

PROPOSED COLLIMATION LAYOUT FOR THE FCC-ee WITH LOCAL CHROMATICITY CORRECTION OPTICS

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Abstract

The Future Circular electron–positron Collider (FCC-ee), with a circumference of approximately 90 km, is designed to push both the luminosity and energy frontiers for high-brightness lepton beams. The unprecedented stored beam energy, reaching up to 17.7 MJ — around two orders of magnitude greater than in any previous lepton collider — poses major challenges for safe operation. Uncontrolled losses could result in high experimental backgrounds, downtime, or even damage to accelerator components, making an efficient and reliable collimation system essential.

Two layouts and optics configurations are currently under consideration for the FCC-ee: the Global Hybrid Correction (GHC) and the Local Chromaticity Correction (LCC) schemes. While a collimation concept has previously been proposed for the GHC optics, this paper presents a new collimation layout specifically designed for the LCC lattice. The collimation performance is then compared between the two optics and layout versions under representative loss scenarios to identify in which optics the collimation system works best.

INTRODUCTION

The FCC-ee [1–3] is a proposed circular e^+e^- accelerator with a circumference of about 90 km, intended to explore both extreme luminosities and the highest energies achievable for this type of machine. Its physics programme is based on four distinct operating modes, with beam energies of 45.6 GeV, 80 GeV, 120 GeV, and 182.5 GeV, each corresponding to optimal production conditions for the Z boson, W boson, Higgs boson, and top-quark pairs, respectively. The very large stored beam energy – reaching approximately 17.7 MJ with high local energy densities in the Z operating mode – implies a substantial potential for damage in the event of uncontrolled beam losses. For this reason, implementing an efficient collimation system is mandatory.

The Local Chromaticity Correction (LCC) optics [4], developed for the FCC-ee since 2022, represents an alternative lattice design that has become the new optics baseline, aimed at enhancing collider performance. The approach emphasises local compensation of chromaticity and non-linearities, ensuring high achromaticity, reduced sensitivity to errors, and improved control of beam dynamics. The LCC scheme facilitates very small β^* values and low emittances while

maintaining flexibility through modular insertions that minimally perturb the overall lattice structure.

LAYOUT CONSIDERATIONS

In the design of a multi-stage collimation system, several key aspects must be carefully considered. Foremost, a robust collimation hierarchy is required to ensure continuous protection of the most restrictive apertures in the machine. At the same time, the primary collimator settings should avoid excessively small jaw openings, as overly tight gaps can adversely affect beam lifetime and increase impedance. This constraint naturally favours locations with large local β -functions for the primary devices.

Furthermore, the phase advance between primary and secondary collimators should be selected as close as possible to the optimal values,¹ to maximise the interception efficiency of halo particles scattered at the primary stage [5].

This dedicated cleaning insertion is complemented with local protection of sensitive aperture bottlenecks, which, for the considered FCC-ee layouts, are the final-focus doublets. These so-called tertiary collimators should, in turn, be positioned approximately at multiples of 180° in phase with respect to the critical aperture bottlenecks, thereby ensuring that these sensitive regions remain within their protected shadow. Finally, the impact of local dispersion must be carefully evaluated and controlled. Note that ensuring a suitable off-momentum cleaning insertion for the LCC lattice is still under discussion, as many factors must be taken into account (such as the induced dose on the sensitive devices in the booster ring, which is hosted in the same tunnel). For the current study, the off-momentum insertion has been preliminarily placed in the long straight section where the booster RF system is hosted, using the injection insertion optics.

An additional concern for the FCC-ee specifically arises from its large circumference, which may limit the effectiveness of relying solely on the betatron tune to clean the transverse halo over all betatron phase advances, especially for fast losses if the dynamic aperture is small. As mitigation, a double-phase collimation scheme can be deployed, with two primary collimators per transverse plane at both 0° and 90° betatron phase. Such a configuration can be integrated into the LCC lattice with relative ease and is adopted as a baseline, since it is significantly more effective than a single-phase scheme for fast losses, as discussed later.

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¹ These are given by $\pm \cos^{-1} \frac{n_1}{n_2}$ (with n_1 the normalised gap in σ of the primary collimator and n_2 of the two secondary collimators).

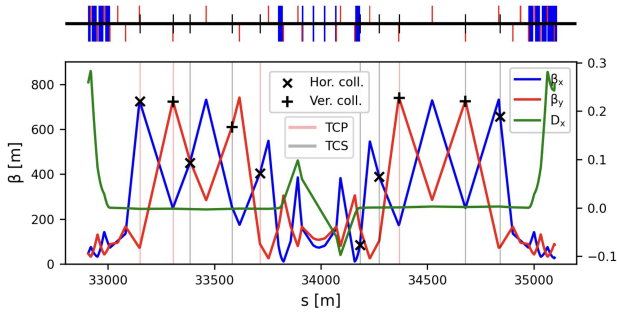


Figure 1: Zoom on the betatron collimation insertion with a double phase layout.

