

CHART Scientific Report (Final Report for Phase 2)

FCC-ee Injector Study and the P³ Project at PSI

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1 Introduction/Original goals of the project

This report presents a summary of the progress and outcomes of the FCC-ee injector study collaboration and the PSI Positron Production (P³) project, as part of the Phase 2 of the Swiss Accelerator Research and Technology (CHART) program. This collaboration brings together PSI and CERN with external partners, including CNRS-IJCLab (Orsay, France) and INFN-LNF

(Frascati, Italy). In addition, the KEK laboratory (Tsukuba, Japan) participates as an external observer, in particular as an advisor for the P³ project. SLAC laboratory also contributed as a technical advisor on various components of the injector complex. The project encompasses two key deliverables. The first deliverable involves a comprehensive review of the FCC-ee Injector Conceptual Design Report (CDR) that was published in 2019, along with a detailed cost estimate. This review re-evaluates the original design and budgetary projections to ensure the project’s feasibility and financial sustainability. During project execution, this deliverable was divided into two stages: the initial report with a cost estimate presented at the FCC Feasibility Study (FS) Mid-Term Review (MTR) in October 2023, and a final report with an optimized layout and revised cost estimate, scheduled for submission by February 2025.

The second deliverable is a proof-of-principle positron source experiment to be installed at the Swiss Free Electron Laser (SwissFEL) facility at PSI. This experiment aims to validate the feasibility and performance of the proposed positron source technology in a real-world setting, providing essential data and insights for further development and potential large-scale implementation.

The following chapters provide an overview of the status of the project and brief description of the results obtained. More details can be found in the three CHART scientific reports published in May 2022, January 2023 and January 2024. In addition, contributions submitted to scientific journals and presented at workshops and conferences are listed in the references.

2 FCC-ee Injector Design Study

The FCC-ee injector complex must provide the electron and positron bunch trains for alternating bootstrapping injection during, both, top-up and filling-from-scratch operations. Considering the charge per bucket and lifetime for this operational mode, an alternating injection of a train of positrons and electrons approximately every few tens of seconds is required to ensure the correct balance between positron and electron bunch charges during collider operation. Figure 1 schematically shows the latest basic layout of the injector complex. It includes two separate

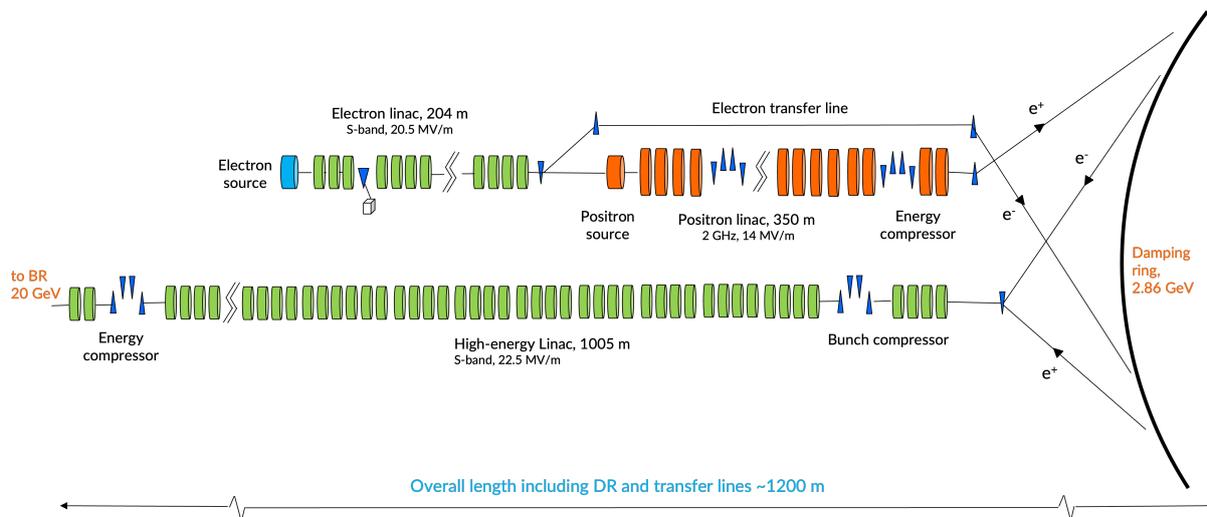


Figure 1: Latest baseline layout of the FCC-ee Injector complex.

