**FCC**

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The contribution to the Future Circular Collider (FCC) design study by the LNF accelerator division was initiated already with the birth of the first proposal TLEP in 2013 and has grown through the years in terms of resources and contribution to different aspects of the study. We focus in this report in the activities performed in the last year and that are ongoing.
FCC has a comprehensive long-term program maximising physics opportunities that foresees two stages:

- Stage 1: FCC-ee as Higgs factory, electroweak and top factory at highest luminosities
- Stage 2: FCC-hh as natural continuation at energy frontier ($E_{cm}$ = 100 TeV)

FCC-ee is a high luminosity and high energy circular electron-positron collider with an optimised circumference of almost 91 km, to be built in the Lake Geneva basin. Its physics goals are to carry out precision studies and searches for rare decays in the centre-of-mass energy range from 90 to 365 GeV. The optics and layout are designed such that the interaction points (IPs) and arcs overlap with those of a successive energy-frontier hadron collider FCC-hh.

Presently FCC is at the Feasibility Study (FCC-FS) phase, which follows the CDR phase, ended with the CDR publication in 2019, in preparation of the European Particle Physics Strategy Update (EPPSU) in 2020. Similarly, we are preparing the FCC-FS report that will be released in time for the next EPPSU in 2026. For this purpose, in 2023 our group deeply contributed to prepare the FCC-FS mid-term report that was presented to the review committees, and eventually to the CERN council. This report was very well received for the excellent work and great progress.

All the INFN accelerator activities related to FCC are contained in the **RD_FCC** activity of CSN1. For this purpose RD_FCC has a dedicated work package named "Accelerator". There are synergetic activities at the LNF and other INFN sections that receive external fundings, but all are represented in RD_FCC. [Visit the RD_FCC section in the Particle Physics chapter of this year report for a short description of the organisation of the RD_FCC group.] The group receives also external fundings from EU-H2020 for the MDI and collective effects studies, being part of the FCC Innovation Study, **FCCIS** proposal. The activity performed for FCCIS is described here, as part of the overall MDI WP design study. We received funding from CHART, Swiss program, through an agreement between CERN and LNF, for the design of the damping ring and their connected transfer lines, as part of the WP on Injector, lead by PSI.

Our group gives substantial contribution to the FCC-FS study with the leadership of the Interaction Region (IR) and Machine-detector-Interface (MDI) design. This is the major activity for most of the team, which includes the development of the engineering mechanical model of the IR, beam backgrounds simulations, collimation studies with the beam losses in the IR, and IR optics. Related to this activity, a new R&D has started in 2023 to build a full-scale mock of the FCC-ee IR to be built at the LNF, thanks to a signed agreement between CERN and INFN. In November 2023 the group organized an international workshop at the LNF to discuss the IR mockup project: `https://agenda.infn.it/event/37720/`.

Our group contributes also to the evaluation of the collective effects for FCC-ee, and to the design on the positron damping ring with their transfer line.

The LNF FCC group has an excellent representation in the FCC governance and has leadership roles. The main responsibilities of the group are:

- Vice-chair of the executive board (M. Boscolo)
- INFN member of the International Collaboration Board (M. Boscolo)
- FCC Coordination Group member (M. Boscolo)
- FCC Physics and Detectors Coordination Group (M. Boscolo)
- Machine Detector Interface FCC-FS WP Convener (M. Boscolo)
- M. Boscolo is FCCIS task leader for the MDI study (Task 2.3)
- Positron damping ring and TL design (C. Milardi)

In the following we describe the MDI studies performed by the LNF group.

## 1 Machine Detector Interface

The MDI challenges vary with the operating energy. On the Z-pole, the FCC-ee will be operating in a high-beam current and high-luminosity mode. By contrast, when running at the $t\bar{t}$ threshold the FCC-ee will face the highest photon energies from synchrotron radiation (SR), albeit at much lower beam current. The IR is one of the key issues of a collider. It has to provide high luminosity that can be used for physics studies in the detectors with tolerable backgrounds and radiation. For this reason it requires a careful design, balancing the requirements from the accelerator and detector sides. The mechanical design of the FCC-ee interaction region is a crucial task for the MDI study. In order to ensure an optimal and feasible engineered design, it is necessary to take into account novel technologies and evaluate every aspect, including the manufacturing process and the assembly strategy for all the MDI components (Figure 1).

