PAUL SCHERRER INSTITUT PSI

EPFL

FUTURE CIRCULAR COLLIDER

CHART

Nicolas Vallis (PSI/EPFL) on behalf of the P^3 team

The P^3 Experiment: e+ Source Demonstrator for Future Lepton Colliders

Swiss and Austrian Physical Societies Joint Meeting - 7 September 2023

Outline

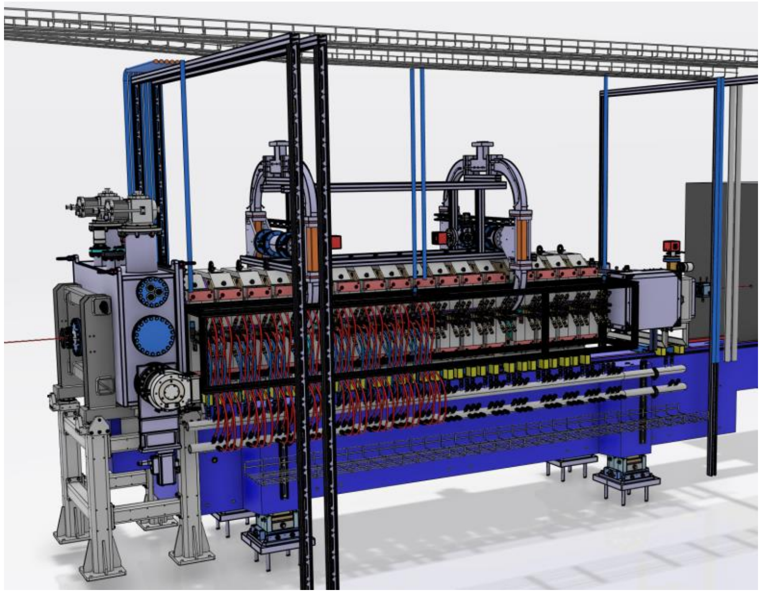
The P³ Experiment

- P^3 or P-cubed stands for **the PSI Positron Production experiment**

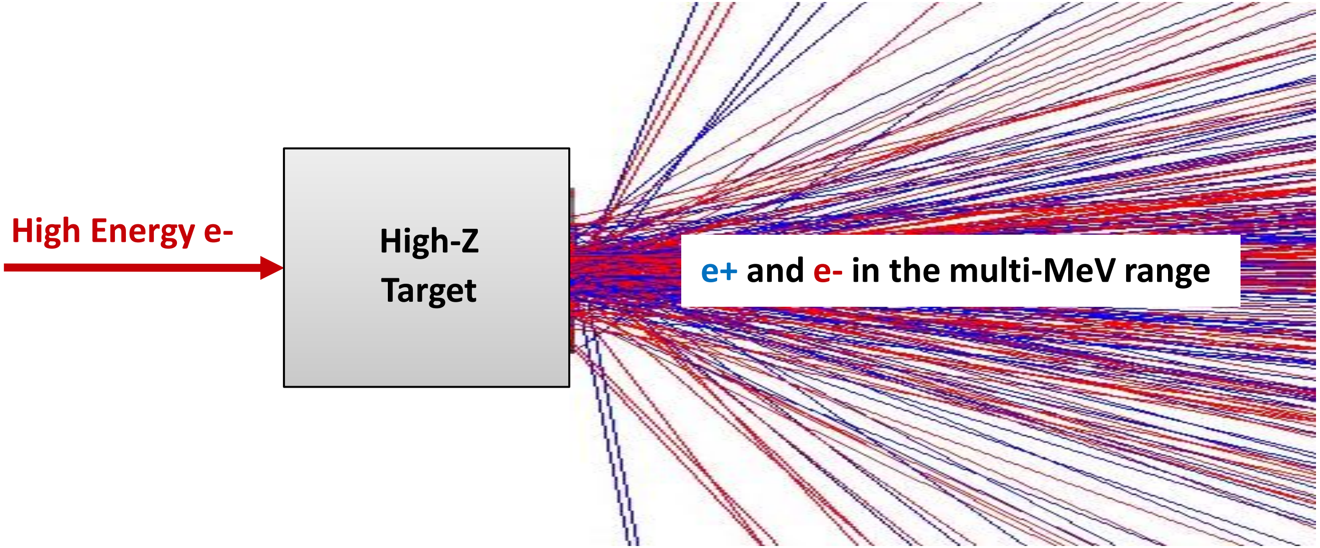
- It is a e+ source demonstrator with potential to improve the present state-of-the-art e+ yield by an order of magnitude -normalized to primary e- energy-.

- The SwissFEL facility will host the experiment –according to schedule- in 2026:
  - Technical design of experiment near completion
  - Installation works ongoing

- P^3 is framed in the FCC-ee injector study, driven by the luminosity requirements of future colliders.

