

DEFINING THE NEW FCC-ee BASELINE OPTICS

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Abstract

The Future Circular electron-positron Collider (FCC-ee), with a circumference of approximately 91 km, is being rapidly developed by CERN and its collaborators. Two collider-ring optics proposals have been developed in parallel over recent years. Each proposal features its own strengths and challenges. The Global Hybrid Correction optics (GHC) came first with a ring-distributed correction of the horizontal chromaticity generated in the Interaction Regions (IRs), using many sextupole pairs. A local conventional chromaticity correction section is used in the IR for the vertical plane. The more recent Local Chromaticity Correction (LCC) scheme proposal uses both vertical and horizontal chromatic correction sections in the IRs and keeps a modular design. A comparison process was carried out between late 2025 and early 2026 to prepare for the review process of the FCC-ee baseline magnetic lattice and optics in view of the Technical Design Report. This contribution presents the comparison process of these two optics designs from the perspective of beam dynamics and performance.

INTRODUCTION

Following the recommendation of the European Strategy for Particle Physics (ESPP) in 2013 [1], CERN has launched the conceptual design phase for Future Circular Colliders (FCC) for an electron-positron (FCC-ee) or a hadron-hadron (FCC-hh) synchrotron storage ring at the luminosity and energy frontiers with a circumference of approximately 100 km for the post High Luminosity Large Hadron Collider (HL-LHC) era [2]. Four conceptual design reports (CDRs) have been published in 2019, which also formed the basis for the input to the following ESPP Update (ESPPU) [3–6].

In 2020 the ESPPU recommended, among others, a future hadron collider at CERN with a centre-of-mass energy of 100 TeV with an electro-weak and Higgs-factory as a possible first stage [7]. The so-called integrated FCC program foresees first the construction of the tunnel, associated infrastructures, and the FCC-ee with about 20 years of operation, followed by the FCC-hh, which would provide high energy physics research until the end of the 21st century. The FCC Feasibility Study (FS) has been launched in 2021 to investigate in detail the technical, geological and financial feasibility of the FCC-ee, and concluded in 2025 with the FS report (FSR) in three public volumes, which have been submitted to the ESPPU in 2025 [8–10].

Including various input of the community, e.g. [11–13], in early 2026 the recommendations have been published,

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with the HL-LHC and the FCC-ee as the, respectively, first and second highest priority for the European community of particle physics [14]. The FCC is currently entering the next phase of the project, the so-called Reference Design Phase, allowing for a possible Council decision in 2028, followed by a Technical Design Report (TDR)-phase currently foreseen to be finished by 2033.

For any present or future collider the accelerator lattice and optics forms the basis for numerous studies and technical designs and must, hence, be designed carefully. The Global Hybrid Correction (GHC) [15] optics has been designed and optimised over more than a decade and represents the baseline presented in the FSR. Over the past three years, the Local Chromaticity Correction (LCC) optics has been developed and investigated in parallel.

To ensure a coherent and cost-effective path towards the TDR a baseline choice between GHC or LCC design must be taken with a first attempt in early 2025 [17]. Therefore, between end of 2025 and beginning of 2026 a detailed comparison between both optics has been performed and summarized in a report. This contribution discusses the path towards the new baseline and focuses on lattice, optics, parameters and performance reach. Technical aspects such as considerations from magnets, power converters, availability, vacuum, or beam instrumentation are not covered, yet further details are provided in the full document [18]. Results described here focus largely on the lowest beam energy of 45.6 GeV per beam corresponding to physics around the Z-pole. Furthermore, first insights on the highest energy of 182.5 GeV, are presented in a separate section.

COMMON OVERALL LAYOUT

Despite several key differences between the GHC and the LCC lattice, both designs respect certain key layout and design principles. The FCC-ee features four experimental Interaction Regions (IRs) and four Long Straight Sections (LSSs). The high energy booster is installed on top of the collider rings, allowing for top-up injection at the collision beam energy. Experimental IRs and LSSs are, respectively, 1400 m and 2032 m long. The LSSs host collimation, RF-cavities for either the FCC-ee or the HEB, injection and extraction, as shown in Fig. 1.

