FCC

M. Boscolo (Resp.), G. Broggi (PhD), S. Cantarella, A. Ciarma (Art.36),
E. Di Pasquale, F. Fransesini (Art.36), G. Nigrelli (PhD),
in collaboration with: S. Lauciani (Tec), P. Tuscano (Tec)

The FCC team within the Frascati accelerator division contributes to the **FCC-ee Machine–Detector Interface (MDI)** since the early Conceptual Design Report phase, continuing through the Feasibility Study and into the ongoing pre-TDR phase. The core activity of the group focuses on the design and optimisation of the interaction region (IR) and its integration with the detector, supported by a dedicated experimental R&D programme aimed at demonstrating the technological feasibility of the proposed layout through a full-scale IR mock-up.

Ref. 4) describes in detail the MDI study performed for the Feasibility Study. An overview of this is reported in Vol. 1 and Vol. 2 of the Feasibility Study Report 1, 2, 3), that contributed to the decision of the 2025 European Strategy for Particle Physics that identified FCC-ee as the preferred option for the next flagship collider at CERN, with a descoped FCC-ee as the preferred alternative.

The LNF FCC group contributes to several key accelerator topics directly impacting the MDI, including:

- IR optics design, including solenoid compensation,
- collimation and beam-loss studies,
- beam lifetime and background simulations,
- synchrotron radiation (SR) evaluation,
- mechanical integration of the MDI.

All activities are carried out within dedicated CERN–INFN-LNF agreements.

The FCC-ee MDI is based on a compact and technologically demanding layout implementing the crab-waist collision scheme. The design must simultaneously satisfy stringent accelerator and detector requirements, with the objective of maximising luminosity across all centre-of-mass energies, from the Z pole to the $t\bar{t}$ threshold. A schematic layout of the IR is shown in Fig. 1.

The activity in Frascati was initiated within the EU Horizon 2020 projects EuroCirCol and FCCIS, which supported early postdoctoral positions during the CDR and Feasibility Study phases. The work is currently supported by the INFN RD_FCC programme, a dedicated R&D initiative structured into six work packages, with WP2 devoted to the accelerator. M. Boscolo serves as WP2 coordinator.

In 2023, a dedicated INFN–CERN special project was launched for the realisation of a full-scale FCC-ee IR mock-up in Frascati, in view of the European Strategy Update. In 2025 this R&D activity has been embedded in the ECFA-DRD8 Collaboration on *Mechanics and Cooling of Future Vertex and Tracking Systems*, within WP1 on Global System Design and Integration.

In the following sections, we summarise the main developments and ongoing studies.

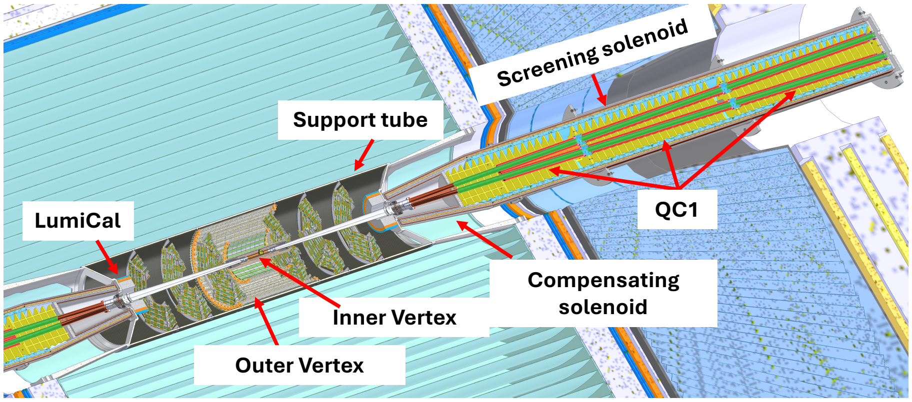


Figure 1: Layout of the FCC-ee interaction region.

1 Interaction Region Optics Design

The group develops the IR optics model of the solenoid compensation scheme in collaboration with CERN, as reported in the recent paper in Ref. 5).

An alternative compensation approach has been proposed with the objective of improving optics performance and engineering design.

The solenoidal field of the detector requires precise compensation to avoid emittance blow-up and luminosity degradation. The IR optics is therefore developed in close connection with final focus quadrupole (FFQ) layout, solenoid compensation configuration, and synchrotron radiation (SR) emission from the IR magnets. The optimisation of these elements is essential to converge toward a stable and mechanically feasible IR layout. The choice of the solenoid compensation scheme has also direct implications on the maximum allowed detector solenoidal field, as well as on the transverse polarization of the beam.

2 Beam backgrounds and Collimation studies

The beam-induced backgrounds simulations carried out at LNF include all kind of sources: Incoherent Pairs Creation (IPC), radiative Bhabha, Beam-gas, Synchrotron Radiation (SR), Touschek, Injection, halo.

IPC is the main source of luminosity backgrounds at FCC-ee. It consists in secondary e^-e^+ pairs produced via the interaction of the beamstrahlung photons with real or virtual photons during bunch crossing, and particles exiting the machine dynamic aperture after a Radiative Bhabha process. First estimates of the IPC contribution have been calculated by the LNF team for IDEA vertex detector and drift chamber and for ALLEGRO liquid Argon Ecal using GuineaPig++ and the turnkey software Key4hep.