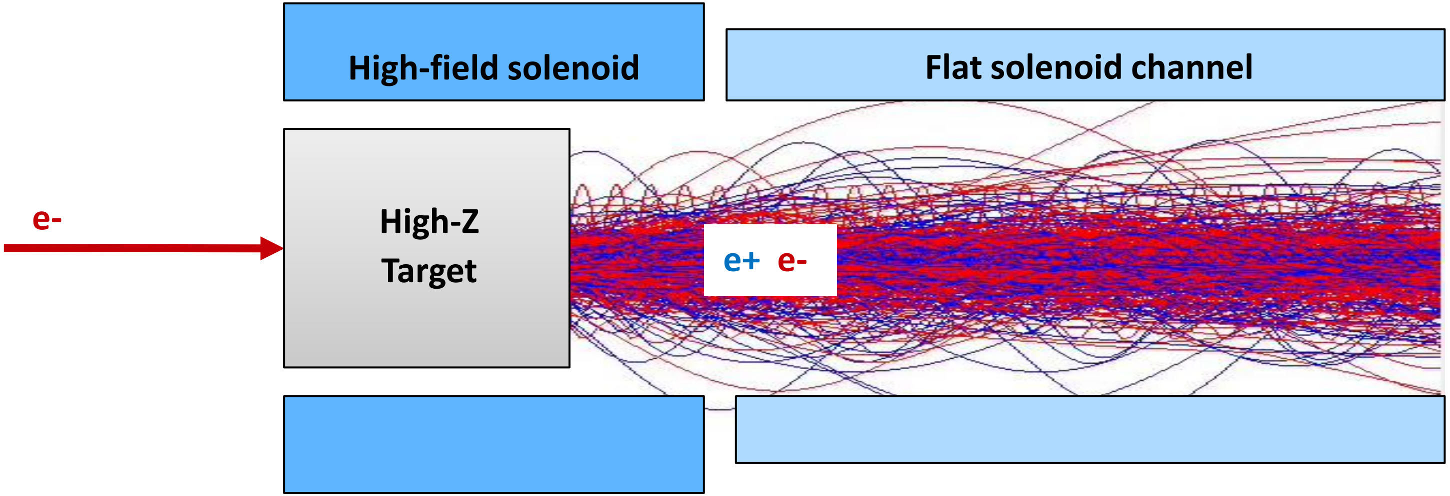


e+ Sources for Particle Accelerators



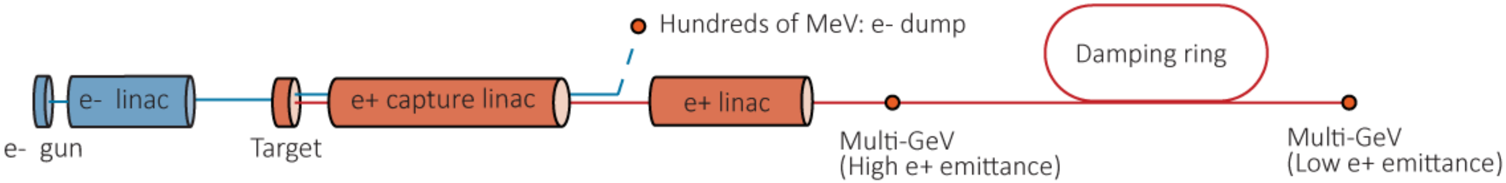
- Almost universally based on e+e- pair production
- Driven by high energy e- beams interacting with high-Z targets
- Despite high yields, beam quality is significantly lower than that provided by equivalent e- gun:
  - High transverse emittance
  - High Energy Spread

e+ Sources for Particle Accelerators (II)



- Solenoids are the standard form of e+ collection. Typically:
  - Strong peak fields around Target
  - Moderately strong plateau along capture linac

e+ Sources for Particle Accelerators (III)



- e+ linacs must transport great emittances up to the damping ring, where the e+ emittance is radiation damped

- Effective e+ yield is computed at the DR:

$$Yield = \frac{Ne^{+}\ accepted\ by\ DR}{Ne^{-}\ primary}$$

- All preceding e+ machines have provided low transmission rates from target to DR due to high emittance and energy spread

State of the art of e+ sources

- High e+ yield at DR is enabled to great extent by:
  - High e- energy
  - Strong solenoid fields around target and along capture linac
  - Large aperture

	SLC (SLAC)	SuperKEKB (KEK)
	1989 - 1998	**ca. 2014 -**
Primary e- energy [GeV]	30 - 33	3.5
Max. sol. field at Target [T]	5.5	3.5
Avg. sol. field along linac [T]	0.5	0.4
Min. RF cavity aperture [mm]	18	30
e+ yield at target exit	~30	~8
Max. meas. e+ yield at DR	~2.5	~0.4

- *J. E. Clendenin, High-Yield Positron Systems for Linear Colliders, in Proc. PAC'89, Chicago, USA (1989), pp. 1107–1112*
- *Chaikovska et al., Positron sources: from conventional to advanced accelerator concepts-based colliders, JINST, 17, P05015 (2022)*
- *SLAC Linear Collider Design Handbook, SLAC-R-714 (1984).*
- *Akai, K. Furukawa and H. Koiso, SuperKEKB Collider, Nucl. Instrum. MethodsPhys. Res., Sect. A 907, 188 (2018).*
- *T. Suwada et al., First simultaneous detection of electron and positron bunches at the positron capture section of the SuperKEKB factory, Sci Rep 11, 12751 (2021).*

State of the art of e+ sources

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	SLC (SLAC)	SuperKEKB (KEK)	P^3 (PSI)
	1989 - 1998	ca. 2014 -	ca. 2026
Primary e- energy [GeV]	30 - 33	3.5	6
Max. sol. field at Target [T]	5.5	3.5	12.7
Avg. sol. field along linac [T]	0.5	0.4	0.45
Min. RF cavity aperture [mm]	18	30	40
e+ yield at target exit	~30	~8	13.77
Max. meas. e+ yield at DR	~2.5	~0.4	~5.64 *expected at Faraday Cups

- *J. E. Clendenin, High-Yield Positron Systems for Linear Colliders, in Proc. PAC'89, Chicago, USA (1989), pp. 1107–1112*
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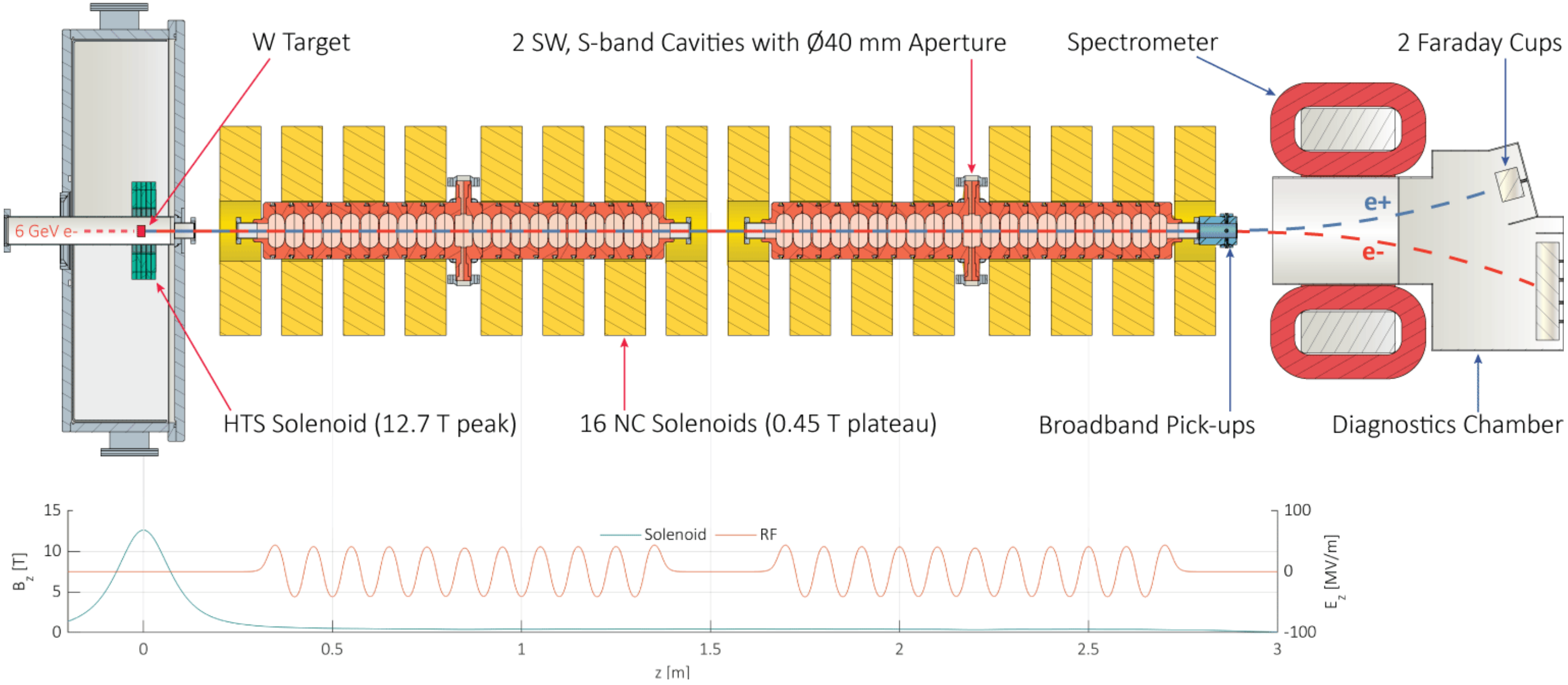
I. P3 Technology Overview