- The overall machine geometry is preserved.
- A circumference is defined by detailed placement and is about 90.6 km.
- Four baseline beam energy stages are considered, namely, 45.6, 80, 120 and 182.5 GeV, corresponding

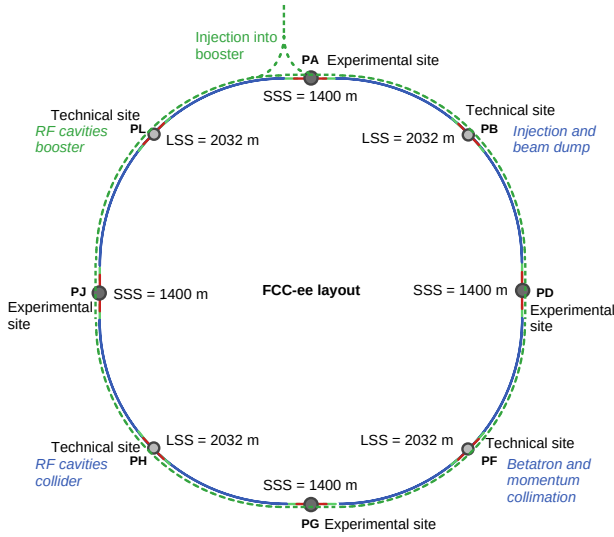


Figure 1: Schematic view of the FCC-ee lattice, with the high energy booster on top of the collider.

to physics at the Z-pole, the W-pair-production, the ZH-peak and above the $t\bar{t}$ -threshold.

- The Synchrotron Radiation (SR) power is limited to a maximum of 50 MW per beam. Since SR losses increase with the fourth power of the beam energy, the beam currents differ by almost three orders of magnitude between the highest and lowest operational energies, such that severe intensity related effects render the machine design even more difficult for operation around the Z-threshold.
- In all experimental interaction regions, the beams collide with a crossing angle of 30 mrad, approaching from the inside outward and exchange aperture in all LSSs.
- Weak bending dipoles are installed upstream of the interaction points to limit the critical energy of SR photons to approximately 100 keV.
- The damping partition numbers are $J_{x,y,z} = (1, 1, 2)$.

GHC AND LCC DESCRIPTION

Despite several common considerations, GHC and LCC feature fundamentally different design strategies, which are recalled here. More details can be found in [17].

The GHC optics [15] is based on a hybrid correction scheme. This combines a global correction of the horizontal chromaticity distributed along the arcs with local correction sections in the IRs for the vertical plane, combined with the crab-waist transformation, as shown in top Fig. 2. The LSSs are identical to ensure a four-fold super-periodicity. The arcs are based on a FODO structure with a large number of non-interleaved sextupole pairs. The GHC optics benefits from extensive optimisation over more than a decade.

In contrast, the LCC optics [16] implements fully local chromaticity correction in both transverse planes within dedicated sections in the IRs and dedicated crab-waist sextupoles,

as shown in bottom Fig. 2. The arcs are based on the Hybrid Focusing Defocusing (HFD) lattice, designed in a modular way, with nested sextupole families to minimise higher-order optics aberrations. The LSSs rely on transparency conditions for each insertion, allowing increased flexibility in lattice design and integration. The current design of the LCC has the IPs shifted outside by approximately 7 m with respect to the GHC.

PROCESS OF COMPARISON AND DECISIONS TAKEN

The comparison between the GHC and LCC optics has been performed as a collaborative exercise within the FCC-ee study, involving multiple working groups covering beam dynamics, lattice design, and accelerator subsystems, up to

