Study of a positron source for FCC-ee based on oriented crystals - Setup optimization and experimental measurements

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Outlook

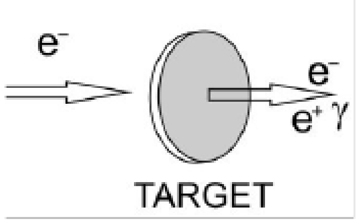
- Short description of positron sources and e+ production schemes
- Novel optimization approach, based on an experimentally validated simulation framework
- Optimized solutions for FCC-ee positron source @ 6 GeV

Why are positron sources critical components of the future colliders?

$$L = \frac{N_1 N_2 f n_b}{2\pi \sqrt{\sigma_{x,1}^2 + \sigma_{x,2}^2}\sqrt{\sigma_{y,1}^2 + \sigma_{y,2}^2}}$$

→ High luminosity at the future machines (especially linear ones) → needs **high average and peak e- and e+ currents** and **small emittances**.

e+ are produced within large 6D phase space (e+/e- pairs produced in a target-converter)



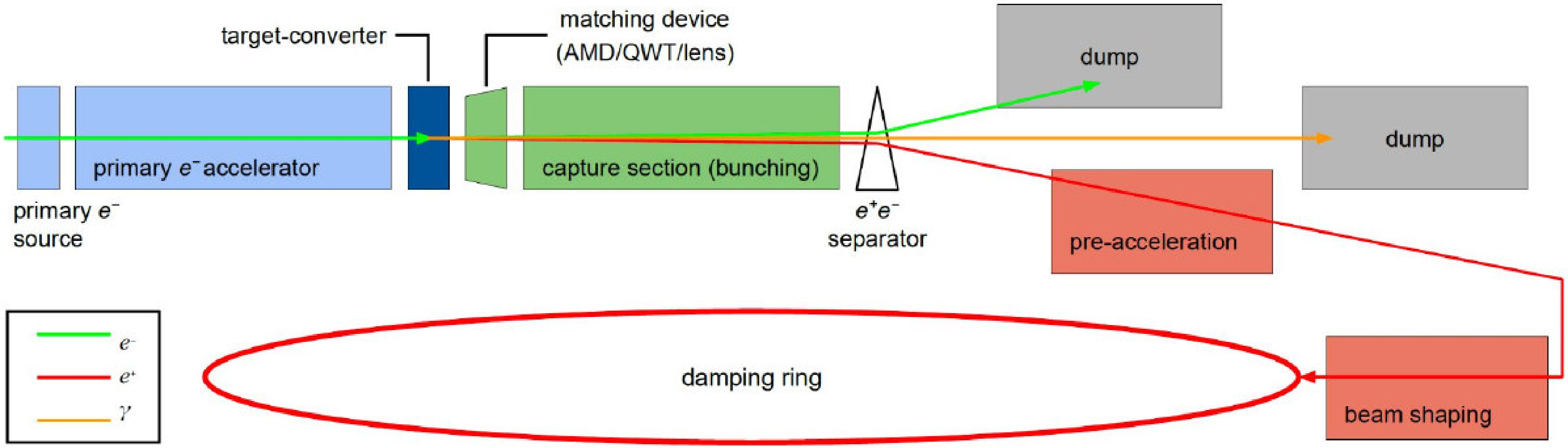
<u>Current</u> => limited in conventional way by the target characteristics
- Average energy deposition => target heating/melting
- Peak Energy Deposition Density (PEDD): inhomogeneous and instantaneous energy deposition → thermo-mechanical stresses due to temperature gradient
  Thermal dynamics and shock waves. Fatigue limit resulting from cycling loading. Material damages. Activation (handling issues)

<u>Emittance</u> → at the production 6D phase space is very large
- After defined by the e+ capture system acceptance.

e+ source set the constraints for the peak and average current, the emittance, the damping time, the repetition frequency → **Luminosity!**

Basic scheme of a positron source

High production e+ divergence → appropriate **capture**, **focusing** and **post acceleration** sections need to be integrated immediately after the target



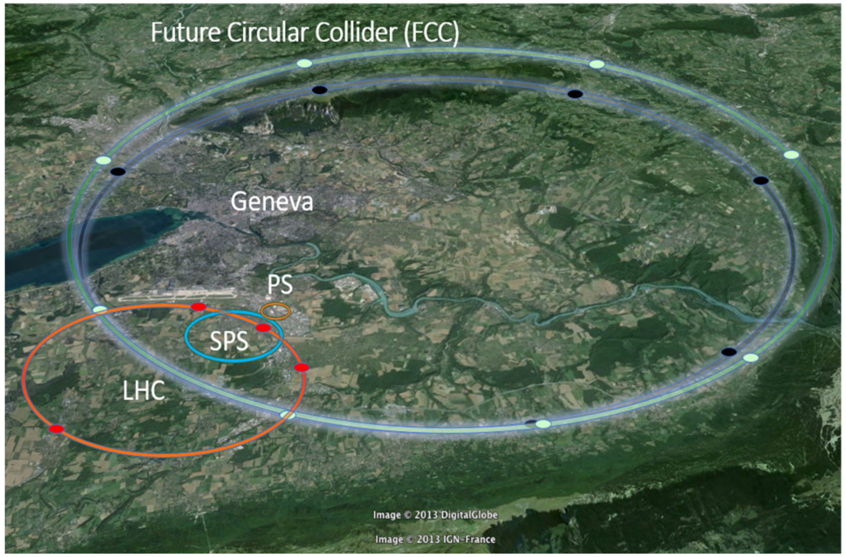
Accepted e+ yield is a function of primary beam characteristics + target + capture system + DR acceptance

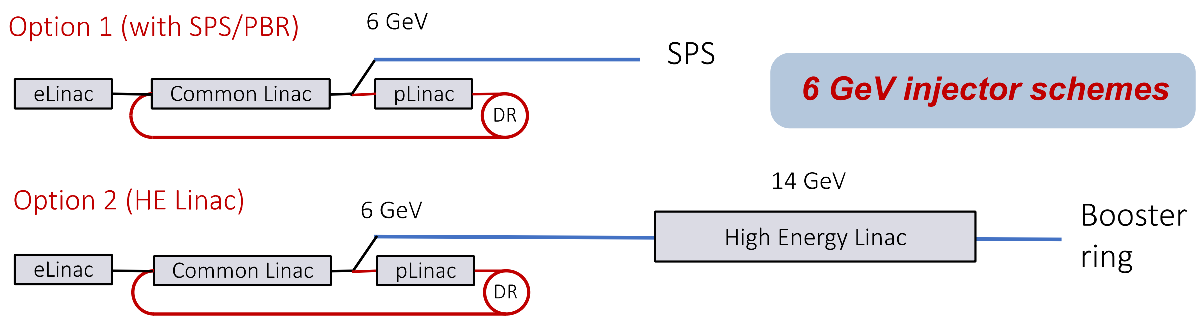
FCC / FCC-ee

- Future CERN collider post LHC
  ~ 91 Km of circumference
- Stages: **FCC-ee**, Fcc-eh, FCC-hh
- High luminosity:
  up to $230 \times 10^{34} cm^{-2} s^{-1}$