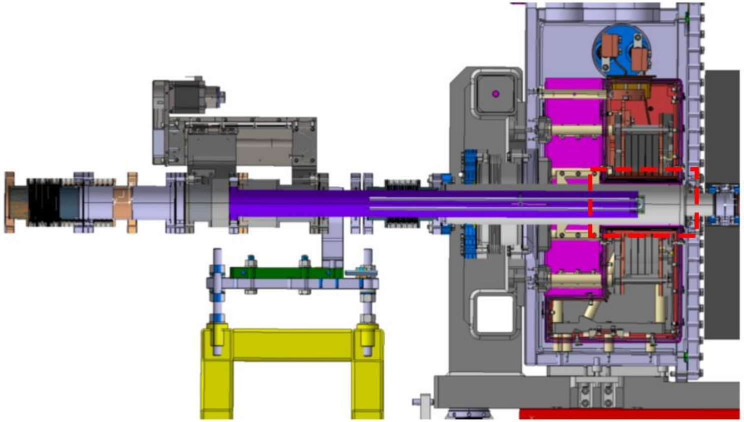
1. e+ Capture Section

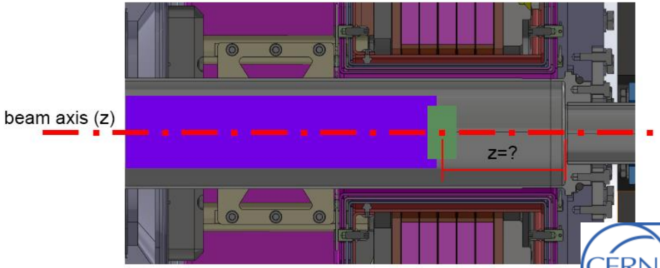
2. Target Insertion Device (In collaboration w/ CERN)

The P3 Experiment Layout



Target Insertion Device





- Z position of target has a great impact on final e+ yield.
- A motorized system will allow for moving the target in the z axis
- +/- 50 mm stroke from nominal position (~Center of the HTS coils)

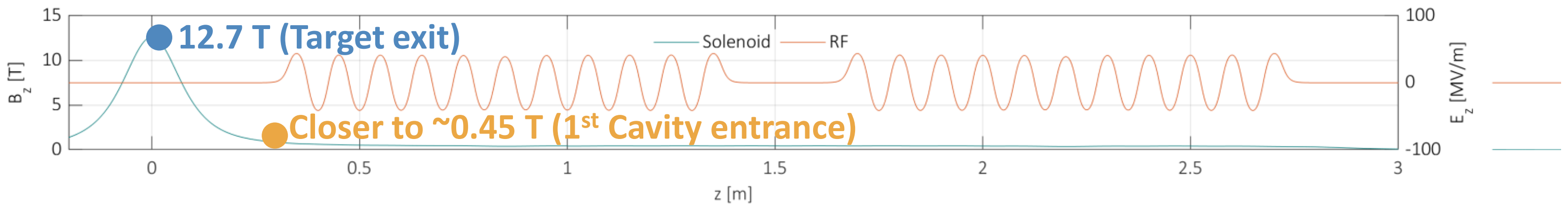
Courtesy of M. Calviani, J.L. Grenard, R. Mena-Andrade, A. Perillo-Marcone (CERN)

