FCC-EE POSITRON CAPTURE SYSTEM BASED ON 3 GHZ RF STRUCTURES

Y. Wang*[1], I. Chaikovska[1], V. Mytrochenko[1,2], R. Chehab[1]
[1]Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France
[2]NSC Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

Abstract

This paper presents a preliminary comparative study of 3 GHz RF options for the FCC-ee positron capture linac. In the FCC-ee Feasibility Study (FS), the reference capture system is based on a 2.86 GeV electron drive beam impinging on a 15 mm-thick tungsten target, followed by a high-temperature-superconducting (HTS) matching solenoid and a 2 GHz RF capture section composed of six travelling-wave (TW) accelerating structures in a 0.5 T solenoidal channel. In this work, several 3 GHz S-band alternatives are investigated, including pure TW, pure standing-wave (SW), and hybrid SW/TW layouts. Their performance is compared with the 2 GHz FS reference using RF-Track for beam-dynamics simulations and Xopt for optimization. A quadrupole-based downstream option is also studied after the separator chicane. The comparison is based on positron yield in the main RF bucket and beam phase-space properties. The results show that the 2 GHz FS reference remains superior in terms of main-bucket yield, while the quadrupole-based downstream configuration provides the most favorable compromise when yield and beam quality are considered together. An Octree-based 6D beam-core analysis is used to complement the yield comparison and to provide a first assessment of 3 GHz capture and downstream-optics options for the FCC-ee positron source.

INTRODUCTION

The production and capture of high-intensity positron beams is one of the key challenges of the FCC-ee injector, especially for operation at the Z pole. In the FCC-ee FS, the reference positron source is based on a 2.86 GeV electron drive beam impinging on a tungsten target, followed by a high-temperature-superconducting (HTS) matching solenoid and a 2 GHz RF capture section [1–4].

Alongside this baseline, alternative 3 GHz capture-linac solutions are being explored as part of the ongoing optimization of the FCC-ee injector chain. These options are attractive because they could benefit from the mature and widely available S-band RF high-power technology [5–7]. In this context, a TW solution is considered as a natural extension of the RF-capture concept adopted in the FS, while an SW solution is investigated on the basis of capture concepts developed for the P-cubed positron-production experiment [8, 9].

Since both the RF frequency and the cavity type can affect the capture dynamics, the comparison cannot be limited to positron yield alone. Beam phase-space properties must also be considered, since the usefulness of the captured beam ultimately depends on its compatibility with downstream transport and, eventually, with damping-ring acceptance. The present study is therefore restricted to the capture linac, the separator chicane, and the downstream accelerating structures. Within this scope, the different configurations are compared using RF-Track for beam-dynamics simulations and Xopt for optimization [10, 11].

CAPTURE LAYOUTS AND EVALUATION METHODOLOGY

Compared Configurations

The drive electron beam and target assumptions adopted for all configurations are summarized as follows: a beam energy of 2.86 GeV, a repetition rate of 100 Hz, four bunches per pulse, a target thickness of 15 mm, and a positron production rate of 7.07. Here, the positron yield at a given location is defined as the ratio of the number of positrons to the number of incoming electrons, $Y_{e^+} = N_{e^+}/N_{e^-}$.

In this study, the comparison is restricted to the positron capture linac, the separator chicane, and the additional RF structures located immediately downstream of the chicane. The chicane removes co-propagating electrons, while the surviving positrons are further accelerated downstream. To ensure a meaningful comparison, all configurations are evaluated using the same input positron-beam distribution at the entrance of the capture section, based on common assumptions for the target and matching device.

The reference case is the 2 GHz FS capture scheme, consisting of six TW accelerating structures. Three alternative 3 GHz capture layouts are considered: a pure TW scheme with five TW structures, a hybrid scheme with two SW cavities followed by four TW structures, and a pure SW scheme with twelve SW cavities. The corresponding RF-structure parameters are listed in Table 1.

Table 1: Main RF-structure parameters of the considered TW and SW options.

Parameter	TW-FS	TW	SW
Length [m]	3.0	3.0	1.2
Structure spacing [m]	0.24	0.24	0.15
Frequency [GHz]	2.0	3.0	2.9988
Gradient [MV/m]	13.3	15	18
Cells	40	66	21
Aperture [mm]	60	40	40

* yuting.wang@ijclab.in2p3.fr

The 3 GHz TW option extends the TW capture concept adopted in the FS while retaining the associated solenoid channel. The 3 GHz SW option is based on the field maps developed for the P-cubed positron-production experiment, with a solenoid configuration derived from the P-cubed design and rescaled from 0.45 T to 0.5 T [8, 9]. A possible advantage of the SW structure is that its couplers are located away from the cavity entrance, leaving more space for the surrounding solenoids. In addition, the accelerating field at the RF entrance may remain higher than in the TW case, which could benefit the early capture process. The hybrid layout is introduced to explore an intermediate solution combining an SW-based front end with TW-based downstream transport.

