Overview and the current status of FCC-ee positron source

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FUTURE CIRCULAR COLLIDER

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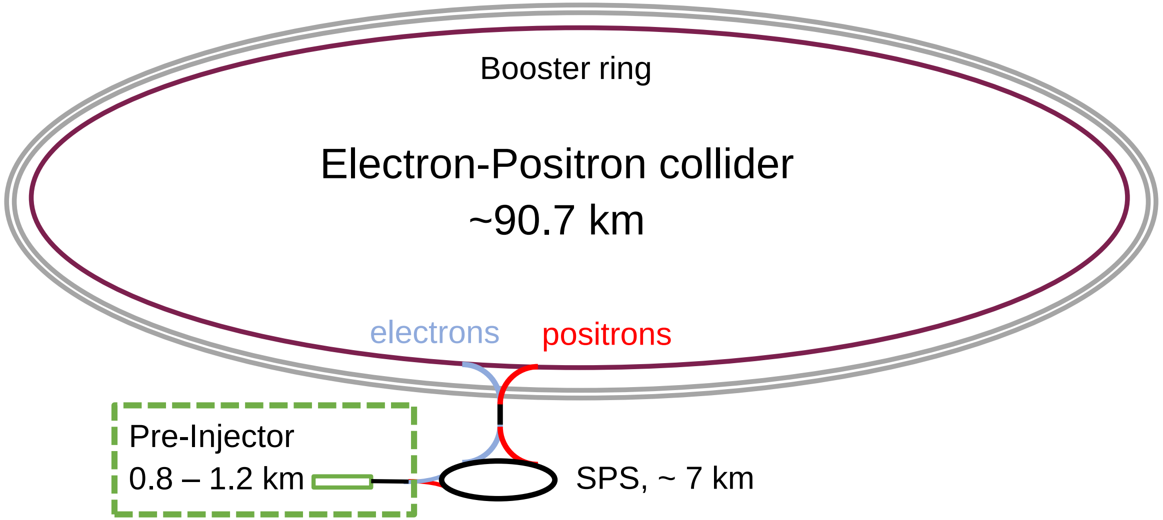
Content

- FCC-ee Overall layout.
- FCC-ee pre-injector layout (Positron source).
- Positron production schemes & capture section.
- Crystal based positron source simulation.
- Proof-of-principle experiment at PSI (P3).

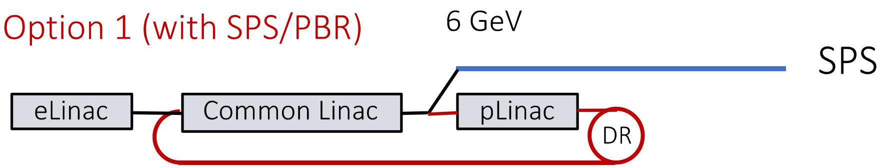
FCC-ee in general.

Operation Mode	Final Energy [GeV]	Beam Current [mA]
Z *	45	1280
W	80	135
H	120	26.7
ttbar	182.5	5

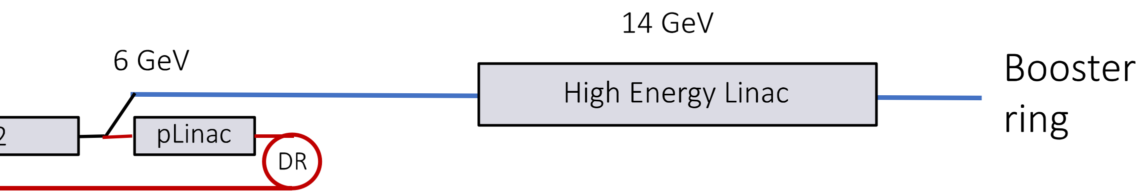
*Most demanding mode for the positron source.



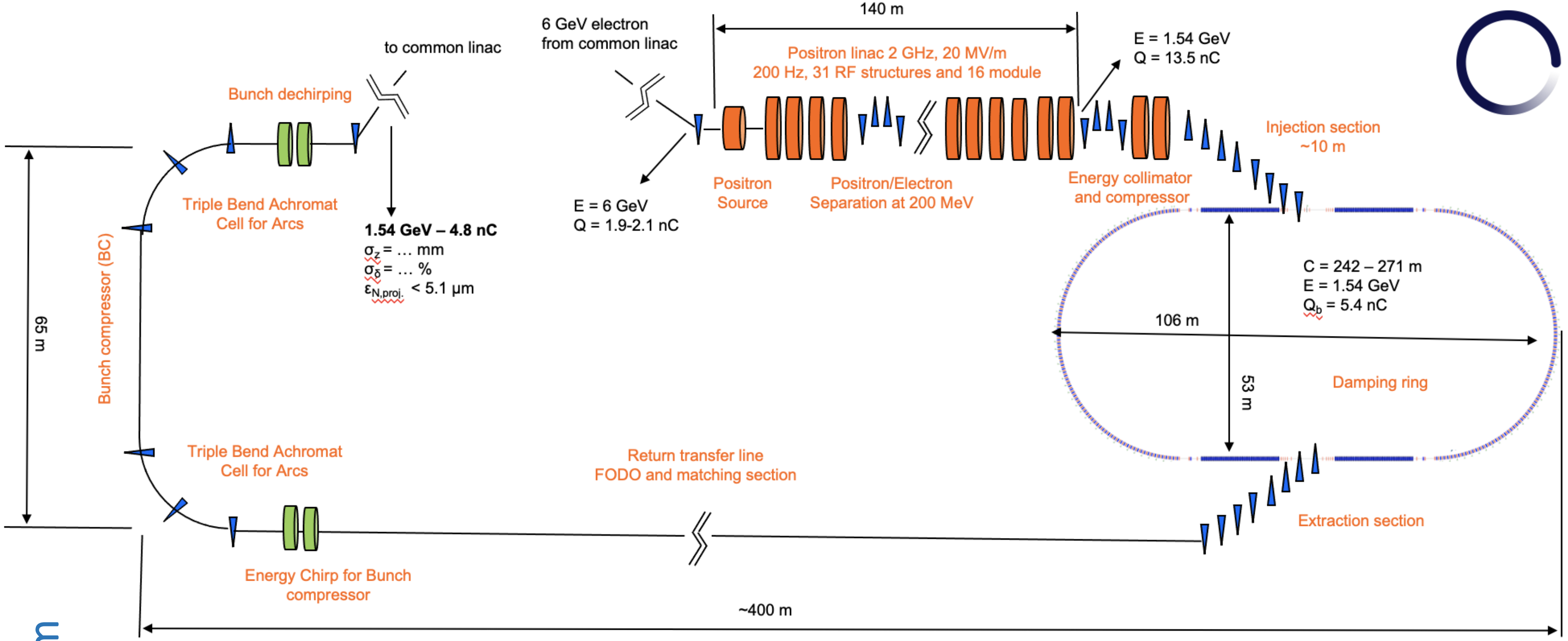
Option 1 (with SPS/PBR)



Option 2 (HE Linac)



FCC-ee pre-injector layout (Positron source).

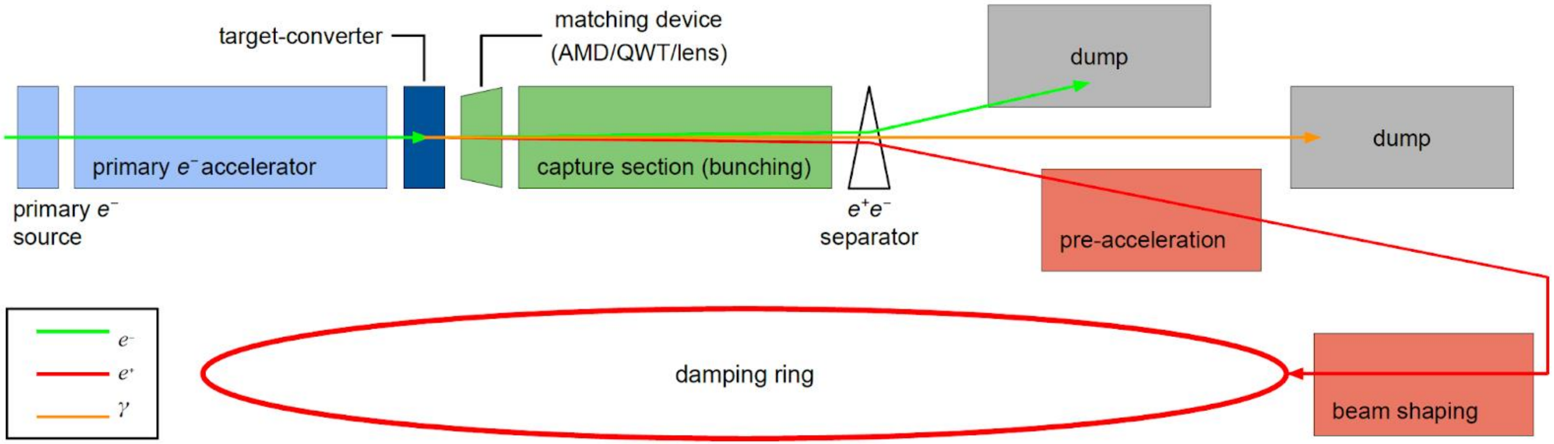


e⁻ drive beam

Beam energy	6 GeV
Bunch charge	~5.6 nC (max)
Bunch length	1 mm
Bunch transverse size	≳ 0.5 mm

Nb of bunches per pulse	2
Bunch separation	25 ns
Repetition rate	200 Hz
Beam power	~13.3 kW (max)

Positron source basic scheme:



Accepted e^+ yield is a function of **primary beam characteristics** + **target** + **capture system** + **DR acceptance**

$$\eta^{e^+}_{\text{Accepted}} = \frac{N^{e^+}_{\text{DR accepted}}}{N^{e^-}_{\text{Primary}}}$$

To estimate the accepted yield:
energy window cut: (1540 ± 58.5) MeV → (±3.8% @ 1.54 GeV)
time window cut: 40° RF (~16.7 mm/c @2 GHz)

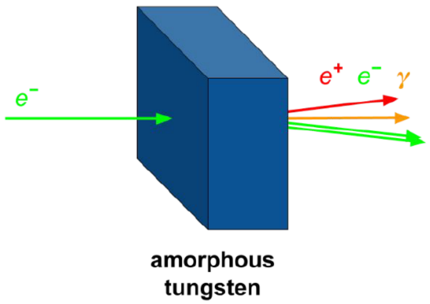
Production schemes:

- **Conventional scheme:**

Bremsstrahlung ->

Pair production

Well understood and used in current and previous positron sources.



