ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST017

DESIGN OF A COLLIMATION SECTION FOR THE FCC-ee*

M. Hofer†, A. Abramov, R. Bruce, K. Oide, F. Zimmermann, CERN, 1211 Geneva, Switzerland
M. Moudgalya, T. Pieloni, EPFL, 1015 Lausanne, Switzerland

Abstract

The design parameters of the FCC-ee foresee operation with a total stored energy of up to about 20 MJ per beam, exceeding those of previous lepton colliders by almost two orders of magnitude. Given the inherent damage potential, a halo collimation system is studied to limit backgrounds and protect the machine hardware, in particular superconducting equipment such as the final focus quadrupoles, from sudden losses. The different constraints that led to dedicating one straight section to collimation will be outlined. In addition, a preliminary layout and optics for a collimation insertion are presented.

INTRODUCTION

The first stage of the Future Circular Collider (FCC) integrated program, the FCC-ee [1], is a proposed double-ring e^+e^- collider with a circumference of about 91 km. Four operation modes are foreseen, with beam energies of 45.6 GeV, 80 GeV, 120 GeV, and 182.5 GeV, referred to as Z, WW, ZH, and $t\bar{t}$ running. At 45.6 GeV, the beam current reaches 1.4 A, whereas only 6.4 mA are stored at 182.5 GeV.

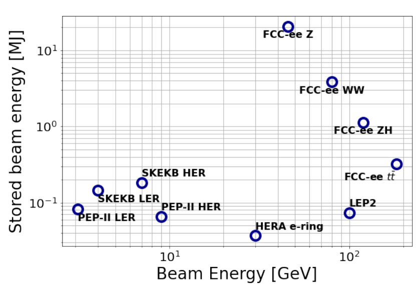


Figure 1: Comparison of stored beam energy between FCC-ee, LEP2, PEP-II, HERA, and SuperKEKB.

In Fig. 1, the stored beam energy for the different FCC-ee modes is compared to other lepton colliders [2–5]. The stored beam energy of about 20 MJ per beam at the Z-operation mode exceeds those of present and past e^+e^- colliders by about two orders of magnitude. The energy stored in either FCC-ee beam is still a factor ~ 20 lower than the energy contained in each of the two proton beams of the Large Hadron Collider (LHC), which is being successfully handled by a multi-stage collimation system. The stored beam energy of the FCC-ee is similar to the one expected for lead ion operation at the High Luminosity LHC [6,7]. Given the damage potential in case of beam loss, as is illustrated by incidents at SuperKEKB [8], a dedicated two-stage halo collimation system will be installed in the FCC-ee, profiting from the experience of the LHC collimation design. The purposes of the FCC-ee collimation are to limit the detector background and to protect sensitive equipment from beam loss induced damage or quench, e.g., the superconducting final-focus quadrupoles.

FCC-ee DESIGN

Since the publication of the FCC-ee conceptual design report [1], the design has undergone several changes. Those with implications on collimation are most notably, the circumference reduction from 98 km to 91 km motivated by a more favourable placement of the surface sites [9]. While the previous tunnel layout featured only a left/right symmetry, the new layout features a four-fold periodicity, a configuration providing the option to have either two or four interaction points (IP). Figure 2 shows the new 4-IP layout.

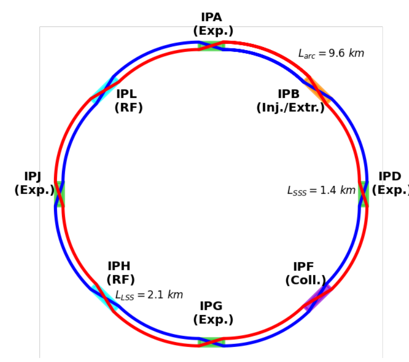


Figure 2: Assumed layout of the FCC-ee.

A final decision on the actual number of IPs will be taken at a much later moment in time. Here, we consider only the optics with 4 IPs and, correspondingly, 4 low-beta insertions. Two arc optics configurations will be used in FCC-ee, one for the two lower energy operation modes Z and WW, and another for the modes ZH and $t\bar{t}$. This change is necessary to achieve the target horizontal emittance at the higher energy modes, while keeping a large momentum compaction α_p at the low energy modes [10]. For the most recent layout [11], the phase advance over the FODO cell will be 90°/90° in all cases, with a variable cell length. In the lower energy modes, the cell will be twice as long compared to the high energy modes. The different arc layouts and the resulting optics are illustrated in Fig. 3.