Relevant is also SR background, coming from the last upstream magnets, both by the last dipoles and by the tails of the final focus quadrupoles. This key topic is under study to characterise this SR in the MDI, both in terms of detector occupancies and data rates, and of power deposition in machine components. Besides, synchrotron radiation emitted in the IR by the combination of the detector solenoid and anti-solenoid produces numerous photons directed toward the next bent section downstream of the IP. This area requires careful attention since other sources, such as beamstrahlung, also converge at the same location. While the beamline incoming to the IP does not feature significant bending, the outgoing one is strongly bent to accommodate the 15 mrad

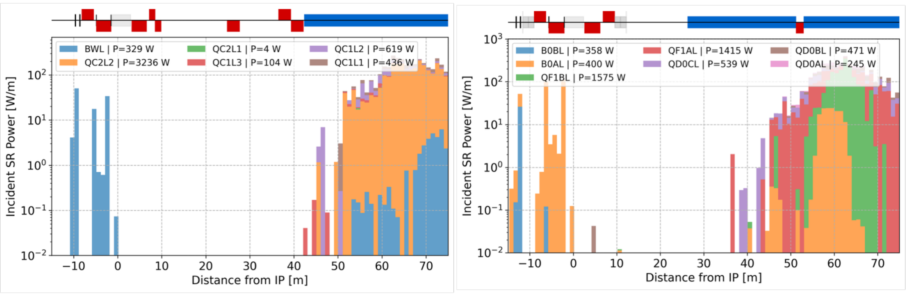


Figure 2: Incident power of synchrotron radiation in the IR beam pipes with the indication of the source location for two optics: (Left) GHC (Right) LCC.

half-crossing angle. This implies a much higher production of synchrotron radiation downstream of the IP, amounting to hundreds of kW already within the first 400 m. The two optics under review, GHC developed by K Oide and LCC by P. Raimondi, show different SR backgrounds levels (see Fig. 2), and this study is being carried out with Xsuite-BDSIM code and presented at the Optics review this 22 January 2026.

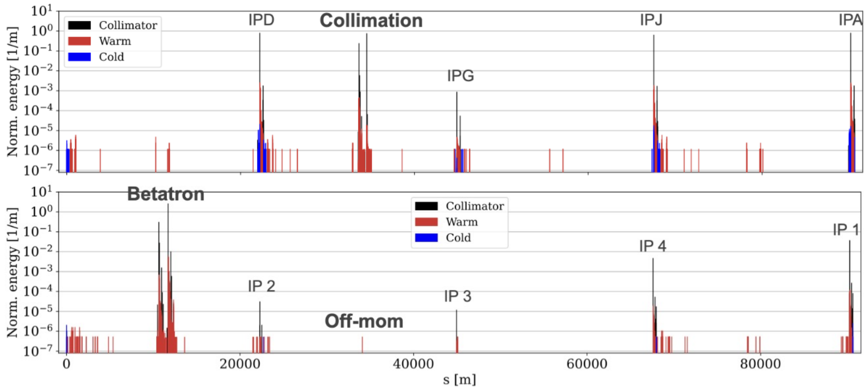


Figure 3: Vertical plane losses for GHC (upper) and LCC (lower) showing a greater collimation efficiency for LCC, thanks to the double phase configuration that brings about five orders reduction of losses at tertiary collimators.

In high-intensity machines, such as the FCC-ee, beam halo losses must be safely disposed to avoid damage to sensitive equipment and keep the background level in the detectors below tolerable levels. For these reasons, a beam halo collimation system is being designed and optimized. High rates of beam losses in the IR coming from the beam halo in the occurrence of a sudden lifetime drop are also carefully studied. Multi-particle tracking studies have been performed to evaluate the effectiveness of the halo collimation system in suppressing beam halo losses on sensitive machine equipment and in the IRs. The first focus was on the FCC-ee Z operation mode, as it is the most challenging from the collimation point of view given the highest stored beam energy of 17.5 MJ. The studies have been performed using the Xsuite-BDSIM simulation tool, which combines particle tracking in the FCC-ee magnetic lattice, performed with Xsuite, and full Monte Carlo particle-matter interaction simulations in the collimators, performed with BDSIM based on GEANT4. In these studies, a number of macroparticles, typically 5×10^6, are tracked through the full FCC-ee nonlinear lattice for 500 machine turns, including the effects of synchrotron radiation (SR), RF cavities and magnetic lattice tapering. For simulation performance, only a beam halo slice impacting directly on one of the primary beam halo collimators is simulated, with a maximum impact parameter (i.e., the transverse depth into the collimator jaw) of 1 μm. The initial mechanism causing the loss is not simulated – as in LHC studies. The beam loss positions are recorded, and their distribution along the longitudinal coordinate s is binned in 10 cm intervals to produce loss maps showing the beam loss distribution along the collider ring. Fig. 3 shows the losses for the two different optics under comparison in case of a vertical blow-up.

The lifetime reduction and beam quality degradation due to beam-gas interactions are primarily caused by inelastic interactions, specifically bremsstrahlung interactions. While elastic interactions like single Coulomb scattering also occur, their effect on the beam is minimal at the FCC-ee beam energies compared to that of bremsstrahlung. Beam-gas interactions are unlikely to significantly affect the lifetime of the FCC-ee, which is primarily determined by Bhabha scattering at the IPs. Even in this pessimistic scenario, low power loads (less than 0.1 W) are expected on most components, with the highest loads recorded on the halo collimators (10-100 W) and SR collimators (1 W). Such power load levels are not a concern.