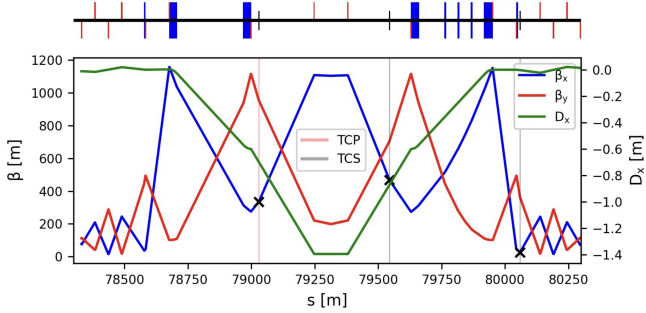


Figure 2: Zoom on the off-momentum collimation insertion, preliminary using the injection insertion optics.

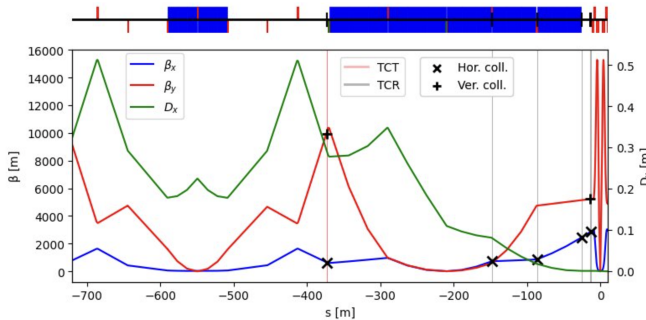


Figure 3: Upstream zoom of one of the experimental regions (collision point at $s = 0$ m), showing the placement of the tertiary collimators and synchrotron absorbers.

COMPARISON TO THE GHC

The Global Hybrid Correction (GHC) optics [6] have been developed over a considerably longer period and benefit from an extensively studied and optimised collimation layout [7–14]. Even though collimation studies using the LCC optics are only at their first footsteps, a direct comparison and important conclusions can already be made.

A fundamental constraint of the GHC scheme is the requirement to preserve a super-periodicity of four in order to achieve the target collider performance [6]. This has resulted in a lattice featuring four identical technical insertions, accommodating injection, RF, diagnostics, and collimation systems within a universal layout. Consequently, the collimation system design is intrinsically constrained by the requirements of the other insertions. In particular, due to the efforts to maximise the local β -functions at the primary collimators to mitigate impedance, the phase advances between

primary (TCP) and secondary (TCS) collimators were not yet optimised further.

In contrast, the LCC lattice decouples the design of individual insertions, such that modifications to one section have a negligible impact on the global optics. This provides significantly greater flexibility for optimising the collimation layout, including improved control over phase advances and collimator placement. However, in its current design, the LCC retains the beam separation in the collimation straight section equal to its value in the arcs. This makes it impossible to generate adequate dispersion, hence requiring a dedicated section for off-momentum collimation. The optimal location for such an insertion remains to be defined. By comparison, the GHC lattice exploits a built-in dispersion bump within the collimation section, enabling simultaneous treatment of betatron and off-momentum halo within a single insertion.

Another important distinction arises from the transverse stability properties of the two optics. The LCC lattice exhibits significantly larger dynamic aperture and momentum acceptance [15], which is advantageous for collimation efficiency. This is particularly relevant in the vertical plane, where in the GHC optics the primary collimator setting (at approximately 50σ) lies well beyond the dynamic aperture (around 25σ). Under such conditions, particles at large amplitudes follow chaotic trajectories, reducing the predictability of their motion and increasing the probability of impacting secondary or tertiary collimators – or even sensitive machine components – before being intercepted by the primaries. This so-called hierarchy-breaking degrades overall cleaning performance and may pose a risk to the collimation system.

PROPOSED LAYOUT FOR THE LCC

Based on the considerations outlined above, a preliminary collimation layout for the LCC lattice has been defined in the straight section PF, with the corresponding settings summarised in Table 1.

In the horizontal plane, the large β -functions provide considerable flexibility in collimator placement, allowing phase advances to be chosen close to optimal. In the vertical plane, however, the small emittance imposes a lower limit on the collimator gaps, effectively requiring placement close to the betatron maxima. While the resulting phase advances remain acceptable, this constraint prevents the installation of secondary collimators at negative phase with respect to each primary, as illustrated in Fig. 1.

The off-momentum insertion PL, shown in Fig. 2, is currently more preliminary and less optimised, and the feasibility of coexistence with the booster RF is uncertain. In its present form, it features a single dispersion bump, such that the negative-phase secondary is located in a region of negligible dispersion and therefore acts as a secondary betatron collimator.

Finally, the placement of tertiary collimators and synchrotron absorbers in the experimental insertion is presented in Fig. 3. The phase advances remain close to optimal.