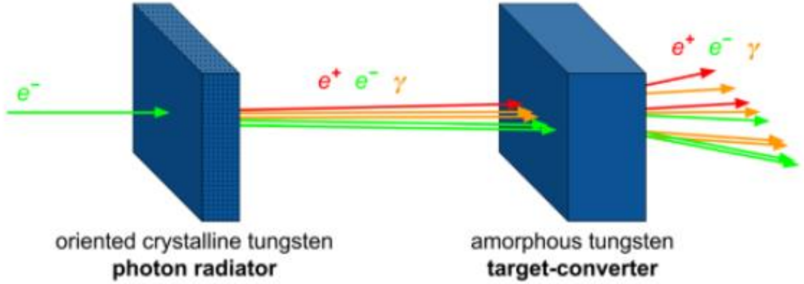
- **Crystal based scheme:**

Channeling radiation ->

Pair production

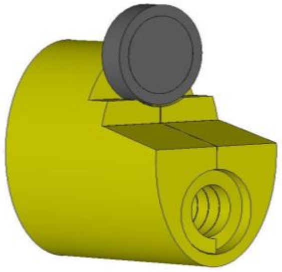
Innovative and the studies are ongoing.

Advantage : Lower THERMAL LOAD in the target.

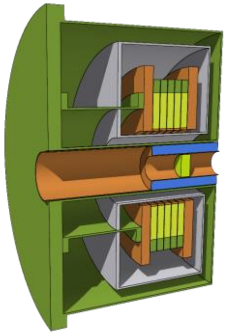


R. Chehab et al., in Proc. of the 1989 IEEE Particle Accelerator Conf., 1989, pp. 283–285

Matching devise: a fast phase space rotation to transform the small size and high divergence in big sizes and low divergence beam.



Flux Concentrator (FC)
Originally designed by BINP.

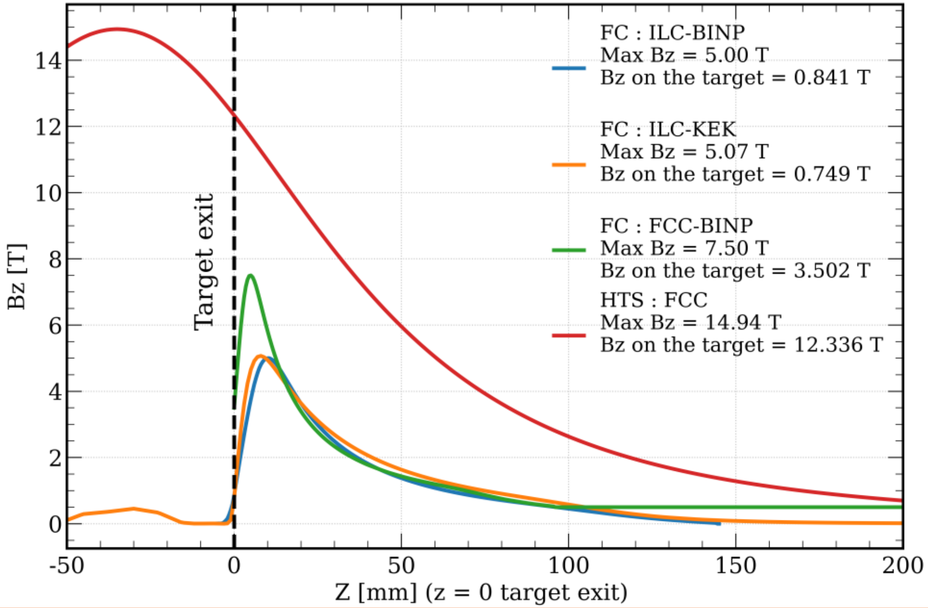


High-Temperature Superconducting (HTS) solenoid
Designed by PSI.

FC: lower peak field and aperture, fixed target position, challenging power source working at 200 Hz, ***robust and reliable solution…***

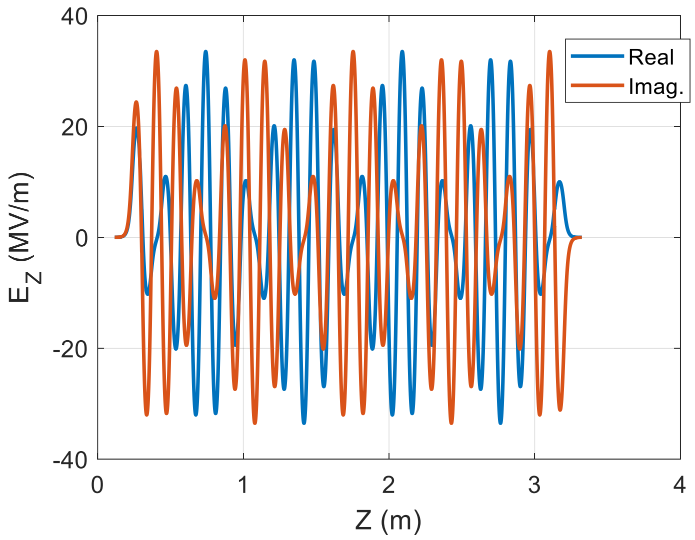
FCC-ee FC: collaboration with ILC and CLIC on high-field large-aperture FC and power supply.

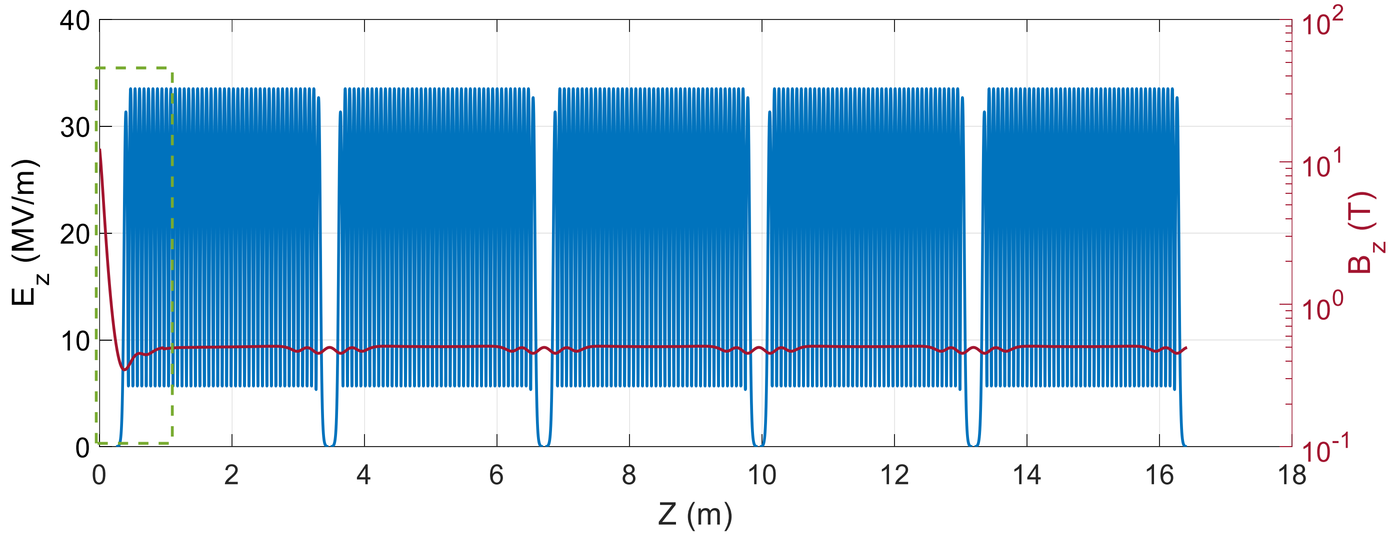
HTS solenoid: higher peak field and aperture, flexibility on the field profile and target position, DC operation, ***innovative solution in application for e^+ capture…***



