The P-cubed Experiment

FCC-ee positron source test facility

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FCC Week Conference, San Francisco, USA, 11 June 2024

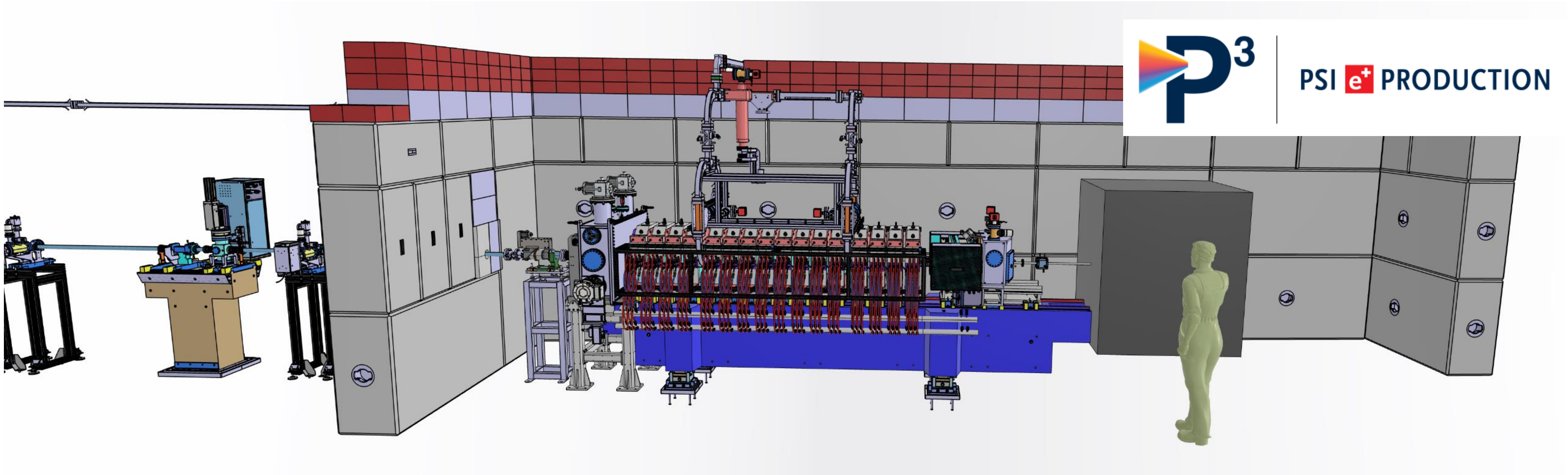
PSI

Contents

Introduction

The PSI Positron Production Experiment

- P^3 or *P-cubed* is a Proof-of-principle study of a e+ source and capture system that can substantially enhance the state-of-the-art e+ yield.
- Based on the conventional principles of pair-production-driven e+ sources, but will use novel technology (e.g. HTS solenoids).
- Integrated in FCC-ee Injector study as the FCC-ee e+ source test facility.
- Design complete and currently in construction at SwissFEL at PSI.
- Operations foreseen in 2026.



Thanks to N. Strohmaier and M. Zykova

Introduction

Positron Sources and Injectors for Particle Colliders

- Positron sources for particle colliders are driven by pair production based on the interaction of high-energy e- and a high-Z target.
    - Large e+ yield.
    - Extreme transverse emittance and energy spread.

- Positron capture linacs rely on high-field solenoid system to transport the secondary e+ beams up to a DR, where e+ have their emittance cooled.
    - Conventional solenoid systems have limited e+ capture capabilities.
    - Only e+ accepted at DR can be injected into the collider.
    - Positron Yield at the DR is the key figure of merit.

- P-cubed will test novel technology for e+ capture systems that can significantly increase the e+ capture efficiency.

Introduction

Rationale

- Critical factors for e+ yield at DR:
  - Primary e- energy
  - Transverse aperture
  - Solenoid strength around the target
  - Solenoid strength along RF linac
- The use of an HTS solenoid with a peak field of 12.7 T around the target can substantially increase state-of-the-art e+ yield.
- According to simulations, the enhancement would be of about an order of magitude with respect to SLC and SuperKEKB.

	SLC 1989 - 1998	SuperKEKB 2014 - Present	FCC-ee (HTS Option) 2040s – 2060s
Primary e- energy [GeV]	30 - 33	3.5	6
Transverse aperture [mm]	18	30	60
Max. Solenoid Strength at target	5.5	3.5	12.7
Avg. Solenoid Strength along linac	0.5	0.4	0.5
e+ Yield at target	~30	~8	13.77
e+ Yield at DR	2.5	0.63	6.5
Yield at DR / e- Energy [GeV $^{-1}$]	**0.079**	**0.180**	**1.083**

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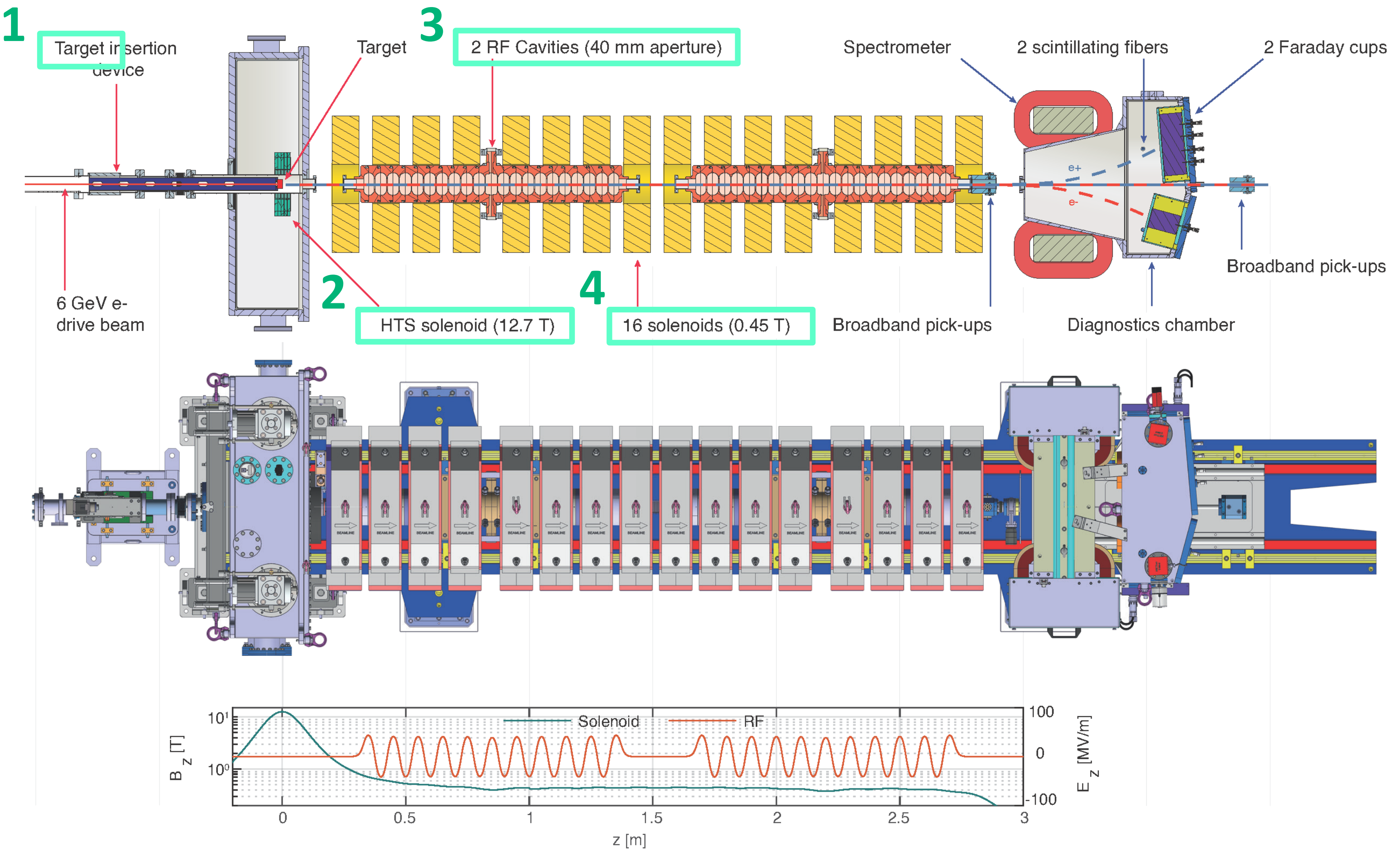
Technology of the P-cubed Experiment