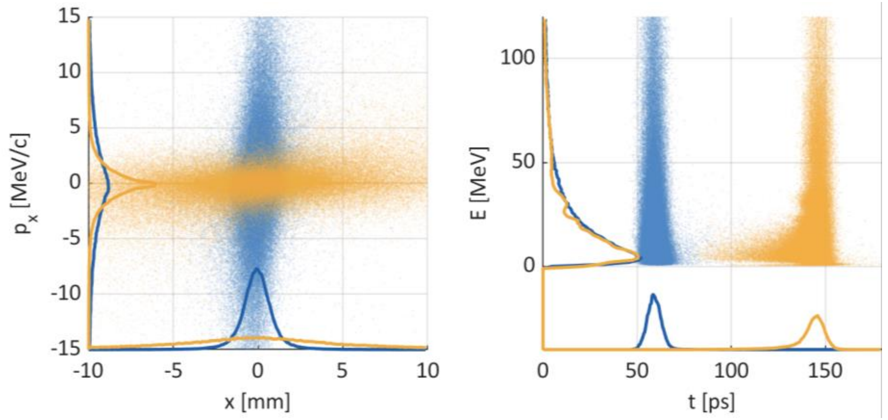
II. Beam Dynamics

1. Transverse

2. Longitudinal

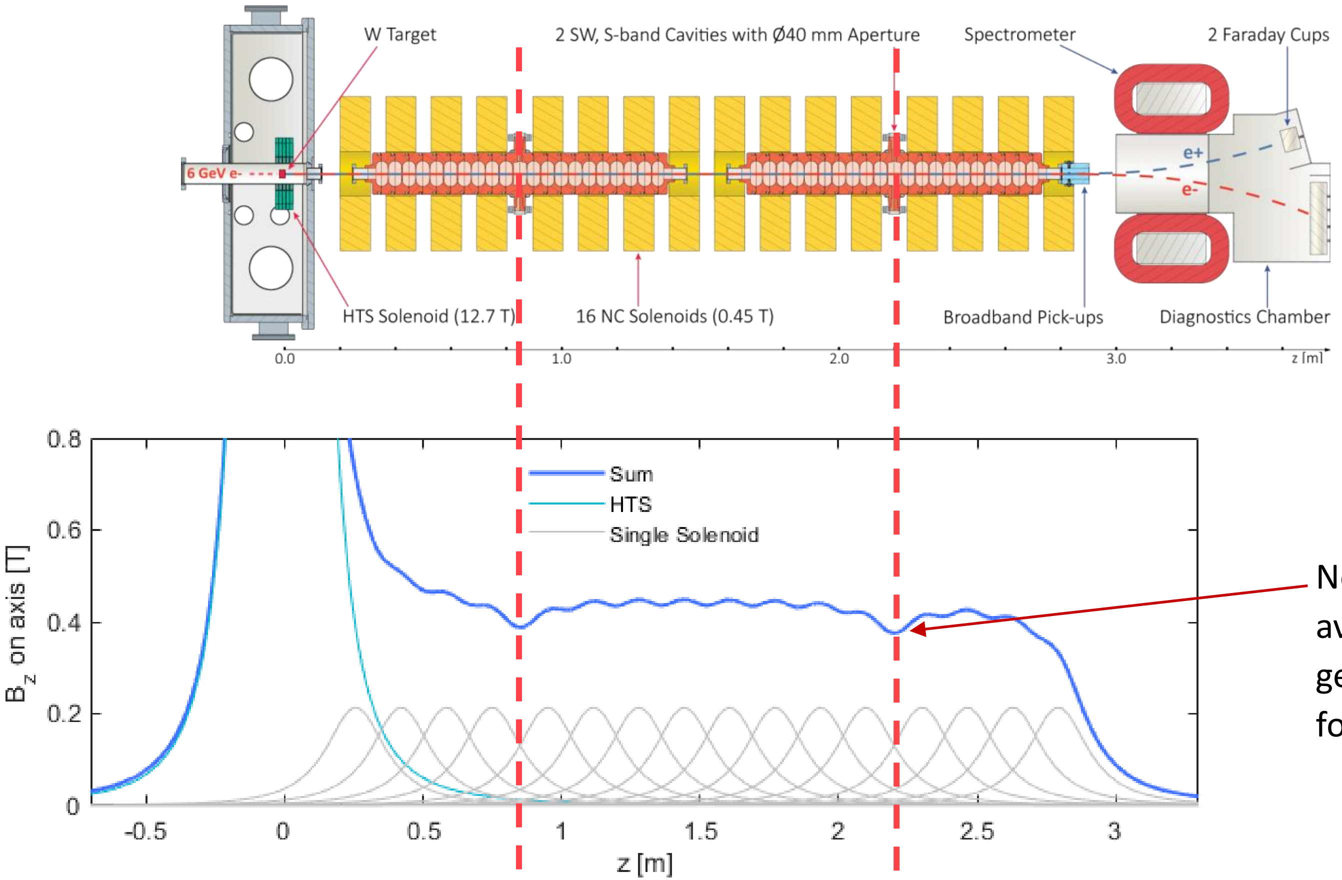
Transverse Beam Dynamics (I)





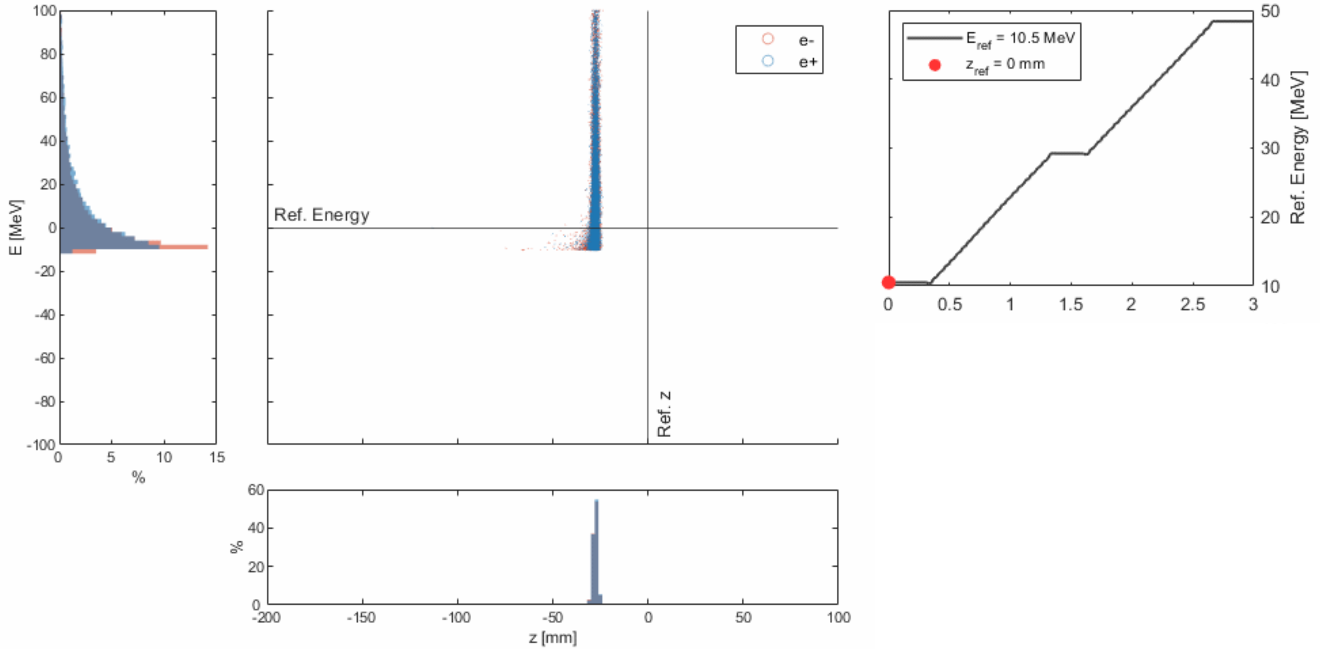
	Target exit	1st RF Cav.
e+ charge [pC]	2754	2334
Yield [Ne+/Ne-]	13.77	11.67
σ_x, σ_y [mm]	1.1	6.2
σ_{px}, σ_{py} [MeV/c]	7.1	2.7
Norm. emit [mm mrad]	11676	12016
σ_t [ps]	5.7	11.3
Energy spread [MeV]	122.8	

Transverse Beam Dynamics (II)



Non uniformities must be avoided. Constraint by physical geometry (e.g. waveguides, space for installation, etc.)

Longitudinal Beam Dynamics (I)



RF fields will bunch consecutive e+ and e- over many buckets.
First two buckets will concentrate most e+ and e- population.