linacs for electrons and positrons up to a beam energy of 2.86 GeV – the Electron Linac (e-Linac) and the Positron Linac (p-Linac), respectively. Following the positron and electron

linacs, both species are injected into the Damping Ring (DR) for emittance reduction. The layout also includes the high-energy (HE) linac, which boosts the beam energy from 2.86 GeV up to 20 GeV in order to inject beams directly into the Booster Ring (BR). The baseline for the positron source is based on a conventional scheme using electrons from the e-Linac impinging on a tungsten target. This approach allows all linacs to operate at 100 Hz with 4 bunches to meet the collider ring filling specification for the more demanding Z running mode.

The optimized injector concept follows the MTR recommendations to reduce acceleration gradients and the system’s repetition rate, resulting in a linac design focused on cost-effectiveness and reduced power density. This approach decreases overall power consumption for the linacs by more than a factor of three, leveraging new accelerating structures with higher shunt impedance, lower gradients (from 29.5 MV/m to 22.5/20.5 MV/m), and a reduced repetition rate (from 200/400 Hz to 100 Hz). Operating at a 100 Hz repetition rate with four bunches per RF pulse, the system incorporates beam-loading compensation and long-range wakefield suppression for enhanced stability. Although the injector complex is now longer, this new layout improves reliability, featuring a damping ring at a higher energy of 2.86 GeV and eliminating the need for a common linac, which would otherwise require doubling the repetition rate. This revised concept provides a more efficient and sustainable solution aligned with performance and operational goals. In recent months, an effort has also been made to implement the injector complex at CERN’s Preveessin site. The project has followed guidelines to maximize functionality and cost-effectiveness, offering several strategic advantages. As can be seen from Figure 2, it seamlessly integrates with the existing infrastructure, minimizing visual impact on the surrounding landscape while providing direct connectivity to experimental halls to enhance operational efficiency and project accessibility. The site’s minimal elevation change over 1200 meters creates ideal conditions for the “cut and cover” construction technique, a cost-effective and efficient approach for shallow underground structures, see bottom right image in figure 2. Primarily situated on CERN-dedicated land, with a small portion extending beyond the fenced area, but within the same urban classification, the project maintains continuity in land use planning. Sustainable practices are incorporated, with excavated material reused as backfill, minimizing waste and promoting environmental management. Overall, this optimized implementation of the injector offers an efficient, sustainable, and safety-conscious solution to support the expansion of CERN’s infrastructure.

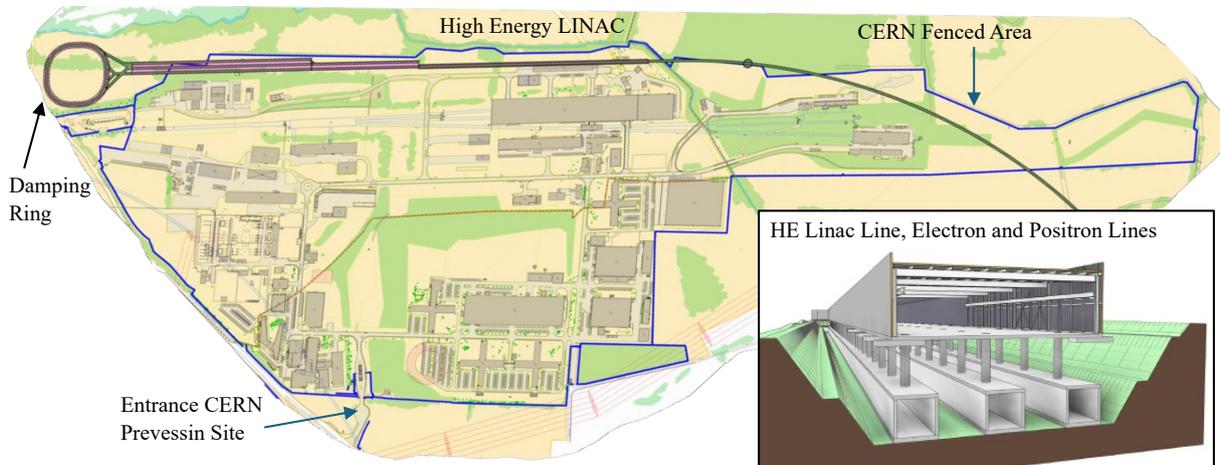


Figure 2: Optimized injector implementation at CERN’s Preveessin site and construction concept (bottom right image).