During this year, the design changed from a conceptual to an engineered one; with this purpose accurate drawings have been created, including some manufacturing details. At the moment the design is based on the IDEA detector concept. The IR vacuum chamber is essential in our design; it is composed of three main parts: the central chamber, starting from 0 to 90 mm from IP; the conical chamber, starting from 90 mm to 1200 mm; the bellows, with two different concepts. The first part studied is the central chamber (Figure 2), made in AlBeMet162 (62% Be, 38%Al), composed of two concentric cylinders, 0.35 mm thick, divided by a gap of 1 mm for the paraffin flow, to ensure the cooling of the pipe. The design has changed during this last year, especially the inlets and outlets have been modified, changing the shape and the material. In the current design the inlets and outlets are made of AlBeMet162, the same material of the chamber, and the geometry is more compact, maintaining the fitting with the vertex detector.

The cooling system is unchanged as is reported in Figure 3.

The second part analyzed is the conical chamber (Figure 4), made in two halves of AlBeMet162, with copper cooling channels.

In order to assemble the chamber with the cryo-magnets system, the bellows has been designed. We proposed two different concepts according to the different elongations needed and the anchoring point of the chamber (Figure 5).

To support the vacuum chamber, the LumiCal, the vertex detector, inner tracker, outer tracker and medium tracker a supporting structure made by a support cylinder with reinforcement

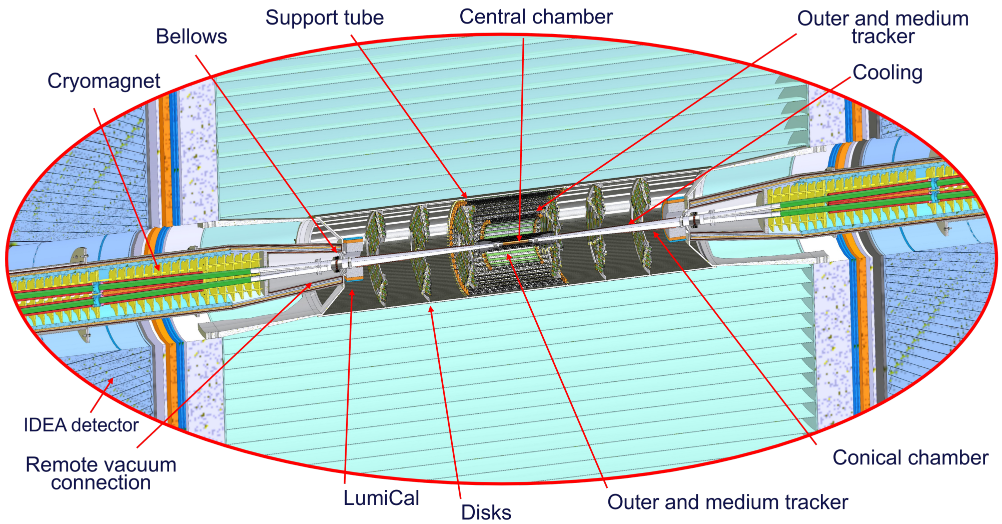



Figure 1: *FCC-ee IR layout.*

ribs and endcaps has been proposed (Figure 6). The cylinder presents a multiple layers structure composed of carbon fiber and honeycomb, adequately arranged.

Another essential part of this study consists in the structural analysis for the support cylinder and the thermo-structural analysis for the vacuum chamber; both are needed to calculate the stress, strain and displacement due to the loads applied over the structures.