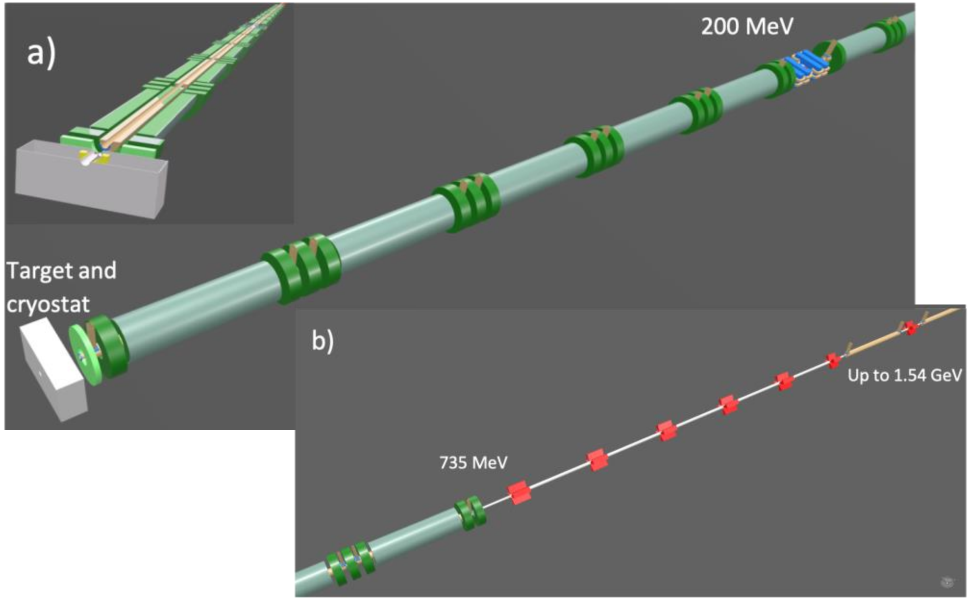
Capture linac:

- **Baseline structure: large-aperture (Φ = 60 mm) TW L-band @ 2 GHz, 9π/10, 3-meter long, 20 MV/m.** F3 structure designed by H. Pommerenke and A. Grudiev (CERN). 5 RF structures are used to accelerate the e^+ beam up to ~200 MeV.
- **Baseline solenoid configuration: 0.5 T NC solenoid.** Configuration designed by M. Schaer, R. Zennaro (PSI). For simplification, 0.5 T uniform NC field used (as the difference in final results was found to be small).





Positron linac up to 1.54 GeV

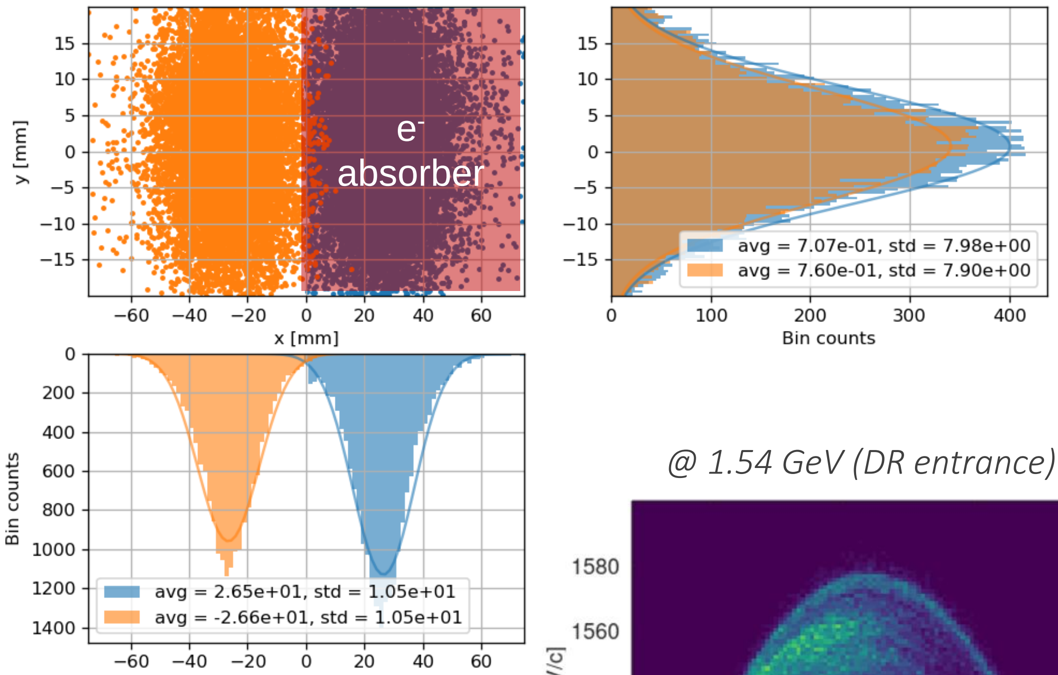


The solenoid focusing is used until ~735 MeV of e^+ beam energy.

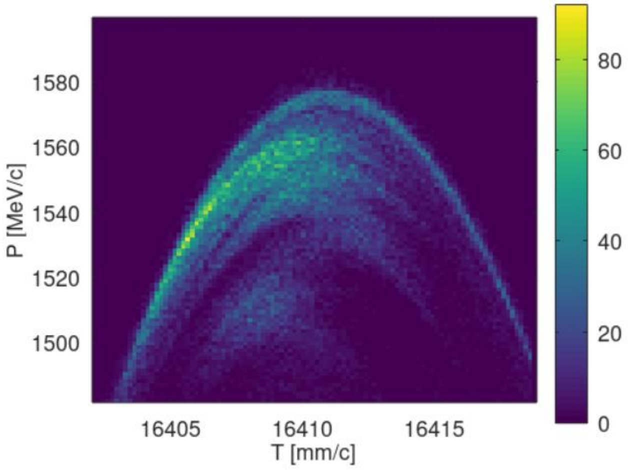
After the matching section at ~735 MeV, the e^+ beam passes to a quadrupole focusing.

ECS is used to increase the number of e^+ within the DR energy acceptance (±3.8%).

e^+/e^- distributions before e^- absorber (chicane center)



@ 1.54 GeV (DR entrance)



Summary of the simulation results

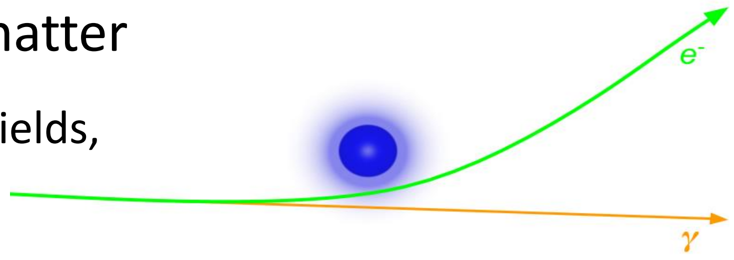
Drive beam parameters	Alternative FC-based capture system		Capture system –v1
Positron production scheme	**Conventional (17.5mm W target)**		
Matching device	BINP FC	SuperKEKB FC	HTS solenoid
Matching device aperture	2a=8-44mm	2a=7-52mm	$2a_{min}$=30 mm (bore 72mm)
Matching device peak magnetic field (@Target) [T]	7.5 (3.5)	4.4 (1.1)	15 (12)
e- beam bunch charge [nC] / e- beam power [kW]	**3.1 / 7.4**	**5 / 12**	**2.1 / 5**
Target deposited power [kW] / PEDD [J/g]	1.7 / 11.1	2.9 / 18.3	1.2 / 3.1
Positron yield @CS [Ne^+/Ne^-]	4.9	3.3	8
Positron yield @DR [Ne^+/Ne^-]	**4.4**	**2.7**	**6.5**
Normalized emittance (rms) [mm.rad]	12.2	11.9	13.7
Energy spread (rms) [%]	1.2	1.1	1.4
Bunch length (rms) [mm]	2.9	2.6	2.9
e+ beam bunch charge [nC]	**13.5**		

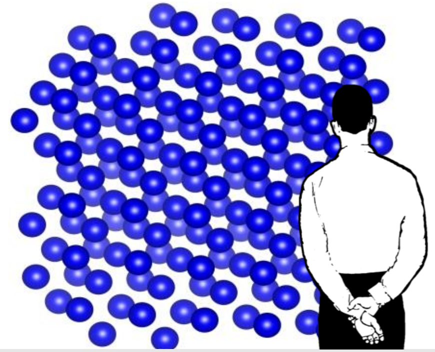
Crystal based positron source simulation

Passage of electrons through amorphous matter

Random interactions with single-nucleus, Coulomb fields, independent on each other

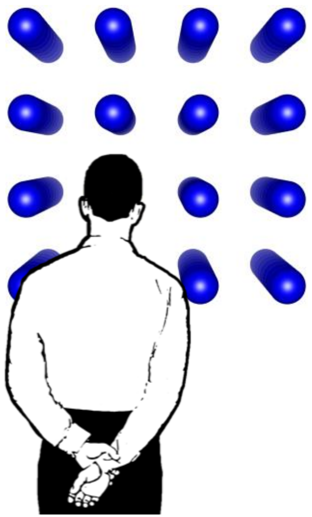
→ standard **Bremsstrahlung** radiation emission



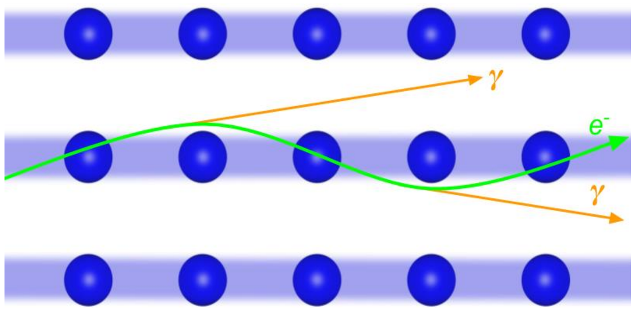


At *small* angle between the particle trajectory and the nuclear strings,

axial condition: *continuous potential along the axes (Lindhard)*



Electromagnetic radiation builds up coherently -> radiation emission enhancement



2mm thick target	**N photons**
<100 MeV, W- amorphous	2.6
<100 MeV, W-crystal <111>	11.3
Photon yield enhancement	~4

Bandiera, L., et al. "Crystal-based pair production for a lepton collider positron source." *The European Physical Journal C* 82.8 (2022): 699.