3 PSI Positron Production Experiment

The PSI Positron Production (P^3) experiment is a demonstrator for the positron source and the goal is to design and install such a demonstrator in the SwissFEL facility, and validate through an experiment a range of novel techniques that, according to simulations, have proven potential to increase the positron yield by one order of magnitude with respect to the state of the art. The P^3 project is driven by the high luminosity requirements of the FCC-ee collider ring and its results will be one of the key outcomes of the feasibility study concerning the injector. The remarkable positron capture capabilities of P^3 are enabled to great extent by the usage of high temperature superconducting (HTS) solenoid around the target region, as well as a novel standing-wave solution for the RF cavities that provides a large iris aperture. Figure 3

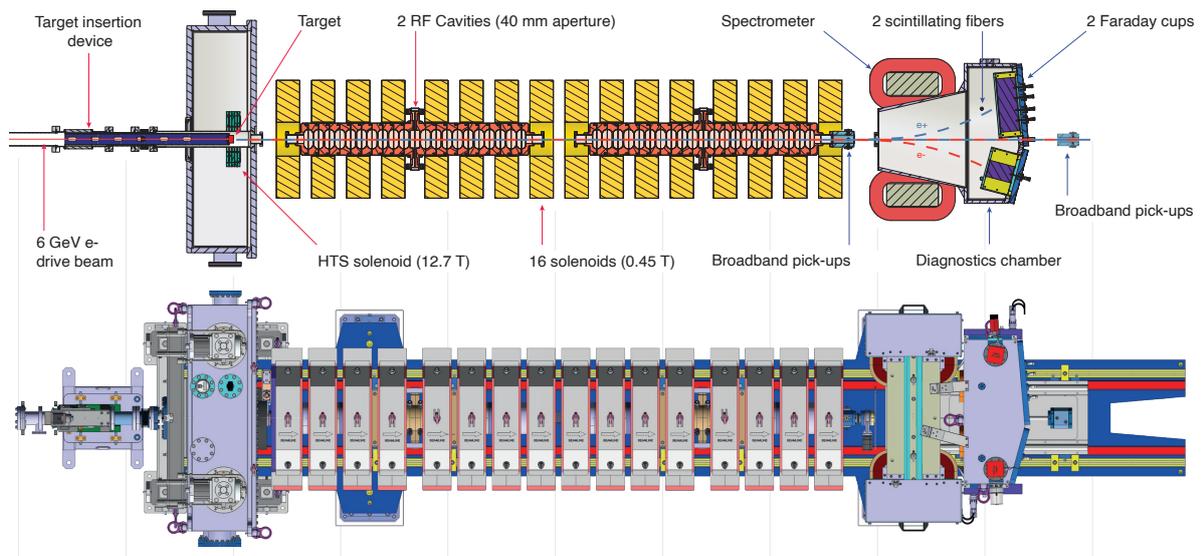


Figure 3: Overview of the technology for the P^3 experiment.

presents a technical drawing of the experiment, illustrating all the technologies developed or under development at PSI and CERN. These technologies have been carefully designed and optimized based on an in-depth study involving advanced beam dynamics simulations. This detailed simulation work made it possible to model and predict the behavior of particle beams under various conditions, thereby refining the experimental setup and ensuring the optimal performance of each component. The figure also illustrates the integration of these technologies, highlighting key aspects such as the integration of the target in the cryostat that houses the HTS coils, the RF structures surrounded by normal conducting solenoids, and the diagnostics chamber that will allow measurement of the charge and energy spectrum of the positrons generated.