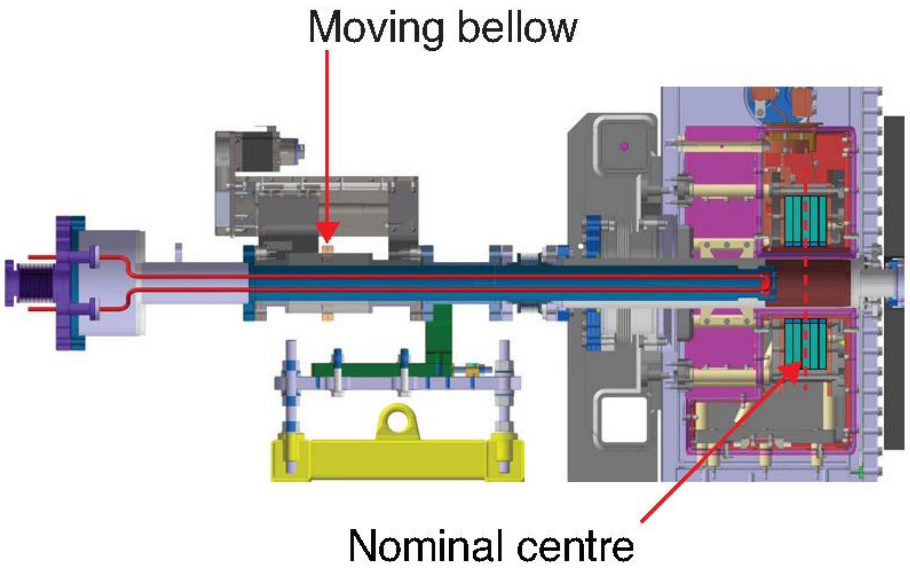
Thanks to M. Zykova

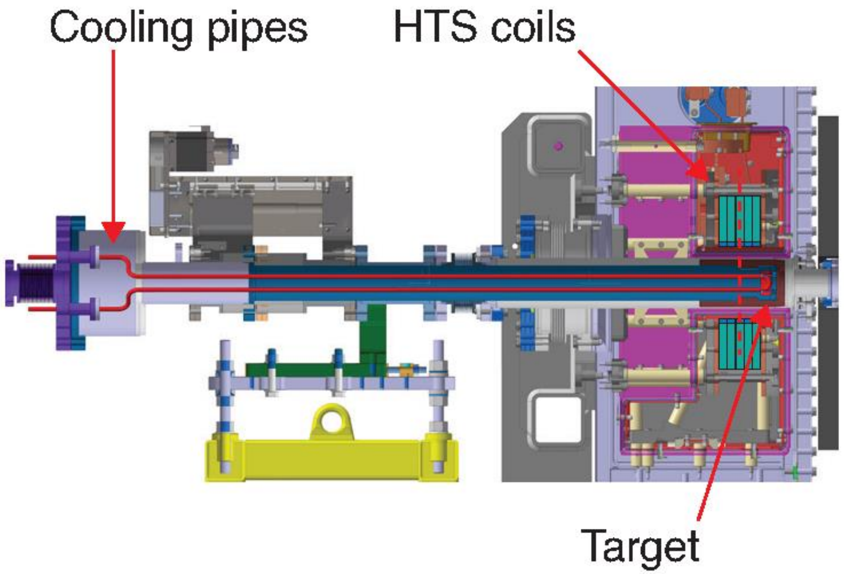
Technology of the P-cubed Experiment

Target System

- P-cubed will test different different targets (baseline 17.5 mm tungsten cylinder).
- The longitudinal position of target has an impact on the e+ yield.

- CERN and PSI have developed a system that allows for:
  - Easily replacing the targets.
  - Remotely adjusting the longitudinal location of the target with a stroke of +/50 mm with respect to the optimal point.