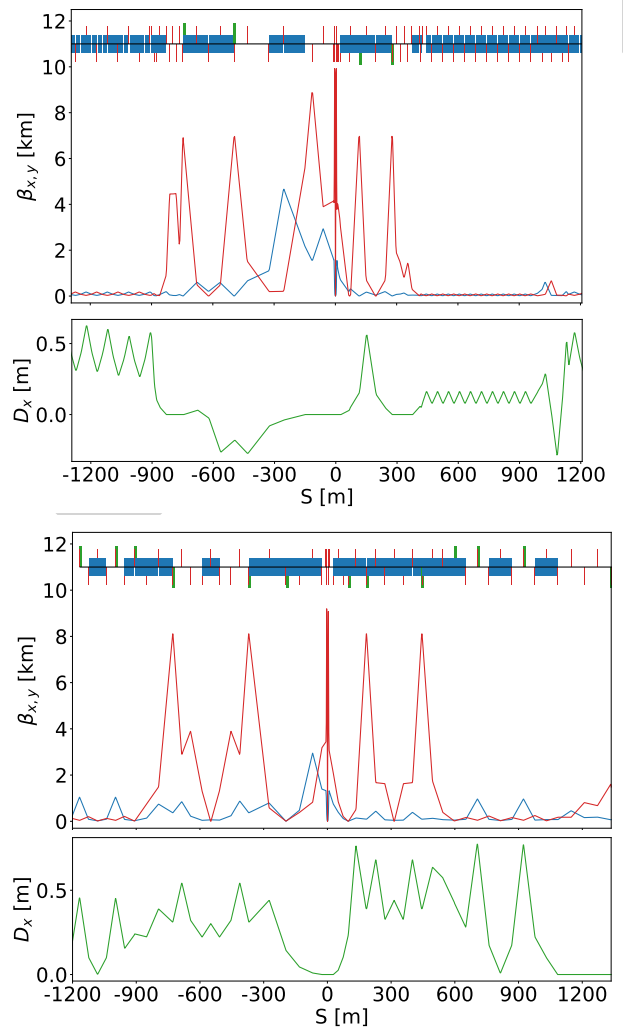


Figure 2: FCC-ee Experimental IR optics at Z operation for GHC (top) and LCC (bottom) optics. Horizontal and vertical β -functions are shown in, respectively, blue and red. Dipoles, quadrupoles and sextupoles are shown, respectively, in blue, red and green. Focusing and defocusing elements, respectively, are shown above and below the horizontal axis.

Table 1: Parameter Table For The GHC And LCC Lattices At Z And $t\bar{t}$ Mode

Optics Mode	GHC		LCC	
	Z	$t\bar{t}$	Z	$t\bar{t}$
Beam energy E (GeV)	45.6	182.5	45.6	182.5
Circumference C (m)	90658.525		90644.816	
Arc-cell setup	90°/90° long	90°/90° short	52°/45°	99°/77°
Mom. comp. factor α_c (1×10^{-6})	28.5	7.3	28.6	9.5
Energy Loss per turn W_0 (GeV)	0.039	10.01	0.035	9.01
Beam Intensity N (1×10^{12} particles)	2400	9.405	2424	9.435
Bunch Intensity N_b (1×10^{11} particles)	2.02	1.85	2.02	2.20
Number of Bunches	12000	51	12000	43
Horizontal β -function at IP β_x^* (cm)	9	90	9	90
Vertical β -function at IP β_y^* (mm)	0.7	1.4	0.7	1.4
Horizontal emit. ε_x (nm)	0.74	1.74	0.70	2.10
Target vert. emit. in collision ε_y (pm)	1.48	1.75	1.40	2.11
Transverse tune Q_x/Q_y	214.16 / 214.20	394.19 / 390.27	194.16 / 170.20	346.19 / 262.27
Chromaticity Q'_x/Q'_y	12 / 5	0 / 0	12 / 5	0 / 0
Harmonic number h at 400 MHz	121200		121200	
Total RF voltage of 400 / 800 MHz (GV)	0.09	2.1 / 8.9	0.09	2.0 / 8.1
Synchrotron tune Q_s	0.031	0.086	0.031	0.111
RF momentum acceptance (%)	1	2	1	2
Bunch length σ_z (non coll./coll.) (mm)	5.4 / 16.3	1.9 / 2.7	5.1 / 16.7	1.9 / 2.8
Rel. mom. spr. σ_p (non coll./coll.) (10^{-3})	0.40 / 1.29	1.58 / 2.21	0.39 / 1.34	1.52 / 2.33
Longitudinal damping time τ_z (turns)	1159	18	1297	20
Crab-waist ratio (%)	55	40	55	40
Beam-beam parameter ξ_x/ξ_y (10^{-3})	1.5 / 80	61.2 / 108.9	1.4 / 90	67.1 / 120
Luminosity \mathcal{L} (1×10^{34} s $^{-1}$ /cm 2)	151	1.54	150	1.45

and including operational aspects such as the capacity to switch between energy points for agile physics data taking.

From the beam dynamics perspective, the comparison has been based on a set of common performance indicators, including luminosity reach, dynamic aperture (DA), momentum acceptance (MA), or beam lifetime, as discussed in detail below. These quantities have been evaluated by simulations studies assuming as far as possible comparable boundary conditions. Given the different levels of maturity at the stage of comparison between the GHC and the LCC optics, the evaluation has combined quantitative simulation results with expert judgement where complete data were not yet available. Complementary progress on optics tuning or energy calibration are presented in [19, 20].