In order to integrate all the IR components, a first assembly strategy has been conceived; the procedure is in continuous update and refinement. Currently the procedure starts with mounting the medium tracker, outer tracker, and disks over one half of the support tube; the subsequent step consists of mounting the LumiCal on the endcaps. At this point, it is possible to slide the chamber and the inner tracker, attached to the chamber, inside the assembled structure; after the alignment of the LumiCal, it is possible to close the support tube mounting the other half and then slide all components inside the main detector. In this process will be inserted a intermediate phase to insert a lightweight cone for supporting the vertex cabling and to create the air cooling channels.

During this year the program for the realization of the IR mockup has been developed. In particular, the mockup will include the vacuum chamber bellows-to-bellows, the bellows and the support tube. For the prototypes of the vacuum chamber the intent is to check the feasibility of the assembly strategy and of the electron beam welding along an elliptical shape, and to test the cooling system.

Figure 2: Three-quarter section view of the Central chamber

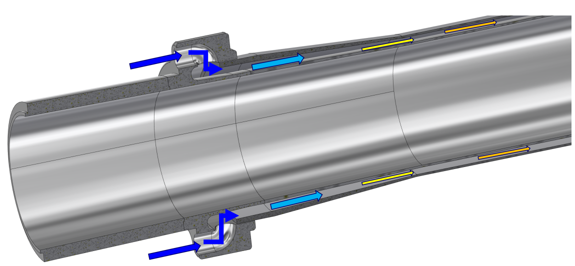


Figure 3: Cooling channel section view of Central chamber

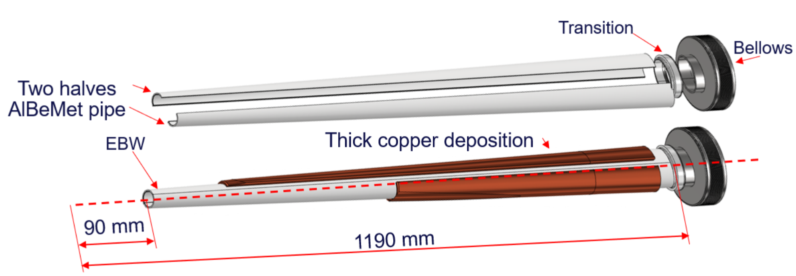
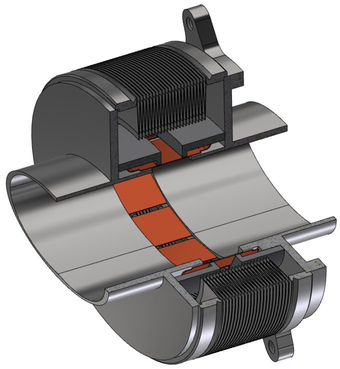
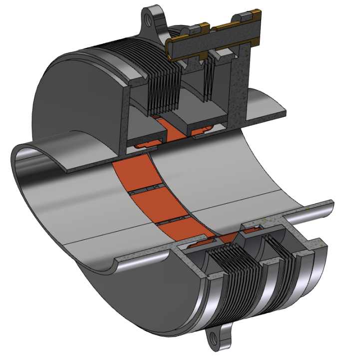



Figure 4: Conical chamber



(a) Single bellows



(b) Double bellows

Figure 5: Bellows concepts of FCC IR

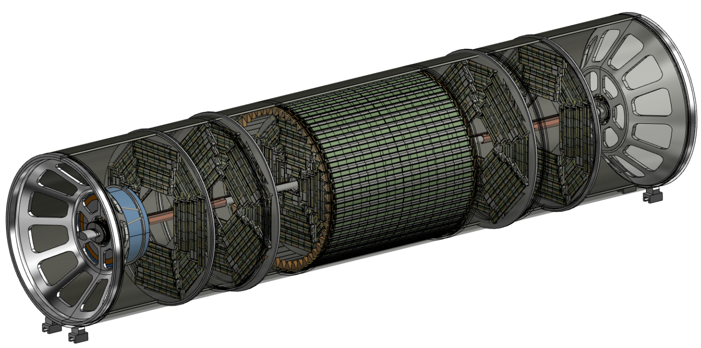
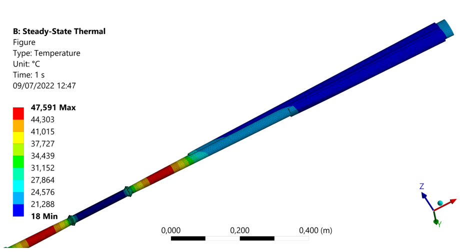
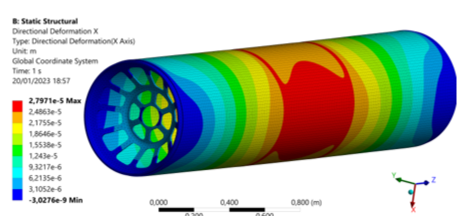