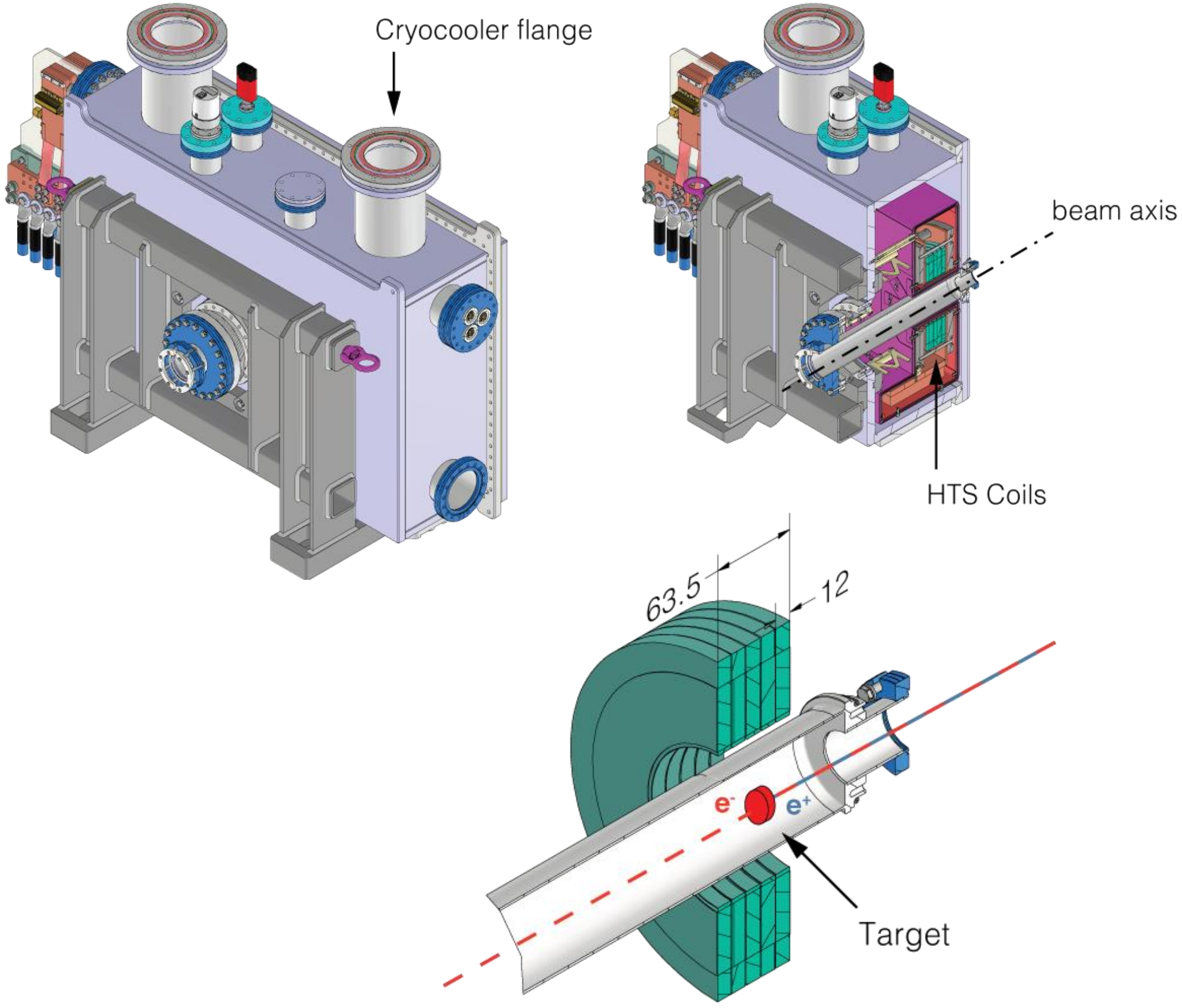




Thanks to R. Mena Andrade, J.L. Grenard, K. Guergar and A. Perillo Marcone

Technology of the P-cubed Experiment
HTS Solenoid

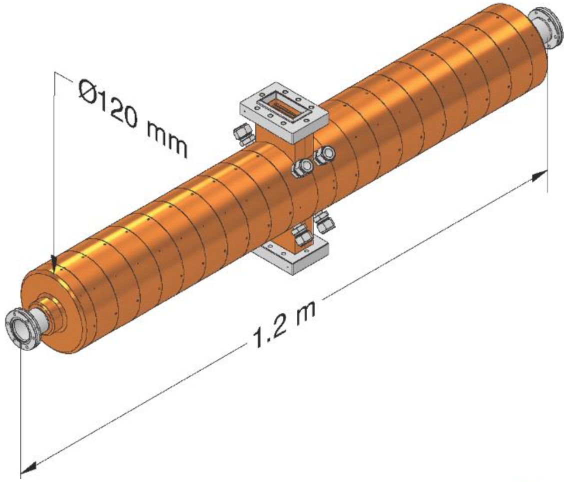
- 12.7 T peak field goal achieved thanks to “cryogen-free” operation at 15 K.
- Made of 5 non-insulated ReBCO tape coils.
- Prototype has been successfully wound, soldered, and stacked at PSI.
- In-house tests have demonstrated “cryogen-free” operation at 15 K and 2 kA, measuring peak magnetic fields of 18 T on-axis.

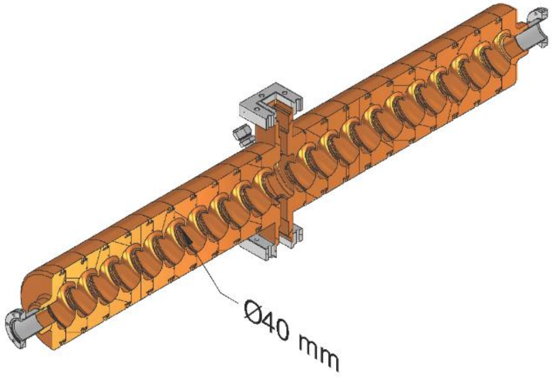


Thanks to J. Kosse, M. Duda, H. Garcia-Rodrigues, B. Auchmann, and colleagues

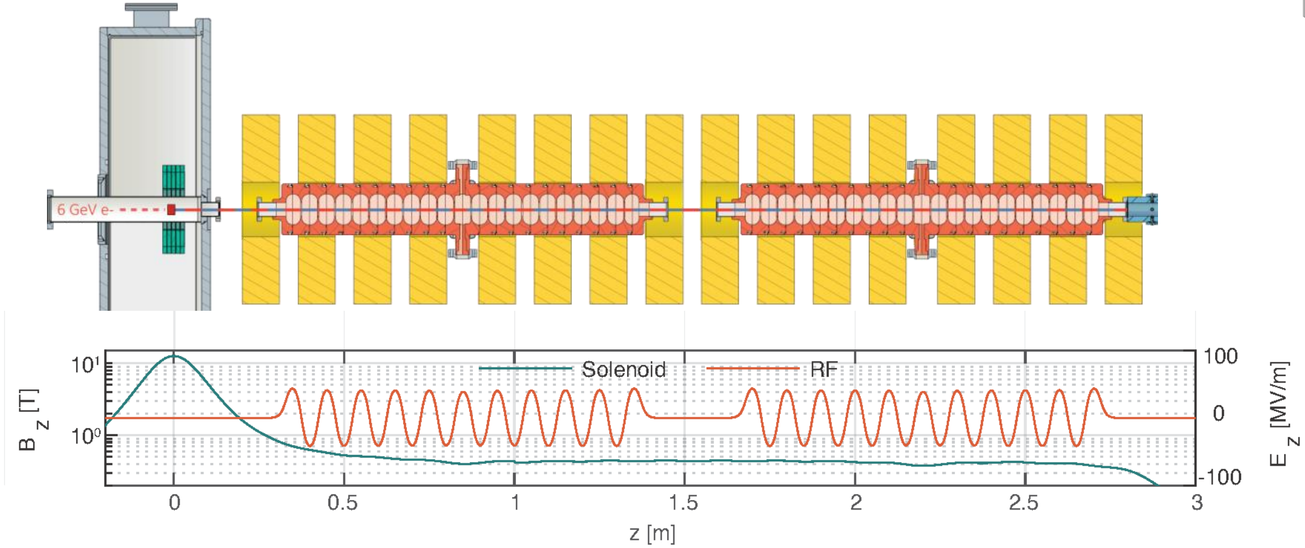
Technology of the P-cubed Experiment

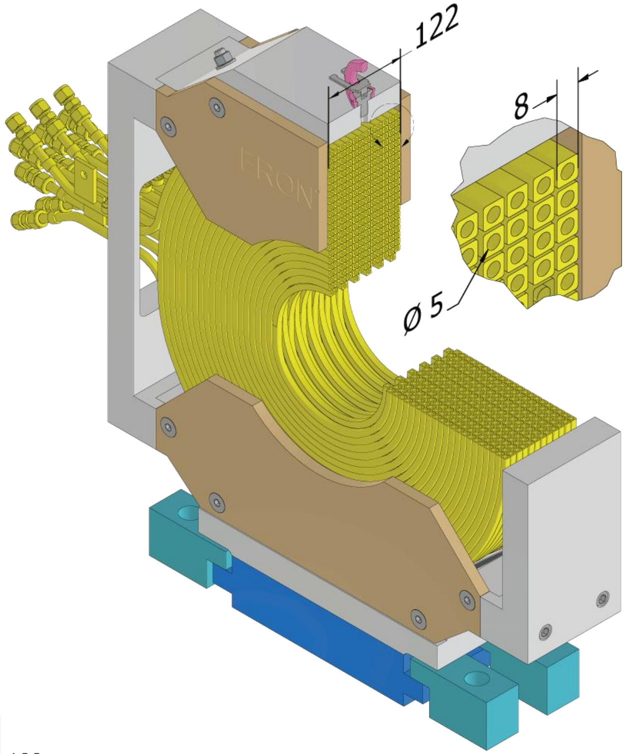
RF Linac (2 RF Structures + 16 NC Solenoids)





- **RF structures in S-band** are based on a novel standing-wave solution that provides a large transverse aperture (40 mm) but reasonably high shunt impedance (13.9 MΩ/m).
- S-band choice determined by the availability of commercial components.
- **16 NC Solenoids** will create a 0.45 T magnetic channel. Each solenoid has a strength of 0.213 T.