FCC-ee Operation Mode	Final Energy [GeV]	Beam Current [mA]
Z	45	1270
W	80	137
H	120	26.7
ttbar	182.5	4.9

Most demaning for the positron source





FCC-ee positron source: current requirements

The complete filling for **Z running** → Requirement ~2.75 × 1010 e+/bunch (4.4 nC) at the Damping Ring (DR)

The conceptual design of the positron source is carried out to have **5.4 nC e+/bunch at the DR*** → **13.5 nC e+/bunch at the exit of the Positron Linac**, considering 60% of losses due to transport, collimation and injection in the DR (safety margin of 2.5). This e+ charge has to be obtained from:

e^- drive beam

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

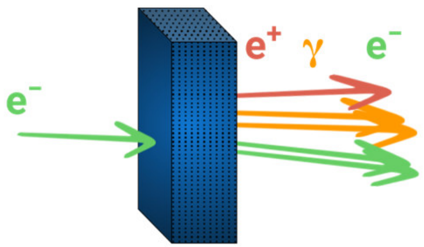
Nb of bunches per pulse	2
Bunch separation	25 ns
Repetition rate	200 Hz
Beam power	~13.3 kW (max)

*positron flux of **~1.35×10^{13} e^+/s.** *Demonstrated at SLC (a world record for existing accelerators):* **~6×10^{12} e+/s**

Crystal-based positron source

Originally proposed by R. Chehab, A. Variola, V. Strakhovenko and X. Artru

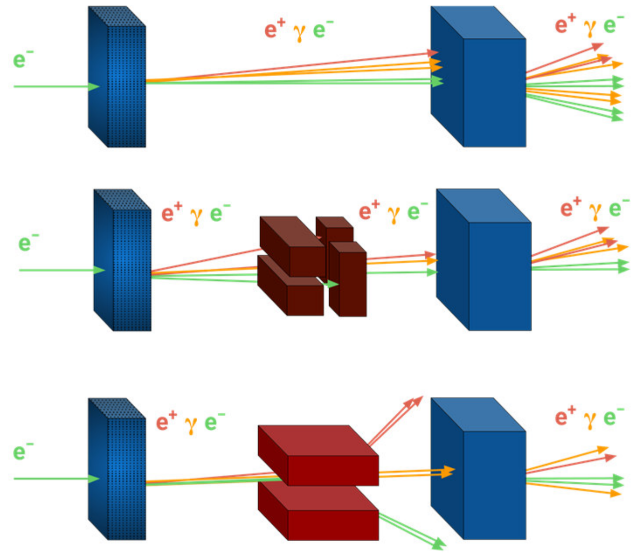
R. Chehab et al., in Proc. of the 1989 IEEE Particle Accelerator Conf., 1989, pp. 283–285



oriented crystalline
target

Use of lattice coherent effects in oriented crystals: **channeling** and **over barrier motion** (and **photon generation**) **→ typical angular range of few mrad at 6 GeV for <111> axis in W**

Hybrid scheme



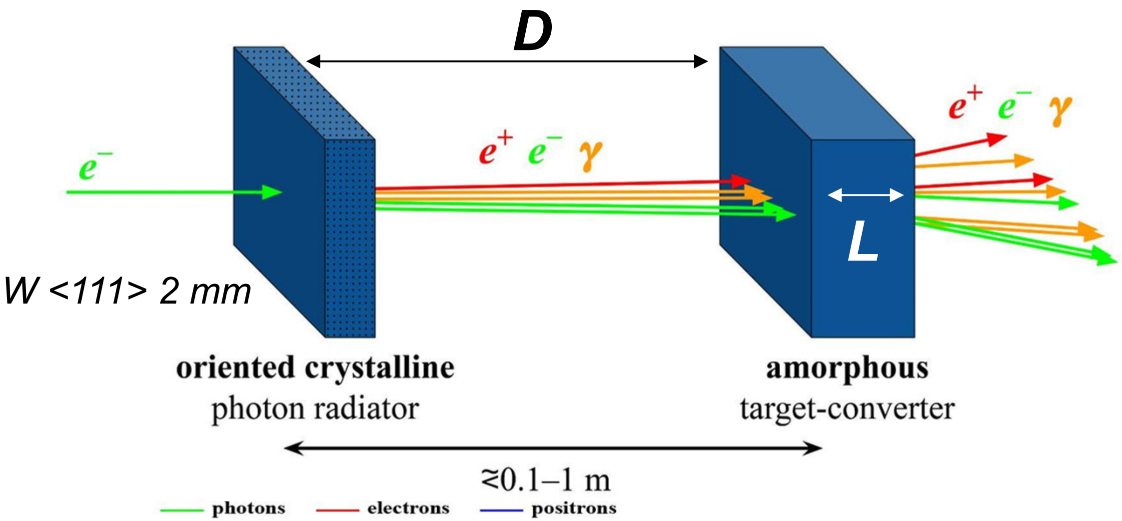
Idea of X. Artru et al., NIM B 266 (2008) 3868

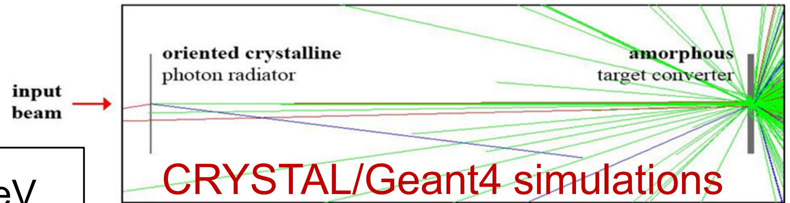
Test at KEK in Japan with a W crystal NIMB 402 (2017) 58

Novel production scheme for positron sources:

- Enhancement of (soft) photon generation in (high Z) oriented crystals → enhancement of pair production / positron charge
- Lower energy deposit and PEDD (with hybrid scheme) in target → lower heating and thermo-mechanical stress (target reliability)

Previous optimization study of a hybrid positron source for FCC-ee @ 6 GeV





E = 6 GeV
σ = 500 µm
σ' = 100 µrad

Scheme	conv.	hybrid						
L_{crys} [mm]	–	2						
D [m]	–	0.6	1			2		
L [mm]	17.6	11.6						
Collimator?	no	no	no	yes	no	no	yes	no
Magnet?	no	no	no	no	yes	no	no	yes
E_{dep} [GeV/e^-]	1.46	1.34	1.32	1.13	1.32	1.27	1.11	1.27
PEDD [MeV/(mm$^3 \cdot e^-$)]	38.3	12.8	8.4	8.2	8.4	4.1	3.8	3.9
Out. e^+/e^-	13.7	15.1	15.1	13.6	15	14.9	13.7	14.9
Out. e^+ beam size [mm]	0.7	1	1.2	1.2	1.2	1.5	1.5	1.5
Out. e^+ beam div. [mrad]	25.9	27.4	26.8	27.7	28.9	29.2	25.6	27.1
Out. e^+ mean energy [MeV]	48.7	46.2	45.6	47.4	45.9	46.1	47.7	46.3
Out. n/e^-	0.37	0.31	0.31	0.27	0.29	0.29	0.26	0.3
Out. γ/e^-	299	310	308	270	307	301	268	301

M. Soldani et al., NIMA 1058 (2024) 168828

Larger beam size and div -> many e+ are not captured by the AMD -> Smaller e+ yield at the DR.
We then optimized, via simulation, the e+ production together with the capture section.