Figure 6: Support tube




(a) FEA chamber




(b) FEA support tube

Figure 7: FEA

The MDI activity includes the beam backgrounds evaluation, and the LNF group is leading this activity. The backgrounds sources can be divided in luminosity backgrounds and single-beam induced backgrounds. In the first category at FCC-ee the most relevant are the Incoherent Pairs Creation (IPC), which consists in secondary $e^-e^+$ pairs produced via the interaction of the beam-strahlung photons with real or virtual photons during bunch crossing, and particles from the beam which exit the dynamic aperture after losing energy during bunch crossing due to Radiative Bhabha process. Among the single-beam induced background sources we find Synchrotron Radiation (SR) coming from the last upstream magnets, and high rates of beam losses in the IR coming from the beam halo after lifetime drop, which we refer to as *failure scenarios.* The backgrounds induced by these processes have been studied for the CLD vertex detector and trackers, using the Key4hep framework. The results are reported in [3].

The Synchrotron Radiation emitted during the collision in the electromagnetic field of the opposing beam is known as beamstrahlung (BS). It is a dominant effect in the beam dynamics and lifetime at FCC-ee due to the high currents and nano-beams. We characterised the intense beamstrahlung radiation produced at the IPs [1]. The flux of the BS photons per unit of bandwidth as a function of their energy at the four working points is shown in Figure 8. Photon mean energies

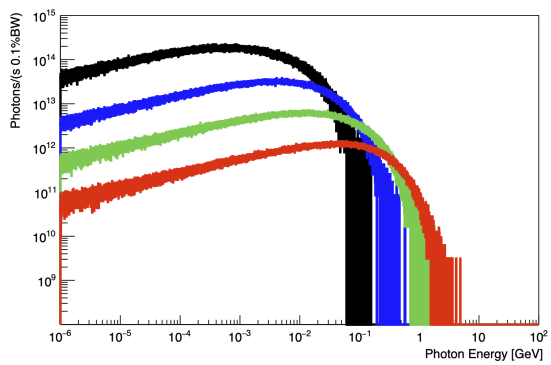



Figure 8: Flux of the BS radiation as a function of their energy, emitted for the four FCC-ee working points, 45.6 GeV (black), 80.0 GeV (blue), 120.0 GeV (green), and 182.5 GeV (red).

range from 2 to 63 MeV, with tails of few hundreds of MeV at the Z-pole and up to few GeV at the $t\bar{t}$ threshold. The highest power value is about 400 kW and is observed at the Z-pole due to the high current at this energy. The strength of the beam-beam force and the intensity of the BS radiation depend on the charge density distribution of the two beams. Figure 9 shows that, due to the long bunches and large crossing angle, the total power is sensible to the vertical offset between the two opposing beams. The beamstrahlung radiation is emitted collinear with the beam, so it will hit the vacuum chamber of the first downstream bending magnet and following elements as shown in Figure 10. The transverse spot size of the photons is $\mathcal{O}(1\,\text{cm}^2)$. These evaluations have been used to consider the feasibility of an extraction photon beam line for a dump at few hundreds meters from the IP.

