elsewhere [6] and [7] the details of the optimization of the EC at the previously used 2.8 GHz for the RF frequency. A relatively moderate $R_{56}$ chicane of 0.55 m was selected, which is essential for multi-bunch operation to keep the time delay among the bunches in the specifications for the injection to the booster. Using the selected HE linac configuration and the optimized EC settings, simulations for a four-bunch train show rms bunch lengths of about 4 mm and rms energy spread of 0.1%, satisfying the booster requirements. The selected EC parameters correspond to a 3 GHz RF system with an integrated voltage of about 640 MV for the multi-bunch use of the EC, as show in Table 3.

Table 3: Main parameters of the selected RF and chicane configuration: RF parameters and dipole angle and length

| $f$ (GHz) | $L_{str}$ (m) | $a/\lambda$ | Integrated voltage (MV) | Angle (deg) | Length (m) |
|---|---|---|---|---|---|
| 3 | 31.343 | 0.12 | 640 | 8.73 | 7.21 |

To ensure proper optics matching, two matching sections are required: one upstream of the chicane and one between the chicane and the RF section, in order to recover the FODO optics. The total length of each matching section is approximately 5 m, giving a total length of the full system of about 100 m including the matching sections, the chicane and the RF modules.

A bunch compressor (BC) is needed upstream of the HE linac to shorten the several-millimetre bunch from the damping ring to the optimal length for acceleration. A baseline design has already been established [8], and further optimization is ongoing. Matching sections were designed at the entrance and exit of the BC to ensure smooth injection and proper rematching to the HE linac lattice. The full layout is about 50 m long, including matching sections, RF modules for energy chirp generation, and the chicane. The current design provides a comfortable horizontal emittance margin against possible CSR effects, although further simulations and experimental validation are planned to refine the beam parameters.

## CONCLUSION

A complete beam-dynamics optimization of the FCC-ee HE linac has been carried out, addressing both transverse and longitudinal performance from the damping ring extraction to the injection to the transfer line upstream of the booster. The transverse lattice was optimized by balancing static emittance preservation, dynamic stability and RF efficiency. The selected baseline configuration satisfies the injector requirements with comfortable margin: the normalized vertical emittance remains well below the allocated budget under realistic static imperfections, while the jitter amplification stays below unity along and at the HE linac exit, demonstrating intrinsic damping of incoming orbit errors.

The longitudinal design was completed by integrating an energy compressor at the HE linac exit and a bunch compressor upstream of the HE linac. The selected energy compressor, based on a moderate-$R_{56}$ chicane and a 3 GHz RF system, reduces the energy spread to the required 0.1% and decompresses the bunch to the 4 mm rms length like needed for booster injection. This and the upstream bunch compressor necessary to tune the bunch length through the HE linac to the optimal value include dedicated matching sections, designed and dimensioned.

Overall, the proposed injector layout fulfills the present FCC-ee performance requirements for efficient and robust injection into the booster ring. The design also retains sufficient operational flexibility and margin to accommodate future refinements of beam parameters. Further studies will focus on CSR effects, multi-bunch collective effects, and experimental validation of the correction and compression schemes.

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