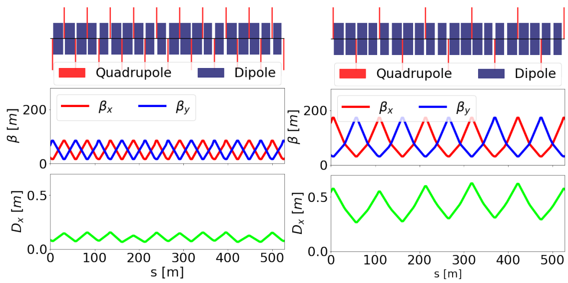
The studies reported in the following focus on the Z and $t\bar{t}$ modes of operation, which correspond to the highest beam current and the largest energy loss from synchrotron radiation, respectively.

APERTURE MODEL

The collimation design requires a detailed aperture model around the ring, allowing to identify loss locations and bot-

* This work is partially supported by the Swiss Accelerator Research and Technology (www.CHART.ch) program.
† michael.hofer@cern.ch

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST017



(a) Arc optics for $t\bar{t}$ operation (b) Arc optics for Z operation

Figure 3: Comparison of the half-cells in both lattices.

tlenecks. Recently, the aperture model for the FCC-ee was completed and first studies to identify the aperture and momentum bottlenecks were conducted [12]. For most parts of the machine, the aperture is modelled as a circular beam pipe with a radius of 35 mm. While the FCC-ee beam screen design features winglets in the horizontal plane, this conservative circular approximation is used to simplify and speed up computations. The beam pipe radius in the final-focus quadrupole is 15 mm. Following recent updates of the interaction region design [13], the central beam pipe radius was further reduced down to 10 mm near the collision point. Additionally, a synchrotron radiation (SR) mask is installed after the last final focus quadrupole upstream of the IP. The aperture around one interaction point is illustrated in Fig. 4.

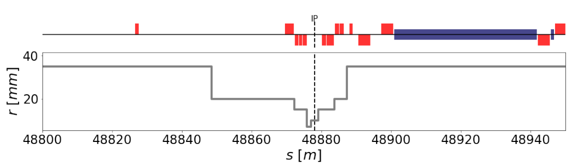


Figure 4: Model of the aperture close to the interaction point.

The clearance of the beam to the aperture in terms of beam size is calculated using the APERTURE module in MAD-X [14]. The optical tolerances, shown in Table 1, which are based on the results of the low emittance tuning studies for FCC-ee [15] and alignment tolerances for different magnet groups used therein were also used as input for the aperture studies. Using the described parameters, the design emittances and the latest optics for the operation modes, the beam stay clear and momentum acceptance for the Z and $t\bar{t}$ were calculated and are shown in Fig. 5.

Table 1: Tolerances used in the MAD-X aperture module. The complete list is found in [12].

Maximum radial closed orbit uncertainty	250 µm
Beam size increase from β-beating	1.1
Parasitic dispersion	0.0

Note that here, no aperture limiting collimators and SR collimators have been included apart from the aforementioned masks close to the final focusing quadrupole. For the $t\bar{t}$ operation mode, the aperture bottleneck is located in the last dipole upstream at the IP, whereas in the Z mode, it is the final focus quadrupole. The aperture bottleneck is located in the horizontal plane in both cases. Recently, it was proposed to reduce the β_x^* at the Z-mode from 15 cm down to 10 cm to mitigate a coherent instability [16]. The lower β_x^* results in a larger β-function in the final focus quadrupole, and accordingly the beam stay clear decreases from 19.3 σ_x, as shown in Fig. 5b, to 15.8 σ_x. The momentum bottleneck is located in one of the quadrupoles after the interaction point in the case of $t\bar{t}$, whereas for the Z mode, it lies in the focusing quadrupoles of the arc. This difference is caused by the change in cell length and associated increase of dispersion in the arcs, which can be seen by comparing Figs. 3a and 3b.

In past studies of top-up injection in the FCC-ee, the minimum aperture requirement for an on-momentum beam was set to 15 σ_x for all operation modes [17]. In both the Z and $t\bar{t}$ operation mode, the minimum beam stay clear is sufficiently above this number such that a collimation hierarchy can be established. On the other hand, the optics with $\beta_x^* = 10$ cm for the Z operation shows little margin and further studies are required. The minimum aperture requirement for top-up injection was based on the assumption that the size of the beam coming from the booster is equal to the one of the collider. Studies are currently ongoing to refine this requirement, accounting for the smaller emittance from the booster and an optics mismatch between transfer line and collider [18], which should decrease the aperture requirement.