Longitudinal Beam Dynamics (II)

2 figures of merit considered for RF phase optimization

1. Capt. e+ charge

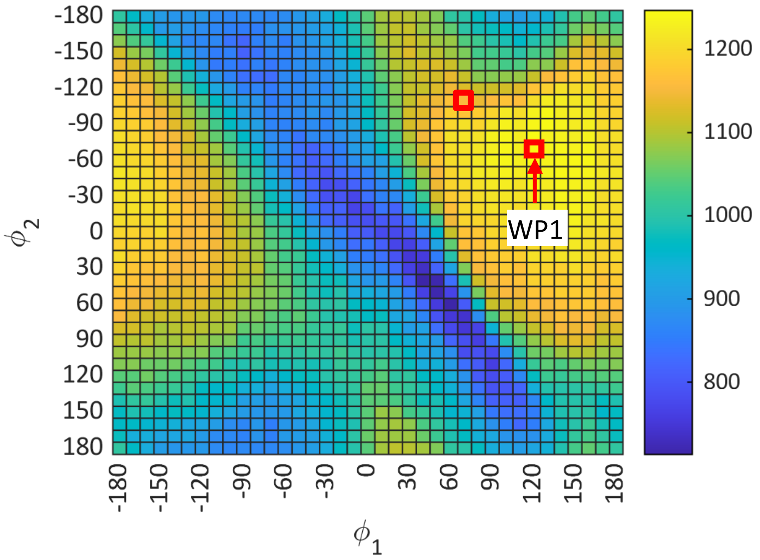
- Real, measurable quantity
- Computed through simulations at the exit of 2nd cavity

2. e+ Yield at FCC-ee DR

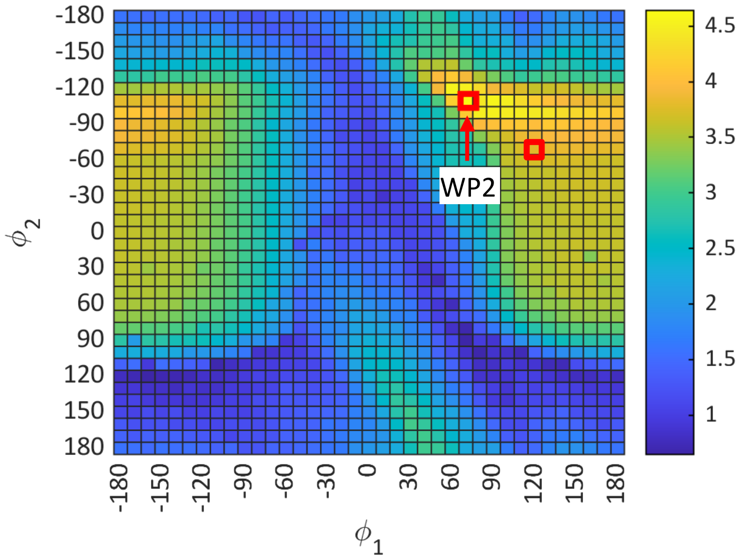
- Correction factor: will provide an equivalence with FCC-ee
- Particle tracking simulation extended to 200 MeV, or 10 RF cavities
- Analytical transformation of longitudinal e+ space up to 1.54 GeV
- +/- 3.8% filter in energy applied.

Longitudinal Beam Dynamics (III)

Working point 1, ϕ = (120, -70)
provides **Max Capt. e+ charge**



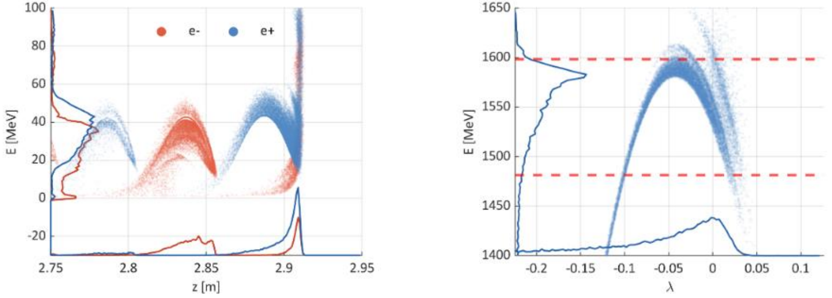
Working point 2, ϕ = (70, -110)
provides **Max. Yield at FCC-ee DR**



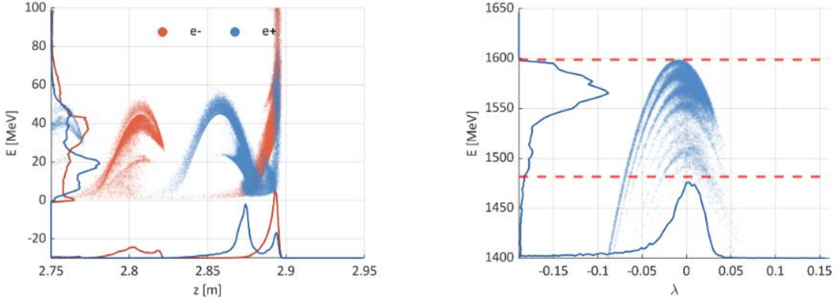
Note: RF phases above are arbitrary and have no particular physical significance (e.g. crest, zero crossing) due to large beam spread.

Longitudinal Beam Dynamics (IV)

Working point 1, ϕ = (120, -70) provides
Max Capt. e+ charge



Working point 2, ϕ = (70, -110) provides **Max. Yield at FCC-ee DR**



		At 2^{nd} Cav. Exit	At FCC-ee DR
WP1 ϕ = (120, -70)	Yield [Ne+/Ne-]	**6.23**	3.84
	e+ Charge [pC]	1246	-
WP2 ϕ = (70, -110)	Yield [Ne+/Ne-]	5.77	**4.64**
	e+ Charge [pC]	1153	-

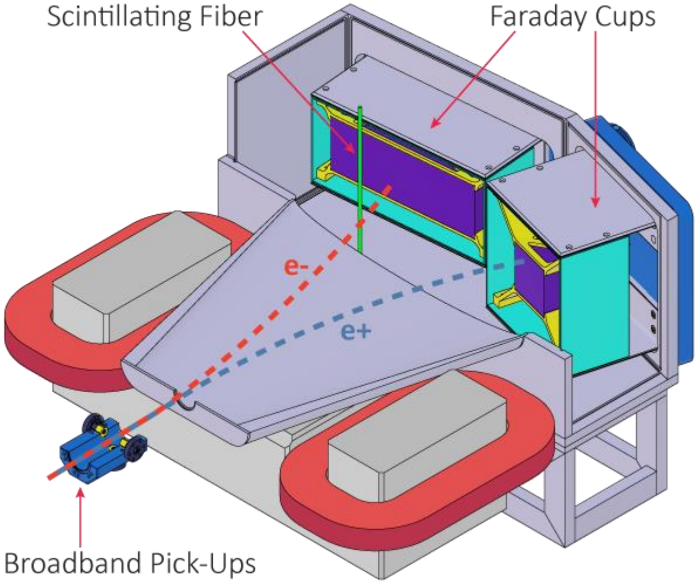
- WP1 provides highest capt. Efficiency
- WP2 provides a better energy compression.

