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# $P^3$: A POSITRON SOURCE DEMONSTRATOR FOR FCC-ee

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*Abstract*

The PSI Positron Production project ($P^3$ or P-cubed) is a demonstrator for a novel positron source for FCC-ee. The high current requirements of future colliders can be compromised by the extremely high positron emittance at the production target and consequent poor capture and transport to the damping ring. However, recent advances in high-temperature superconductors allow for a highly efficient matching of such an emittance through the use a solenoid around the target delivering a field over 10 T on-axis. Moreover, the emittance of the matched positron beam can be contained through large aperture RF cavities surrounded by a multi-Tesla field generated by conventional superconducting solenoids, where simulations estimate a yield higher by one order of magnitude with respect to the state-of-the-art. The goal of $P^3$ is to demonstrate this basic principle by implementing the aforementioned solenoids into a prototype positron source based on a 6 GeV electron beam from the SwissFEL linac, including two RF capture cavities and a beam diagnostics section.

## INTRODUCTION

The Future Circular Collider (FCC) study group published in 2019 a Conceptual Design Report for an electron-positron collider (FCC-ee) with a centre-of-mass energy from 90 to 365 GeV and a beam current up to 1.4 A [1]. This high current requirement depends largely upon an injector complex (see Fig. 1) consisting of two separate sources and linacs for electrons and positrons up to 1.54 GeV, a damping ring (DR) to cool the positron emittance and a common linac up to 6 GeV [2].

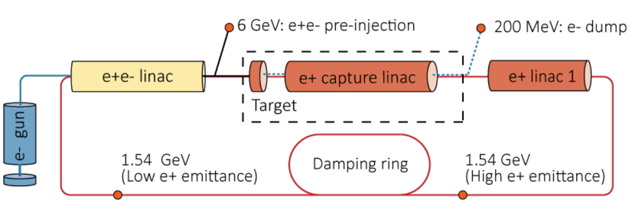


Figure 1: Latest proposal for the FCC-ee Injector Complex.

The principle method for positron production at FCC-ee is based on a 6 GeV electron beam impinging a 17.5 mm-thick (or $5X_0$) amorphous W target, which generates a positron yield around 13 $N_{e+}/N_{e-}$ at the target exit [3]. However, the extremely high emittance and energy spread of the secondary distribution can lead to poor capture rates, compromising the yield of positrons accepted at the DR. The state-of-the art for a similar positron source is that of the SuperKEKB factory, allowing for 0.5 $N_{e+}/N_{e-}$, based on a 3.2 GeV electron drive beam with a bunch charge of 10 nC [4]. By contrast, the FCC-ee injection requires yield of 1 $N_{e+}/N_{e-}$ at the DR, plus a safety factor of 2 in the design [5].

The PSI Positron Production project ($P^3$ or P-cubed) was proposed as a demonstrator for a novel solution for the FCC-ee positron source and capture linac. The baseline design of $P^3$ (see Fig. 2) consists of an adiabatic matching device (AMD) based on high-temperature superconducting (HTS) solenoids surrounding the target with a max. field on-axis of 12.7 T and two standing-wave (SW) capture RF cavities in S-band with a large iris aperture of 20 mm radius surrounded by conventional superconducting solenoids with a max. 1.5 T field on-axis. A beam diagnostics section will provide the first exprerimental estimations of the positron yield, which according to simulations is expected to improve the SuperKEKB record by one order of magnitude.

$P^3$ will use a 6 GeV drive electron beam generated at the SwissFEL linac. On the one hand, SwissFEL can provide the desired beam energy and transverse size with extreme precision. On the other hand, due to the radioprotection limitations at SwissFEL, the drive beams of $P^3$ and FCC-ee show substantial differences regarding bunch charge and time structure (see Table 1). This results in a significantly lower radiation load in the $P^3$ target, excluding any thermo-mechanical studies from the scope of the experiment.

Table 1: Main Drive Linac Parameters

| | FCC-ee | $P^3$ (SwissFEL) |
|---|---|---|
| Energy [GeV] | 6 | |
| $\sigma_{x,RMS}$ [mm] | 0.5 - 1.0 | |
| $Q_{bunch}$ [nC] | 0.88 - 1.17[1] | 0.20 |
| Reptition rate [Hz] | 200 | 1 |
| Bunches per pulse | 2 | 1 |

[1]Based on 5.0 - 5.5 nC requirements at booster ring and preliminary yield estimations of 4.7 - 5.7 $N_{e+}/N_{e-}$.