The collimation scheme has been adapted to the two optics now being considered and under comparison, GHC and LCC. A study in terms of collimation efficiency for the two optics shows a preference for LCC.

During bunch crossings, radiative Bhabha scattering produces off-energy particles that may exit the machine acceptance at the first quadrupoles. Events are generated with BBBrem, including beam–beam smearing via GuineaPig++, and tracked through the lattice using FLUKA to evaluate power deposition and detector backgrounds. Particular attention is devoted to superconducting FFQs, where cumulative radiation load may induce quenching or long-term degradation. These studies guide the design and dimensioning of internal shielding.

The LNF MDI team set-up a repository of beam-induced background particles samples for detector studies, now being used by various sub-detector groups, resulting extremely useful to assess hit rates and occupancies.

3 IR Mechanical Integration and Experimental R&D

A dedicated experimental R&D programme is being carried out in Frascati to validate the technological feasibility of the FCC-ee IR through the construction of a **full-scale mock-up**.

The mock-up reproduces the key elements of the MDI, including:

- thin, lightweight, actively cooled beam pipes,
- air-cooled inner vertex detector prototype, outer vertex, and disks,
- composite carbon-fibre cylindrical support structure,
- bellows,
- two prototypes for the luminosity calorimeters.

The objective is to experimentally validate the integration concept under realistic mechanical and thermal conditions, complementing detailed 3D CAD models and finite-element simulations.

The mock-up programme enables the assessment of several critical aspects, including mechanical stability, vibration behaviour, alignment tolerances, thermal management, and integration compatibility between accelerator and detector components. This experimental validation is essential to reduce technological risks and to support the consolidation of a robust IR layout for the pre-TDR phase. Figure 4 illustrates the FCC-ee MDI.

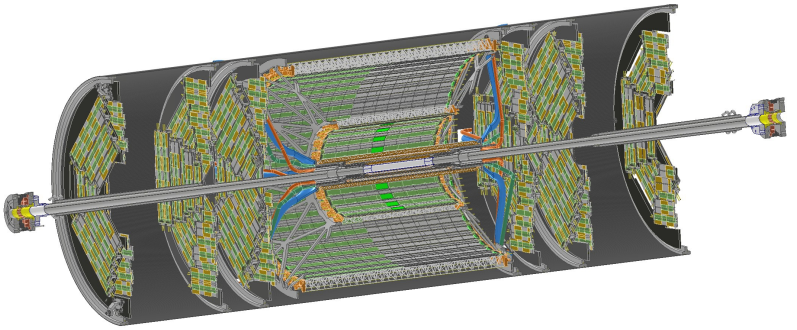


Figure 4: Section view of the Machine-Detector Interface region of the FCC-ee.

The central beam pipe is a 18 cm long cylinder made in AlBeMet[1], actively cooled with paraffin by a double layer wall structure, as required by the heat load in this region. An internal 5 μm coating layer of gold ensures a good electrical conductivity to minimise the beam heat load and to shield the vertex detector from residual high energy SR photons. The geometry is optimized to minimise the material budget, provide mechanical stability, and to guarantee a proper coolant flow to remove the heat load. Fig. 5a shows the prototype fabricated in aluminium used to test the cooling system in paraffin. This test was successfully conducted at the end of 2025 showing the expected performance.

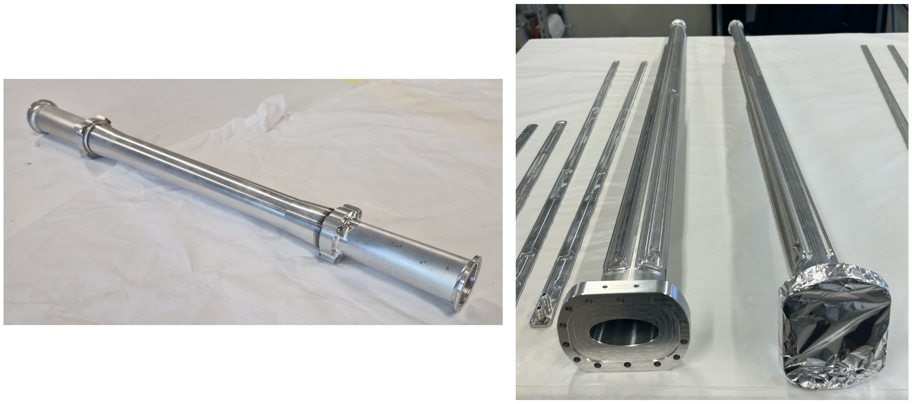
The ellipto-conical chamber bifurcates into two symmetrical beam pipes of 15 mm radius at 1.28 m from the IP. This point is also known as *crotch*. The impedance was minimised by carefully designing the smooth transition from the circular shape of the central beam pipe to an elliptical shape for the lateral one. These lateral beam pipes have been fabricated in aluminium with the water cooling manifolds, to test its cooling efficiency. Fig. 5b shows these beam pipes before the TIG welding of the covers onto the cooling manifolds.

The first phase of the mock-up activities has focused on thermal testing of the central beam pipe. The test setup includes a cooling circuit, temperature sensors, precision pressure gauges, and flow meters, operating at flow rates between 0.5 and 2 l/min. An internal ohmic heater simulated the wakefield heat load, with a nominal power of about 30 W, adjustable up to 100 W. Initial water-based tests followed by paraffin confirmed the expected thermal performance. Unfavorable scenarios were performed, increasing the power up to 100 W while reducing the coolant flow rate to 0.5 l/min and increasing its inlet temperature to 22^{o}C. This result confirmed the effectiveness of the cooling system even in non-ideal working scenarios of the cooling system during operations. Similar thermal tests on the ellipto-conical beam pipes are planned in the next weeks.