III. Beam Diagnostics

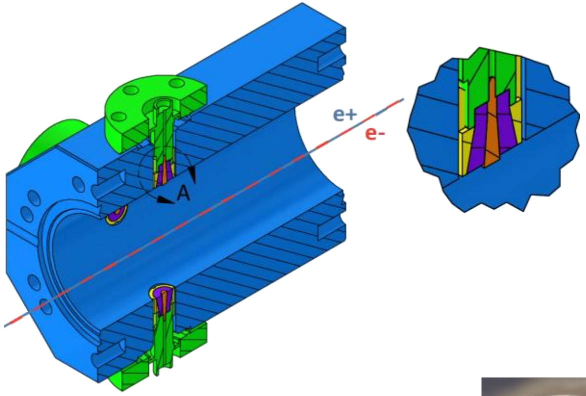
1. Broadband Pick-ups

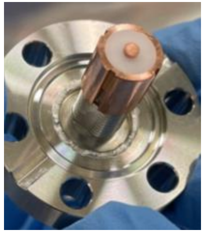
2. Faraday Cups

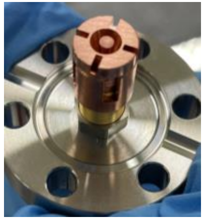
3. Scintillating Detectors



Beam Diagnostics: BBPs



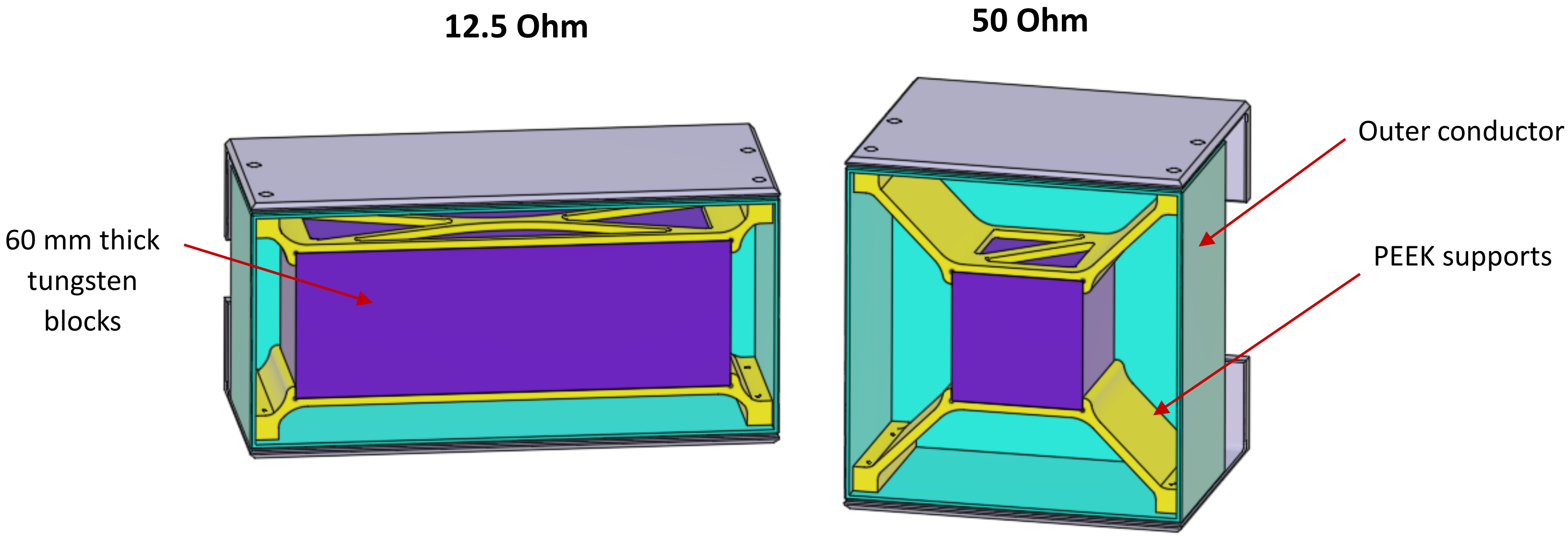




- An arrangement of 4 broadband pick-ups will detect the time structure of the e+e- bunches after 2nd cavity
- typical distribution will consist of alternating e+ and e- bunches of 33 ps length, and separated by 167 ps (half S-band period)
- Two chambers assembled based on 27 GHz and 65 GHz pick-up arrangements.

Thanks to F. Marcellini, E. Ismaili, M. Zykova and CLEAR facility at CERN

Diagnostics: Faraday Cups (I)

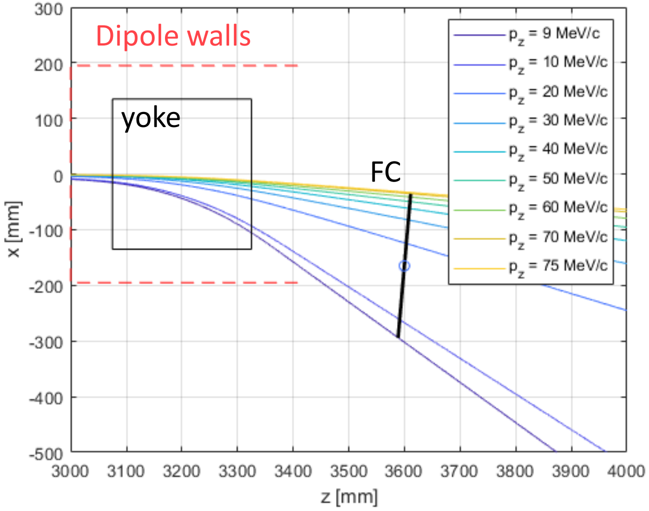


- Two coaxial Faraday cups will measure e+ and e- charge separately
- Based on two different principles, and different impedances. One goal: Measure a highly transverse spread beam

Diagnostics: Faraday Cups (II)

12.5 Ohm

- Large transverse size (260x90 mm) will capture particles in a wide energy range (9 – 75 MeV).



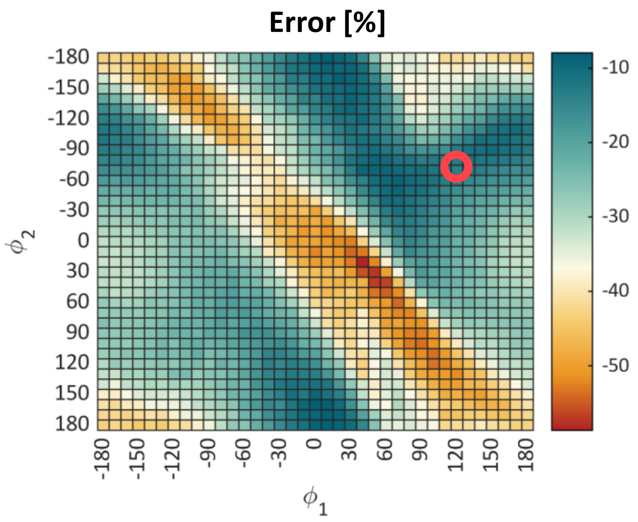
50 Ohm

- More compact size (80x80 mm) will not be able to capture broad energy spectra in a single shot.
- Measurement is done in 6 separate readings.