The procurement and assembly of most accelerator and diagnostic components are progressing on schedule, ensuring timely completion of the project milestones. A key achievement has been the successful demonstration of the HTS solenoid at PSI, which achieved magnetic fields up to 18 T, a significant step forward for this advanced component. Figure 4 shows photos of the P^3 component production process, including the HTS coils and their cryostat, the broadband pickups, and the first accelerating RF structure. Overall, the P^3 experiment is making steady progress, with installation work at SwissFEL proceeding smoothly during scheduled shutdown periods, which take place three times a year. Essential infrastructure components, such as segments of the extraction line and the high-voltage klystron-modulator system, are being installed

in the tunnel according to plan. The primary installation phase is expected to conclude by the end of 2025, paving the way for the experiment to begin positron operations in 2026. It

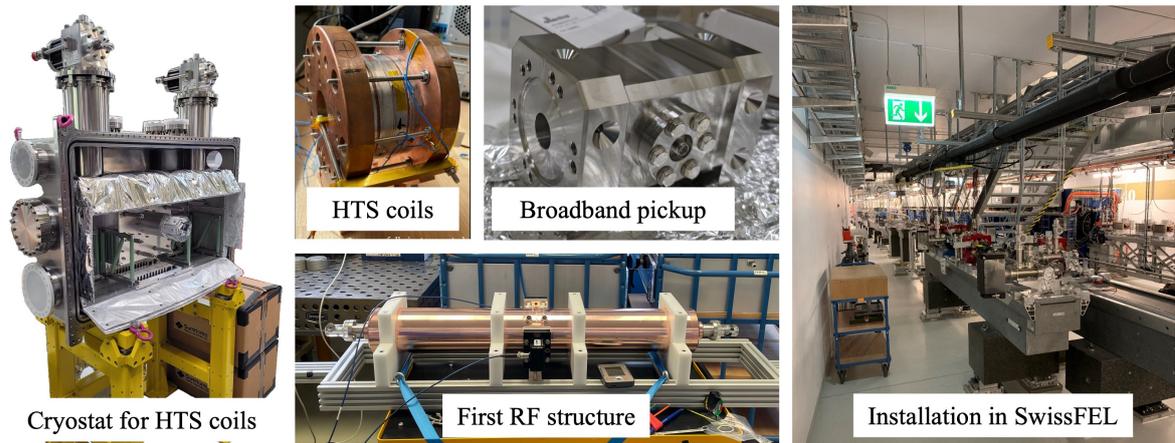


Figure 4: P³ components production and installation in SwissFEL.

is worth noting that the SwissFEL facility is an ideal location for hosting the P³ experiment, as it can deliver an electron beam energy of up to 6 GeV, matching the maximum drive beam energy required for the FCC-ee positron source. Currently, two beamlines (Aramis and Athos) are operational at SwissFEL, and the accelerator tunnel has reserved space for a future third beamline (Porthos). This layout provides sufficient room for the temporary installation of the P³ experiment and switchyard. Figure 5 illustrates the current design of the P³ experiment in its planned final configuration within the SwissFEL tunnel.

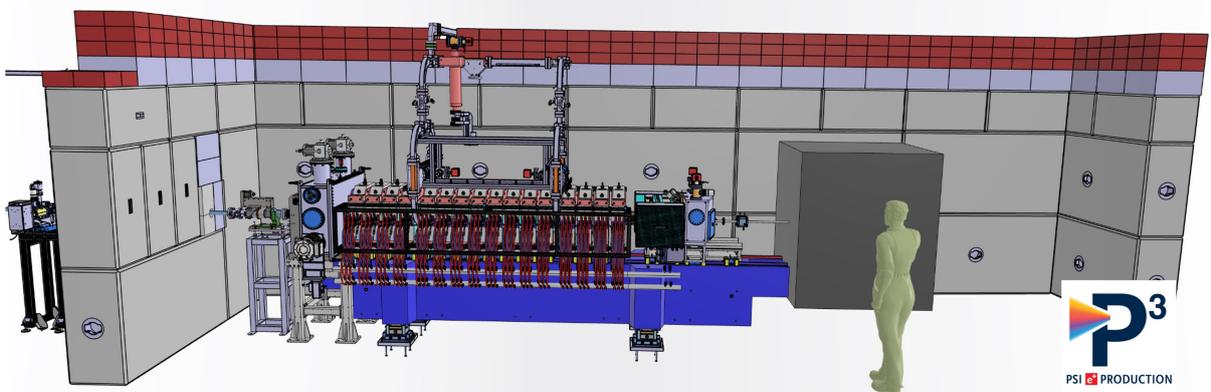


Figure 5: The PSI Positron Production (P³) Experiment.