The IR bellows design is inspired on the ones successfully implemented at ESRF-EBS, design at LNF. Electrical continuity is ensured using copper-beryllium ($CuBe_2$) RF fingers, which surround the elliptical vacuum chamber. A blade pusher maintains the desired electrical contact. A prototype is under fabrication, and will be used to impedance and assembly tests. In fact, the bellows will be attached between the conical chamber and the remote vacuum flange near the superconducting IR magnet system. Due to space constraints, they must be compact while allowing for misalignment adjustments and thermal expansion compensation.

---

[1] AlBeMet162 is an alloy of commercially pure beryllium and aluminium, 62 % and 38 % in weight, respectively



(a) (b)

Figure 5: (a) The central chamber fabricated in aluminum with its cooling inlets and outlets. (b): Ellipto-conical vacuum chambers.

A support tube concept has been developed to ease the integration of the accelerator and detector components into a single rigid structure. The support tube, shown in Fig. 4, is an empty lightweight cylindrical structure, and is designed to provide a cantilevered support for the pipe, support the LumiCal, and the outer vertex and disks. Its walls are made of a multiple layer structure. The support tube is longitudinally split in two half-cylinders. At both ends, two rigid lightweight aluminium structures support the LumiCal and the vacuuum tubes. Six aluminium ribs are fixed to the inside of the tube to support the outer vertex and the disks. The insertion of the support tube in the detector is foreseen either with a few sleds or with longitudinal rails fixed to its external surface. A possible option could then be to slide these sleds (rails) inside hollow carbon fibre rails, permanently fixed on the inside wall of the tracker to guarantee the structural rigidity while inserting the support tube.

The IR mockup includes also the vertex detector, under assembly at INFN-Pisa. Presently at INFN-Pisa a wind tunnel mockup has been realised to validate air-cooling for the inner layer.

All the mockup components are foreseen to be delivered in 2026, allowing integration and assembly tests.

Conclusions

The FCC-ee MDI represents a critical interface between accelerator performance and detector integration. Its design requires a balanced optimisation of optics, beam dynamics, mechanical feasibility, and technological constraints.

Significant progress has been achieved during the Feasibility Study phase thanks to the LNF activity, including IR optics development, background simulations, SR mitigation studies, and the initiation of a full-scale IR mock-up programme. These activities provide a solid basis for the ongoing pre-TDR phase.

4 List of Invited Talks in year 2025

1. M. Boscolo, News e introduzione alle attivita' di macchina, RD_FCC Riunione di collaborazione, Bologna, 16 dicembre 2025
2. M. Boscolo, MDI e IR mockup obiettivi per il 2026, RD_FCC Riunione di collaborazione, Bologna, 16 dicembre 2025
3. M. Boscolo, FCC-ee MDI, International School of Particle Accelerators, Erice, Italy, 26 November -1 December 2025
4. M. Boscolo, Design of the FCC-ee IR, prototyping and MDI, 7th International Workshop on Future Tau Charm Facilities Huangshan, China, 23 - 27 November 2025
5. M. Boscolo, Challenges of MDI for future Higgs factories, The 2025 International Workshop on the High Energy Circular Electron Positron Collider, Guandzhou 4-10 November 2025
6. G. Nigrelli,, Machine-detector interface: overview of background sources and simulation status, 1st FCC-ee TDAQ Workshop, CERN, Nov. 2025
7. M. Boscolo, Machine-detector interface: inputs for the FCC-ee beam-optics decision, 1st FCC-ee TDAQ workshop, CERN, 6 November 2025
8. A. Ciarma, Software: MDI geometries and detector simulation, 1st FCC-ee TDAQ workshop, CERN, 6 November 2025
9. M. Boscolo, FCC-ee detector beam pipe, FCC-ee vertex detector workshop, Pisa, 30 October 2025
10. M. Boscolo, FCC-ee beam induced backgrounds, FCC-ee vertex detector workshop, Pisa, 30 October 2025
11. F. Fransesini, Status of the FCC-ee IR beampipe prototyping, 2nd DRD8 Collaboration meeting, CERN, 14 October 2025
12. S. Lauciani, Ultra-thin beam pipe design and manufacturing for FCC-ee, WP1 DRD8 general meeting, CERN, 14 October 2025
13. G. Nigrelli, Simulations of losses from top-up injection and fast instabilities in the FCC-ee, 111 Congresso Nazionale Società Italiana di Fisica, Palermo, Italia, Settembre 2025
14. M. Boscolo, Status and perspectives for FCC-ee detector background studies, EPS-HEP Conference Marseille, France, 10 July 2025
15. M. Boscolo, FCC-ee IR mockup status and perspectives at Frascati, Forum on tracking detector mechanics 2-25, Bristol, UK, 18 June 2025
16. F. Fransesini, Multistage structural optimization for FCC-ee IR support structures, Forum on tracking detector mechanics 2-25, Bristol, UK, 18 June 2025
17. G. Broggi, Collimation Studies or future circular colliders, 2025 European Edition of the International Workshop on the CEPC, 17 June 2025, Barcelona, Spain
18. G. Broggi, IR beam losses and MDI collimators, FCC WEEK 2025, 17 May 2025, Wien, Austria