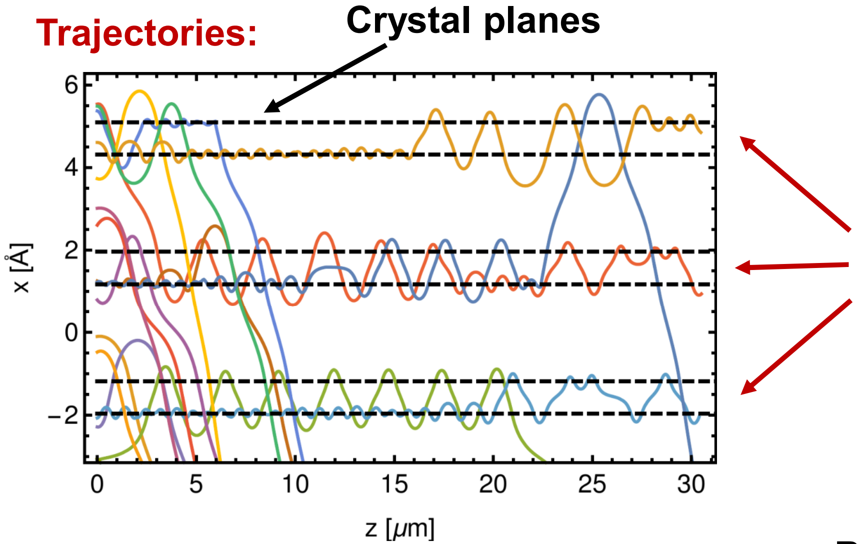
Channeling simulation in Geant4: novel ***G4ChannelingFastSimModel*** and ***G4BaierKatkov*** classes were developed and embedded in Geant4 (since 11.2.0 version). These models are based on CRYSTALRAD code

Main conception: simulation of classical trajectories of charged particles in a crystal in averaged atomic potential of planes or axes. Multiple and single scattering, as well as ionization, simulation at every step. Photon emission simulated through MC integration of Baier-Katkov formula (**see A. Sytov presentation**)

This model together with standard or pre-calculated (through B-K) pair-production model, allows us to simulate a wide **variety of applications**

coherent pair production model under test…

Trajectories:



European Commission

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GEANT4 A SIMULATION TOOLKIT

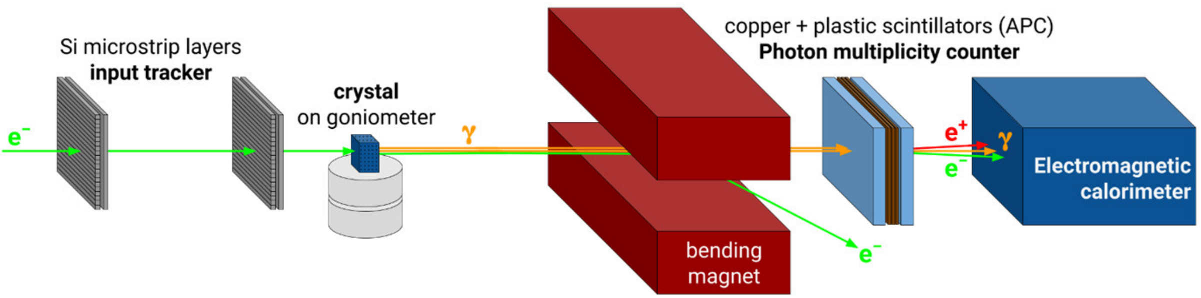
Baier-Katkov formula:

$$dN = \omega d\omega d\Omega \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[\left(E^2 + E'^2\right)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1 - x_2)}$$

A.I. Sytov, V.V. Tikhomirov. NIM B 355 (2015) 383–386.
L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015)
**A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)*
A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

Validation of Geant4 channeling model against experimental data

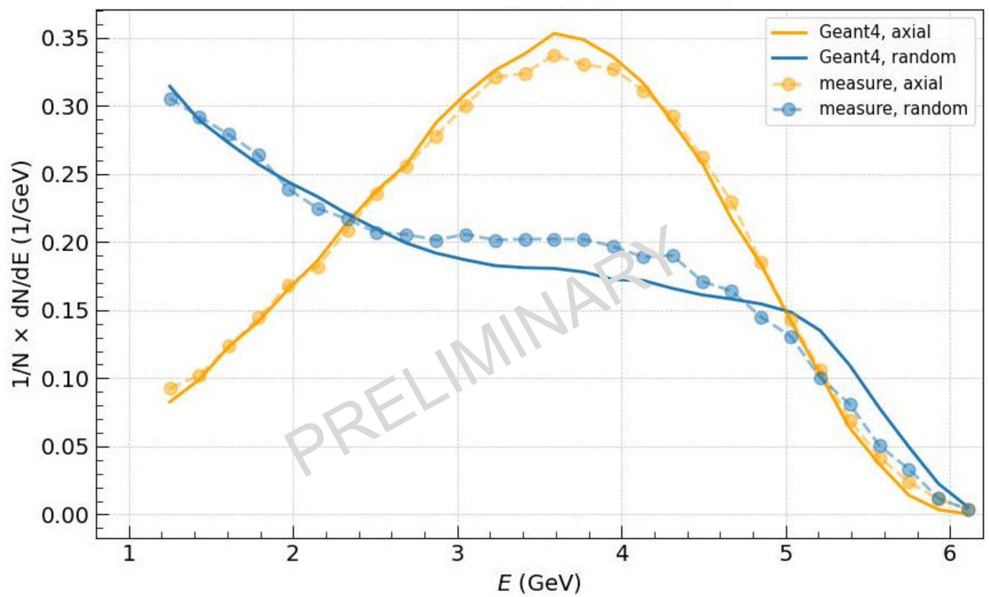
Setup @CERN PS T9 beamline



Electron beam energy: 6 GeV
Crystal target: W <111>, 2 mm long

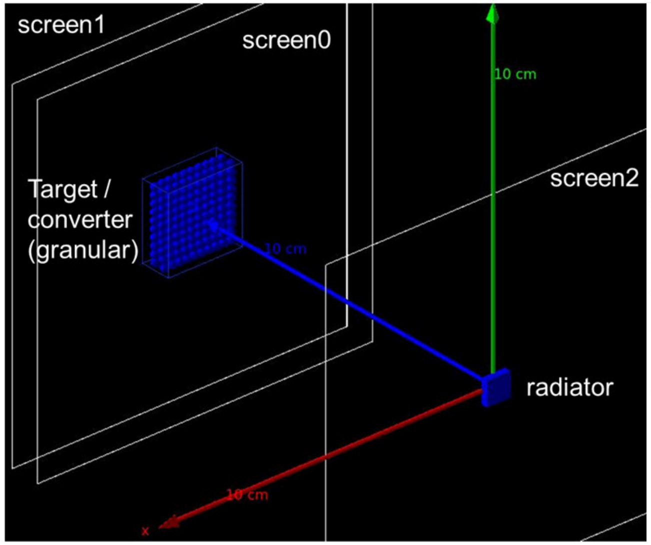
***Set-up similar to the one desribed in**: L. Bandiera et al., Eur. Phys. J. C 82, 699 (2022), where there is a also compoarison with simulations in which coherent interactions of e- in the W crystal were **simulated with CRYSTAL code** (by V. Tikhomirov).*