Crystal based positron source simulation

European Commission

Trillion

INFN Istituto Nazionale di Fisica Nucleare

KiSTi www.kisti.re.kr Korea Institute of Science and Technology Information

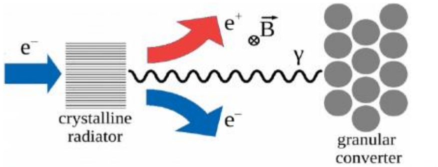
Main goal: The **implementation** of both physics of **electromagnetic processes in oriented crystals** and the design of specific applications of crystalline effects into **Geant4** simulation toolkit as Extended Examples to bring them to a large scientific and industrial community and under a free Geant4 license.

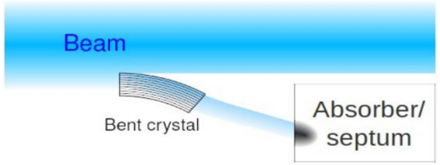
- By **A. Sytov** – project coordinator
- To **implement into** GEANT4 A SIMULATION TOOLKIT
- Crystal-based positron source:
- Crystal-based extraction from an accelerator:
- Crystalline undulator:

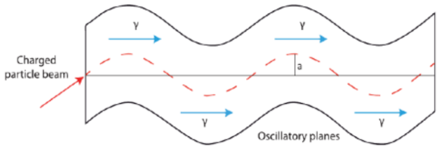
Already in geant4-11.2.0 !

geant4-v11.2.0/source/parameterisations/channeling/

https://www.fe.infn.it/trillion/







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DESY.

for more details : Alexei Sytov

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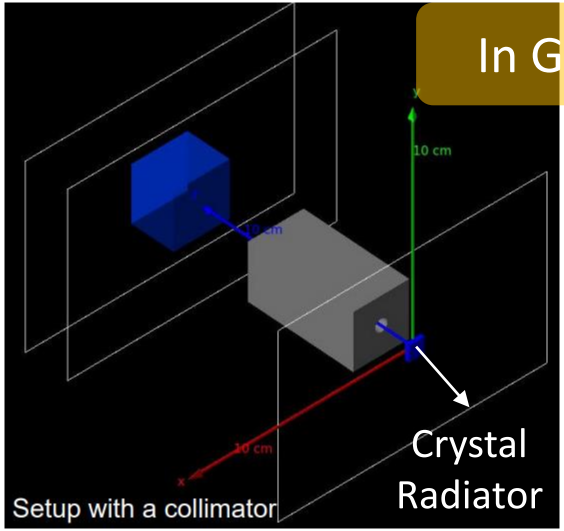
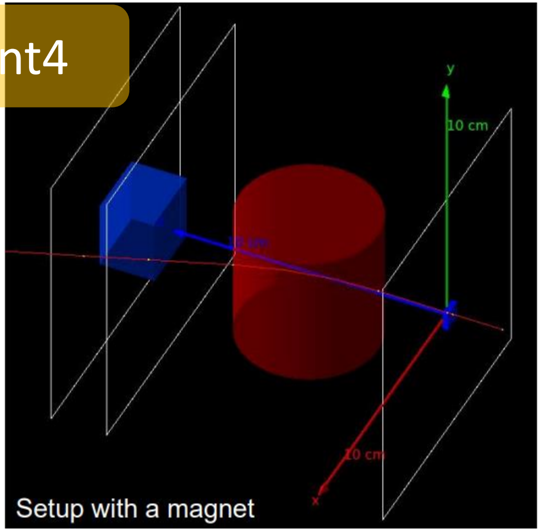
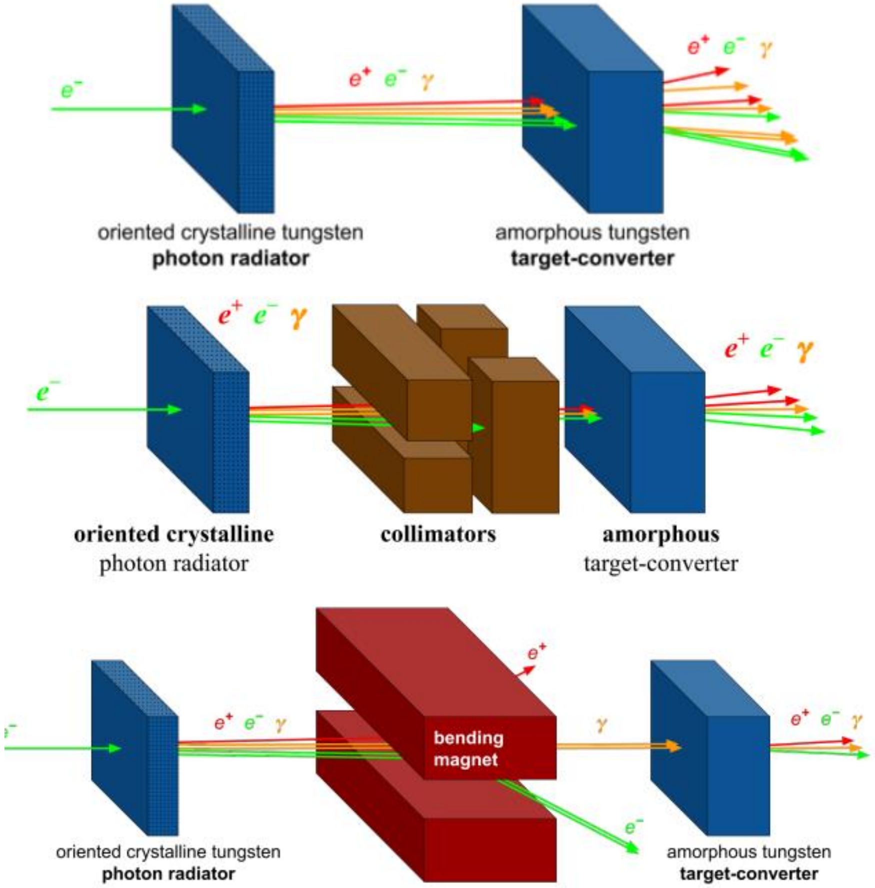
Crystal based positron source simulation

- Production scheme is composed of two elements :
  1) Oriented crystal (Channeling radiation)
  2) Amorphous target (Pair production)
- 8 different configurations (0.6m, 1m, 2m)
  - **W-Crystal <111> thickness = 2mm**
  - **Amorphous target thickness = 11.6mm (optimized)**

In Geant4

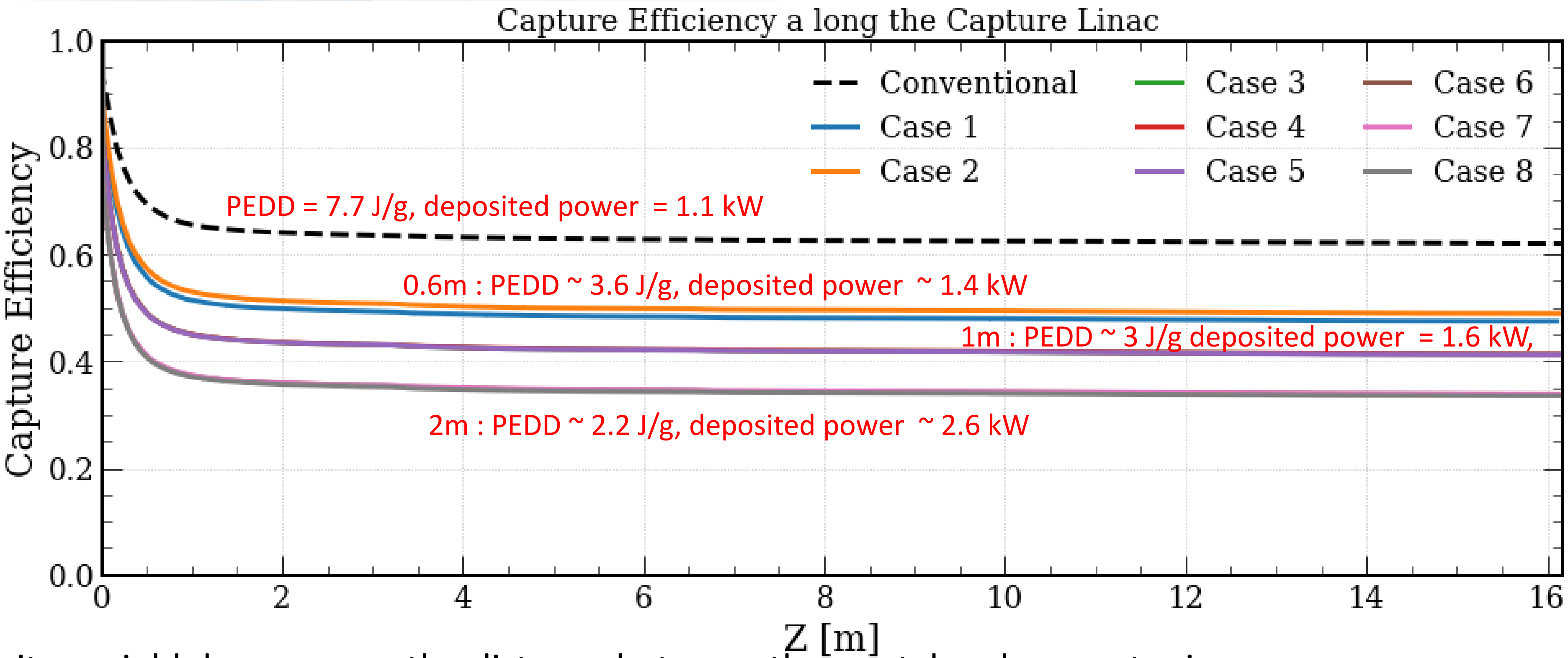






* " Radiation in oriented crystals: innovative application to future positron sources"

