THE PSI POSITRON PRODUCTION PROJECT

N. Vallis[1]*, P. Craievich, M. Schaer, R. Zennaro,
B. Auchmann, M.I. Besana, M. Duda, R. Fortunati, H. Garcia-Rodrigues, D. Hauenstein,
R. Ischebeck, E. Ismaili, P. Juranic, J. Kosse, A. Magazinik, F. Marcellini, M. Pedrozzi,
G.L. Orlandi, M. Seidel[1], M. Zykova, Paul Scherrer Institute, Villigen-PSI, Switzerland
R. Mena-Andrade, J.L. Grenard, A. Perillo-Marcone,
CERN, Geneva, Switzerland
[1]also at EPFL, Lausanne, Switzerland

Abstract

The PSI Positron Production experiment, known as P^3 or *P-cubed*, is a proof-of-principle positron source and capture system that can greatly improve the state-of-the-art positron yield. The P^3 project is led by the Paul Scherrer Institute in Switzerland, and addresses the long-standing challenge faced by conventional injector facilities to generate, capture, and damp the emittance of high-current positron beam, which is a major limiting factor for the feasibility of future electron-positron colliders. P^3 follows the same basic principles as its predecessors, utilizing a positron source driven by pair-production and an RF linac with a high-field solenoid focusing system. However, it incorporates pioneering technology, such as high-temperature superconducting solenoids, that can outperform significantly the present positron capture efficiency rates. The P^3 experiment will be hosted at PSI's SwissFEL, and will serve as the positron source test facility of CERN's FCC-ee. This paper outlines the concept, technology, infrastructure, physics studies and diagnostics of P^3.

CONCEPT, TECHNOLOGY AND INFRASTRUCTURE

Particle colliders depend on pair-production-driven e^+ sources, which yield large amounts of secondary e^+e^- pairs through the interaction of high-energy photons and a high-Z amorphous target. Typically, high-energy photons are created by bremsstrahlung as a primary multi-GeV e^- beam is fired directly at the target. However, the particle showers involved in e^+ production are associated with an extreme transverse emittance and energy spread, substantially higher than those in an equivalent e^- source [1]. Therefore, one a critical challenge for collider injectors is to produce, capture, and damp the emittance of e^+ in sufficient quantities to achieve the desired luminosity [2].

The PSI Positron Production experiment, known as P^3 or *P-cubed*, is a proof-of-principle study of a e^+ source and capture system with the potential to substantially enhance the current state-of-the-art e^+ yield [3]. The P^3 project is led by the Paul Scherrer Institute (PSI) in Villigen, Switzerland, and will be hosted at PSI's SwissFEL facility, a free-electron laser that houses a 6 GeV e^- drive linac [4]. P^3 will serve as the e^+ source test facility for FCC-ee [5], utilizing SwissFEL's drive beam and a tungsten target to make up a pair-production-driven e^+ source, which will then be captured by a highly efficient capture system and detected by various beam diagnostics setups, as illustrated in Fig 1. Instead of a conventional FC, P^3 will use a high-temperature superconducting (HTS) solenoid around the target. The HTS solenoid will deliver a peak field above 12 Tesla, the highest field ever used for e^+ capture in a particle accelerator [2]. In addition, the large aperture of the HTS solenoid design allows for a full immersion of the target in the magnetic field, enabling the optimal conditions for positron capture. The target will be followed by two RF accelerating cavities based on a pioneer standing wave (SW) scheme with a large iris aperture. The cavities will be surrounded by a flat solenoid focusing channel provided by an arrangement of sixteen normal conducting (NC) solenoids.

SwissFEL presents multiple advantages as the host facility of the P^3 experiment. First and foremost, the SwissFEL linac can produce 6 GeV e^- beams, corresponding to the nominal drive energy of FCC-ee, and has the required room and infrastructure for a relatively large installation like a e^+ source. Table 1 compares the baseline drive e^- beam parameters of P^3 and FCC-ee. Most parameters are equivalent since the same beam dynamics behavior is desired in both facilities. However, due to the radiation protection limits of SwissFEL, the differences are prominent in terms of bunch charge, repetition rate and the number of bunches per pulse. A dedicated radiation protection bunker will be built inside the SwissFEL tunnel as additional protection for personnel and nearby accelerator equipment.

Table 1: Primary e- of FCC-ee Linac and SwissFEL

	FCC-ee [6]	**P^3**
Energy [GeV]	6	
σ_t [ps]	3.33	
σ_x, σ_y [mm]	0.5	
Target length [mm]	17.5	
Q_{bunch} [nC]	1.7 - 2.4	0.20[1]
Reptition rate [Hz]	200	1[1]
Bunches per pulse	2	1[1]