Furthermore, to allow an as transparent as possible comparison several decisions have been taken to define common parameters described in the following. SR power was fixed to a maximum of 50 MW per beam. This set the beam currents available for the GHC optics. For the comparison, it has further been decided to assume the same beam currents for GHC and LCC to be on par for most beam dynamics effects. But, due to lower SR losses in the LCC lattice, the SR power is also slightly lower for a given beam current. This could be factored as an operational saving for the project or as an operational margin to increase the luminosity for the LCC optics. Another assumption underlying the designs are that Twiss β -functions at the IPs β^* of around 1 mm (from 0.7 mm at Z to 1.4 mm at $t\bar{t}$) and maximum vertical beam-beam tune shifts around 0.1 (ranging from about 0.09 at Z to 0.12 at $t\bar{t}$ operation) per IP are feasible. Assuming that the bunch spacing is limited by electron instabilities, at

Z a maximum of 12000 bunches is assumed, which imposes a lower boundary on the bunch population.

The comparison of the optics was written up in a report prepared as a collection of independently written chapters, but with common assumptions. The report was evaluated by an external review panel composed of eight accelerator and large facility experts from diverse laboratories in Europe, North America, Japan and China. The Panel gave its recommendation to choose the LCC optics as the new baseline optics for the study. The Study management has endorsed this recommendation, along with the recommendations for clarifications and further studies issued by the Panel.

PARAMETERS AND PERFORMANCE

Many considerations to determine the main machine parameters are driven by studies on beam-beam interactions. Colliding long bunches with the so-called nano-beam collision scheme and very large Piwinski angles is mandatory for low energy operation in order to identify scenarios compatible with the foreseen intensities. Both designs, hence, incorporate the crab-waist collision scheme with strong crab-sextupoles $(n + \frac{1}{2})\pi$, $n \in \mathbb{N}$ vertical phase advance upstream from the IP for both beams.

Equilibrium horizontal emittances increase significantly with the beam energy for given lattice, and hence, different phase advances are foreseen at low and high energies. Furthermore, at low energies the lower phase advance leads to lower tunes and a larger momentum compaction factor, which improves beam stability. At the start of the optimisation of the vertical emittance, it is assumed to be a factor

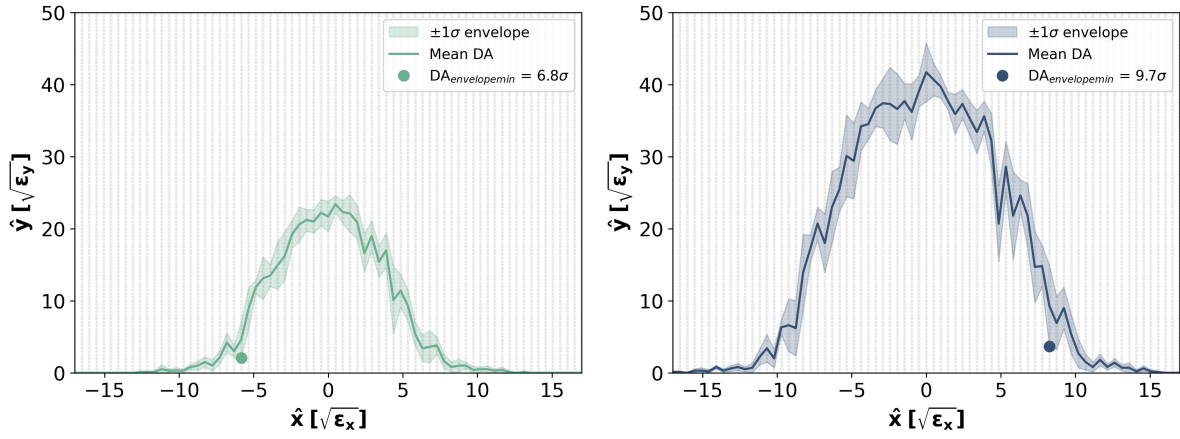


Figure 3: DA for Z mode for GHC (left) and LCC (right) with SR, QF and beam-beam.