19. G. Broggi, Collimation studies for the FCC-ee, FCC WEEK 2025, 17 May 2025, Wien, Austria
20. G. Nigrelli, First look at injection backgrounds, FCC WEEK 2025, 17 May 2025, Wien, Austria
21. M. Boscolo, MDI overview and IR mockup status, FCC WEEK 2025, 17 May 2025, Wien, Austria
22. M. Boscolo, MDI summary, FCC WEEK 2025, 17 May 2025, Wien, Austria
23. M. Boscolo, FCC-ee MDI Overview and Experience at Other Colliders, FCC-ee tracking detectors and software workshop, BNL, USA, 7 May 2025
24. A. Ciarma, Overview of machine induced backgrounds, FCC-ee tracking detectors and software workshop, BNL, USA, 7 May 2025
25. M. Boscolo, Activities and plans at INFN-LNF, ECFA-DRD8 WP1 Kick-off meeting, 27 March 2025, online
26. M. Boscolo, FCC-ee MDI, 70th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders, Tsukuba, Japan, 5 March 2025
27. M. Boscolo, Highlights WG5 MDI session, 70th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders, Tsukuba, Japan, 5 March 2025
28. A. Ciarma, Backgrounds at FCC-ee, 70th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders, Tsukuba, Japan, 5 March 2025
29. M. Boscolo, FCC-ee MDI, Workshop on FCC-ee and lepton colliders 2025, 22 January 2025, Frascati
30. M. Boscolo, MDI summary and prospects, 8th FCC Physics workshop, 17 January 2025, CERN
31. G. Broggi, Beam losses in the IR, 8th FCC Physics workshop, 17 January 2025, CERN
32. G. Nigrelli, Beam losses from fast instability, 8th FCC Physics workshop, 17 January 2025, CERN
33. A. Ciarma, Backgrounds on detectors, 8th FCC Physics workshop, 17 January 2025, CERN
34. F. Fransesini, IR beam pipes, 8th FCC Physics workshop, 17 January 2025, CERN

Publications

1. M. Benedikt *et al.* [FCC], Eur. Phys. J. ST **234** (2025) no.19, 5713-6197 doi:10.1140/epjs/s11734-025-01967-4 [arXiv:2505.00274 [physics.acc-ph]].
2. M. Benedikt *et al.* [FCC], Eur. Phys. J. C **85** (2025) no.12, 1468 doi:10.1140/epjc/s10052-025-15077-x [arXiv:2505.00272 [hep-ex]].
3. M. Benedikt *et al.* [FCC], Eur. Phys. J. ST **234** (2025) no.17, 5113-5383 [erratum: Eur. Phys. J. ST (2025)] doi:10.1140/epjs/s11734-025-01958-5 [arXiv:2505.00273 [physics.acc-ph]].

4. M. Boscolo, F. Palla, G. Ammirabile, K. D. J. Andre, G. Baldinelli, P. B. de Sousa, F. Bosi, G. Broggi, R. Bruce and H. Burkhardt, *et al.* “Status of the FCC-ee interaction region design,” EPJ Tech. Instrum. **12** (2025) no.1, 4 doi:10.1140/epjti/s40485-025-00117-3

5. M. Boscolo, A. Ciarma and H. Burkhardt, “Non-local solenoid compensation scheme at the future e+e− circular collider,” Nucl. Instrum. Meth. A **1083** (2026), 171135 doi:10.1016/j.nima.2025.171135

6. G. Broggi, A. Abramov, M. Boscolo, R. Kersevan, R. Bruce and S. Redaelli, “Beam losses due to beam-residual gas interactions in the FCC-ee,” JACoW **IPAC2025** (2025), MOPM036 doi:10.18429/JACoW-IPAC2025-MOPM036

7. G. Nigrelli, G. Broggi, M. Boscolo, R. Bruce, S. Redaelli and X. Buffat, “Simulations of losses from fast instabilities in the FCC-ee,” JACoW **IPAC2025** (2025), MOPM032 doi:10.18429/JACoW-IPAC2025-MOPM032

8. A. Frasca, A. Ciarma, A. Lechner, C. Welsch, G. Lerner, H. Burkhardt, J. Manczak, M. Boscolo and N. Kumar, “Radiation load from radiative Bhabha scattering in the FCC-ee experimental insertions,” JACoW **IPAC2025** (2025), 478 doi:10.18429/JACoW-IPAC2025-MOPM067

9. G. Broggi, A. Abramov, A. Natochii, F. Van der Veken, G. Iadarola, J. Salvesen, M. Boscolo, R. Bruce, S. Terui and S. Redaelli, *et al.* “Comparison of Xsuite simulations with measured backgrounds at SuperKEKB,” JACoW **IPAC2025** (2025), MOPM035 doi:10.18429/JACoW-IPAC2025-MOPM035

10. G. Broggi, A. Abramov, M. Boscolo, R. Bruce, D. Mirarchi and S. Redaelli, “First studies of crystal collimation for the FCC-ee,” Nucl. Instrum. Meth. A **1076** (2025), 170479 doi:10.1016/j.nima.2025.170479

11. M. Abbrescia *et al.* [IDEA Study Group], “The IDEA detector concept for FCC-ee,” [arXiv:2502.21223 [physics.ins-det]].