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* nicolas.vallis@psi.ch

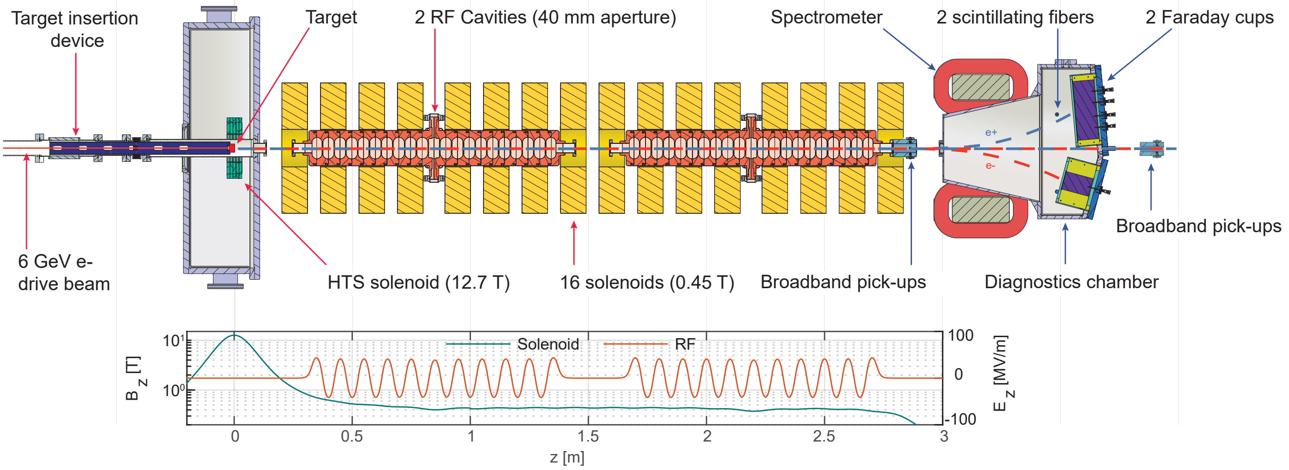

Figure 1: Schematic layout of the P^3 experiment. Key components of the e$^+$ source and capture system are indicated with red arrows and diagnostics with blue arrows. Solenoid (in log scale) and RF fields are included at the bottom.

PHYSICS STUDIES

According to Geant4 [7] simulations, the e+ production scheme described in Table 1 will yield a secondary e+ distribution of 2754 pC, which amounts to 13.77 secondary e+ per primary e-. At the target exit face, the secondary e+ beam will have a moderate beam size ($\sigma_x \approx 1$ mm) and bunch length ($\sigma_t \approx 3.3$ ps), but a very high energy spread ($\Delta E_{RMS} \approx 115$ MeV) and transverse momentum ($\sigma_{px} \approx 8$ MeV/c).

Transverse Beam Dynamics

The HTS and NC solenoids are arranged to form an adiabatic matching device (AMD) [8], which gradually transitions the magnetic profile from the 12.7 T peak to the 0.45 T plateau. According to ASTRA [9] simulations, This AMD transforms the e+ transverse profile at the target, characterized by a moderate σ_x and large σ_{px} into a beam with a large σ_x (≈ 6 mm) and moderate σ_{px} (≈ 2.5 MeV). This maximizes the acceptance rate of the RF cavities, which have a transverse aperture of 40 mm in diameter. The NC solenoids create a magnetic channel that transports the accepted e+ beam along the RF cavities, aiming for minimum e+ losses by achieving maximum flatness and strength.

Longitudinal Beam Dynamics

The RF fields will capture the secondary e+e- distribution in consecutive e+ and e- bunches over many RF buckets. Fig. 2 shows the total e+ output at the exit of the second RF cavity over a scan of the two RF phases. The maximum is achieved at $\phi = (120,-70)$, which provides charge of 1250 pC, or 6.25 e+ per primary e-. Fig. 3 shows a second 2D RF phase scan that estimates the maximum acceptance at the FCC-ee damping ring (DR). For this purpose, the simulation is extended up to 1.54 GeV and a longitudinal acceptance window of an RF bucket in time and ±3.8% in energy is applied [10]. In this case, the maximum is achieved at $\phi = (70,-110)$ with 4.64 e+ accepted at the DR per primary e-. This is achieved by maximizing the energy compression, by deceleration at the first cavity [11].

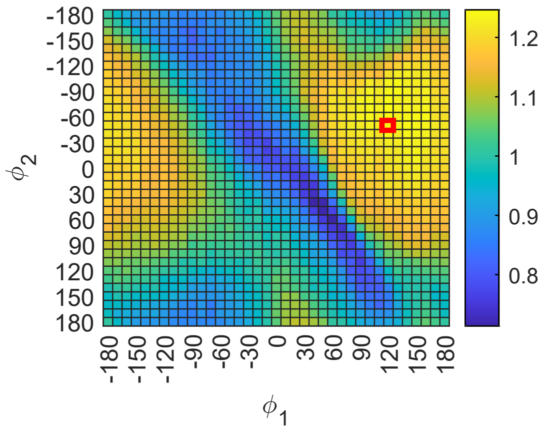

Figure 2: Total e$^+$ (in pC) output at the 2nd RF cavity over 2D RF phase scan. Maximum $\phi = (120,-70)$ in red.