Thanks to R. Zennaro and N. Strohmaier

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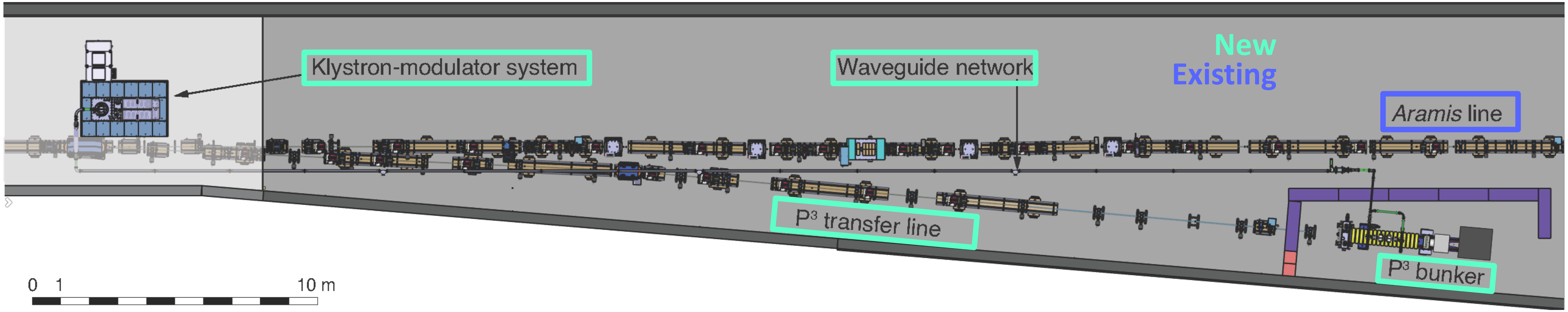
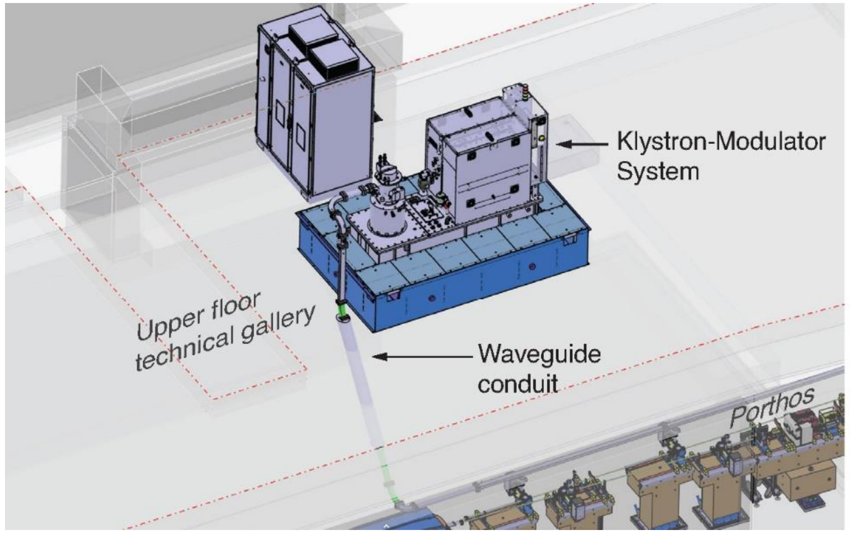
Infrastructure of the P-cubed experiment
Operation with e+ at SwissFEL

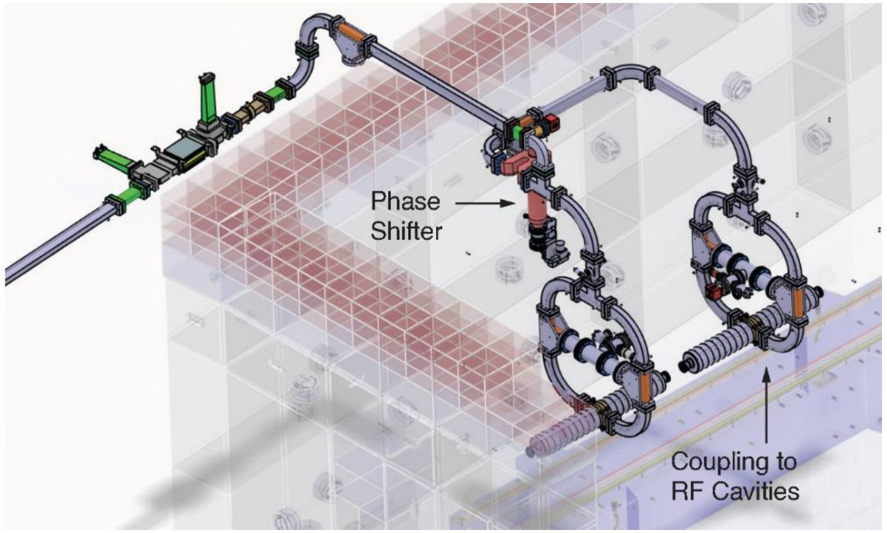
- SwissFEL is a free electron laser facility at PSI.
- Has the required space for a e+ source.
- It can provide a 6 GeV primary e- beam for e+ production.
- P^3 will use a significantly lower drive beam current:
  - Does not affect beam dynamics
  - SwissFEL radiation protection limits must be met

	FCC-ee	**P^3 (SwissFEL)**
Energy [GeV]	6	
σ_E	0.1%	
σ_t [ps]	3.3	
σ_x, σ_y [mm]	0.5	
σ_{px}, σ_{py} [MeV/c]	0.06	
Target Length [mm]	17.5	
Bunch charge [nC]	1.7 – 2.4	0.2
Rep. Rate [Hz]	200	1
Bunches/pulse	2	1

Infrastructure of the P-cubed experiment







Thanks to M. Schär, D. Hauenstein and M. Zykova

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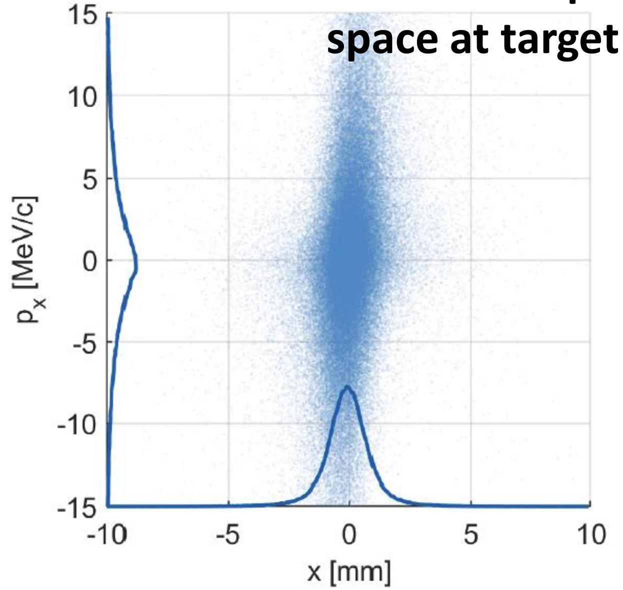
Physics studies
e+ Production at the Target

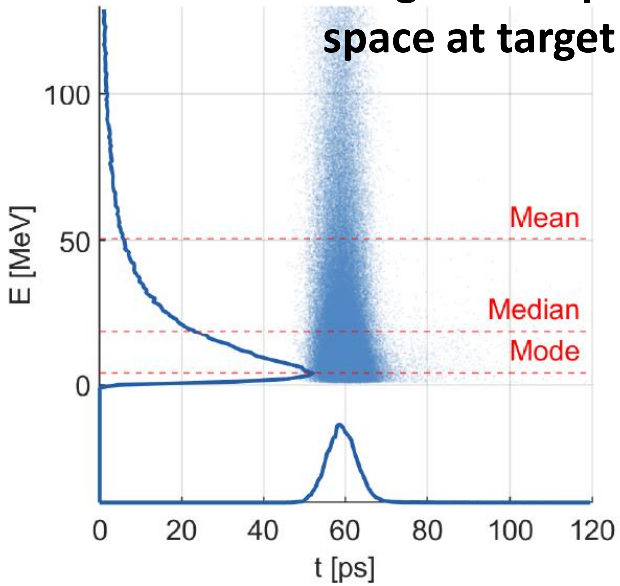
- e+ beam dynamics dominated by the transverse momentum (which translates into transverse emittance) and energy spread.