4 Conclusion and Outlook

The FCC-ee injector feasibility study is progressing as scheduled, despite initial delays caused by COVID-19, setbacks in finalizing the budget, and an extended hiring process. However, the highly effective CHART collaboration, together with key contributions from external partners, provided essential support for the project and kept it on schedule. Key milestones have been achieved, notably in the PSI positron production experiment, which remains on track to produce first positrons by 2026. Following the mid-term review, which endorsed the reports, documentation, and cost estimates provided, valuable recommendations have led to a re-baselining of the

injector concept, including a new implementation at CERN's Preveessin site.

As the study advances towards the Technical Design Report (TDR) phase, there is strong support from Switzerland and PSI to continue and strengthen the CHART collaboration. The injector project team, consisting of PSI and CERN members and external partners, is preparing a comprehensive proposal to be included in the CHART program for the financial period 2025-2028, complete with detailed resource and cost estimates, which should be completed by the end of 2024. In the next phase, several critical areas will require focused attention. The updated baseline design includes a 2.86 GeV damping ring, which must be integrated into the forthcoming technical design study. The current baseline design assumes an RF frequency in the linacs compatible with the main rings to retain operational flexibility. However, the limited availability of suitable power sources on the market presents a challenge, prompting efforts to adopt a commercial S-band frequency for the RF system in the linacs. Additionally, the positron linac will undergo optimization to shift from the current 2 GHz setup to a more widely available S-band frequency. Reliability and availability of the injector complex will be key factors in the injector's design, particularly for continuous "top-up" operation, which requires for a low-gradient injector configuration with an experimentally validated RF breakdown rate. Assessing the impact of short interruptions caused by RF breakdowns in top-up operation will also be critical for ensuring stable performance.

The involvement of international partners will remain crucial as the injector study moves to the technical design and construction stages. Following the feasibility study phase, a preliminary TDR (pre-TDR) is planned for mid-2027, based on the SwissFEL linac technology for RF accelerating structures and related upgrade projects. This pre-TDR will also leverage the expertise of international partners experienced with synchrotron light and positron source operations. Its primary objective will be to define detailed specifications for accelerator and technical infrastructure requirements essential for initiating civil engineering design. These specifications will ensure that all system and subsystem requirements are addressed, making the initial construction phase and mass production of critical components smoother.

By the end of 2028, a comprehensive TDR for both the accelerator and associated technical infrastructure will be completed. The TDR's completion will be pivotal, enabling further engineering design efforts and finalizing all necessary specifications for civil engineering work. This phase is essential to confirm that all design elements undergo rigorous examination and are fully integrated into the project, ensuring a seamless transition to the construction phase. A prototyping phase will be critical in this context. During this phase, RF accelerator structures will undergo exhaustive testing to validate their performance and reliability. Additionally, the electron source concept, based on a photo-cathode RF gun, will be demonstrated to reliably support top-up operation for injection into the collider ring. This demonstration is essential to confirm that the chosen technology can meet operational requirements and integrate smoothly into the overall system.

Furthermore, the P^3 positron production experiment at PSI will be completed and commissioned, with subsequent development focusing on a hybrid scheme expected to reduce the power dissipated on the target while keeping the efficiency of positron production. This development phase will refine the specifications for the positron source, ensuring that all components meet the operational criteria for integration into the injector complex.

5 Publications, Conferences and Outreach

Note: This final report is only a very brief summary of all activities. More detailed CHART scientific reports are published at <https://chart.ch/reports/> and an extensive summary can also be found in *Full report on the FCC Feasibility Study mid-term review*, CERN/SPC/1218/RA and CERN/FC/6734/RA, 2023.