Crystal based positron source simulation

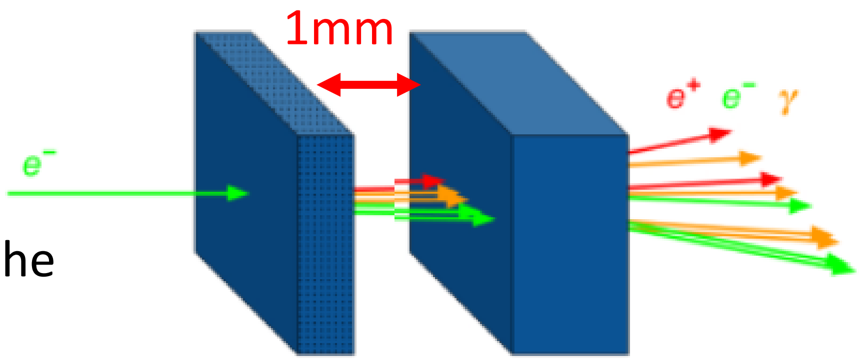


- Positron yield decreases as the distance between the crystal and converter increases.
- PEDD is highly reduced by increasing the distance.
- Yield and PEDD are not affected by placing a magnet or collimators in between the two targets.
- After preforming a loss study , the main reason for the lower yield is the large beam size at the exit of the target.

Crystal radiator adjacent to the amorphous converter.

- In order to keep the beam size after the crystal as small as possible : crystal is placed adjacent to the converter (1mm gap).
- W-crystal <111> thickness: 1mm, 2mm, 3mm.
- For each crystal thickness a scan is performed to optimize the

  converter thickness [5:1:14] mm



W-crystal
1mm, 2mm, 3mm

W-amorphous
[5:1:14]mm

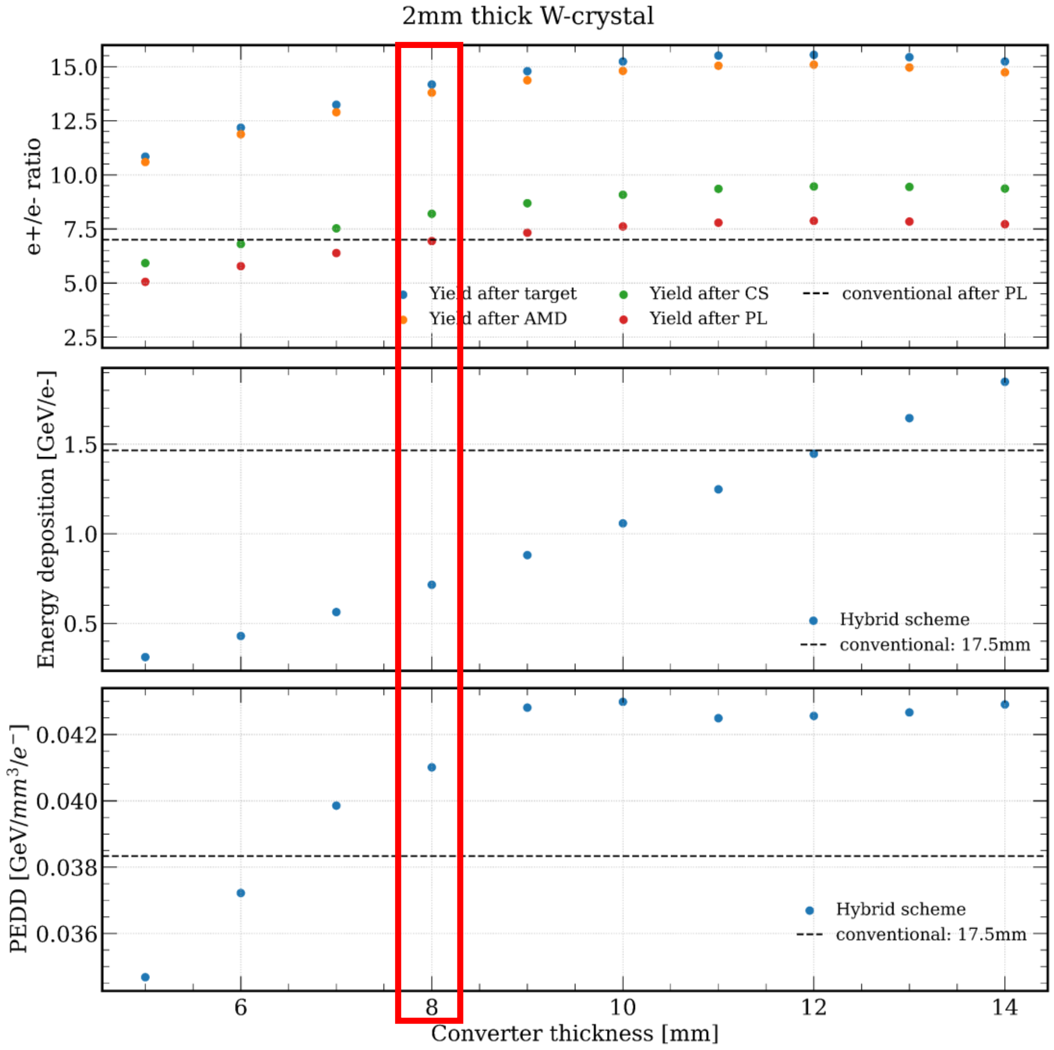
Crystal based positron source simulation

- An example of the optimization study with 2mm thick W-crystal in comparison with the conventional scheme.

  - Accepted yield: is comparable to the conventional for a shorter overall thickness (2mm + 8mm)

  - Energy deposition: significantly lower than the conventional (~50%).

  - PEDD: slightly higher than conventional (~7%)



Crystal based positron source simulation

Cases with final accepted yield is comparable with the conventional scheme

13.5nC at DR

Case	Thickness [mm]	Target				AMD	Capture Linac	Positron Linac	e- beam	Target	
		Rate	σx [mm]	Edep [GeV/e-]	PEDD $[\frac{MeV}{mm^3}/e^-]$	Yield (AMD) R = 30mm	Yield	Accept Yield	Drive beam charge [nC]	PEDD [J/g]	Power Deposited [kWs]
Conventional	17.5	14.4	0.85	1.46	38.3	13.1	8.6	7.0	1.93	7.67	1.12
1mm – 10mm	11	14.4	0.64	0.81	40.1	14	8.3	7.04	1.91	8	0.62
2mm – 8mm	10	14.2	0.64	0.73	41	13.8	8.2	6.9	1.96	8.33	0.57
3mm – 7mm	10	14.3	0.63	0.7	41.2	13.9	8.3	7.03	1.92	8.22	0.54

Crystal based scheme advantages in comparison with Conventional scheme :

- Shorter overall thickness (lower radioactive environment around the target) ?
- Comparable yield and PEDD with:

significantly lower power deposited in the target -> lower cooling requirement.

Proof-of-principle experiment at PSI

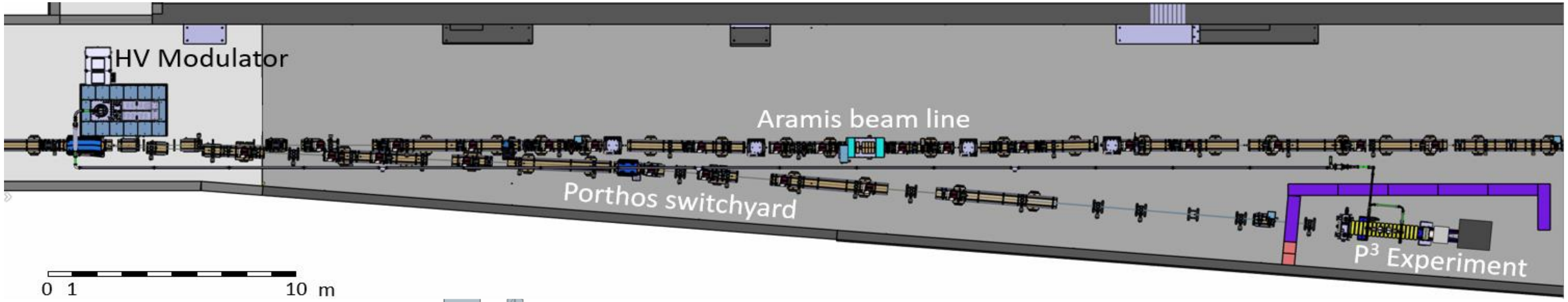
- P^3 or P-cubed stands for **the PSI Positron Production experiment**
- It is a e+ source demonstrator with potential to improve the present state-of-the-art e+ yield by an order of magnitude.
- The SwissFEL facility will host the experiment – according to schedule- in 2026.
- P^3 is framed in the FCC-ee injector study, driven by the luminosity requirements of future colliders.
- For more details : *N. Vallis et al., Proof-of-principle e+ source for future colliders, Phys. Rev. Accel. Beams 27, 013401 – 2024*