	Primary e-	Secondary e+	
Charge	200	2754	pC
Yield	-	13.77	
σ_x, σ_y	0.5	1.1	mm
σ_{px}, σ_{py}	0.06	7.1	MeV/c
$\varepsilon_{x,norm}$, $\varepsilon_{x,norm}$	-	11676	*π mm mrad*
σ_t	3.3	5.7	s
Energy (mean)	6000	50.5	MeV
Energy (median)	6000	18.9	MeV
Energy (mode)	6000	4	MeV
σ_E	6	122.8	MeV

Transverse phase space at target exit



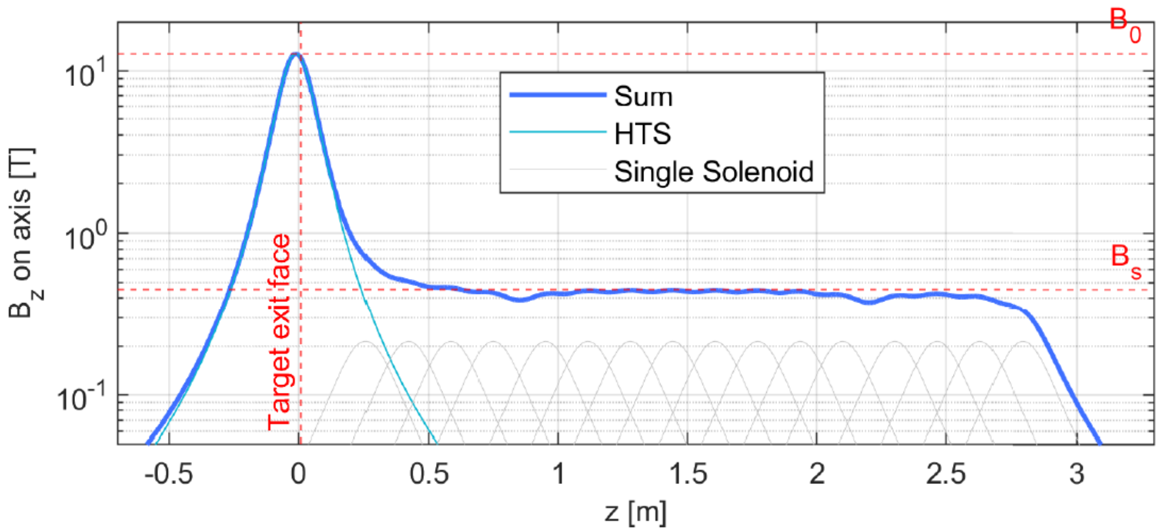
Longitudinal phase space at target exit



Based on Geant4 simulations

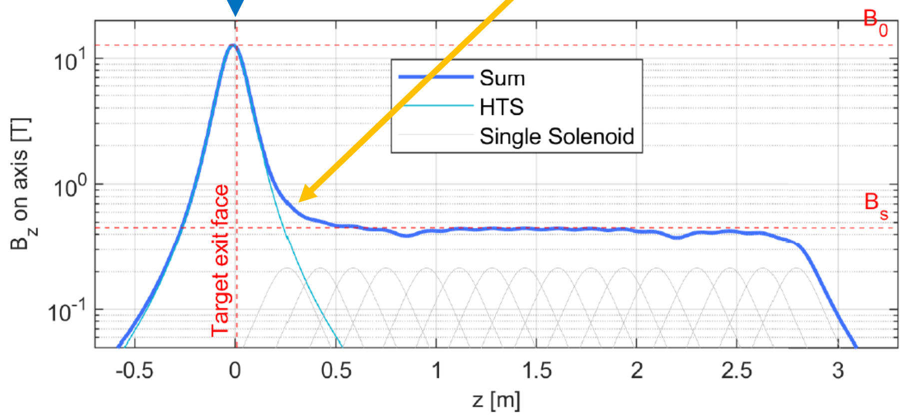
Physics studies
Transverse Beam Dynamics

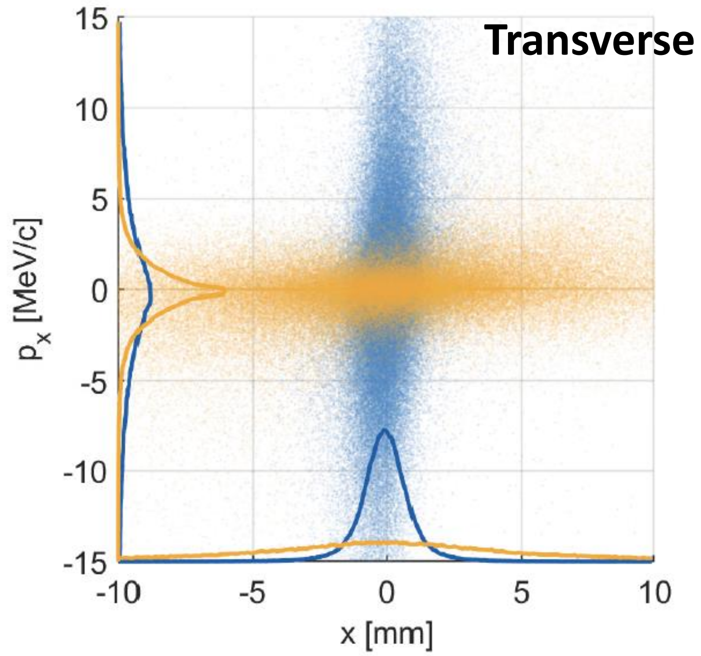
- Transverse e+ capture relies on an adiabatic matching device (AMD), a high-acceptance capture system ideal for high-emittance and high-energy spread beams.
- The AMD for P^3 is based on an arrangement of an HTS solenoid delivering a 12.7 T field around the target and 16 NC solenoids that create a nearly flat 0.45 T magnetic channel along the linac.
- AMDs transform the e+ transverse profile at the source (moderate $\sigma(x)$ and large $\sigma(p_x)$) to fit the acceptance of the linac (large $\sigma(x)$ and moderate $\sigma(p_x)$).

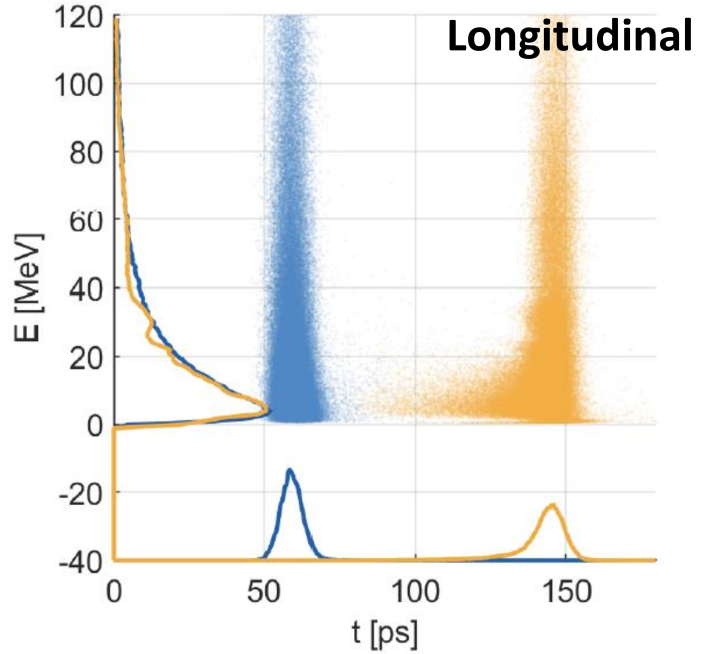


Physics studies
Transverse Beam Dynamics (II)

	Target exit	Secondary e+	
Charge	2754	2334	pC
Yield	13.77	11.67	
σ_x, σ_y	1.1	6.2 (<20)	mm
σ_{px}, σ_{py}	7.1	2.7	MeV/c
$\varepsilon_{x,norm}$, $\varepsilon_{x,norm}$	11676	12016	*π mm mrad*
σ_t	5.7	11.3	s
σ_E	122.8	122.8	MeV