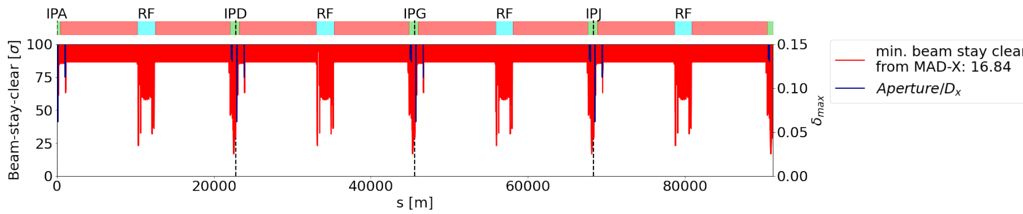
COLLIMATION INSERTION LAYOUT

Given the damage potential of the FCC-ee beam, a two-stage collimation system was chosen as a first approach, similar to LEP [19, 20] and LHC [21–23]. Installation of the collimation system in one or more straight sections is favoured for multiple reasons. The use of a straight section allows orders of magnitude larger β-functions compared to the arc cells, leading to larger collimator half gaps. This is beneficial both for mechanical alignment and impedance. Moreover, the dispersion and β-functions can be decoupled to a certain degree in a straight section, allowing independent tuning of the betatron and momentum cuts.

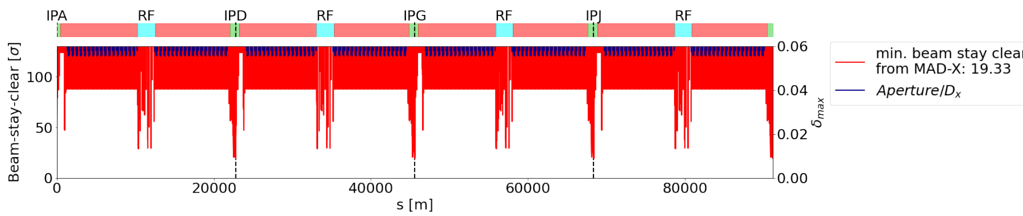
While the four shorter straight sections (A, D, G, J) will house the experiments, the RF cavities will be installed in the two long straight sections H and L on the right hand side. The location for the RF was chosen as access to the surface sites and infrastructure is preferential there [24]. As such, the 2.1 km long straight section F was chosen for the collimation system, with the straight section B potentially hosting the hardware for the top-up injection.

A candidate layout was integrated and matched to the two different arc optics. The optics and location of the collimators are presented in Fig. 6. With the long straight section located between two experimental insertions, the incoming beam will be on the outside and has to cross to the inside. This is illustrated in Fig. 2 and follows from the FCC-ee IR design which foresees the incoming beam to be on the

13th Int. Particle Acc. Conf. IPAC2022, Bangkok, Thailand JACoW Publishing
ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST017



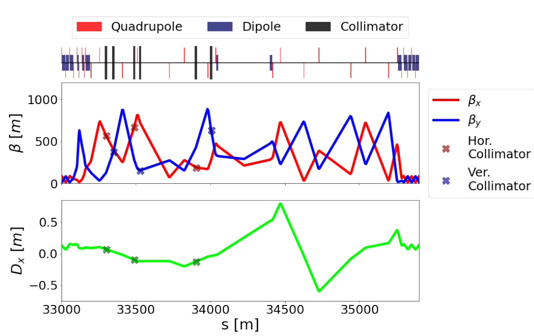
(a) Beam stay clear and momentum acceptance for $t\bar{t}$



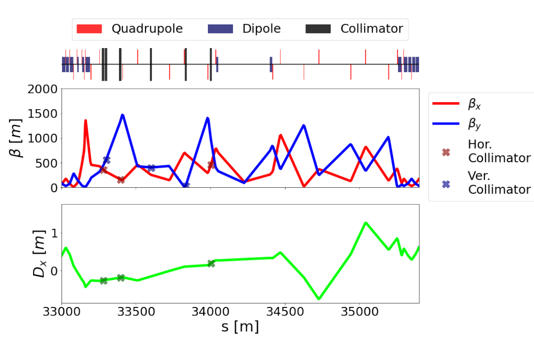
(b) Beam stay clear and momentum acceptance for Z