The LNF MDI group is also optimising the optics of the solenoid compensation scheme. The detector solenoidal field is 2 T. This field induces coupling on the beams and cause an increase on the vertical emittance. The baseline compensation scheme uses a -5 T anti-solenoid in the IR to cancel the $\int B_z ds$ before the first quadrupole. Such element poses strong mechanical constraints in the design of the MDI region, and produces about 80 kW in Synchrotron Radiation due to the strong fringe fields. An alternative compensation scheme proposed by P. Raimondi would allow for the removal of this antisolenoid. The so called "standard" solenoid compensation scheme is similar

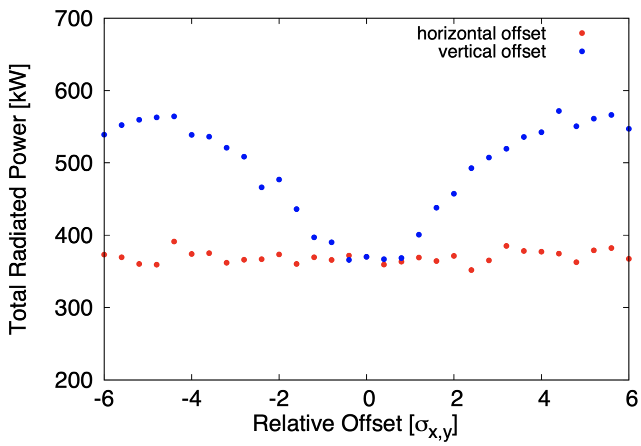



Figure 9: Total power radiated via BS as a function of the relative horizontal (red) and vertical (blue) offset between the bunches.

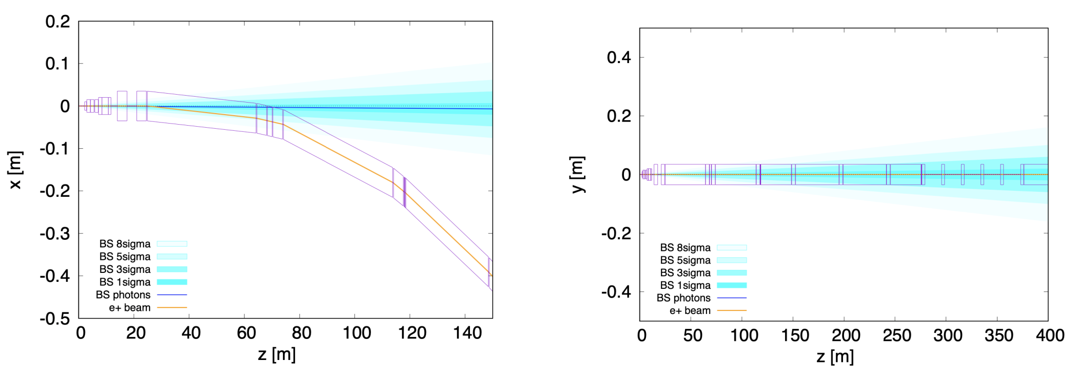



Figure 10: Left: BS photons path on the x-z plane with respect to the downstream vacuum chamber for the Z-pole c.o.m. energy. Right: corresponding path on the y-z plane.

to that used in DAΦNE. Skew quadrupolar components winded on the Final Focus Quadrupoles (FFQs) are used to minimize the vertical emittance increase, and the correctors in the IR are used to close the orbit bumps generated by the beams passing with an angle through the detector field. We are studying the application of the standard scheme to FCC-ee, and the study will be presented at the next IPAC24 [18].