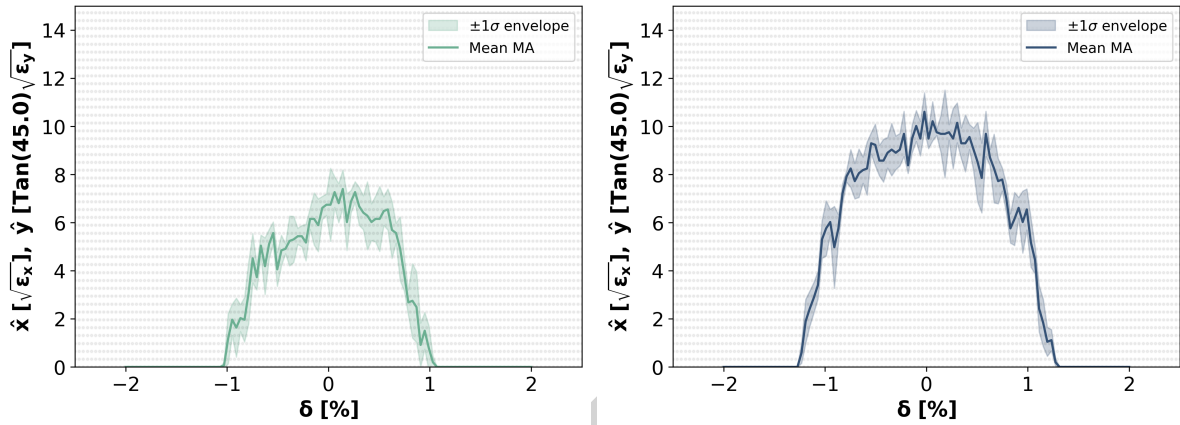


Figure 4: MA for Z mode for GHC (left) and LCC (right) with SR, QF and beam-beam.

1000 lower than the horizontal one. Based on this, the vertical emittance is increased further by beam-beam interactions, which is important to achieve bunch line densities and, in turn, bunch intensities such that the maximum available intensity can be exploited.

Q_x is set close above the integer resonance between its synchrotron sidebands (X-Z instability). Q_y is set above Q_x with minimal separation to keep detrimental effects from coupling under control yet ensuring a large tune space for the beam-beam footprint below the half integer. At Z-energy, studies for GHC use a RF voltage of 90 MV to minimize transient beam loading, while also ensuring a small spin modulation index. For comparison the same value is used for the LCC. Luminosity is estimated with Xsuite [21] using a single IP set-up with the soft Gaussian strong-strong beam-beam model including beamstrahlung together with an effective representation of the lattice based on transfer matrices between the IP and thin crab-sextupoles. The resulting parameters used for comparison are given in Table 1.

DA, MA, and beam lifetime are computed using 6D tracking simulations with SR and Quantum Fluctuations (QF), studied with beam-beam interactions and Beamstrahlung effects. Results are averaged over multiple seeds to mitigate stochastic fluctuations. At Z-energy, the LCC optics exhibits a significantly larger DA compared to the GHC, indicating

improved robustness for injection and beam stability. The MA is also slightly enhanced in the LCC configuration, although the difference between the two optics remains modest. Comparison plots are shown in Figs. 3 and 4. More information on DA and MA with errors is reported in [20]. Beam lifetime studies, using 10 000 turns, equivalent to 3 s, corresponding to the time interval between consecutive top-up injections, both lattices show excellent results.

Operational flexibility in the presence of beam-beam kicks plays a central role in determining achievable luminosity and beam lifetime. At Z-energy, both optics provide comparable horizontal emittance preservation, while differences arise in the available tune space and vertical emittance blow-up. The LCC optics exhibits a larger region of stable tune space with acceptable lifetime, indicating increased operational flexibility.

Delivering the design performance for lattices with misalignments and field errors is one of the major challenges for the FCC-ee [22–25]. Parallel BBA for 20 quadrupoles shows an rms accuracy below $10 \mu\text{m}$ for both, with, however, significant outliers in the GHC, partially stemming of 90° arc phase advance. Linear optics tuning studies with incomplete error sets achieve similar performance, with, however, clearly reduced MA in presence of beam-beam, indicating the need for non-linear corrections.

STATUS OF $\bar{t}\bar{t}$ OPTICS

The performance at $\bar{t}\bar{t}$ energy currently remains a critical point for both optics, since the GHC and the LCC optics exhibit poor beam lifetime at nominal $\xi_y \geq 0.12$ per IP. We note, that, in addition the Z-mode, only $\bar{t}\bar{t}$ is assessed in more detail and other energy points are currently not discussed here. Therefore, the limitations discussed below may also be relevant for operation at the ZH energy, which, however, remains to be investigated.