12. I. Drebot, F. Zimmermann, G. Broggi, S. Gessner and S. Redaelli, “Laser Compton backscattering for precision beam intensity control in the FCC-ee electron-positron collider,” JACoW **IPAC2025** (2025), 429 doi:10.18429/JACoW-IPAC2025-MOPM047

13. G. Broggi, A. Abramov, A. Natochii, F. Van der Veken, G. Iadarola, J. Salvesen, M. Boscolo, R. Bruce, S. Terui and S. Redaelli, *et al.* “Comparison of Xsuite simulations with measured backgrounds at SuperKEKB,” JACoW **IPAC2025** (2025), MOPM035 doi:10.18429/JACoW-IPAC2025-MOPM035

14. S. Marin, A. Lechner, A. Perillo Marcone, G. Broggi, L. Giacomo, M. Calviani, M. Widorski and R. Bruce, “Power deposition studies for the FCC-ee halo collimation system,” JACoW **IPAC2025** (2025), MOPM069 doi:10.18429/JACoW-IPAC2025-MOPM069

15. J. P. T. Salvesen, G. Iadarola, G. Broggi, K. Oide, F. Zimmermann, P. N. Burrows and H. Sugimoto, “Modelling optics and beam-beam effects of SuperKEKB with Xsuite,” JACoW **IPAC2025** (2025), MOPM034 doi:10.18429/JACoW-IPAC2025-MOPM034

16. B. Lindstrom, A. Abramov, F. Van der Veken, G. Broggi, R. Bruce, S. Solstrand, S. Redaelli, S. Gibson and S. Boogert, “Xcoll-BDSIM coupling for beam collimation,” JACoW **IPAC2025** (2025), MOPS030 doi:10.18429/JACoW-IPAC2025-MOPS030

FCC-ee Injector: Damping Ring and Transfer Lines Activity

C. Milardi (Coordinator), S. Bilanshvili, A. De Santis[1], S. Spampinati, M. Zobov

1 Introduction

This work has been supported by the MoU FCC–GOV–CC 0205 (KE 4907) + ADDENDUM between INFN and CERN and it is inserted within the CHART3 initiative for the FCCee injector design study. The Work Package of the LNF group is focused on Damping Ring and Transfer Lines design for the injector complex.

The 2025 activity on the FCC-ee Damping Ring and its transfer lines has been developed starting from the release of the *FCC Feasibility Study Report, Volume 2: Accelerators, Technical Infrastructure and Safety* [1].

The dedicated section establishes the baseline functional requirements for the injector complex, emphasizing tune selection, resonance avoidance, dynamic and momentum acceptance, longitudinal stability, and synchronization with the Booster Ring .

After the release of the Feasibility Study, the work has been focused on developing the layout proposed as the baseline by exploring lattice refinements, alternative arc solutions, working point adjustments, and updated transfer line configurations in order to validate and strengthen the baseline assumptions of the Feasibility Study. In parallel, the work on impedance modeling and beam stability studies has started.

2 The Feasibility Study

The Damping Ring (DR) is a critical component of the injector chain, whose performance directly impacts the efficiency and reliability of the full FCC-ee complex. The DR must deliver beams with sufficiently low transverse emittance (in principle 1.8 nm rad) and controlled energy spread (below 0.1 %) while maintaing large enough acceptance for the incoming positron beam to ensure stable injection into the Booster Ring (BR). At the same time, tune selection must avoid low-order resonances and guarantee operational robustness under realistic magnet errors and nonlinear effects.

A further key requirement concerns synchronization: the damping time, circumference, bunch structure, and RF parameters must be compatible with the BR cycle and the overall collider filling scheme. These constraints define the operational envelope within which any lattice design must operate.

3 Lattice Configuration at 2.86 GeV

Starting from the baseline functional requirements, a 2.86 GeV DR configuration has been developed. The chosen energy is compatible with the injector staging strategy while keeping the possibility to store and damp polarized beams.

The ring geometry adopts a compact hexagonal layout composed of six arcs and six straight sections within the available footprint. This geometry allows to have higher super-periodicity, useful to suppress betatron resonances and ensure the possibility to have specialized straight sections for injection/extraction equipments, RF cavity and wiggler for damping purpose. For the initial design all magnets have been limited to normal conducting scheme.

Two arc configurations were evaluated during 2025: A Ten-Bend cell (10B) used in the feasibility study and a Six-Bend Achromat (6BA) structure, presented at FCCWeek 2025 [2]. Betatron amplitudes and dispersions in the arc cells are shown in Fig. 1. Both options have the a natural emittance below the limit imposed by the BR requirements, but a long transverse

---

[1] Corresponding author: antonio.desantis@lnf.infn.it

damping time: 17 and 14 ms, respectively. These values are too large to ensure enough flexibility for the Main Rings injection scheme. A summary of the lattice parameters for both options are reported in the Tab. 1.