## 2 List of Invited Talks

1. A. Ciarma, Status and Perspectives for FCC-ee Detector Background Studies, 6th FCC Physics Workshop, Krakow, Jan. 2023
2. F. Fransesini, Mechanical model of FCC-ee MDI, 6th FCC Physics Workshop, Krakow, Jan. 2023
3. M. Boscolo, Introduction by Conveners, 6th FCC Physics Workshop, Krakow, Jan. 2023
4. M. Boscolo, Future plans: MDI, 6th FCC Physics Workshop, Krakow, Jan. 2023

5. M. Boscolo, FCC Feasibility study and INFn activity in FCC-FS, Seconda giornata acceleratori, Catania, 2-3 March 2023
6. A. Ciarma, Background Calculations in the FCC-ee, 1st US FCC Workshop, Brookhaven National Laboratories, 23-25 Apr. 2023
7. M. Boscolo, Challenges of the FCC-ee MDI, 1st US FCC Workshop, Brookhaven National Laboratories, Apr. 2023
8. M. Boscolo and J. Keintzel, Diagnostics and components in the FCC-ee IR, 1st US FCC Workshop, Brookhaven National Laboratories, 23-25 Apr. 2023
9. A. Ciarma, Background Calculations in the FCC-ee, FCCWeek 2023, London, Jun. 2023
10. F. Fransesini, Mechanical model of the MDI, FCCWeek 2023, London, Jun. 2023
11. M. Boscolo, MDI Overview, FCCWeek 2023, London, Jun. 2023
12. M. Boscolo, MDI Summary, FCCWeek 2023, London, Jun. 2023
13. G. Broggi, Beam Losses in the MDI, FCCWeek 2023, London, Jun. 2023
14. C. Milardi, Damping ring and transfer lines for the FCC-ee pre-injector complex, FCCWeek 2023, London, Jun. 2023
15. A. Ciarma, Status and Perspectives for FCC-ee Detector Background Studies, EPS-HEP2023, Hamburg, Aug. 2023
16. M. Boscolo, Interaction region design of the future circular collider FCC-ee, Second ECFA workshop on e+e- Higgs-electroweak-top factories, Paestum, Italy, 11-13 October 2023
17. M. Boscolo, FCC-ee MDI Overview, 2023 International Workshop on CEPC, 23-27 October 2023
18. M. Boscolo, MDI status & plan, FCCIS 2023 WP2 Workshop, Rome, Nov. 2023
19. G. Broggi, Collimation status, FCCIS 2023 WP2 Workshop, Rome, Nov. 2023
20. C. Milardi, DAFNE as a possible test bench for FCC-ee, FCCIS 2023 WP2 Workshop, Rome, Nov. 2023
21. M. Zobov, Interplay between beam-beam interaction and collective effects and its impact on the parameters, FCCIS 2023 WP2 Workshop, Rome, Nov. 2023
22. A. Ciarma, Conventional Solenoid Compensation Scheme, FCC-ee MDI & IR Mockup Workshop, Frascati, Nov. 2023
23. F. Fransesini, Design and requirements in the +/- 2m region of the IR, FCC-ee MDI & IR Mockup Workshop, Frascati, Nov. 2023
24. F. Fransesini, Mockup for the AlBeMet chambers, FCC-ee MDI & IR Mockup Workshop, Frascati, Nov. 2023
25. M. Boscolo, IR mockup goals and testing of critical concepts, FCC-ee MDI & IR Mockup Workshop, Frascati, Nov. 2023

26. E. Di Pasquale, Frascati workshop facility, FCC-ee MDI & IR Mockup Workshop, Frascati, Nov. 2023
27. S. Lauciani, Mockup for the bellows, FCC-ee MDI & IR Mockup Workshop, Frascati, Nov. 2023