Based on ASTRA simulations

Physics studies

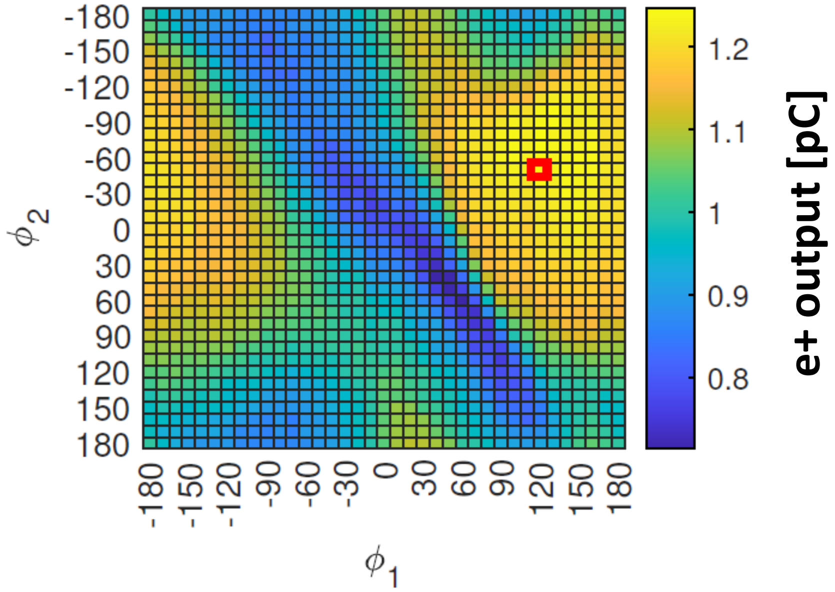
Longitudinal Beam Dynamics

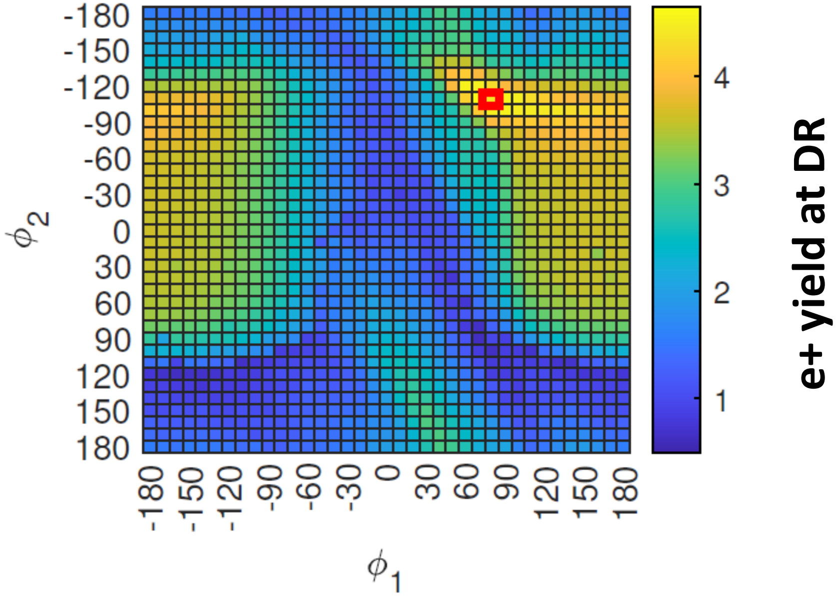
First FOM: Total e+ output at 2nd RF structure.

- It is a real, measurable quantity that can be detected by the Faraday cups.
- Max. 1246 pC (or 6.23 e+ per primary e-) at at ϕ = (120, -70).

Second FOM: e+ yield at the FCC-ee ramping ring (DR).

- Sets an equivalence with FCC-ee based on simulations.
- The calculation method is consistent with FCC-ee simulations:
  - Particle tracking up to 200 MeV (10 RF structures).
  - Analytical transformation up to 1.54 GeV.
  - Longitudinal window of one RF bucket and +/-3.8% in energy (current FCC-ee DR baseline).
- Max. 4.64 e+ at DR per primary e- at ϕ = (70, -110).

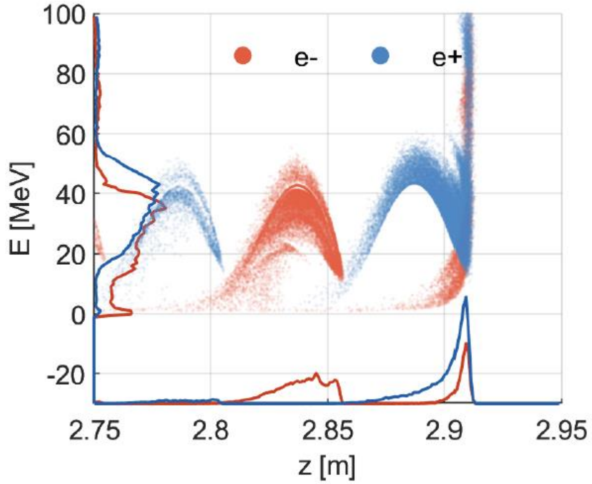


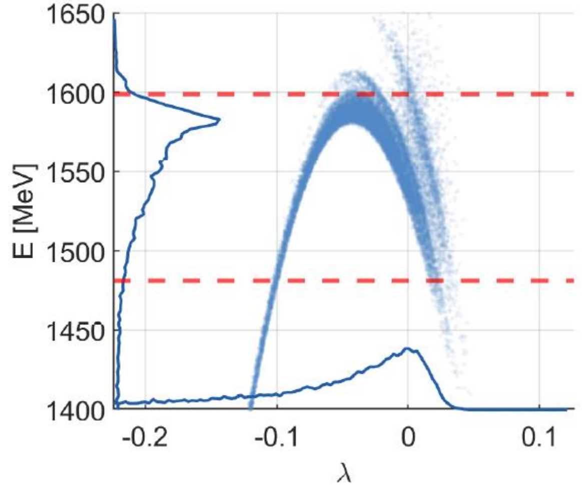


Physics studies
Longitudinal Beam Dynamics (II)

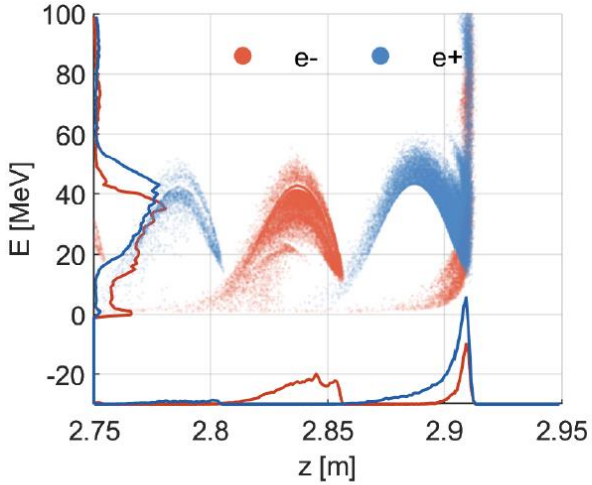
Exit of 2nd RF Str.	Entrance of FCC-ee DR

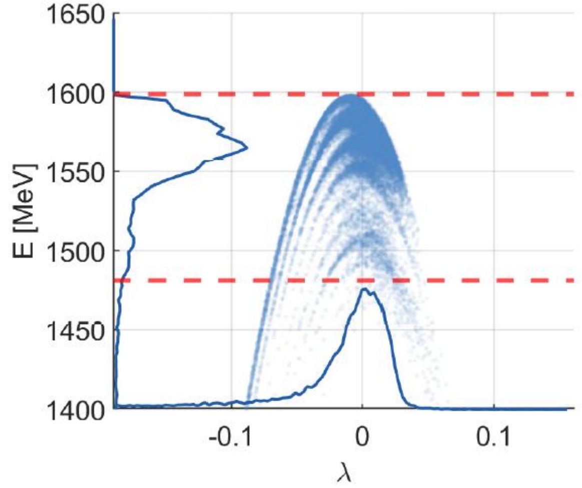
First RF Working Point of interest:
Max. 1246 pC (or 6.23 e+ per primary e-) at
at ϕ = (120, -70):
- Highest capture efficiency
- Not the best energy compression