For consistency with the FS reference, all 3 GHz layouts use the same target position, located 40 mm downstream of the peak field of the HTS matching solenoid, and the entrance of the first RF structure is fixed at 0.346 m. A tuning solenoid is also retained in all 3 GHz configurations to compensate the longitudinal magnetic-field profile B_z between the HTS matching solenoid and the RF-section entrance. The corresponding on-axis field profiles for the FS, TW, hybrid, and SW configurations are shown in Fig. 1.

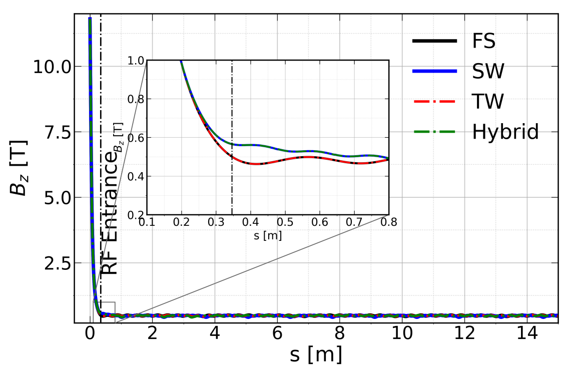

Figure 1: On-axis solenoid magnetic field profile B_z from the target to the end of the capture system for the considered schemes. The position $s = 0$ denotes the target exit plane, and this convention is used throughout the following discussion.

Downstream of the separator chicane, the TW-based configurations, including the 2 GHz FS reference and the 3 GHz pure TW layout, are followed by two additional TW structures, whereas the pure SW layout is followed by four additional SW structures. In all cases, beam tracking is stopped at the end of the corresponding downstream RF section, hereafter denoted as S0, where the beam energy reaches about 300 MeV.

Evaluation Metrics and Optimization Procedure

Beam tracking is performed with RF-Track from the target exit to the end of S0, including the capture linac, the separator chicane, and the downstream RF structures [10]. The main figures of merit are the positron yield and the energy gain, as shown in Fig. 2.

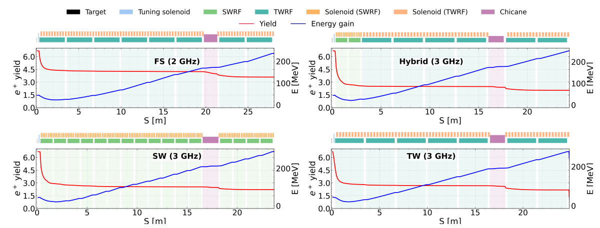

Figure 2: Comparison of the considered layouts in terms of positron yield and beam-energy evolution.

All configurations are optimized within a common Xopt-based workflow, with the main-bucket yield as the objective function and the RF phases as optimization variables. With this criterion, the 2 GHz FS reference reaches a main-bucket yield of 3.54, while the optimized 3 GHz layouts give 2.03 for the hybrid scheme, 2.10 for the pure SW scheme, and 2.11 for the pure TW scheme. As indicated by Fig. 2, a significant part of this difference already originates in the capture section. The lower yield of the 3 GHz options can be attributed, at least in part, to their smaller aperture, which leads to stronger positron losses near the entrance of the capture linac, where the beam still has large divergence.

These results show that, under the present assumptions, the 2 GHz FS reference remains clearly superior in terms of main-bucket capture efficiency. However, yield alone does not fully characterize the useful beam, which motivates the beam-core studies discussed below.

Alternative Downstream Optics Based on Quadrupole Focusing

In addition, a dedicated study of the downstream optics was carried out for the 3 GHz TW capture scheme taken as a reference. In the nominal configuration, the positron beam is further accelerated downstream of the separator chicane in a solenoid channel. Here, this downstream section is replaced by a quadrupole-based lattice to investigate whether the transport performance can be maintained or improved while reducing the use of solenoids and the associated power consumption.