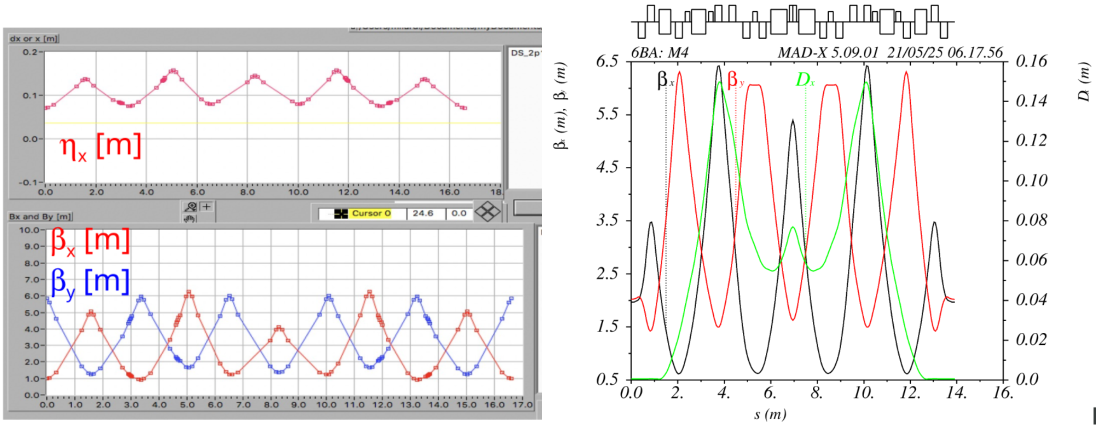


Figure 1: Arc cell optics: 10B cell of the feasibility study (left) and 6BA cell from the FCCWeek (right).

Preliminary tracking simulations were performed with sextupoles active and realistic physical apertures for the 6BA option. The results indicate stable motion over 1000 turns for injected beams with expected emittances, but also show that the dynamic aperture and momentum acceptance remain below the desired operational margin. This finding identifies areas where further nonlinear optimization is required. The localization of chromatic correction in the arcs and the definition of three sextupole families constitute the starting point for continued refinement.

The RF system considered in the 2025 studies operates at 400 MHz with superconducting cavities, consistent with the baseline assumptions. Voltage configurations between 4 MV and 8 MV were evaluated, yielding synchrotron tunes of order 10^{-3} and bunch lengths in the few-mm range. The harmonic number and momentum compaction factor were chosen to ensure adequate RF acceptance while maintaining compatibility with BR synchronization constraints.

Table 1: Damping Ring parameters: Feasibility Study baseline vs. 6BA lattice (FCCWeek 2025).

Parameter	**FS Baseline**	**Six-Bend Achromat**
Energy [GeV]	2.86	2.86
Circumference [m]	373.46	403.08
Revolution period [μs]	1.2457	1.343
Arc Cell	Multi-bend	6BA
Energy loss per turn (WGL on/off) [keV]	422.2 / 246.7	571
Nat. emittance [nm rad] (WGL on/off)	1.3 / 2.3	1.82
Damping time $\tau_{x,y}$ (WGL on/off) [ms]	16.9 / 29.4	13.5
Momentum compaction [10^{-3}]	1.55 / 1.57	0.758
Natural Chromaticity (x/y)	−38.2 / −28.3	−50.5 / −36.9 (nat.)
Nat. energy spread (WGL on/off) [10^{-4}]	7.1 / 5.2	7.3
Betatron amplitude max (x/y) [m]	9.66 / 6.49	6.09 / 8.32 (β_{max})
Dipole #, length [m], field [T]	180; 0.7–1.13; 0.34–0.39	0.5–0.7 m; 0.69 T
Wiggler #, length [m], field [T]	3; 3.5; 1.8	3; 3.5; 1.8 T
Cavity #, length [m], voltage [MV]	1; 1.5; 4	

4 Beam Stability and Impedance Modeling

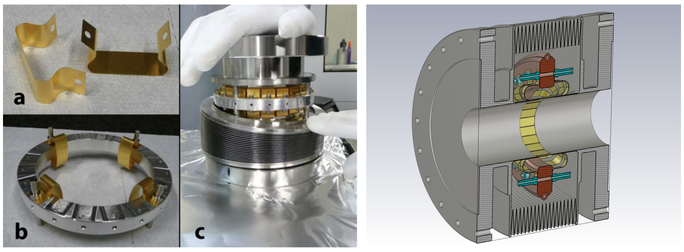
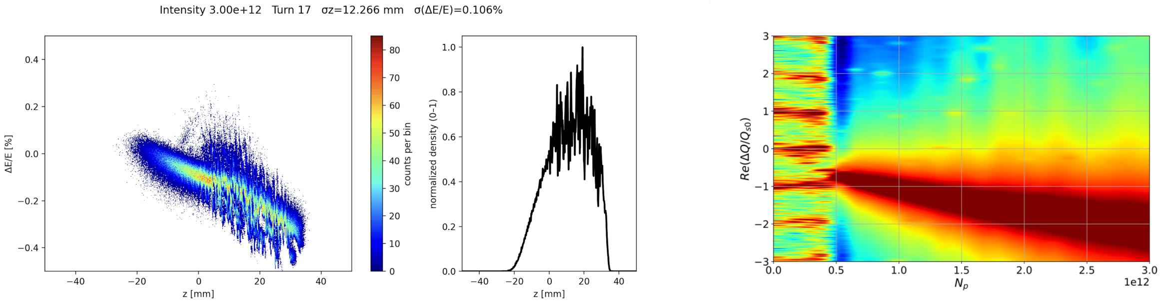


Figure 2: Left: Bellows structure from DAΦNE used as a reference ((a) View of gold coated strip, (b) supporting annular ring, (c) RF shielded bellows assembly.). Right: Bellows structure considered for the DR impedance model.

Optimization strategies applicable to the design of the FCC-ee Damping Ring vacuum chamber components and hardware have been reviewed and analyzed, with the goal of reducing the beam coupling impedance while preserving the operational capabilities of the devices. Most of the considered solutions are already in use, for example Fig. 2, and their performance has been validated in particle colliders and modern synchrotron light sources. In addition to the general strategy, several novel design solutions have also been analyzed [3].