Second RF Working Point of interest:
Max. 4.64 e+ at DR per primary e-
at ϕ = (70, -110).
- Not the highest capture efficiency
- Best energy compression





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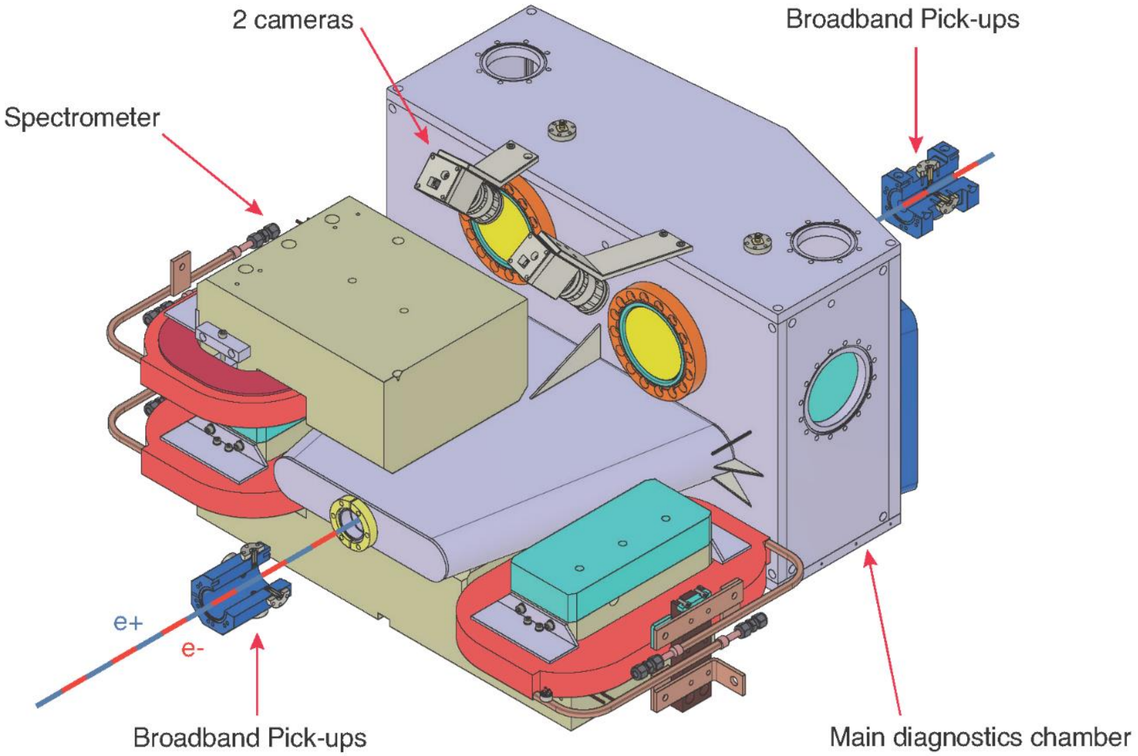
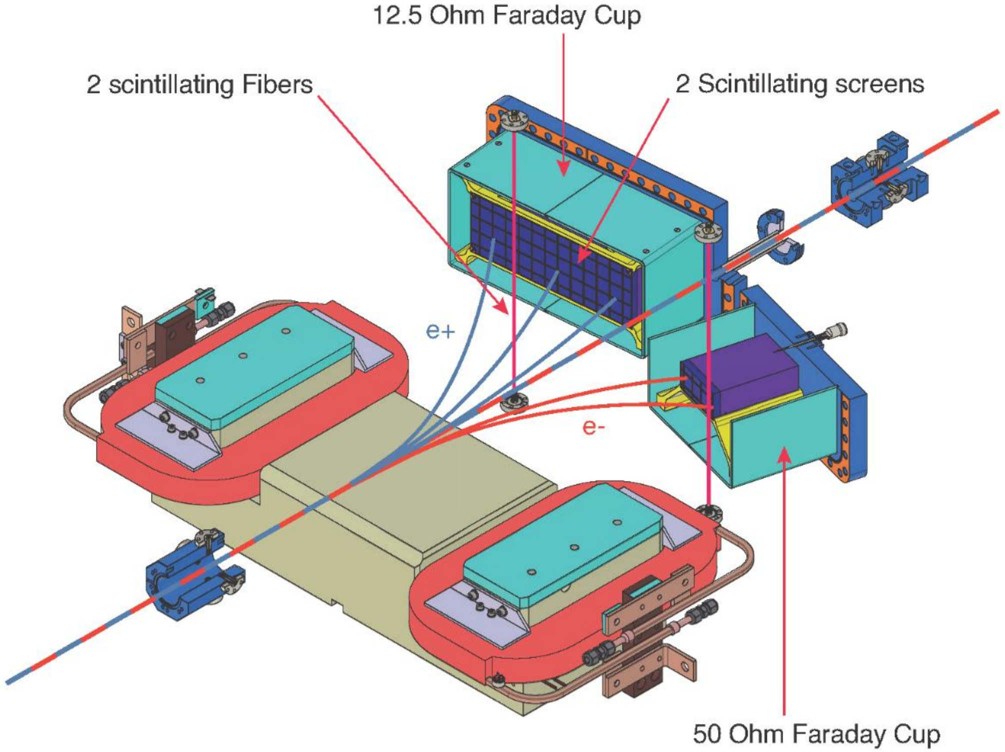
Diagnostics (Poster)

- The diagnostics will help researchers optimize the operation of the e+ source and provide a proof-of-principle demonstration of the e+ yield.
- The setup will measure the charge and longitudinal profile of the e+ and e-