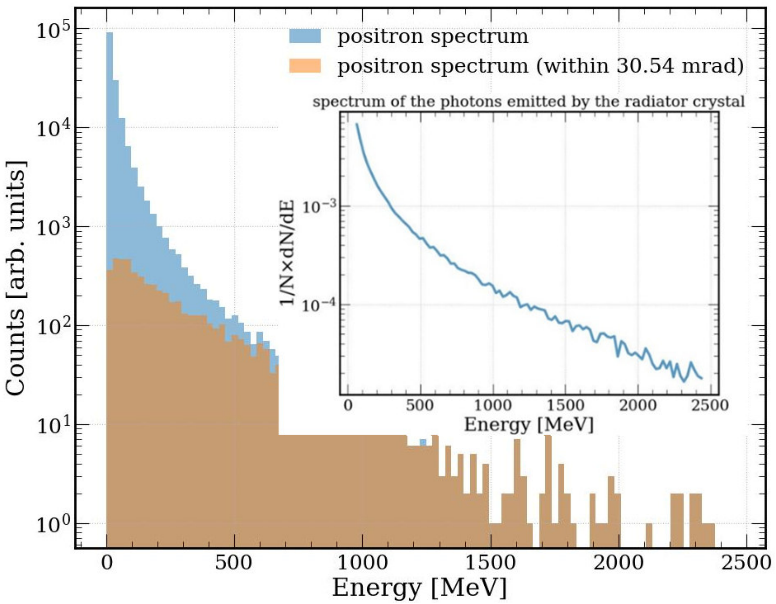
Radiative energy loss measured by the Ecal

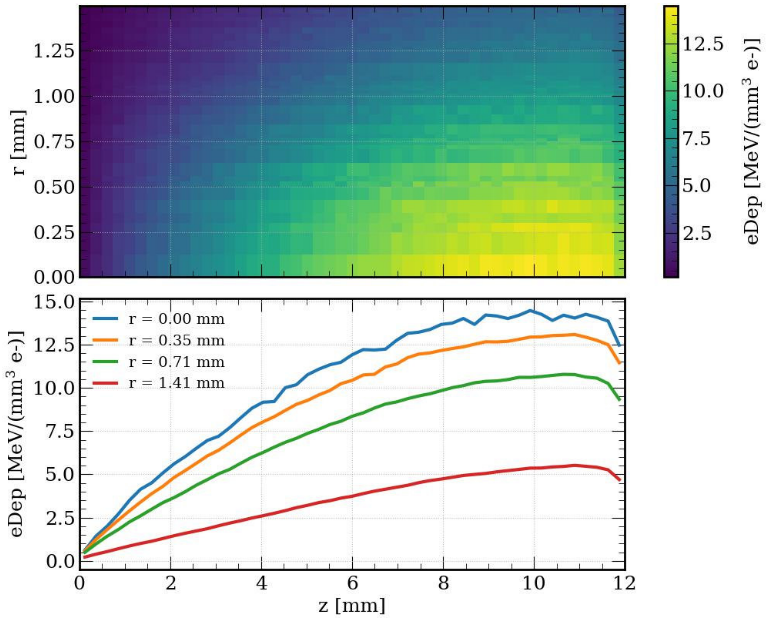


Simulation performed with Geant4 taking advantage of the novel ***G4BaierKatkov*** and ***G4ChannelingFastSimModel***.

Simulation of the e+ production stage: Geant4 **PositronSource** application







- It allow us to simulate a **crystal-based positron source**.
- The code relies on ***G4ChannelingFastSimModel*** or a phase-space (e.g. from CRYSTAL code) can be imported.
- A collimator or magnetic fields can be included in the simulation.
- Scoring of particle phase space at exit of crystals and of energy distribution inside them.
- The application is fully compatible with **multi-threading**.

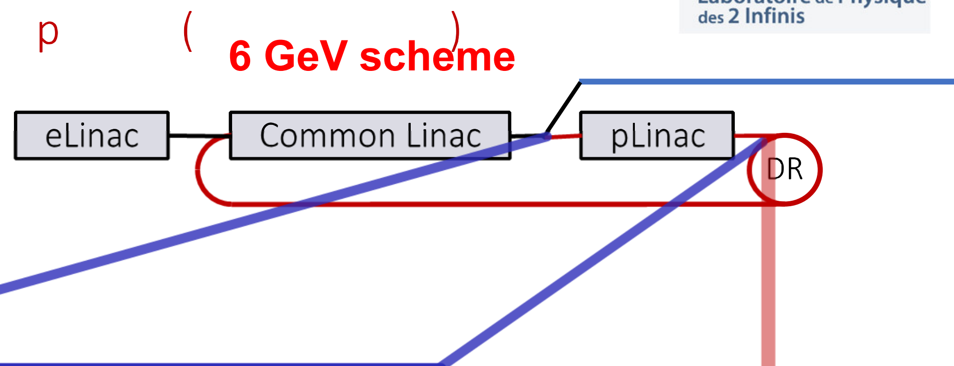
Simulation of the capture / pre-acceleration stages

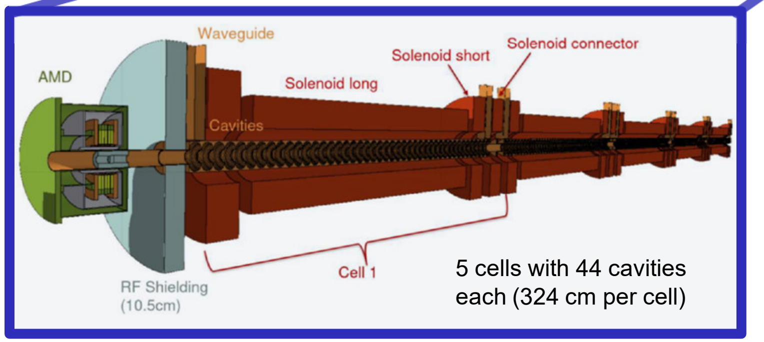
- After the production, the pair is captured in the pre-injector system.

- The main stages of the pre-injector are simulated through a set of dedicated ***RF-Track**** scripts.