For the GHC optics, the main challenge arises from the loss of the ideal four-fold super-periodicity, since at this energy, a dedicated RF straight section hosting the 400 MHz and 800 MHz RF systems is required, with optics and beam trajectory differing from the other technical insertions, which leads to a significant degradation of performance with beam-beam. In particular, the tune footprint crosses several resonance lines in tune space, including the $Q_y = n/4$ resonances. In order to recover a beam lifetime on the scale of 1000 s, the bunch intensity and the vertical beam-beam parameter must be reduced, which lowers the luminosity to about $0.9 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in a realistic configuration (-40%).

In contrast to the GHC optics, the LCC is not based on a strict super-periodicity. The LCC optics has exhibited an even more significant loss of lifetime, for nominal parameters reported in Table 1. This reduction is likely linked to the larger transverse emittances.

Several mitigation strategies have been explored. For the GHC optics, two possibilities are identified. The beam-beam parameter could be reduced by reducing the bunch population, which, however, lowers the luminosity by about 25-40%. Alternatively, an additional dummy RF section, located on the opposite site of the actual RF section, to recover an approximate two-fold super-periodicity, allowing a luminosity of $1.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with a vertical beam-beam parameter of 0.1 and sufficient lifetime. For the LCC optics, detailed investigations are still ongoing. Nevertheless, a reduction of the beam-beam parameter by about 25% restores an acceptable lifetime in the present configuration, which, however, also leads to a comparable luminosity drop. In parallel, reducing the emittance appears to enhance beam lifetime. Current investigations and efforts are targeted towards the potential decrease of the emittance.

CONCLUSION

A detailed comparison between the GHC and the LCC optics have been carried out, evaluated by an independent and international review panel. Based on this assessment the LCC is recommended as the preferred baseline option.

The recommendation is based on several key features of the LCC design including its modular design approach, larger improved DA and MA for the ideal lattices, enhanced flexibility in insertion design, fewer number of sextupole circuits in the arcs and reduced SR thanks to a higher dipole filling factor. Nevertheless, several advantages of the GHC optics have been identified, such as a simpler interaction

region lattice with only local vertical chromaticity correction scheme and fewer magnets.

OUTLOOK AND STEPS FOR THE REFERENCE DESIGN PHASE

Following the recommendation of the independent review panel and the subsequent decision to adopt the LCC as the new baseline optics, the FCC-ee project is entering the Reference Design Phase in preparation for the TDR.

In the immediate short term, the priorities are to make the LCC optics available at all four energy points, to provide consolidated tables of reference beam and machine parameters and to address the specific studies identified by the review panel. These include a deeper understanding of simulation results in the presence of realistic errors, updated DA and MA studies after optics tuning including magnet manufacturing errors. Further short-term tasks include extending polarization and energy calibration studies beyond the Z energy, evaluating the impact of the shorter sextupole magnetic lengths in the LCC lattice on corrector performance and investigating effects observed in simulations such as the unexpectedly large vertical emittance growth in the LCC optics after tuning.

Through the end of 2026, the scope expands to cover both beam dynamics studies and the technical consolidation of the LCC design. On the beam dynamics side, the longer-term panel recommendations are to be addressed, covering commissioning simulations, beam lifetime and luminosity performance at all collision energies including $\bar{t}\bar{t}$, integrated simulations of beam-beam and collective effects, top-up injection and a determination of the achievable peak luminosity at each energy point. On the technical side, a layout compatible with civil engineering requirements is to be established, covering the experimental and technical insertions, arc design and compatibility with the future FCC-hh. This includes the design of the collimation, RF, injection and dump insertions. This period also targets the consolidation of the magnet catalog, the optimization of magnetic circuits, power converter class requirements and the definition of corrector hardware, solenoid compensation strategy and many other aspects to be finalized into a coherent and integrated design.

Looking further ahead into the Reference Design Phase, the objective is a fully consolidated optics design supported by a complete and realistic set of beam dynamics simulations. These simulations will define the baseline operational scenario, drive further optimizations to maximize performance and integrated luminosity and provide the equipment specifications. All of these aspects are key milestones towards a possible CERN Council construction decision in 2028 and will act as the foundation of the TDR phase.

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