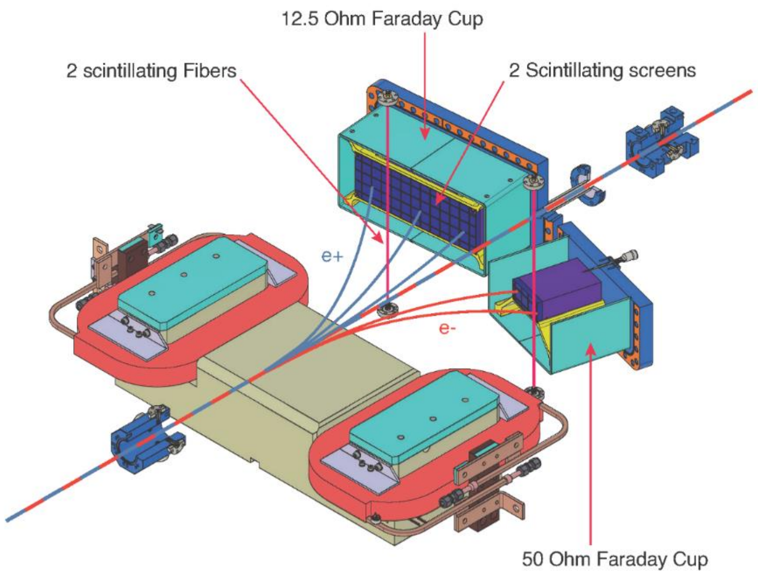


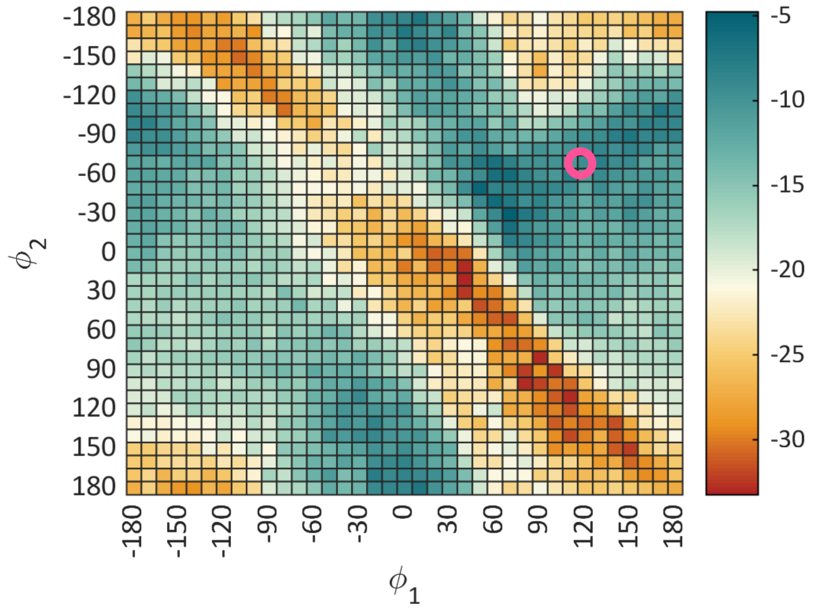


Thanks to R. Zennaro, M. Zykova, E. Ismaili, R. Ischebeck, P. Juranic, F. Marcellini, G.L. Orlandi and N. Strohmaier

Diagnostics (Poster)
Faraday Cups

- Two Faraday cups will measure the e+ and e- output from the RF cavities.
- The Faraday cups are based on different measurement principles.
- According to simulations the Faraday Cups will detect up to 1079 pC (or **5.64** e+ per primary e-) at the RF working point of maximum e+ charge output.



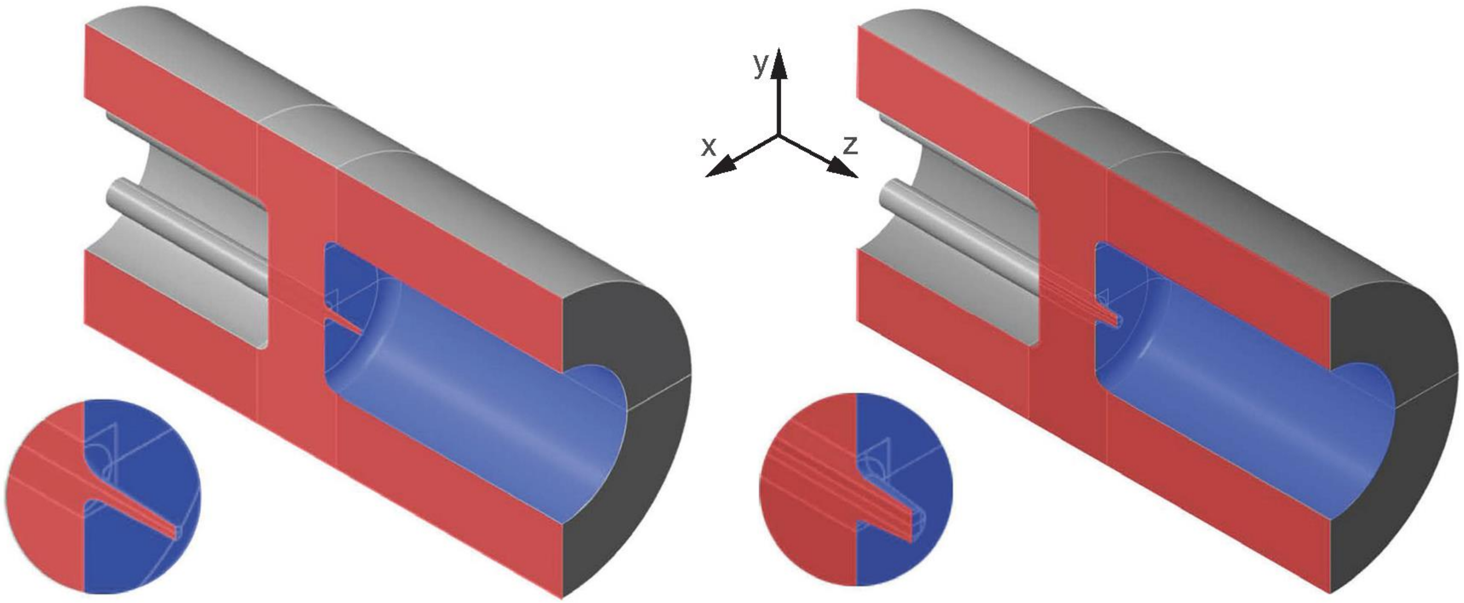


At Phi = (120, -70):
- 1246 pC expected
- 1079 pC measured
- **Error = -13.4 %**

Thanks to R. Zennaro, M. Zykova

Conical Targets (Poster)

- Study of tungsten targets with a finite transverse radius, comparable to that of the e+ beam, and a conical profile to enhance the baseline e+ yield.
- Two optimal geometries are proposed for the two beam size options for FCC-ee, σ_x = 0.5 mm and σ_x = 1 mm, which could nearly duplicate the e+ production at the target and enhance the e+ yield at the FCC-ee DR by 70 %.
- Research includes thermo-mechanical studies with FCC-ee beam and mechanical implementation toward future tests during the P-cubed experiment.



Thanks to R. Mena Andrade, B. Humann and Y. Zhao

Contents

Conclusion

Key performance figures

- Our research has developed one of the most advanced e+ source designs worldwide and provided a significant amount of data that supports its feasibility.

- The expected e+ yield normalized to the drive linac energy is about 4-5 times higher than SuperKEKB's e+ source. In the case of SLC, the enhancement would be of nearly an order of magnitude.

	SLC 1989 - 1998	SuperKEKB 2014 - Present	FCC-ee (HTS) 2040s – 2060s	P-cubed (ca. 2026)	
Primary e- energy [GeV]	30 - 33	3.5	6	6	
e+ Yield at target	~30	~8	13.77	13.77	
e+ Yield at DR	2.5	0.63	6.5	5.64(*)	4.64(*)
Yield at DR / e- Energy [GeV $^{-1}$]	**0.079**	**0.180**	**1.083**	**0.94**	**0.773**

(*) Measured by Faraday Cups (**) Estimation of Yield at DR based on simulations.

Conclusion

Current Status

- The installation works at SwissFEL are progressing smoothly:
  - parts of the dedicated extraction line and the HV klystron-modulator system accommodated in the tunnel.
  - procurement and assembly of most accelerator and diagnostics components is progressing on schedule.
  - operation of the HTS solenoid, which is arguably the most critical component of the experiment, has been successfully demonstrated at PSI.

- Based on the current progress, the major part of the installation work is expected to conclude by the end of 2025, making it possible to start the operation with e+ in 2026.

Conclusion

Impact

- P-cubed design published in *Physical Review Accelerators and Beams*. Selected as an editors' suggestion.

- Research featured in *Physics World* magazine and described as a potential "boost" for future colliders.

Editors' Suggestion

Proof-of-principle e^+ source for future colliders

N. Vallis, P. Craievich, M. Schär, R. Zennaro, B. Auchmann, H. H. Braun, M. I. Besana, M. Duda, R. Fortunati, H. Garcia-Rodrigues, D. Hauenstein, R. Ischebeck, E. Ismaili, P. Juranić, J. Kosse, A. Magazinik, F. Marcellini, T. Michlmayr, S. Müller, M. Pedrozzi, R. Rotundo, G. L. Orlandi, M. Seidel, N. Strohmaier, and M. Zykova

Phys. Rev. Accel. Beams **27**, 013401 (2024) – Published 17 January 2024

A positron source demonstrator with the potential to increase the yield by an order of magnitude.

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New positron source could give lepton colliders a boost

09 Feb 2024

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P-cubed team

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