	Spectrom. strength [T]	Meas. E. range [MeV]
12.5 Ω FC	0.053	9 - 75
	0.212	50 - 90
	0.120	28 - 50
50 Ω FC	0.068	16 - 28
	0.038	9 - 16
	0.021	5 - 9
	0.012	3 - 5

Diagnostics: Faraday Cups (III)

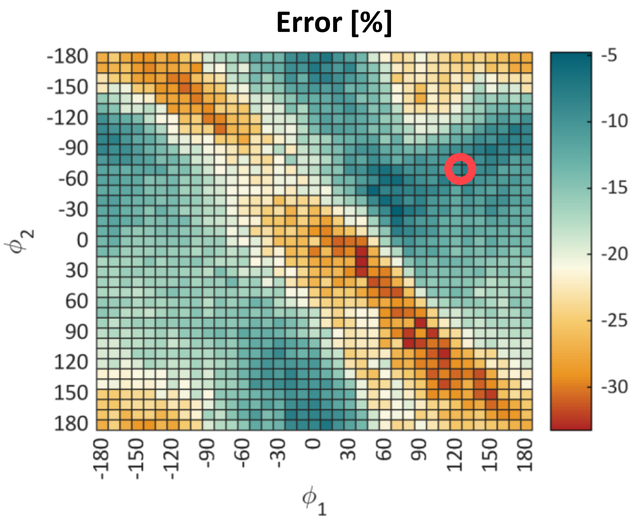
12.5 Ohm



@ **WP1 Phi = (120, -70):**

- 1246 pC expected
- 1077 pC measured
- **Error = -13.6 %**

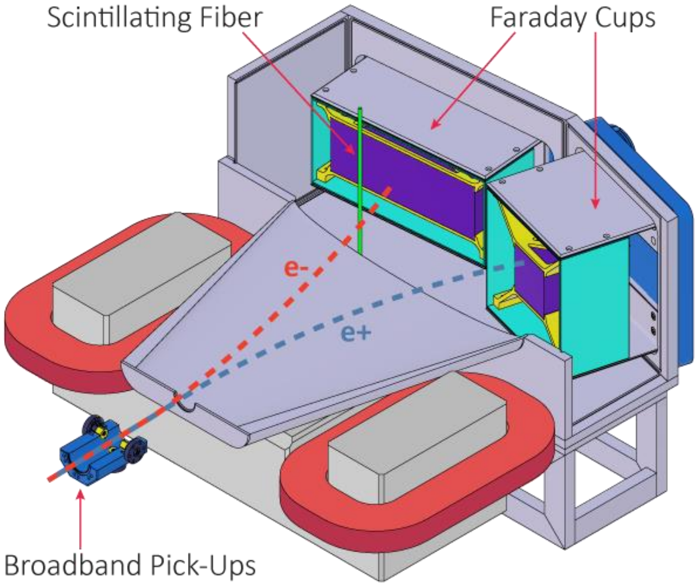
50 Ohm



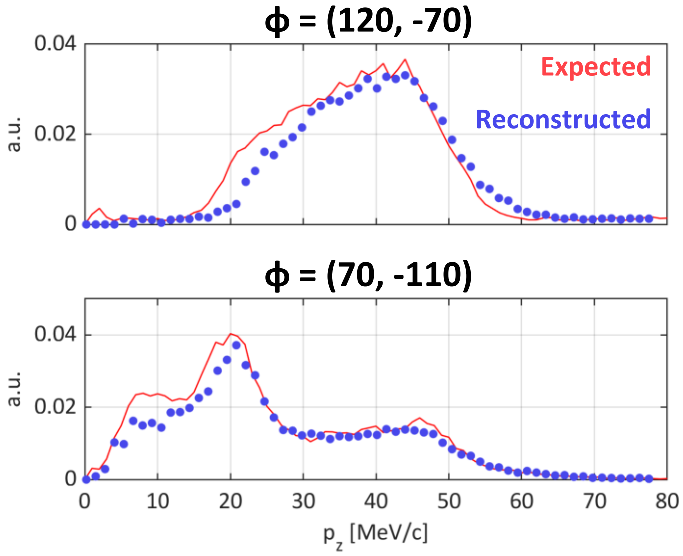
@ **WP1 Phi = (120, -70):**

- 1246 pC expected
- 1129 pC measured
- **Error = -9.4 %**

Beam Diagnostics: Scintillating Fibers

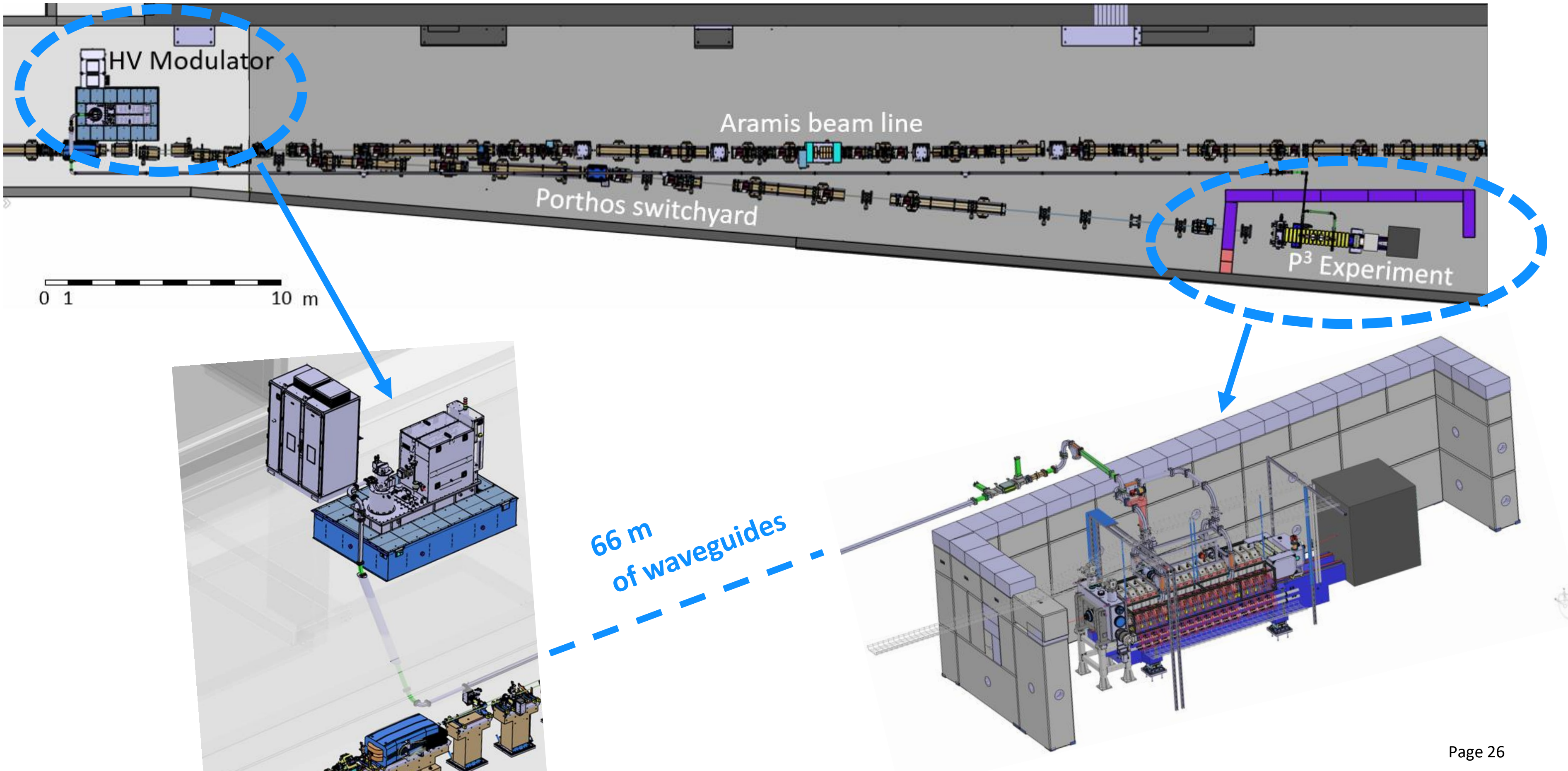


- 61 readings: from 0 to 0.3 T, step of 0.005 T
- Fiber at z = 350, x = -150 mm (w.r.t center of dipole)
- Reconstruction of 2 RF WPs of interest



Final Remarks

Installation at SwissFEL

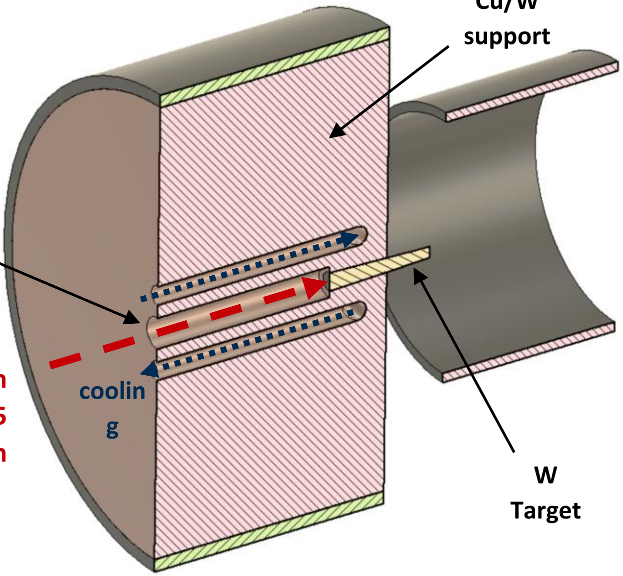


General Status Overview

Concept design
Engineering in progress
Ready for Order
Delivered

Physics Studies	Parameter Optimization	**Complete**
	Conical Targets Study	**In progress**
Capture Section	HTS Solenoids	**Design complete, components ordered**
	2 RF Cavities	**Ordered, cups delivered**
	16 NC Solenoids	**Design complete, waiting for offers**
Diagnostics	Broadband Pick-ups	**Assembled at PSI, tests with beam at CERN Nov. 23**
	Faraday Cups	**Mechanical design in progress**
	Scintillating Fibers	**Location defined, technical design to be developed**
	Diagnostics Chamber	**Mechanical design in progress, to be reviewed with diagnostics team**
	Spectrometer	**Mechanical modification design in progress**
Installation at SwissFEL	Klystron-Modulator system	**Procurement of key components in progress**
	Waveguide Network	**Waveguide network layout complete. Most waveguide components borrowed from CERN**
	Porthos Switchyard	**Design complete, components ordered and partially delivered, preliminary installation works**
	Radiation Protection	**Study complete, to be discussed with BAG**

Conical Targets for e+ Production



- e+ through conical converter studies is under study. Basic principles:
  - Part of the target protruding in vacuum
  - Most secondary particles emerge from de sides
- Preliminary studies indicate a yield increase in the FCC-ee DR of at least +70% with respect to baseline
- Thermo-mechanical studies in progress

Thanks to colleagues at CERN: R. Mena-Andrade, Y. Zhao, B. Humann, A. Latina and A. Lechner

Scientific Output