*https://doi.org/10.5281/zenodo.4580369

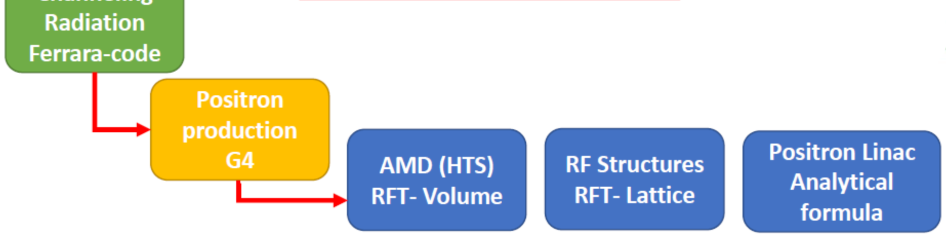
FCC-ee Injection Group - positron source task
Leader I. Chaikovska (IJCLab)





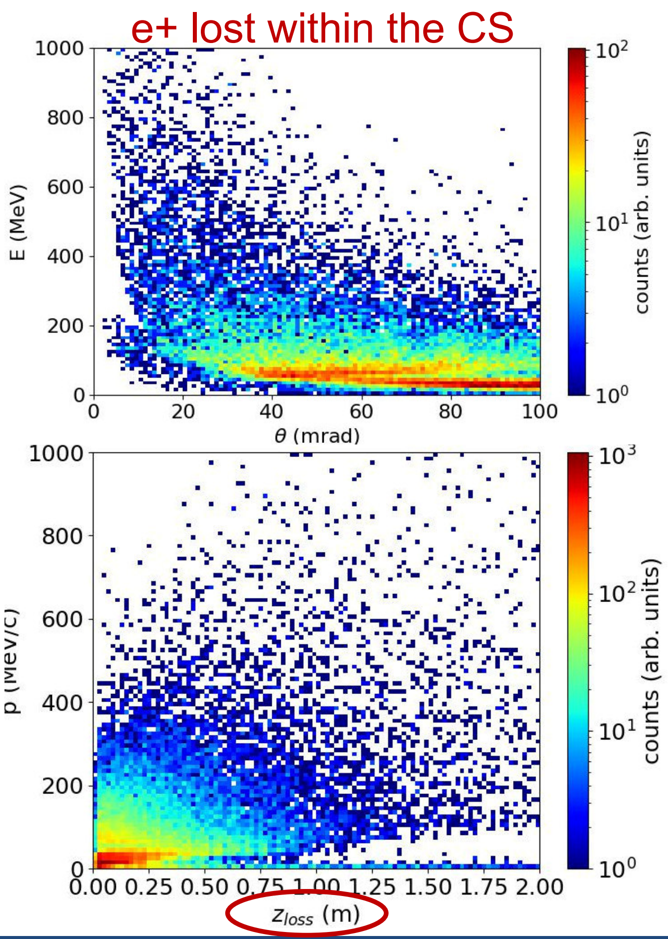
We measure the performances of e^+ sources **before the damping ring** where cooling occurs

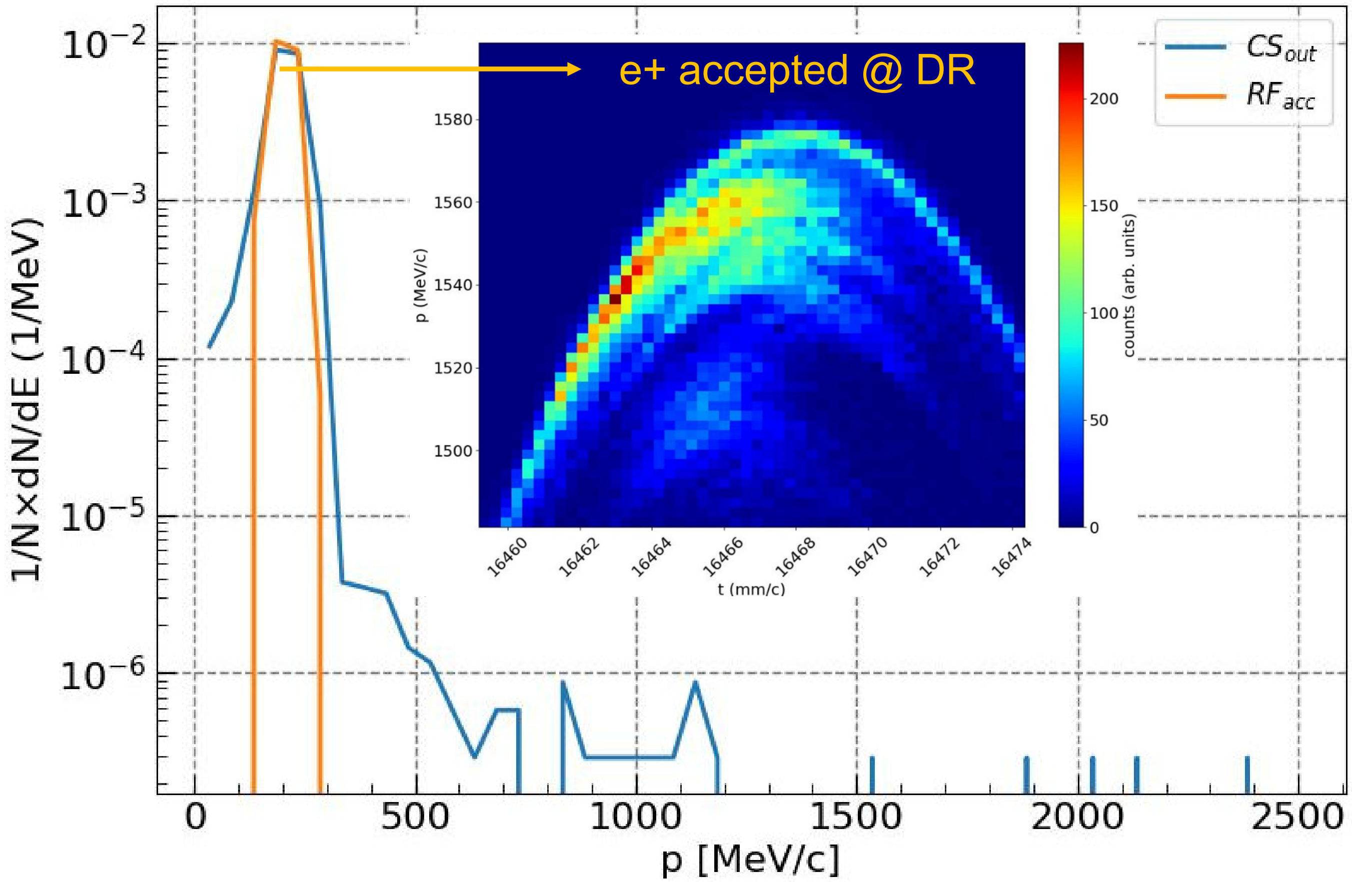
Simulation environment



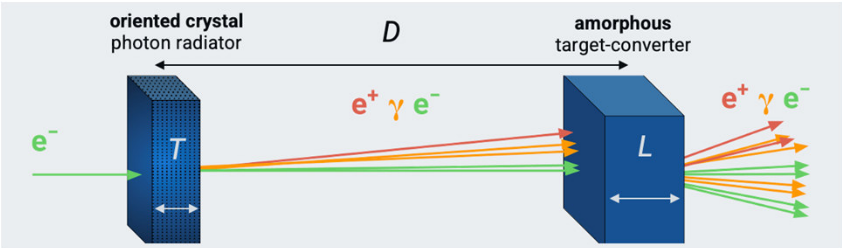
(See **F. Alharthi presentation** for details @ 2.86 GeV)