## KEY TECHNOLOGY

### *HTS Adiabatic Matching Device*

HTS solenoids will be used to deliver a peak on-axis field of 12.7 T around the target in order to match the extremely high positron emittance. This technology can lead to significantly higher yields with respect a conventional, normal-conducting flux concentrator (FC) [6]. The solenoids will be

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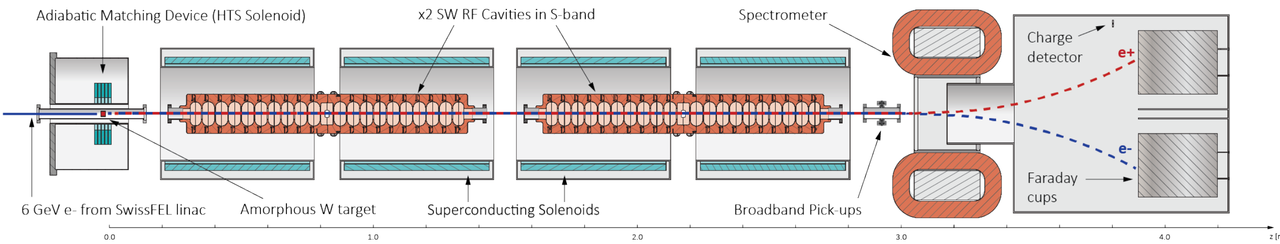


Figure 2: Baseline design of the $P^3$ experiment.

implemented with non-insulated ReBCO tape, which does not require a high-temperature or high-pressure treatment, and can be assembled in-house [7]. A reliable operation over 20 T in the conductor at 20 - 30 °K of a 4 ReBCO coil prototype (see Fig. 3) has been demonstrated experimentally at PSI, whithout the need of helium cooling, and showing a great self-protection against quenching. In addition, simulation studies show no critical radioprotection issues with the FCC-ee beam [8]. At this stage, major advances have been made towards a technical design of the AMD for $P^3$, including of 5 HTS coils and a relatively compact cryostat (see Fig. 3).

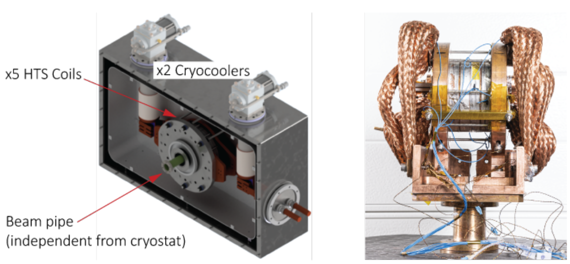


Figure 3: AMD cryostat (left) and HTS demonstrator (right).

## *S-band, SW Cavities*

The capture of secondary positrons into stable RF buckets is provided by two SW RF cavities in S-band, the main parameters of which are shown in Table 2. The SW design allows for a large aperture of 20 mm radius and a good RF efficiency without the need of a pulse compressor. The operation in S-band was chosen based on the availability of commercial klystrons and conventional waveguide components, instead of the L-band baseline for the FCC-ee injector. A single klystron modulator can provide the required peak power and RF pulse length to fill the two cavities and reach a gradient of 18 MV/m. A waveguide coupler placed centrally is used to increase the mode separation.

## *Superconducting Solenoids around RF Cavities*

The use of NbTi, a conventional low-temperature superconductor, remains the preferred technology the solenoids around the RF cavities. A concept design for this superconducting solution is depicted in Fig. 2, where the goal is to generate a flat, 1.5 T field on-axis, as shown in Fig. 4g. However, the feasibility and cost-effectiveness of NbTi is under study, and the use of normal-conducting solenoids providing a 0.4 T field on-axis is still under consideration.

Table 2: Main Parameters of the SW Cavities

| Parameter | Value |
|---|---|
| Length [m] | 1.2 |
| RF frequency [GHz] | 2.9988 |
| Nominal gradient [MV/m] | 18 |
| Number of cells | 21 |
| $R/L$ | 13.9 MΩ/ m |
| Aperture [mm] | 40 |
| Mode separation (in $\pi$ mode) [MHz] | 5.3 |
| RF Pulse length [µs] | 3 |
| Coupling factor | 2 |

# BEAM DYNAMICS

Figure 4 shows the $P^3$ beam simulated with ASTRA [9] according to the reference working point, where experiment parameters have been optimized to provide a maximum yield of 8 $N_{e+}/N_{e-}$ at the DR[1]. The key techniques to obtain this high yield are elucidated below.

## *Emittance Matching and Containment*

HTS solenoids work as an AMD, matching the positron emittance through an adiabatically decreasing $B_z$ profile. The matching power is maximized with the remarkably high magnetic strength (12.7 T), which leads to a significantly better yield with respect to conventional solutions (see Refs. [6, 10]). In order to contain such emittance and avoid beam explosion, a strong and flat magnetic channel around the RF cavities is applied. Simulation studies show a great impact of the field strength and flatness: first, normal-conducting solenoids at 0.4 T would imply a factor 3 reduction of the capture efficiency as compared to the 1.5 T superconducting scheme; in addition, Figs. 4g and 4e show how small variations in the magnetic field profile cause significant positron losses. These losses tend to decrease after a few RF cavities as the beam energy increases, and the emittance reaches a stable value. The $P^3$ simulations show a capture efficiency rate of 76% and an RMS emittance around $15\,000\,\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ after the second cavity.