Such a replacement requires dedicated matching, because upstream of the chicane the beam is transported in a solenoidal channel, where the transverse motion is coupled, whereas the quadrupole-focusing lattice is based on uncoupled optics. Two transition strategies are considered. In the first, the beam is matched directly upstream of the chicane, where the on-axis field is still about 0.28 T. In the second, the solenoid field is linearly tapered from the middle of the sixth TW structure, reducing the field at the chicane entrance to about 0.013 T. The corresponding layouts and B_z profiles are shown in Fig. 3.

The matching section consists of four quadrupoles upstream of the chicane, four quadrupoles downstream of the chicane, and two additional quadrupoles before the first regular FODO cell. Their initial strengths are obtained from MAD-X matching and then further optimized with Xopt to match the beam to the quadrupole-focusing lattice [12]. In

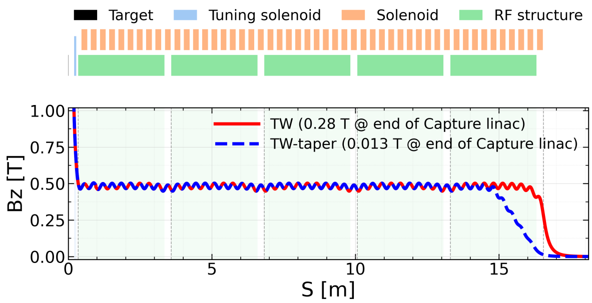

Figure 3: On-axis solenoid magnetic field, B_z, along the capture linac for the two TW-based transition layouts considered for the transition from the solenoidal capture section to the downstream quadrupole-focusing lattice.

a second step, the RF phases in the downstream section are also varied. With this procedure, the TW+Quad and tapered-solenoid TW+Quad configurations reach main-bucket yields of 2.47 and 2.41, respectively, as shown in Fig. 4.

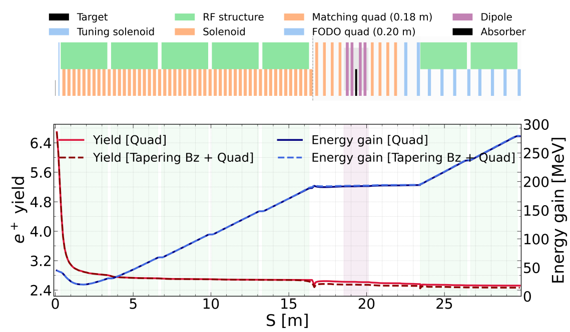

Figure 4: Comparison of the two TW+Quad matching strategies, showing the layouts together with the corresponding positron yield and beam-energy evolution.

Although these values remain below the 2 GHz FS reference, they are significantly higher than those of the other optimized 3 GHz capture layouts considered here.

Beam-Core Comparison

A complete assessment of the positron yield accepted by the 2.86 GeV damping ring is still ongoing. To enable a more informative comparison of the positron-linac performance at this stage, an additional beam-core analysis is performed using a combined Octree and highest-density-region (HDR) description in 6D phase space [13].

Unlike the total positron yield alone, this 6D analysis provides a more global characterization of the beam by identifying the most populated region in phase space. It therefore makes it possible to compare the different configurations while accounting simultaneously for beam intensity and phase-space quality.

Figure 5 shows a clear trade-off between yield and beam quality. The 2 GHz FS reference reaches the highest yield, but with significantly larger emittance, especially at high yield. By contrast, the 3 GHz configurations remain in a lower-emittance region, although with lower maximum yield.

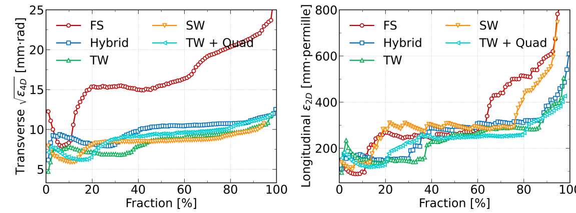

Figure 5: Comparison of the considered configurations in terms of yield and beam-core fraction as a function of the emittance, based on the Octree+HDR 6D analysis. The beam-core fraction is normalized to the total positron population of each configuration: 3.59 (FS), 2.04 (hybrid), 2.17 (TW), 2.22 (SW), and 2.52 (TW+Quad).

Within this phase-space-based comparison, the FODO-based downstream option provides the most favorable compromise between yield and emittance, while the difference between the nominal and tapered-solenoid TW cases remains small.