- N. Vallis et al., *Proof-of-principle e+ source for future colliders*, Phys. Rev. Accel. Beams 27, 013401 (2024), <https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.27.013401>
- *New positron source could give lepton colliders a boost* Accelerators and Detectors, Physics World, 2024, <https://physicsworld.com>.
- N. Vallis, *Proof-of-Principle Positron Source for Future Colliders*, doctoral thesis, EPFL Lausanne, October 10, 2024, [10.5075/epfl-thesis-11349](https://doi.org/10.5075/epfl-thesis-11349).
- Z. Vostrel, S. Doebert, *Design of an electron source for the FCC-ee with top-up injection capability*, Nuclear Instruments and Methods in Physics Research Section A, 1063 (2024), 169261, doi.org/10.1016/j.nima.2024.169261.
- T. Brezina, *Electron source and pre-injector design for the FCC-ee*, Bachelor's Thesis, Masaryk University, Faculty of Science, Brno, Czech Republic, 2022, doi.org/10.5281/zenodo.6922020.
- F. Alharthi et al, *Modeling of the positron sources: an experiment-based benchmarking*, to be submitted in Phys. Rev. Accel. Beams.
- R. Chehab, I. Chaikovska, F. Alharthi, H. Guler, V. Mytrochenko, S. Wallon, P. Sievers, *Advantages of hybrid positron sources with granular converters*, Nuclear Instruments and Methods in Physics Research Section A, 1060 (2024), 168994.
- F. Alharthi, I. Chaikovska, R. Chehab, Y. Zhao, A. Latina, Y. Enomoto, F. Miyahara and V. Mytrochenko, *Benchmarking the FCC-ee positron source simulation tools using the SuperKEKB results*, Journal of Physics: Conference Series. Vol. 2687: 022010, IOP Publishing, 2024.
- M. Soldani et al., *Radiation in oriented crystals: Innovative application to future positron sources*, Nuclear Instruments and Methods in Physics Research Section A, 1058 (2024), 168828, doi.org/10.1016/j.nima.2023.168828.
- I. Chaikovska, R. Chehab, V. Kubytskyi, S. Ogur, A. Ushakov, A. Variola, P. Sievers et al., *Positron sources: from conventional to advanced accelerator concepts based colliders*, Journal of Instrumentation 17, no. 05 (2022): P05015.
- L. Bandiera, L. Bomben, R. Camattari, G. Cavoto, I. Chaikovska, R. Chehab, D. De Salvador et al., *Crystal-based pair production for a lepton collider positron source*, The European Physical Journal C 82, no. 8 (2022): 699.
- J. Kosse et al., *Reliability engineering of cryocooler-based HTS magnets for FCC-ee*, IEEE Trans. Appl. Supercond., 2024.

Workshops and Conferences

- 65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022), Sep 12–16, 2022, INFN Frascati National Laboratories, several contributions, <https://agenda.infn.it/event/21199/>.
- FCC-ee Injector Studies Mini-Workshop, Nov 24–25, 2023, IJCLab, Orsay, Paris <https://indico.ijclab.in2p3.fr/event/8920/>.
- FCC-ee Injector Studies Mini-Workshop, Apr 20-21, 2023, INFN Frascati National Laboratories, <https://agenda.infn.it/event/34369/>.
- IPAC 2022 (12.6-17.7.2022): <https://www.ipac22.org/>
 - B. Humann et al., Radiation Load Studies for the FCC-ee Positron Source with a Superconducting Matching Device, <https://accelconf.web.cern.ch/ipac2022/papers/thpotk048.pdf>
 - P. Craievich et al., FCCee Pre-Injector Complex, <https://accelconf.web.cern.ch/ipac2022/papers/wepopt063.pdf>
 - S. Ogur et al., Target Studies for the FCC-ee Positron Source, <https://accelconf.web.cern.ch/ipac2022/papers/wepopt054.pdf>
 - Y. Zhao et al., Optimisation of the FCC-ee Positron Source Using a HTS Solenoid Matching Device, <https://accelconf.web.cern.ch/ipac2022/papers/wepopt062.pdf>
 - O. Etisken et al., Collective Effects Estimates for the Current Damping Ring Design of the FCC-e+e-, <https://accelconf.web.cern.ch/ipac2022/papers/thpost003.pdf>
- Linac conference 2022 (28.08-02.09) <https://linac2022.org/>
 - H. W. Pommerenke et al., RF design of traveling-wave accelerating structures for the FCCee injector complex, <https://accelconf.web.cern.ch/linac2022/papers/thpojo08.pdf>
 - N. Vallis et al., The PSI Positron Production project, <https://accelconf.web.cern.ch/linac2022/papers/tupori16.pdf>
- IPAC 2023 (7-12 May, Venice, Italy): <https://www.ipac23.org/>
 - N. Vallis et al., A positron source demonstrator for future colliders, <https://accelconf.web.cern.ch/ipac2023/doi/jacow-ipac2023-tupa086/>
 - V. Mytrochenko et al., On positron beam dynamics an initial part of a large aperture FCC-ee capture linac, <https://accelconf.web.cern.ch/ipac2023/doi/jacow-ipac2023-mop1086/>
 - F. Alharthi et al, Benchmarking the FCC-ee positron source simulation tools using the SuperKEKB results, <https://accelconf.web.cern.ch/ipac2023/doi/jacow-ipac2023-mop1094/>
 - I. Chaikovska et al, Update on the FCC-ee positron source design studies, <https://accelconf.web.cern.ch/ipac2023/doi/jacow-ipac2023-mop1095/>