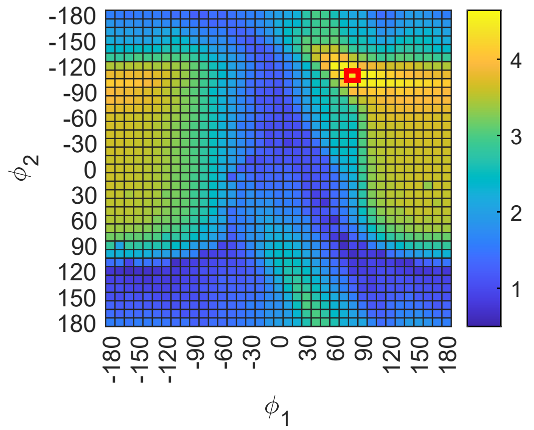

Figure 3: Estimated e$^+$ yield at the FCC-ee DR over 2D RF phase scan. Maximum at $\phi = (70,-110)$ red.

Table 2: Overview of e+ Yields in SLC, SuperKEKB, and P^3

	SLC	**SuperKEKB**	**P^3**
Operation period	**1989–1998**	**2014–Present**	**2048–2063**
e^+ Yield at target	$\approx 30^a$	$\approx 8^a$	13.7
E_0 [GeV]	30-33	3.5	6
e^+ yield at DR	2.5	0.63	4.64
Yield / E_0 [GeV^{-1}]	0.079	0.180	0.773

[a] *Approximate values derived from [12] and [13].*

BEAM DIAGNOSTICS

Different diagnostic setups will measure different beam characteristics downstream from the 2nd RF cavity. First, two sets of broadband pick-ups will measure the time structure of the e^+e^- beam. The first one is placed immediately after the RF cavities, while the second is at the downstream end of the experiment. Both broadband pick-ups will simultaneously detect the e^+ and e^-. A spectrometer, based on a 0.3 T large-gap dipole, will separate and deflect the e^+ and e^- streams inside a vacuum chamber, which will host two Faraday Cups (FCs) and two kinds of scintillating detectors. The FCs function based on different measurement principles to detect the captured e^+ and e^- charge. According to simulations, the FCs could detect up to 1079 pC of e+ charge, which amounts to 5.64 detected e+ per primary e-. Finally, an arrangement of two cameras and two scintillator screens will measure the beam's longitudinal momentum distributions of each particle species, and two scintillator fibers will provide additional high-resolution measurements of the longitudinal momentum spectrum.

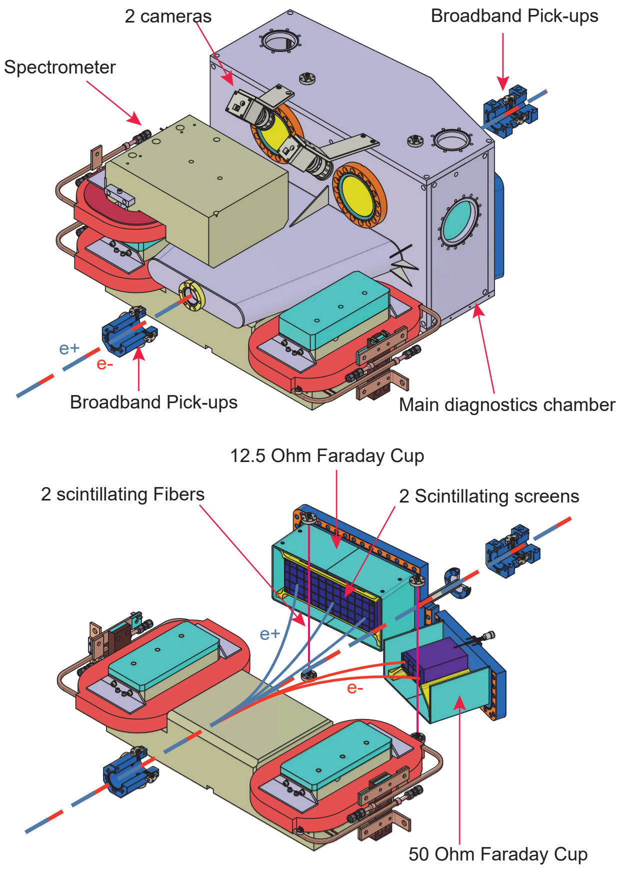

Figure 4: Diagnostics section of P^3. Displaying main components outside (top) and inside (bottom) diagnostics chamber. Note that several parts are omitted, simplified or cut to enhance the visualization. Particle trajectories are approximate.

CONCLUSION

The paper outlined the key aspects of the P^3 experiment, which is proposed as a proof-of-principle study of a new e+ source and capture system that can substantially enhance the e+ yield for future particle colliders. In summary, simulations indicate that the maximum expected e+ output at the exit of the 2nd RF cavity is 1246 pC, from which the Faraday cups could detect up to 1079 pC. On the other hand, the maximum equivalent positron yield at the FCC-ee DR is of 4.64 e+ per primary e-. Table 2 this yield with that of two state-of-the-art e+ sources, SLC [12] and SuperKEKB [13]. This comparison shows that the expected e+ yield normalized to the drive linac energy (E_0) would be about 4 times higher with respect to SuperKEKB's e+ source. In the case of SLC, the enhancement would be nearly an order of magnitude.

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