Simulation of the capture / pre-acceleration stages



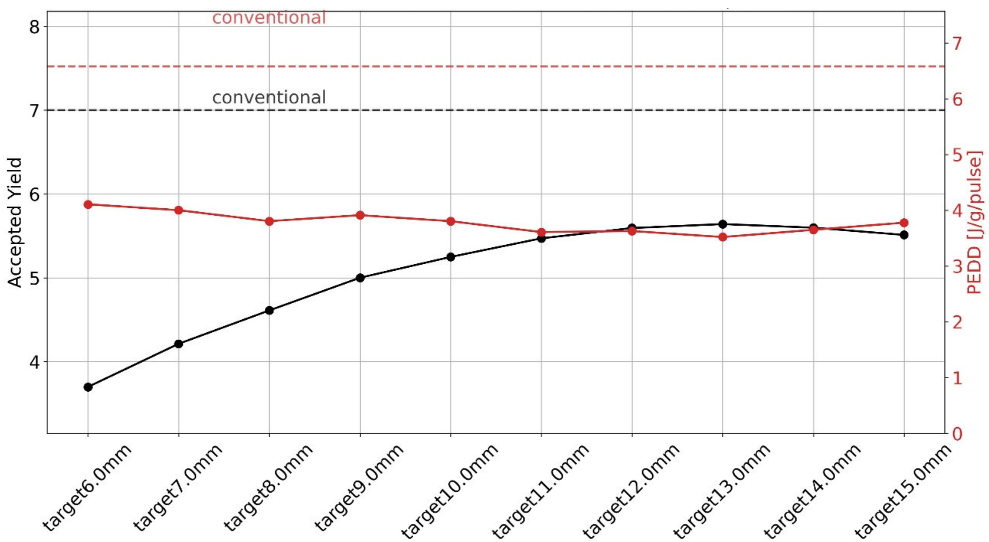


Simulation results: e+ yield after the positron linac

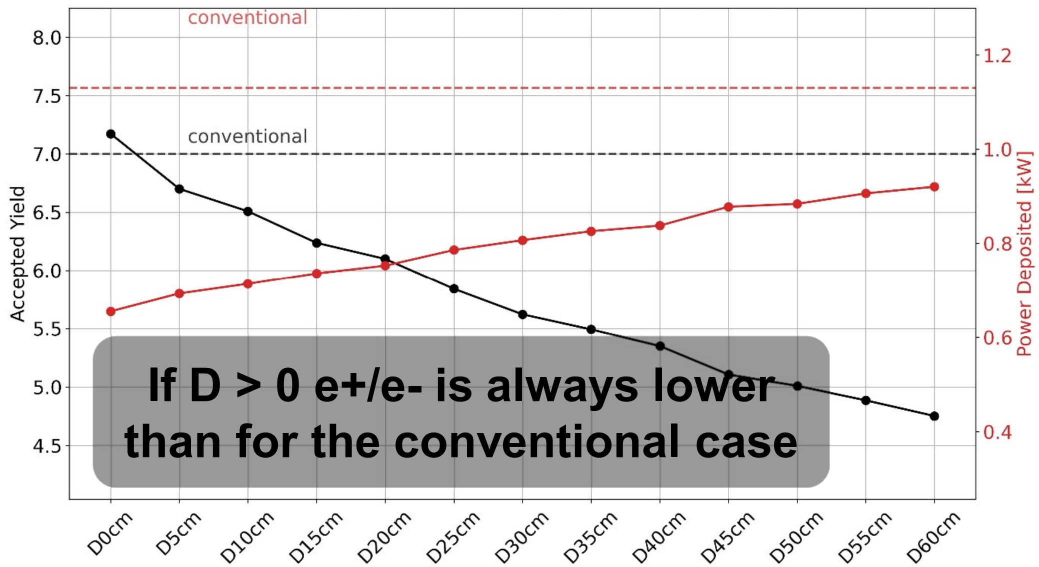


Positron yield, energy deposit and PEDD can be reduced tuning radiator *thickness (T), amorphous thickness (L)* and the distance between them (*D*)

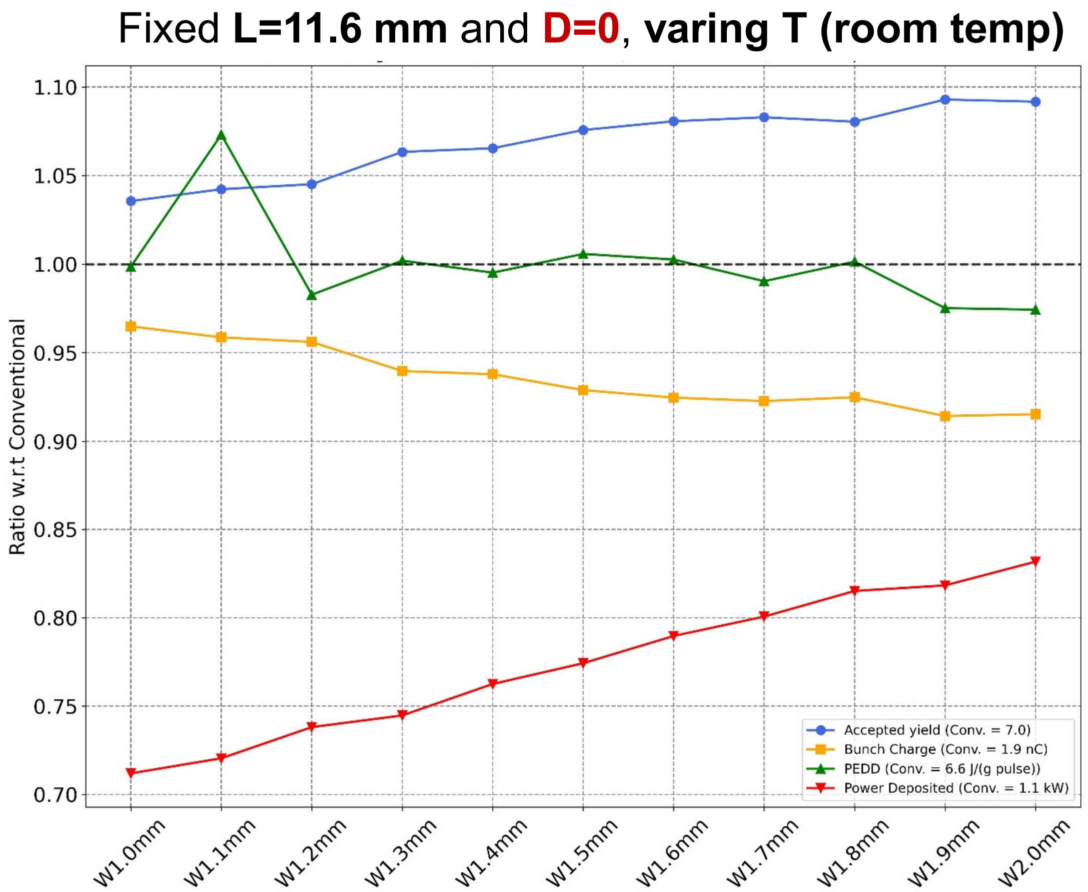
Fixed **T=2 mm** and **D=50 cm**, **varing L**