- Y. Zhao et al., Use of a superconducting solenoid as a matching device for the compact linear collider positron source,
<https://accelconf.web.cern.ch/ipac2023/doi/jacow-ipac2023-mop1096/>
- S. Spampinati et al., Damping ring and transfer lines of FCC-ee injector complex,
<https://accelconf.web.cern.ch/ipac2023/doi/jacow-ipac2023-mopa112/>
- O. Etisken et al., Considerations for a new damping ring design of the FCC-ee pre-injector complex,
<https://accelconf.web.cern.ch/ipac2023/doi/jacow-ipac2023-mop1175/>
- FCC-ee week 2023 (5–9 Jun 2023, Millennium Gloucester Hotel London Kensington:
<https://indico.cern.ch/event/1202105/>
 - Full-energy booster, A. Chance (CEA).
 - Pre-injector baseline and options, P. Craievich (PSI).
 - Positron production, capture and acceleration until the damping ring, I. Chaikowska (CNRS/IJCLab).
 - Design of the FCC-ee positron source target: current status and challenges, R. F. Mena Andrade (CERN).
 - Damping ring and transfer lines for the FCC-ee pre-injector complex, C. Milardi (INFN-LNF).
 - Linac beam dynamics, S. Bettoni (PSI).
 - Layout and design of positron and electron linacs up to 20 GeV, A. Grudiev (CERN).
 - SPS pre-booster option, H. Bartosik (CERN).
 - Siting and transfer lines, W. Bartmann (CERN).
- IPAC 2024 (19-24 May, Nashville, Tennessee, USA): <https://ipac24.org/>
 - N. Vallis et al., *The PSI Positron Production project*,
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 - F. Zimmermann, *Selected advances in the accelerator design of the Future Circular Electron-Positron Collider (FCC-ee)*, <https://doi.org/10.18429/jacow-ipac2024-wepr14>.
 - S. Spampinati et al., *Emittance and energy distribution reduction in the positron injector of FCC-e+e-*, <https://doi.org/10.18429/jacow-ipac2024-wepr19>.
 - A. Kurtulus et al., *Accelerating structures for the FCC-ee pre-injector complex: RF design, optimization, and performance analysis*, <https://10.18429/JACoW-LINAC2024-MOPB036>.
- FCC-ee week 2024 (10–14 Jun 2024, The Westin St. Francis San Francisco on Union Square: <https://indico.cern.ch/event/1298458>
 - High-energy booster overview, A. Ghribi (GANIL).
 - RF-based optimisation of the booster cycle, A. L. Vanel (CERN).
 - Booster and collider filling scheme, H. Bartosik (CERN).
 - Injector complex: status and outlook, P. Craievich (PSI).
 - Injection/extraction systems across the complex, S. Yue (CERN).

- Static and dynamic beam dynamic effects in the e-, common and HE-linacs, S. Bettoni (PSI).
- RF Design Studies of Accelerating Structures for the FCC-ee Pre-injector Complex, A. Kurtulus (CERN).
- Positron source and capture system (HTS-solenoid vs FC options), I. Chaikovska (CNRS/IJCLab).
- Damping ring: status and outlook (including DR at higher energy), A. De Santis (INFN Frascati).
- Positron bunch and energy compressor (to/from damping ring), S. Spampinati (INFN Frascati).
- PSI Positron Production (P-cubed) project, Nicolas Vallis (PSI/EPFL).
- Development of p-cubed and FCCee positron source targets at CERN, R. F. Mena Andrade (CERN).
- Positron source design and experiment for FCC, SuperKEKB and ILC, Yoshinori Enomoto (KEK).
- Polarized injector for CEPC, Z. Duan (IHEP).