CONCLUSION

A preliminary comparison of 3 GHz positron-capture options for the FCC-ee positron source has been carried out with respect to the 2 GHz reference configuration of the FCC FS. Three 3 GHz capture layouts were considered: pure TW, hybrid SW+TW, and pure SW. With optimization based on the positron yield in the main RF bucket, the 2 GHz FS reference remains clearly superior, with a yield of 3.54, compared with 2.11, 2.10, and 2.03 for the pure TW, pure SW, and hybrid layouts, respectively.

A quadrupole-based downstream option was also investigated for the 3 GHz TW case. Using a dedicated matching procedure with MAD-X and Xopt, the optimized TW+Quad and tapered-solenoid TW+Quad configurations reach comparable main-bucket yields of 2.47 and 2.41. To complement the yield comparison while the damping-ring acceptance study is ongoing, an Octree+HDR-based 6D beam-core analysis was performed. Under the present conditions, the quadrupole-based downstream option provides the most favorable compromise between yield and emittance, while the difference between the nominal and tapered-solenoid TW cases remains small. This observation is relevant to the ongoing study of stronger solenoid magnetic channels.

ACKNOWLEDGEMENT

We acknowledge the FCC-ee Injector Collaboration and thank Andrea Latina for his valuable input on RF-Track simulations and his fruitful suggestions on the Octree analysis. This work is supported by ANR, Agence Nationale de la Recherche, under Grant No. ANR-21-CE31-0007. The research leading to these results has received funding from the European Union's Horizon Europe MSCA under grant agreement No. 101086276.

REFERENCES

[1] P. Craievich *et al.*, "The FCCee Pre-Injector Complex", *JACoW*, vol. IPAC2022, pp. 2007–2010, 2022. doi:10.18429/JACoW-IPAC2022-WEPOPT063

[2] M. Benedikt *et al.*, "Future Circular Collider Feasibility Study Report: Volume 2, Accelerators, Technical Infrastructure and Safety", *Eur. Phys. J. ST*, vol. 234, no. 19, pp. 5713–6197, 2025. doi:10.1140/epjs/s11734-025-01967-4

[3] F. Alharthi *et al.*, "FCC-ee positron source from conventional to crystal-based", *Nucl. Instrum. Meth. A*, vol. 1075, p. 170412, 2025. doi:10.1016/j.nima.2025.170412

[4] F. Alharthi, "Design and validation studies of the FCC-ee positron source", Ph.D. thesis, université Paris-Saclay, IJCLab - Laboratoire de Physique des 2 Infinis Irène Joliot-Curie - IN2P3 - Institut National de Physique Nucléaire et de Physique des Particules du CNRS - Université Paris-Saclay - CNRS - Centre National de la Recherche Scientifique, CERN - European Organization for Nuclear Research - CERN [Genève], High energy accelerator research organization - KEK, 2025.

[5] P. Craievich, "Injector concept and parameters", Presentation at Scientific Advisory Committee #08, University of Cambridge, 18–20 November 2024, Nov. 2024,

[6] P. Craievich, "Fcc-ee injector overview and outlook", Talk presented at FCC Week 2025, Hofburg Vienna, Vienna, Austria, 21 May 2025, May 2025,

[7] A. Grudiev, "Fcc-ee injector linacs: the design and the rf frequency choices for the tdr", Talk presented at FCC Week 2025, Hofburg Vienna, Vienna, Austria, Indico contribution; presentation materials available online, May 2025,

[8] N. Vallis *et al.*, "Proof-of-principle e+ source for future colliders", *Phys. Rev. Accel. Beams*, vol. 27, no. 1, p. 013401, 2024. doi:10.1103/PhysRevAccelBeams.27.013401

[9] N. Vallis *et al.*, "The PSI positron production project", *JACoW*, vol. IPAC2024, TUPC50, 2024. doi:10.18429/JACoW-IPAC2024-TUPC50

[10] A. Latina, "RF-Track Reference Manual, version 2.5.4", https://doi.org/10.5281/zenodo.17641882, 2025, doi:10.5281/zenodo.17641882,

[11] R. Roussel, A. Edelen, A. Bartnik, and C. Mayes, "Xopt: a simplified framework for optimization of accelerator problems using advanced algorithms", in *Proc. IPAC'23*, Venezia, pp. 4796–4799, May 2023. doi:doi:10.18429/jacow-ipac2023-thpl164

[12] N. F. Martínez, "Mad-x simulation code", 2024, https://cds.cern.ch/record/2928179/files/document.pdf,

[13] H. Samet, "Octree-related data structures and algorithms", *Computer Graphics and Image Processing*, vol. 20, no. 4, pp. 367–386, 1982.