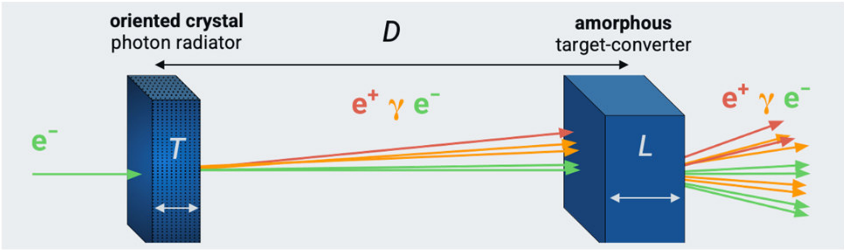


Fixed **T=2 mm** and **L=9 mm**, **varing D**



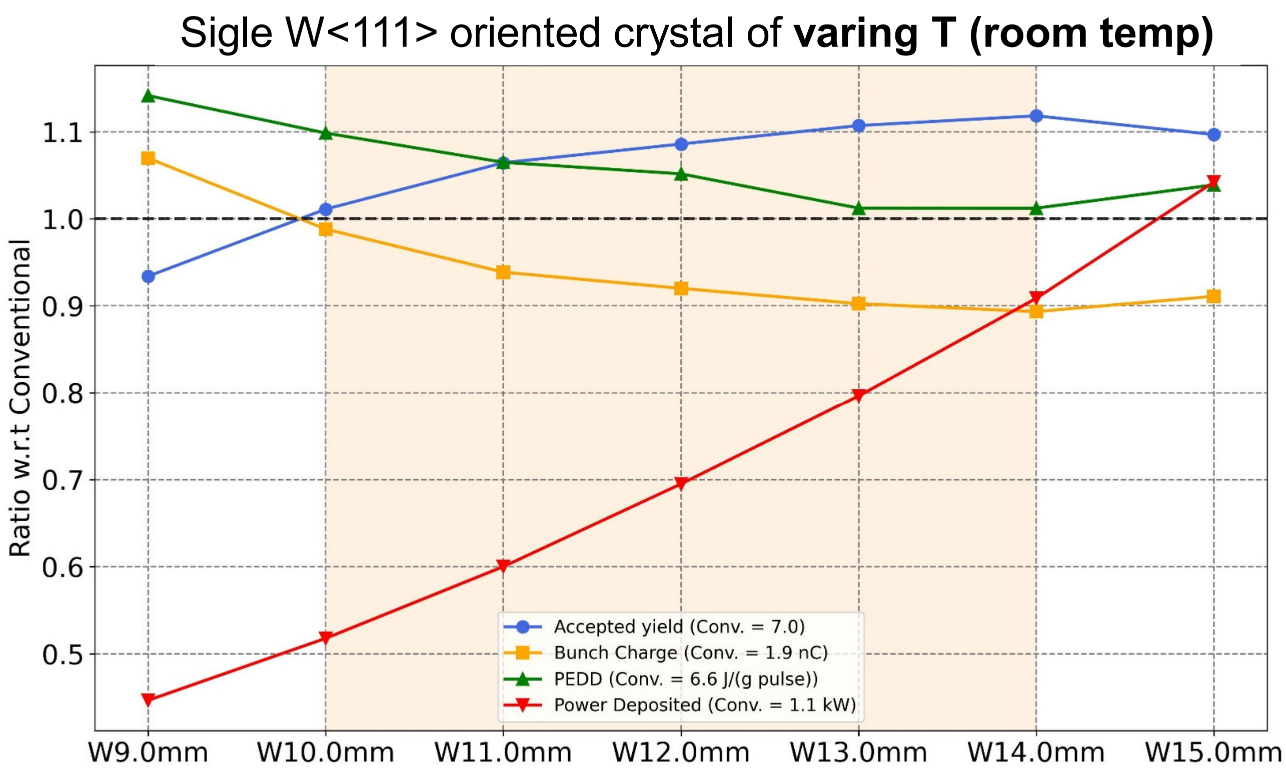
Simulation results: e+ yield after the positron linac

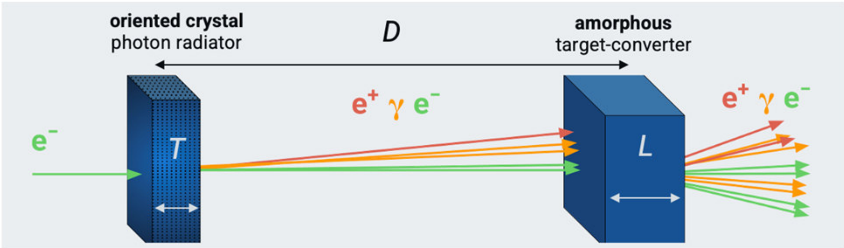




The **yield** after the capture system (and the Edep, which is however lower than for conventional) **increases with L**. The PEDD is almost constant.

Simulation results: e+ yield after the positron linac





Simulation studies converge to a **total W thickness of about 12-13 mm** (~3.4 / 3.7 X0) → need **D~0** (2 targets) or **1 thick single-crystal**

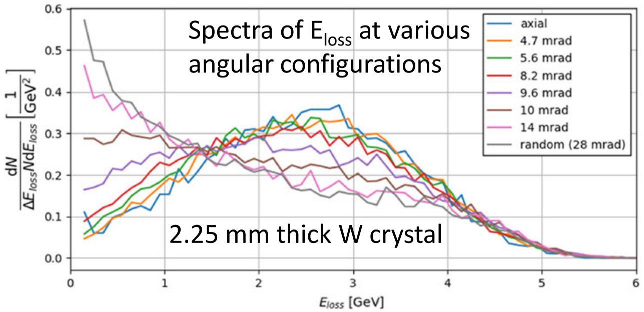
The Single Crystal **PEDD** is **acceptable** considering FCC-ee parameters [max 10.5 J/g/pulse (max measured for W 35 J/g)].

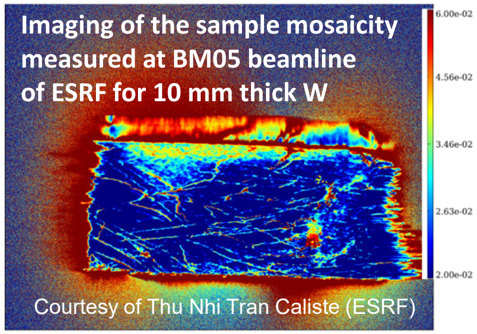
We can use **just one device** to optimize the positron source of FCC-ee

Integration and operation of the crystal target: effect of misalignments and high temperature