[1] Yield at DR is estimated by simulating the beam to 200 MeV (10 Cavities) and applying an analytical transformation of the longitudinal plane to 1.54 GeV and a rectangular filter of ±3.8 % in energy and $\pm\lambda/2$ in z

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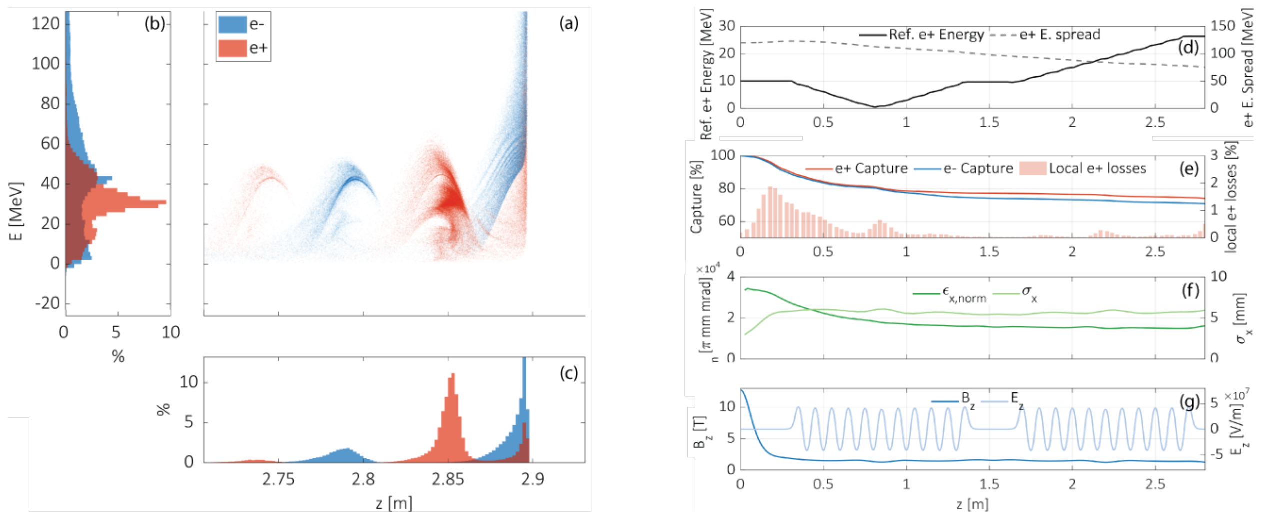

Figure 4: Longitudinal profile of P$^3$ beam at z = 2.85 m a to c) and evolution of main parameters (d to g).

### *Bunching by Deceleration*

Due to the extremely high energy spread at the source, the beam is non-relativistic over the first RF cells, which allows for bunching through RF deceleration [11]. Simulations show that yield is maximized through partial deceleration over the first cavity and on-crest acceleration over the second (see Fig. 4d). This working point leads positrons to bunch around the second bucket (see Fig 4a).

## BEAM DIAGNOSTICS

### *Broadband Pick-ups*

Broadband pick-ups (BBPs) placed after the second RF cavity can provide a high resolution measurement of the time structure of the beam that would allow to distinguish consecutive electron and positron bunches [12].

### *Faraday Cups*

As seen in Fig. 2, electrons and positrons will be separated by a spectrometer and dumped into independent Faraday cups that will provide a charge measurement integrated over many bunches. In pursuit of a compact design, these faraday cups are implemented through a 25 Ω coaxial layout, matched to the standard 50 Ω through two parallel coaxial guides. Due to the significant losses in the spectrometer walls and the rather small size of the faraday cups, only 68% and 65% of captured positrons and electrons are eventually measured.

### *Narrow Charge Detector*

The spectrum of the longitudinal momentum ($p_z$) of the beam can be measured through varying the spectrometer field strength and placing a screen of narrow width within the vacuum chamber. The obtained distribution of measurements can be transformed into a histogram of $p_z$ by applying the magnetic rigidity law. The optimum position (x = -350 mm, z = 3800 mm) of the charge detector has been determined and preliminary simulations show an accurate reconstruction of the $p_z$ spectrum through a scan up to 0.3 T of the dipole field. The technology of the detector is still under discussion.

## CONCLUSION

Major advances have been made regarding the development of P$^3$. On the one hand, the highly advanced design stage allows to initiate the material purchase of the RF cavities and the AMD. Regarding the latter, a reliable operation of HTS solenoids at fields above the P$^3$ requirements on-axis has been demonstrated and no prohibitive radiation protection issues have been found [8]. On the other hand, while the technology of the solenoids around the RF cavities is still under discussion, superconducting (1.5 T) and normal conducting (0.4 T) options have been studied, the first being the baseline option due to the outstanding capture efficiency provided. The same conclusion applies to the beam diagnostics section, where despite absence of a final technological choice, preliminary simulations show a reliable performance of the arrangement of BBPs, two faraday cups and a narrow charge detector. For all these reasons, we can conclude that the delivery of a full technical design is feasible and on-schedule for the next few months.

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