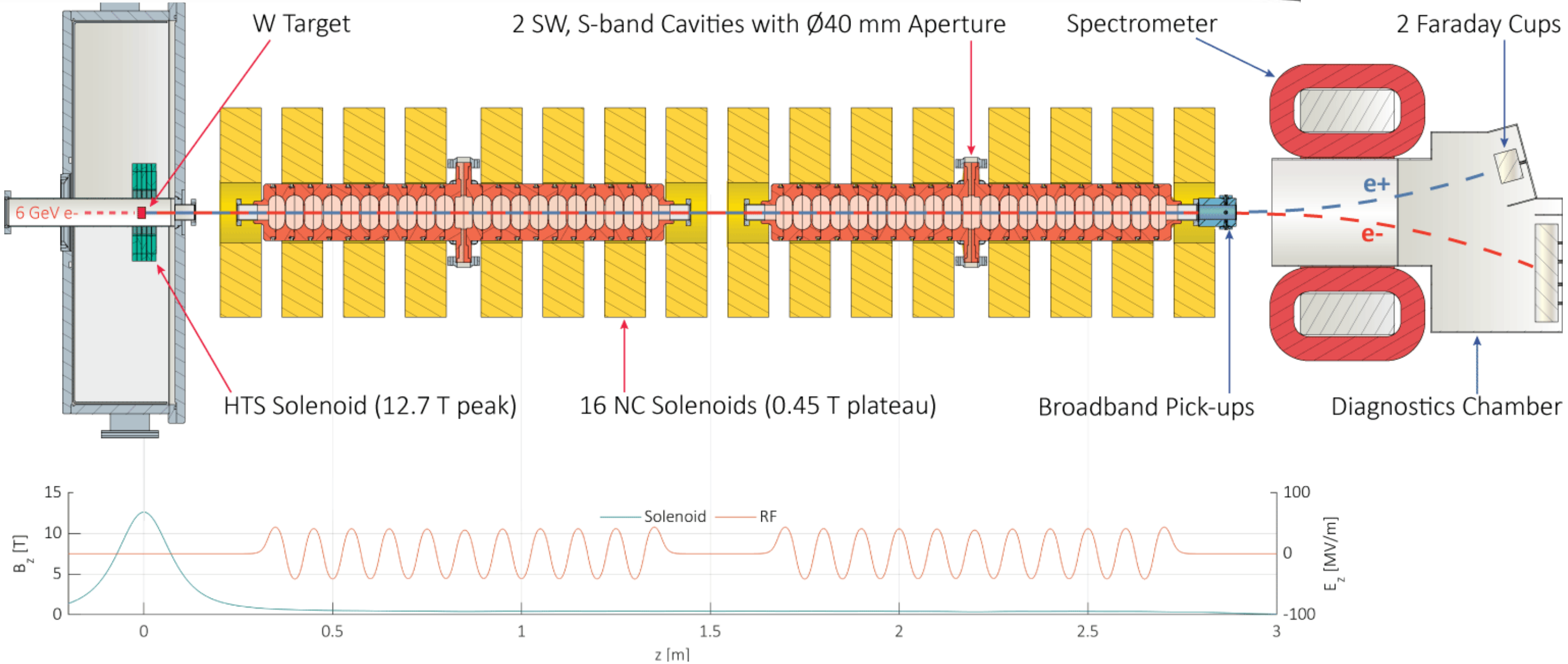
TABLE II. Main e^+ source parameters of FCC-ee and P^3.

	FCC-ee [9]	P^3
Energy (GeV)	6	
Maximum solenoid field at target (T)	tbd	12.7
Average solenoid field along linac (T)	0.5	0.45
Minimum rf cavity aperture (mm)	60	40
σ_E	0.1%	
σ_t (ps)	3.33	
σ_x, σ_y (mm)	0.5	
σ_{px}, σ_{py} (MeV/c)	0.06	
Target length (mm)	17.5	
Q_{bunch} (nC)	1.7–2.4	0.20
Repetition rate (Hz)	200	1
Bunches per pulse	2	1

Courtesy of N.Vallis (PSI)

Proof-of-principle experiment at PSI





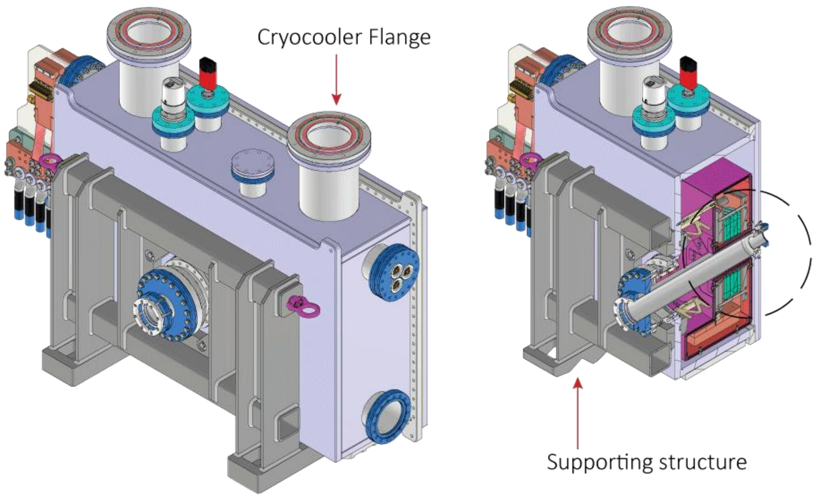
Courtesy of N.Vallis (PSI)

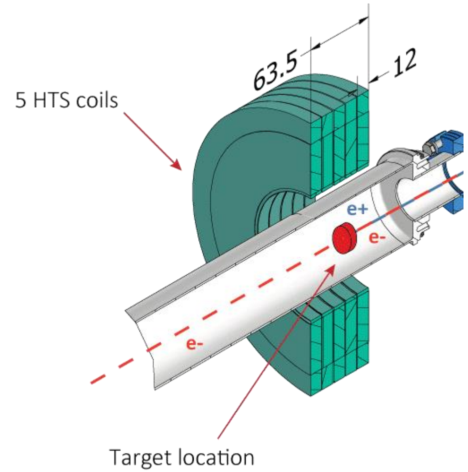
Key Technology:

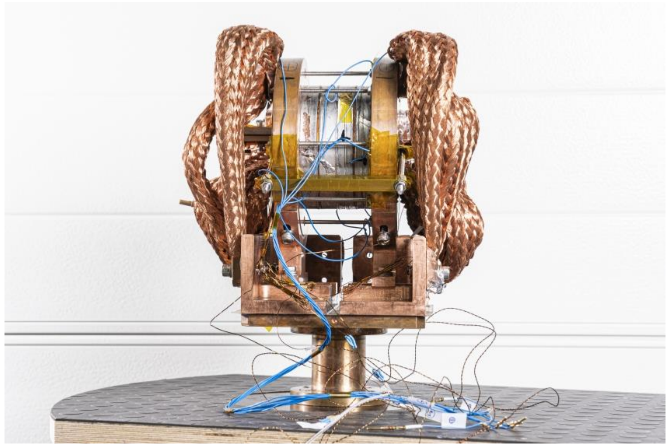
High-Temperature Superconducting (HTS) solenoid

PSI e+ PRODUCTION

- P^3 experiment will use a high temperature superconducting (HTS) to deliver a peak 12.7 T on-axis field near the target exit
- Based on the arrangement 5 coils made out of non-insulated ReBCO tape winded in-house at PSI.







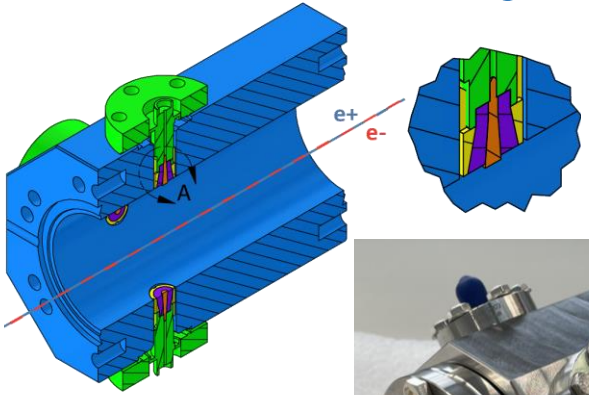
Courtesy of N.Vallis (PSI)

Proof-of-principle experiment at PSI

PSI e+ PRODUCTION

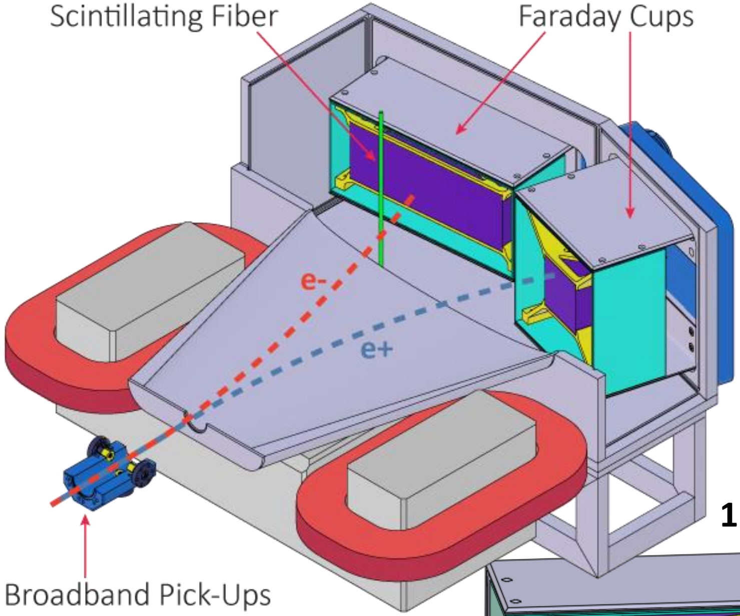
Key Technology:

Beam diagnostics

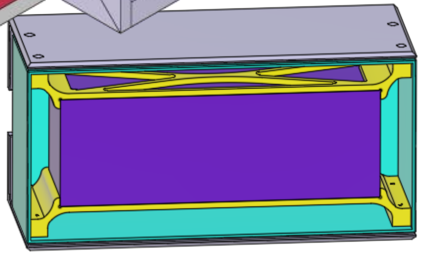


- Typical distribution will consist of alternating e+ and e- bunches of 33 ps length, and separated by 167 ps (half S-band period)

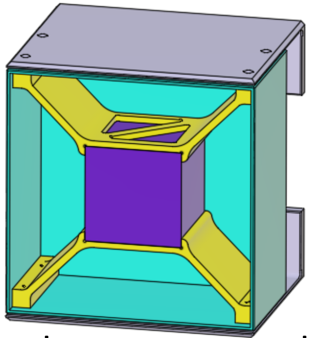
Courtesy of N.Vallis (PSI)



12.5 Ohm

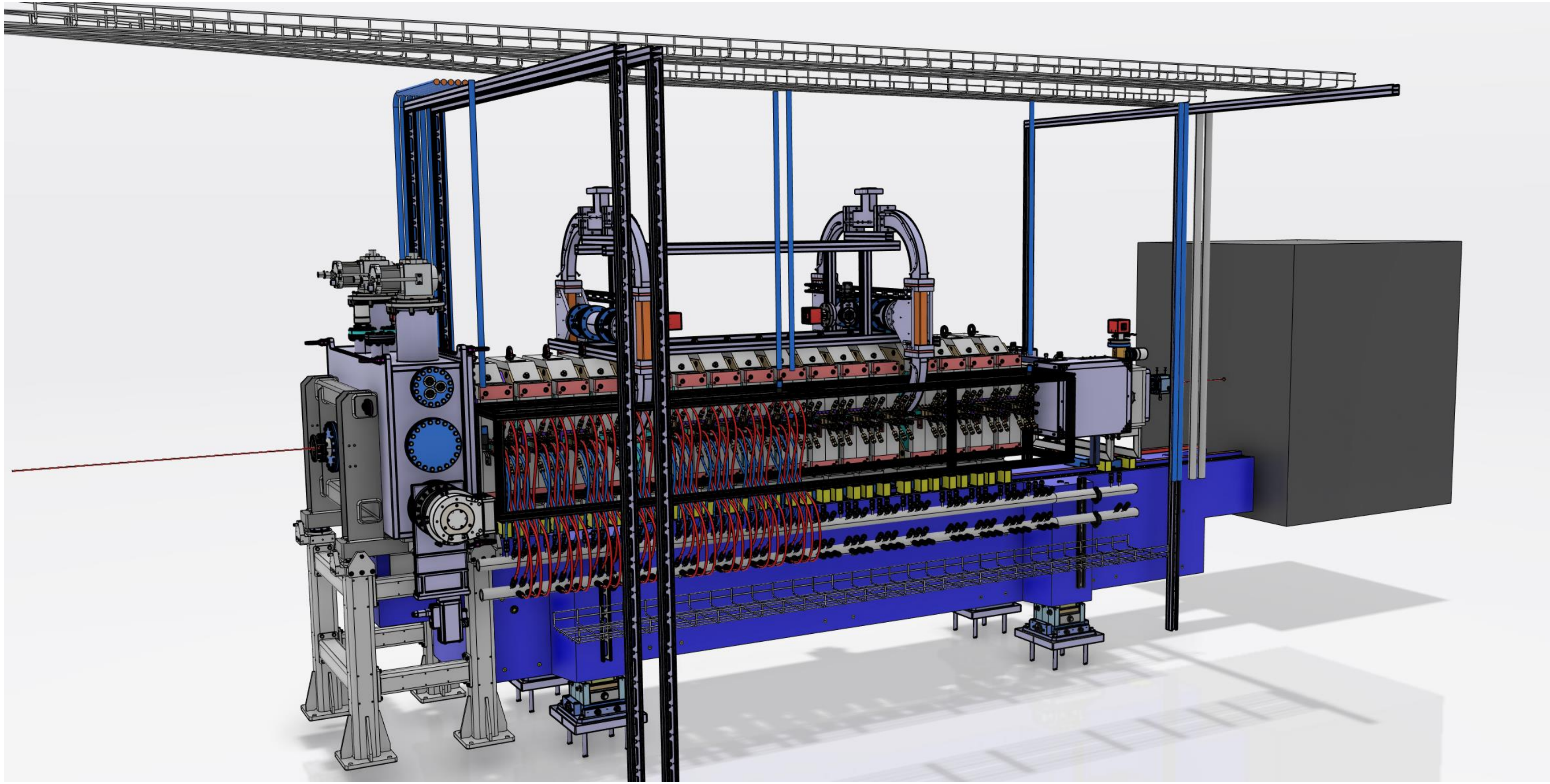


50 Ohm



- 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.

Proof-of-principle experiment at PSI



Courtesy of N.Vallis (PSI)

Thank you.

Backup

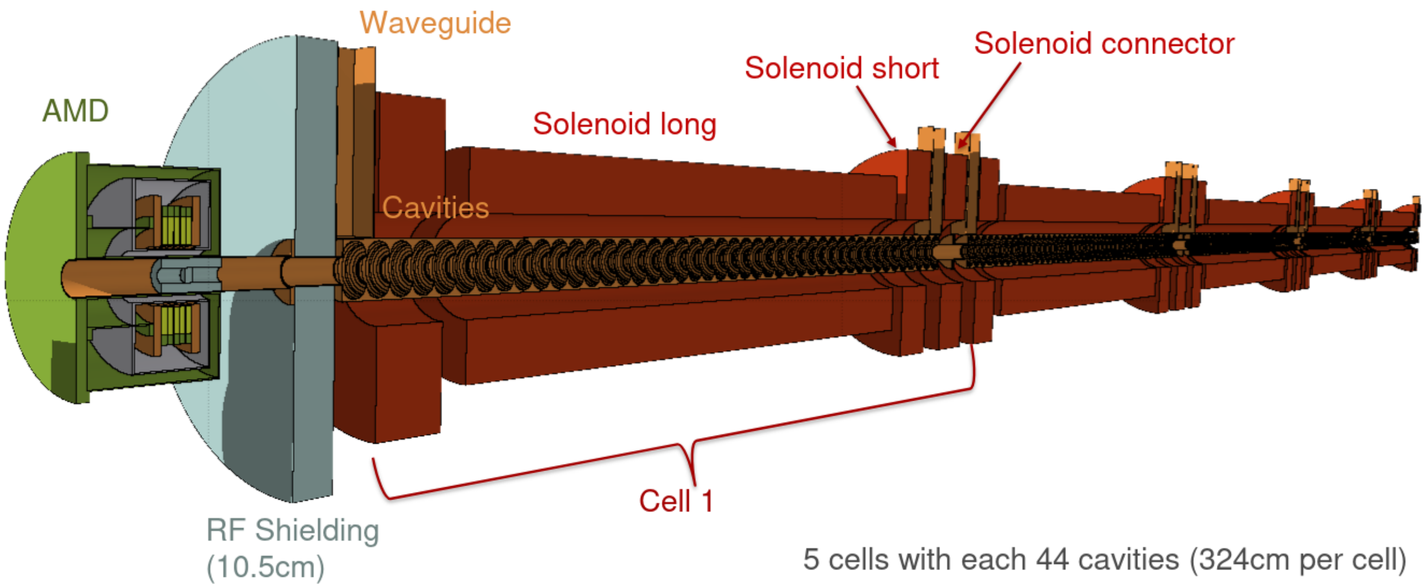
Radiation load studies and status of target design

Currently, the radiation load and target design studies focused exclusively on the HTS solenoid-based system (capture system –version 1)

FLUKA model of the FCC-ee positron source to assess

Heat load on the target/HTS solenoid/capture linac/solenoid
- Total deposited power
- Power density

Long term radiation effects
- Dose
- Displacement per atom (DPA)



→ Design feasibility and mechanical integration
→ Reliability of the positron source system