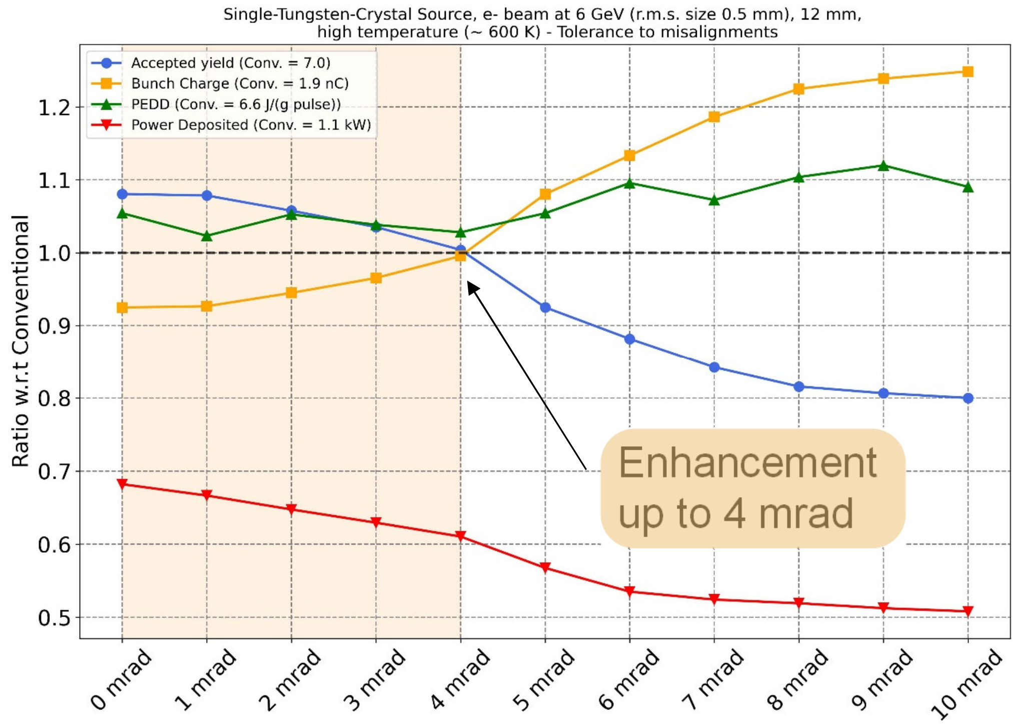
- **Crystal heating:** The photon yield drops insignificantly for temperatures ∼600 K
- **Crystal alignment:** No goniometer inside the AMD-HTS. The typical precision of the pre-alignment procedure ∼1 mrad (margins of improvement).
- **Crystal quality:** The crystalline quality of ∼ 10 mm thick W sample is lower than for a thin sample → lower yield, but larger acceptance angles.

Beam test at the DESY TB 21 with 5.6 GeV



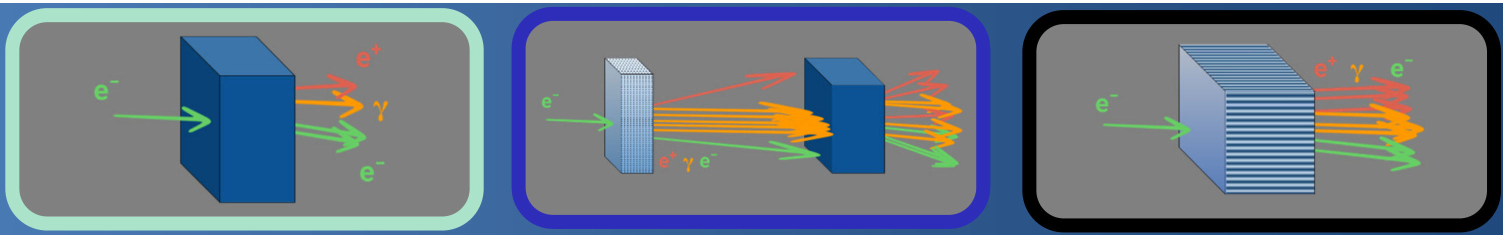


<u>At local level:</u> mosaicity is contained within 0.2 – 0.4 mrad
<u>At larger scale:</u> separate crystal domains (on 10x10x10 mm^3, total angular distribution of all the crystals domains is within 8.7 mrad)



Experimental studies and validation are needed! (tests @MAMI, DESY, CERN, potential target design validation at P3)

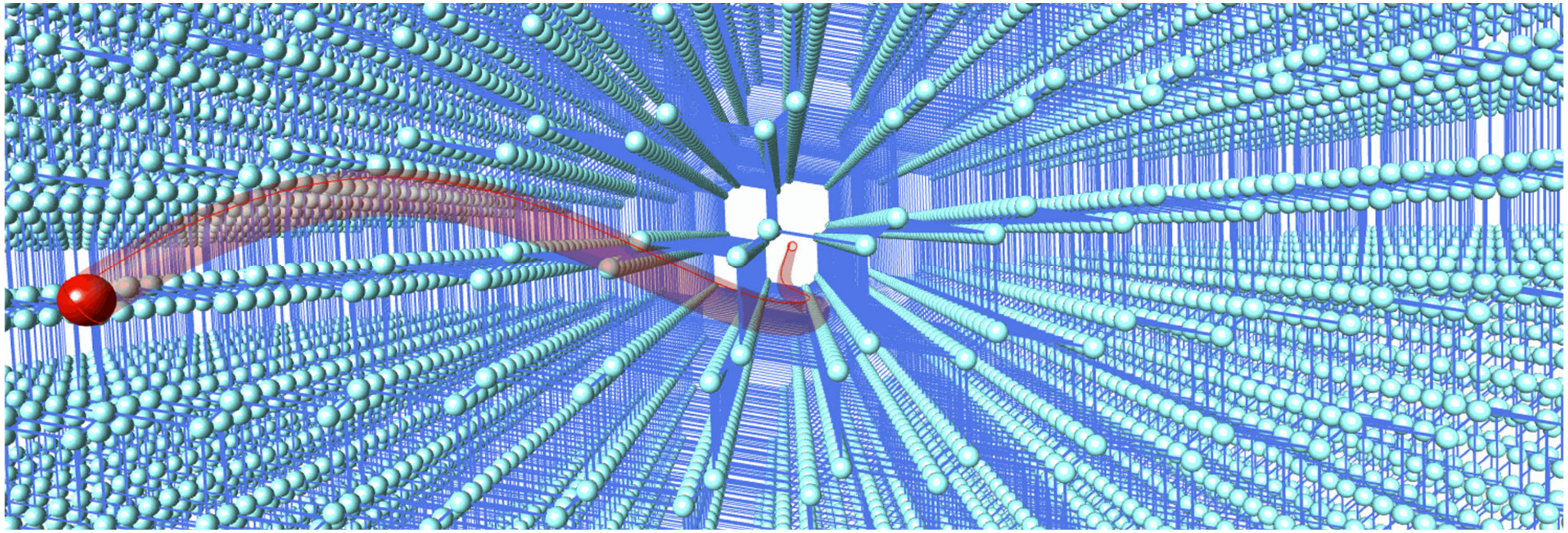
Summary and Conclusions



for 13.5 nC e^+ bunch charge @ 6 GeV	**conventional source**	**Hybrid source (D=0)**	**Single crystal**
e^+ beam energy	6 GeV	6 GeV	6 GeV
e^+ yield @ DR	7 N_{e+}/N_{e-}	7.46 N_{e+}/N_{e-} **(+6.6%)**	7.75 N_{e+}/N_{e-} **(+11%)**
Target thickness	17.5 mm (5 X_0)	11.6 + 1.4 mm (~3.7 X_0)	13 mm (~3.4 X_0)
Target deposited Power	1.13 kW	0.86 kW **(-24%)**	0.90 kW **(-20%)**
Primary e^- bunch charge	1.93 nC	1.81 nC **(-6%)**	1.74 nC **(-10%)**
Target PEDD	6.58 J/g/pulse	6.55 J/g/pulse	6.66 J/g/pulse

- A **reliable simulation framework** from the target to the positron linac **is available**.
- The **design** of a **crystal-based positron source** for the FCC-ee @ **6 GeV** is well advanced.
- **Next steps**: Carry on the **optimization @ 2.86 GeV** (see **F. Alharthi** presentation)
- **Next steps**: **integration studies** and **beam tests** with potential **proof-of-principle** at P^3 experiment @ PSI (and future CHART projects)

Thank you



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