The P³ Experiment: A Positron Source Demonstrator for Future Lepton 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.U. Michlmayr, S. Müller, M. Pedrozzi, R. Rotundo, G.L. Orlandi, M. Seidel,[*] N. Strohmaier, and M. Zykova
Paul Scherrer Institut, Villigen, Switzerland[‡]

(Dated: September 1, 2023)

The PSI Positron Production (P^3 or P-cubed) experiment is a demonstrator for an electron-driven positron source and capture system with potential to improve by an order of magnitude the state-of-the-art positron yield normalized to the drive linac energy. The experiment is framed in the FCC-ee injector study and will be hosted in the SwissFEL facility at the Paul Scherrer Institute in Switzerland. This paper is an overview of the P^3 design at an advanced stage, with a particular emphasis on a novel positron capture system and its associated beam dynamics. Additionally, a concept for the experiment diagnostics is presented, as well as the key points of the ongoing installation works.

Conclusion

- The P3 design is at an advanced stage:
  - Capture section technical design complete and partially ordered
  - Diagnostics mechanical design in progress
- Core physics studies complete:
  - e+ production, transverse and longitudinal dynamics
  - 2 RF working points of interest found
- Preliminary error studies on Faraday Cups -> Yield of 5.64 would be detected
- Installation works at SwissFEL currently on schedule – Complete in 2025
- Operation in 2026

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Acknowledgement

The P-cubed core team:

P. Craievich, D. Hauenstein, M. Schär , N. Strohmaier, N. Vallis, R. Zennaro, M. Zykova

and

B. Auchmann, H.H. Braun, M.I. Besana, M. Duda, R. Fortunati,
H. Garcia-Rodrigues, D. Hauenstein, R. Ischebeck, E. Ismaili, P. Juranic, J. Kosse, A. Magazinik, F. Marcellini,
T.U. Michlmayr, S. Muller, M. Pedrozzi, R. Rotundo, G.L. Orlandi, M. Seidel

and colleagues from the **RF Section** and other **technical groups** participating in the experiment installation

M. Calviani, J.L. Grenard, R. Mena-Andrade, A. Perillo-Marcone
and colleagues from **CERN**, **IJCLab**, **INFN** and **KEK** and the rest of the **FCC** collaboration

Prof. Mike Seidel (EPFL)

This work was done under the auspices of **CHART** (Swiss Accelerator Research and Technology, chart.ch)

KEK Insight through Accelerators. IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis CERN CHART FUTURE CIRCULAR COLLIDER INFN LNF Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati EPFL