**Publications**

1. M. Boscolo and A. Ciarma, ”Characterization of the beamstrahlung radiation at the future high-energy circular collider”. Physical Review Accelerators and Beams, 26. 10.1103/PhysRevAccelBeams.26.111002.
2. M. Boscolo, A. Ciarma, F. Fransesini, S. Lauciani, *et. al*, ”The status of the Interaction region design and machine detector interface of the FCC-ee”. JACoW IPAC2023 (2023) MOPA091. 10.18429/JACoW-IPAC2023-MOPA091
3. A. Ciarma, M. Boscolo, G. Ganis and E. Perez, ”Machine Induced Backgrounds in the FCC-ee MDI Region and Beamstrahlung Radiation”. JACoW eeFACT2022 (2023), 85-90 doi:10.18429/JACoW-eeFACT2022-TUZAT0203
4. M. Boscolo *et al.*, ”The FCC-ee interaction region, design and integration of the machine elements and detectors, machine induced backgrounds and key performance indicators (FCC note)”. doi:10.17181/w4kws-rne05 (2023) https://cernbox.cern.ch/s/FQEHOkF9kTeBsBh
5. M. Behtouei, E. Carideo, M. Zobov, M. Migliorati, ”Wakefields excited in the FCC-ee collimation system.” JINST 19 (2024) 02, P02014 10.1088/1748-0221/19/02/P02014
6. M. Migliorati, M. Behtouei, E. Carideo, A. Rajabi, Y. Zhang, M. Zobov, ”Studies of FCC-ee Single Bunch Instabilities with an Updated Impedance Model”. JACoW IPAC2023 (2023) WEPL165 10.1088/1742-6596/2687/6/062010
7. Y. Zhang, M. Migliorati, M. Zobov, ”Study of beam-beam interaction in FCC-ee including updated transverse and longitudinal Impedances.” JACoW IPAC2023 (2023) WEPL164 10.1088/1742-6596/2687/6/062025
8. J. Bauche *et al*, ”The status of the energy calibration, polarization and monochromatization of the FCC-ee”, JACoW IPAC2023 (2023) MOPL059 10.18429/JACoW-IPAC2023-MOPL059
9. F. Zimmermann *et al*, ”Power Budgets and Performance Considerations for Future Higgs Factories”, JACoW eeFACT2022 (2023), 256-261 10.18429/JACoW-eeFACT2022-FRXAS0101
10. M. Boscolo, F. Palla, F. Bosi, F. Fransesini, S. Lauciani, ”Mechanical model for the FCC-ee interaction region”, EPJ Tech. Instrum. 10 (2023) 1, 16 10.1140/epjti/s40485-023-00103-7
11. A. Novokhatski, M. Boscolo, F. Fransesini, S. Lauciani, L. Pellegrino, ”Estimated heat load and proposed cooling system in the FCC-ee interaction region”, JACoW IPAC2023 (2023) MOPA092 10.1088/1742-6596/2687/2/022031
12. E. Montbarbon, A. Dominjon, F. Poirier, G. Balik, L. Brunetti, M. Boscolo, S. Grabon, ”First studies of final focus quadrupoles vibrations of the z lattice of FCC-ee”, JACoW IPAC2023 (2023) MOPL077 10.18429/JACoW-IPAC2023-MOPL077
13. O. Etisken, C. Milardi, P. Raimondi, ”Considerations for a new damping ring design of the FCC-ee pre-injector complex”, JACoW IPAC2023 (2023) MOPL175 10.18429/JACoW-IPAC2023-MOPL175

14. G. Broggi, "Tracking studies for the FCC-ee collimation system design", Nuovo Cimento, in publication 2023

15. A. Abramov, G. Broggi, K. D. André,M. Hofer,R. Bruce,S. Redaelli, "Studies of layout and cleaning performance for the FCC-ee collimation system", JACoW IPAC2023 (2023) MOPA128 10.18429/JACoW-IPAC2023-MOPA128

16. G. Broggi,A. Abramov,R. Bruce, "Beam dynamics studies for the FCC-ee collimation system design", JACoW IPAC2023 (2023) MOPA129 10.18429/JACoW-IPAC2023-MOPA129

17. A. Abramov *et al.* "Collimation simulations for the FCC-ee", JINST 19 (2024) 02, T02004 10.1088/1748-0221/19/02/T02004

18. A. Ciarma, M. Boscolo, H. Burkhardt, K. Oide, P. Raimondi, "Optics design of the solenoid compensation scheme at FCC-ee", IPAC2024

19. F. Fransesini, A. Novokhatski, E. Di Pasquale, M. Boscolo, P. P. Valentini, S. Lauciani "Mechanical design, structural requirements and optimization of the FCC e+e- interaction region components", IPAC2024