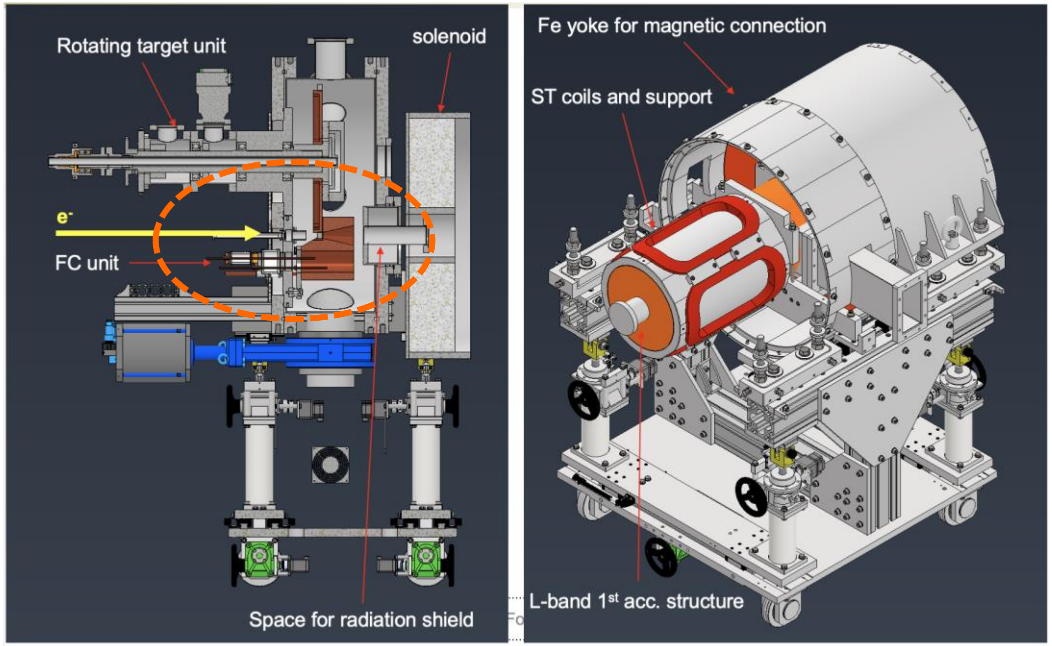
ILC – Flux Concentrator

- FCC-ee FC original design is made by BINP. *Very simple model (not realistic in terms of ohmic loss and high-power requirement for the pulsed power supply).* **Needs more realistic simulations.**
- FC-based capture system successfully works at SuperKEKB → starting point for the FCC-ee capture system studies. **FC is currently considered as a baseline for the ILC e$^-$-driven and CLIC positron sources.**

Compared to SuperKEKB FC, high rep. rate (up to 300 Hz) and ideally higher max. field value/aperture are requested for the future collider projects.

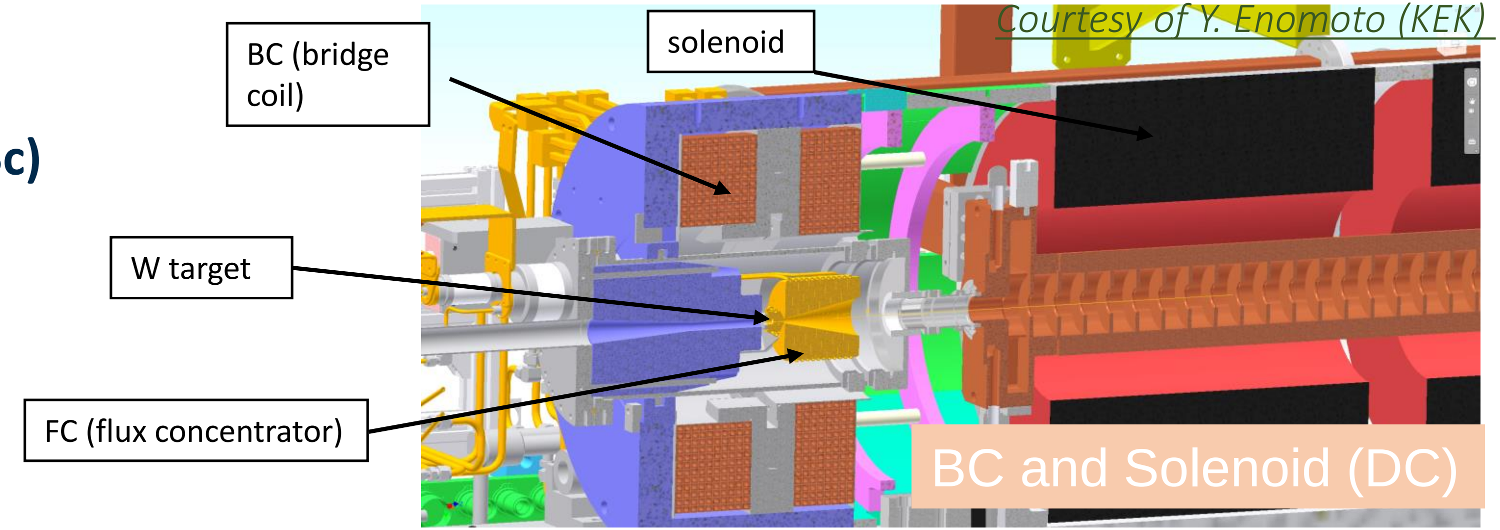
Make use of the SuperKEKB experiences and join the effort on the FC design between FCC/ILC/CLIC collaborations to arrive to a more realistic model.

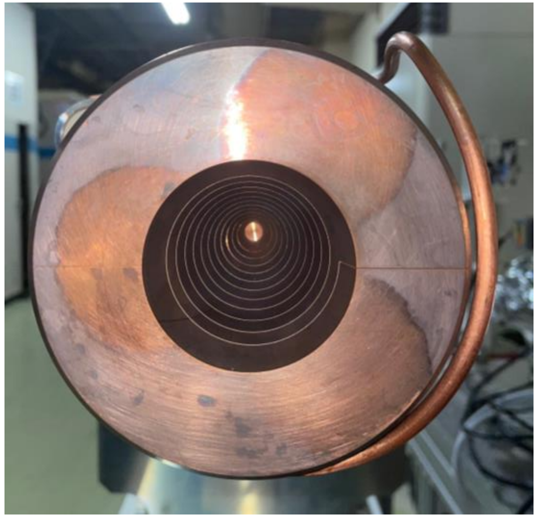
Prototype of the positron source for ILC

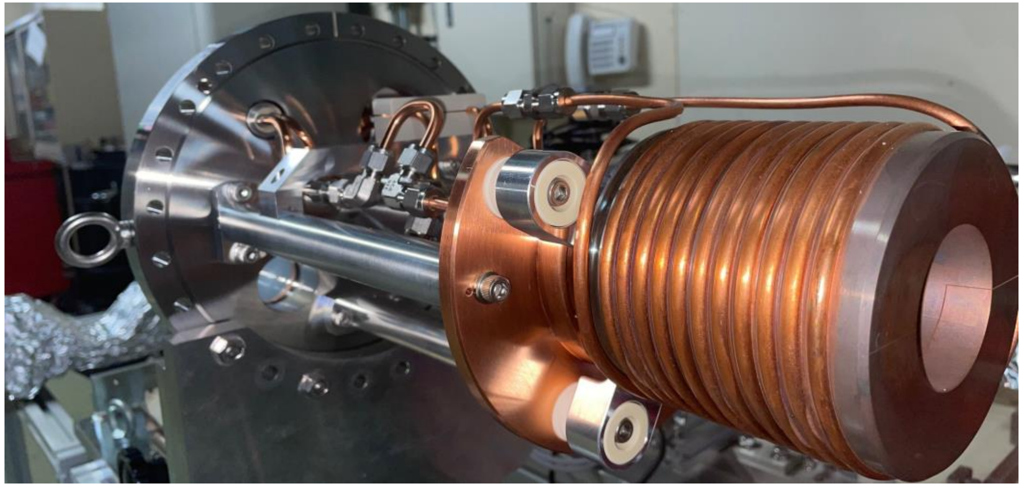


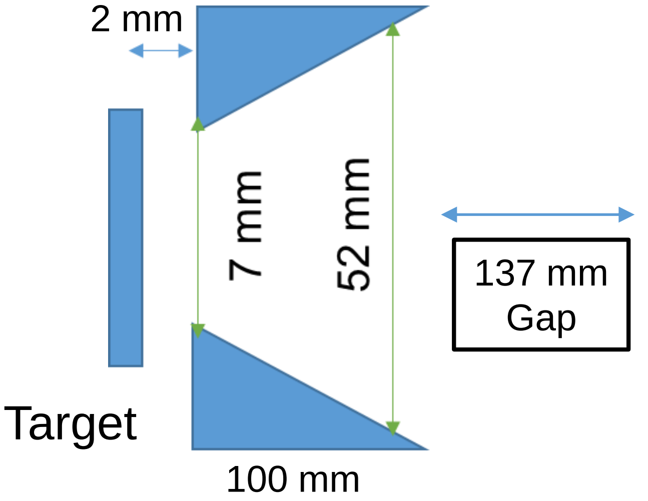
AMD consists of : Flux concentrator (FC) + Bridge coil (Bc)

- FC field : 3.5T at 12.5kA (pulsed)





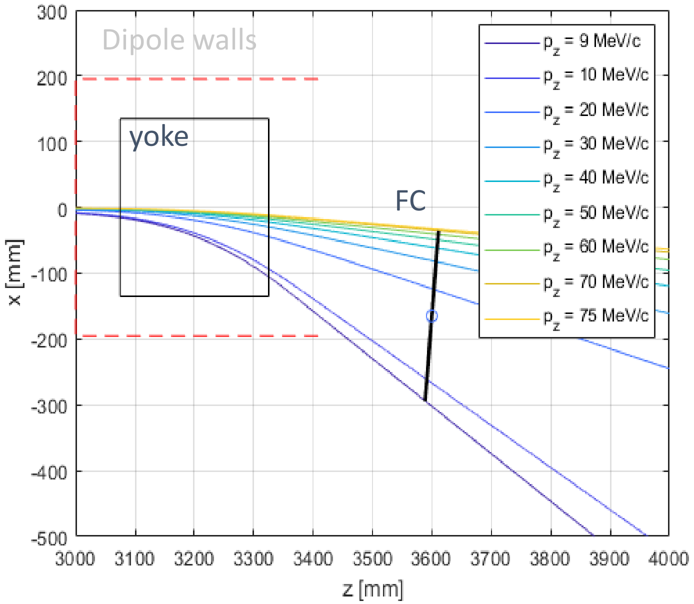




Diagnostics: Faraday Cups (P3)

12.5 Ohm

- Large transverse size (260x70 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