Table 1: Proposed settings for the LCC lattice, using a horizontal emittance of 0.74 nm and a vertical of 1.34 pm. The global aperture bottleneck, assuming maximally 250 μm orbit distortion and 20% β -beating, is 15σ at QF1BR in the horizontal plane and 90σ at QD0BR in the vertical plane.

Name	Material	Length [cm]	Gap [σ]	Jaw [mm]	$\Delta\mu$ [$^\circ$]	$\Delta\mu_{\text{optimal}}$ [$^\circ$]	δ_{cut} [%c]
TCP.H	C-based	10	9	6.5	–	–	–
TCS.H1	Mo-based	30	11	6.3	35.09	35.10	–
TCS.H2	Mo-based	30	11	5.8	144.86	144.90	–
TCP.HH	C-based	10	9	4.9	89.98	90.00	–
TCS.HH1	Mo-based	30	11	2.7	126.91	125.10	–
TCS.HH2	Mo-based	30	11	7.6	234.87	234.90	–
TCP.V	C-based	10	60	1.9	–	–	–
TCS.V1	Mo-based	30	75	2.2	36.89	36.87	–
TCP.VV	C-based	10	60	1.9	83.01	90.00	–
TCS.VV1	Mo-based	30	75	2.4	122.82	126.87	–
TCP.HP	C-based	25	18	8.7	–	–	1.25
TCS.HP1	Mo-based	30	24	13.8	41.40	41.41	1.58
TCS.HP2	Mo-based	30	24	3.3	138.13	138.59	–
TCT.H	C-based	25	13	8.7	–	–	3.02
TCR.H3	W-based	10	15	10.7	170.58	180.00	10.72
TCR.H2	W-based	10	15	11.8	175.17	180.00	50.26
TCR.H1	W-based	10	15	19.9	177.56	180.00	–
TCR.H.C2	W-based	10	15	21.7	177.85	180.00	–
TCT.V	C-based	25	75	9.0	–	180.00	–
TCR.V.C2	W-based	10	90	7.8	179.93	180.00	–

SIMULATED PERFORMANCE

Dedicated tracking simulations of beam losses were carried out using Xsuite [16–18], in particular its Xcoll module [19–21], which is interfaced to Geant4 through BDSIM [22–24] for detailed modelling of particle–matter interactions. A range of scenarios was considered to evaluate beam loss distributions (loss maps), including both slow diffusion — modelled via a soft blow-up — and fast coherent instabilities, in which a large fraction of the beam is lost within only a few turns [25].

As a representative case, results are presented for a vertical blow-up, which constitutes the most critical plane for the GHC lattice and is known to exhibit hierarchy breaking, consistent with its limited vertical dynamic aperture. The corresponding results for the LCC lattice, employing a double-phase collimation scheme, are shown in Fig. 4. In this case, no hierarchy breaking is observed. Moreover, losses are effectively confined within the betatron collimation section, with negligible leakage (up to $6 \cdot 10^{-5}$ of total losses) to other regions of the ring. This improved perform-

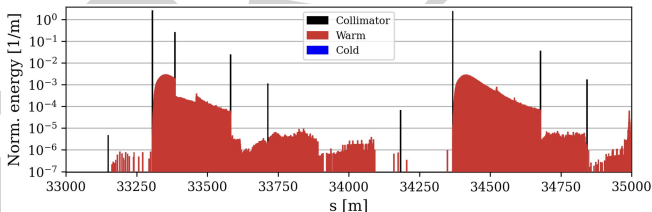


Figure 4: Losses in the collimation insertion for a vertical blow-up simulation. The two major loss peaks are on both primary collimators; hence, no hierarchy breaking is present.

ance is further supported by simulations of fast instabilities, which confirm the strong suppression of losses in sensitive regions and highlight the effectiveness of the double-phase collimation approach.

CONCLUSION

The LCC lattice offers several advantages for collimation, including large β -functions, improved control of phase advances, and an efficient double-phase collimation scheme. In addition, larger-aperture bottlenecks and a significantly increased vertical dynamic aperture provide greater flexibility and are essential for maintaining a robust hierarchy and for efficient beam cleaning.

While the GHC lattice benefits from integrating off-momentum collimation within the same insertion, the results presented here show that the superior betatron cleaning performance of the LCC — particularly in a double-phase configuration — outweighs this advantage. Simulations demonstrate effective confinement of losses within the collimation section and the absence of hierarchy breaking, which is critical for machine protection. Although off-momentum cleaning in the current LCC design remains less optimised, this is a reasonable trade-off given the substantial gains in transverse cleaning efficiency. Overall, the LCC double-phase collimation layout emerges as a highly promising solution for achieving reliable and performant beam loss control in the FCC-ee. These conclusions have supported the selection of the LCC optics as the new FCC-ee optics baseline.

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