(a) Microwave instability.

(b) Transverse mode coupling instability.

Figure 3: Resistive wall impedance related instabilities.

A simulation workflow to generate wake inputs for Xsuite, a collection of Python packages for beam dynamics simulations in particle accelerators, has been accomplished. Using this workflow, simulations and first studies of resistive-wall–driven single-bunch instabilities have been started, including microwave instability. Fig. 3a and transverse mode-coupling instability, Fig. 3b.

Electron cloud formation was also investigated for FCC-ee DR [4]. The simulations performed are comparable with the estimated value based on the analytical calculation. These electron densities may indicate instability and require further investigations in the following process.

5 Transfer Lines and Compression Studies

The injection and extraction lines for the DR has been designed in order to match the beam transport from electron/positron sources to the ring and from the DR to the High-Energy LINAC (HE-LINAC).

For the extraction line, a bunch compression from approximately 5 mm to 1 mm is needed in order to meet the extracted bunch length into the HE-LINAC requirements. The resulting horizontal emittance growth of about 20% remains acceptable at this stage but motivates further optimization. These compression studies extend the baseline by quantifying achievable performance and highlighting areas for refinement. A schematic view of the compression scheme is shown in the Fig. 4, which consists of a magnetic chicane formed by four C-shaped bending magnets. Each magnet has a magnetic length of 1.9 m and a maximum magnetic field strength of 1 T. The linear momentum compaction factor R56 is -0.336 m, and the bending angle of each magnet is 11 degrees, resulting in a maximum dispersion of 0.98 m. The distance between dipoles 1 (3) and 2 (4) is 2.9 m, while the separation between dipoles 2 and 3 is 2 m. To induce the necessary energy chirp for compression, two RF structures, providing a maximum accelerating voltage of 122 MV, are employed. Additionally, four RF structures are utilized to partially remove the residual chirp in order to meet the specifications of the HE-LINAC. These structures operate with a maximum accelerating voltage of 256 MV. Beam dynamics simulations were performed using the ELEGANT code for a bunch with a maximum charge of 5 nC.

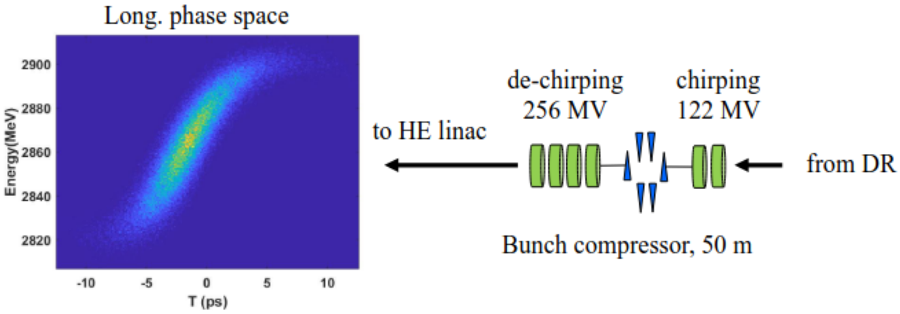


Figure 4: Bunch compressor at 2.86 GeV placed between the DR and the HE-linac. Left: longitudinal phase space after the compression and de-chirping. Right: schematic layout and overall length.

6 Conclusions

In 2025 the FCC-ee Damping Ring design has been consolidated starting from the baseline defined in the FCC Feasibility Study [1], while extending the analysis through lattice refinements, transfer line development, and the initiation of beam stability studies.

Both the Ten-Bend (10B) cell adopted as baseline and the Six-Bend Achromat (6BA) solution presented at FCCWeek 2025 [2] achieve the required emittance at 2.86 GeV, although the transverse damping time remains a critical parameter for injection flexibility. Preliminary nonlinear tracking confirms stable particle motion, but dynamic and momentum acceptance require further optimization. The RF system parameters are compatible with Booster synchronization constraints. Beam stability and impedance modeling activities have been launched, including wakefield simulations and first electron cloud studies, establishing the framework for future collective effects analysis.

The extraction line bunch compressor successfully reduces the bunch length to approximately 1 mm, with a horizontal emittance growth of about 20%, which is acceptable at this stage.

In 2026, priority will be given to nonlinear optimization, error studies, collective effects evaluation, and further refinement of the compressor and lattice design to strengthen the technical maturity of the Damping Ring within the FCC-ee injector chain.

References

1. M. Benedikt *et al.* [FCC], "Future Circular Collider Feasibility Study Report: Volume 2, Accelerators, Technical Infrastructure and Safety," Eur. Phys. J. ST **234** (2025) no.19, 5713-6197 doi:10.1140/epjs/s11734-025-01967-4 [arXiv:2505.00274 [physics.acc-ph]].

2. A. De Santis, *et al.*, *New Damping Ring at 2.86 GeV*, Presentation at FCCWeek 2025, Vienna, May 2025.

3. S. Bilanishvili and M. Zobov, *Approach for low impedance design of the FCC DR vacuum chamber*, Presentation at FCCWeek 2025, Vienna, Austria, May 2025.

4. O. Etisken, *et al.*, *Electron cloud studies for DAΦNE collider and e+e− future circular collider damping ring*, Nucl. Instrum. Meth. A **1082** (2026), 171019. doi:10.1016/j.nima.2025.171019