Figure 5: Comparison of beam stay clear and momentum acceptance.

inside and with only a weak bending upstream of the IP to limit the energies of the SR photons emitted towards the IP [25]. Therefore, a beam crossing was installed in the middle of the insertion. The distance of 400 m between the 15 m long dipoles was chosen such that the critical energy of the synchrotron radiation from those dipoles does not exceed that of the arc dipole. Both the betatron and momentum cleaning need to be located in one straight section. In the candidate layout, the betatron collimation section is located upstream of the beam crossing and features low dispersion. The momentum collimators will be located downstream of the beam crossing, where the dispersion is large. This split insertion allows to independently tune the betatron and momentum collimator settings. A combined system, where the



(a) Collimation layout for $t\bar{t}$ running



(b) Collimation layout for Z running

Figure 6: Collimation section optics at low and high energy.

primary collimator is both aperture and momentum bottleneck, could feature a lower number of collimators. However, the cuts in such a system are tightly coupled and can only be independently adjusted by rematching the optics. For a given location of the primary collimator, the location of the secondary collimators is then chosen such that the phase advance from the primary collimator is [26]

$$\mu = \arctan\left(\frac{\sqrt{n_2^2 - n_1^2}}{n_1}\right), \tag{1}$$

where n_1 and n_2 are the openings of the primary and secondary collimators in units of RMS beam size. Based on the requirements for top-up injection, the opening of the horizontal primary collimator is tentatively set to $n_1 = 15\ \sigma_x$. Assuming a retraction of 2 σ for the secondary collimators in this plane, those are then set to $n_2 = 17\ \sigma_x$. In the case of $t\bar{t}$ operation mode, the secondary opening slightly exceeds the beam stay clear at the bottleneck. Further studies will explore tighter mechanical tolerances for specific elements to increase the beam stay clear, and review the top-up injection needs. For the vertical plane, the chosen collimator openings are $n_1 = 80\ \sigma_y$ and $n_2 = 90\ \sigma_y$ for the primary and secondary collimator, respectively, which can be compared to the minimum beam-stay-clear of 91 σ_y at $t\bar{t}$ and 110 σ_y at Z.

SUMMARY AND OUTLOOK

The FCC-ee will face a stored beam energy which is unprecedented for a lepton collider. To protect sensitive machine equipment and limit backgrounds, a collimation system is being developed, partly inspired by the LHC's. A first aperture model of the FCC-ee was implemented and the aperture bottlenecks were identified. A first design of a collimation system has been developed, with separate betatron and momentum cleaning systems in one long straight section. The detailed design and efficiency of the proposed system is to be studied through simulations, which is an ongoing effort [27].

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOST017

REFERENCES

[1] A. Abada *et al.*, "FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2", *Eur. Phys. J. Spec. Top.*, vol. 228, pp. 261-623, 2019.

[2] C. Wyss (Ed.), "LEP design report, v. 3: LEP2", CERN, Geneva, Rep. CERN-AC-96-01-LEP-2, Jun. 1996.

[3] Y. Ohnishi *et al.*, "Accelerator design at SuperKEKB", *Prog. Theor. Exp. Phys.*, vol. 2013, no. 3, p. 03A011, Mar. 2013. 10.1093/ptep/pts083

[4] "PEP-II, An Asymetric B factory. Conceptual Design Report", Jun. 1993. doi:10.2172/10112145

[5] "HERA, A proposal for a large electron-proton colliding beam facility at DESY", DESY, Hamburg, Germany, Rep. DESY-HERA-81-10, Jul. 1981.

[6] I. Béjar Alonso *et al.*(Eds.), "High-Luminosity Large Hadron Collider (HL-LHC): Technical design report", CERN, Geneva, Switzerland, CERN Yellow Reports: Monographs, Rep. CERN-2020-010, 2020. doi:10.23731/CYRM-2020-0010

[7] R. Bruce *et al.*, "Performance and luminosity models for heavy-ion operation at the CERN Large Hadron Collider", *Eur. Phys. J. Plus*, vol 136, p. 745, 2021. doi:10.1140/epjp/s13360-021-01685-5

[8] T. Ishibashi *et al.*, "Movable collimator system for SuperKEKB", *Phys. Rev. Accel. Beams*, vol. 23, p. 053501 2020.

[9] J. Gutleber *et al.*, "FCC baseline V1.0 and fallback scenarios", 144th FCC-ee Optics Design Meeting & 15th FCCIS WP2.2 Meeting, 16. Sep. 2021.

[10] I. Agapov, P. Charitos, K. Oide, T. Raubenheimer, D. Shatilov, F. Zimmermann, "Collider performance, beam optics and design considerations baseline (1.0)", Zenodo. 10.5281/zenodo.5643134

[11] FCC-Collaboration, "FCC-ee lattice V22.1", Mar. 2022. 10.5281/zenodo.6364964

[12] M. Moudgalya, "First studies of the halo collimation needs in the FCC-ee", Department of Physics, Imperial College London, July, 2021, https://cds.cern.ch/record/2808768.

[13] M. Boscolo *et al.*, "Challenges for the interaction region design of the Future Circular Collider FCC-ee", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 2668–2671. doi:10.18429/JACoW-IPAC2021-WEPAB029

[14] MAD-X, https://madx.web.cern.ch/madx/

[15] T. K. Charles, B. J. Holzer, K. Oide, and F. Zimmermann, "Update on the low emittance tuning of the e+/e- Future Circular Collider", in *Proc. 12th Int. Particle Accelerator Conf. (IPAC'21)*, Campinas, Brazil, May 2021, pp. 2601–2604. doi:10.18429/JACoW-IPAC2021-WEPAB011

[16] Y. Zhang *et al.*, "Beam-beam simulation with 4IP parameters and analysis work of combined effect between Beam-beam and longitudinal impedance", 150th FCC-ee Optics Design Meeting & 21st FCCIS WP2.2 Meeting, 24. Feb. 2022.

[17] M. Aiba *et al.*, "Top-up injection schemes for future circular lepton collider", *Nucl. Instrum. Methods Phys. Res. A*, vol. 880, pp. 98-106, Mar. 2015. doi:10.1016/j.nima.2017.10.075

[18] R. P. Fliller, "Optimal twiss parameters for top off injection in a Synchrotron Light Source", in *Proc. 1st Int. Particle Accelerator Conf. (IPAC'10)*, Kyoto, Japan, May 2010, paper TUPEC040, pp. 1814–1816.

[19] F. Bertinelli and R. Jung, "Design and construction of LEP collimators", in *Proc. 12th Particle Accelerator Conf. (PAC'87)*, Washington D.C., USA, Mar. 1987, pp. 1564–1567.

[20] P. Lepeule, C. Menot, and R. Veness, "Design and implementation of synchrotron radiation masks for LEP2", in *Proc. 5th European Particle Accelerator Conf. (EPAC'96)*, Sitges, Spain, Jun. 1996, paper MOP035L, p. 2503.

[21] R. W. Assmann *et al.*, "The final collimation system for the LHC", in *Proc. 10th European Particle Accelerator Conf. (EPAC'06)*, Edinburgh, UK, Jun. 2006, paper TUODFI01, pp. 986.

[22] R. Bruce *et al.*, "Simulations and measurements of beam loss patterns at the CERN Large Hadron Collider", *Phys. Rev. ST Accel. Beams* vol. 17, p. 081004, 2014. 10.1103/PhysRevSTAB.17.081004

[23] R. Bruce *et al.*, "Reaching record-low β^* at the CERN Large Hadron Collider using a novel scheme of collimator settings and optics", *Nucl. Instrum. Methods Phys. Res. A*, vol. 848, p. 19, 2017. 10.1016/j.nima.2016.12.039

[24] K. Hanke, "Placement of the two RF points", 144th FCC-ee Optics Design Meeting & 15th FCCIS WP2.2 Meeting, 16. Sep. 2021.

[25] K. Oide *et al.*, "Design of beam optics for the future circular collider e^+e^- collider rings", *Phys. Rev. Accel. Beams*, vol, 19, p. 111005, 2016. 10.1103/PhysRevAccelBeams.19.111005

[26] J. B. Jeanneret, "Optics of a two-stage collimation system", *Phys. Rev. ST Accel. Beams*, vol. 1, p. 081001, 1998.

[27] A. Abramov *et al.*, "Development of collimation simulations for the FCC-ee", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, paper WEPOST016, this conference.