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A crystal-based positron source for lepton colliders

Prague ICHEP 2024

Nicola Canale

on behalf of F. Alharthi, L. Bandiera, I. Chaikovska , R. Chehab, S. Carsi, D. De Salvador, V. Guidi, V. Haurylavets, G. Lezzani, L. Malagutti, S. Mangiacavalli, P. Monti Guarnieri, A. Mazzolari, V. Mytrochenko, R. Negrello, G. Paternò, M. Prest, M. Romagnoni, A. Selmi, F. Sgarbossa, M. Soldani, A. Sytov, V. Tikhomirov, E. Vallazza

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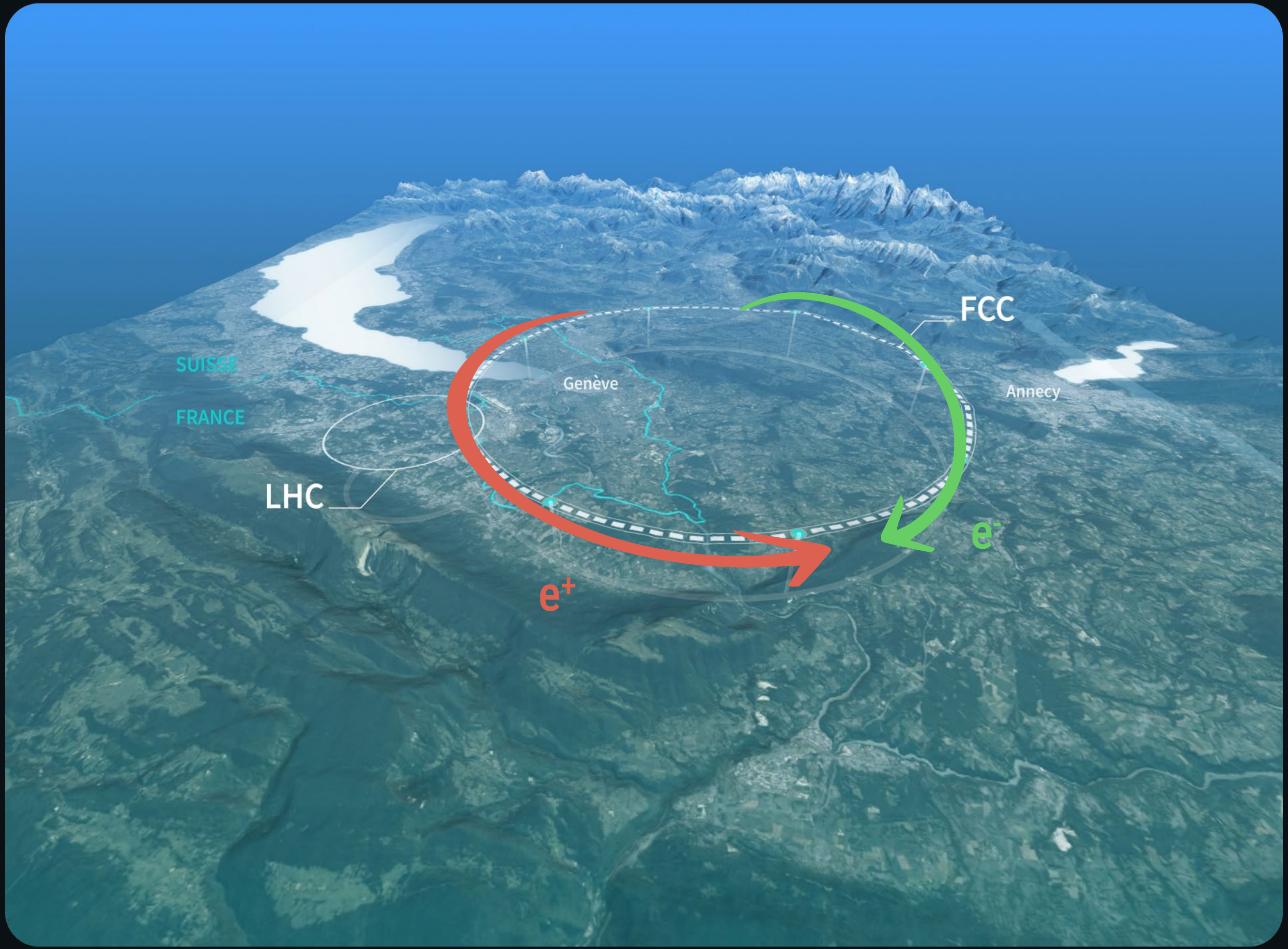
Future Circular Collider

- Future CERN collider post LHC
  ~ 91 Km of circumference
- First Stage :
  FCC-ee
- High luminosity:
  $\text{L up to } 230 \times 10^{34} cm^{-2}s^{-1}$
- CM energy :
  $\text{up to } 366\ GeV$



Fcc-ee

FUTURE CIRCULAR COLLIDER

FCC-ee operation modes

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

Frank Zimmermann, FCCWeek2024 [1]

Fcc-ee

FUTURE CIRCULAR COLLIDER

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Z*	45	1270
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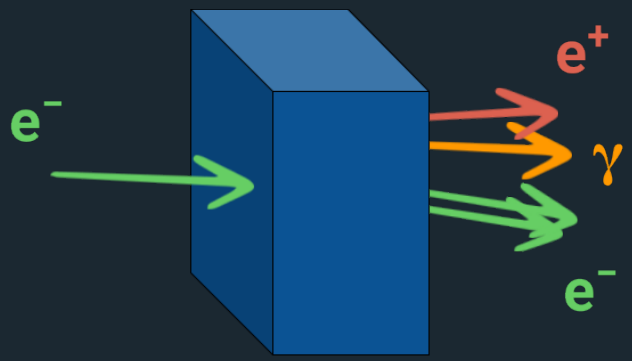
*Most demanding mode for the positron source.

Frank Zimmermann, FCCWeek2024 [1]

e^+ sources are critical for the future high-luminosity colliders

Conventional scheme



Thick amorphous
target

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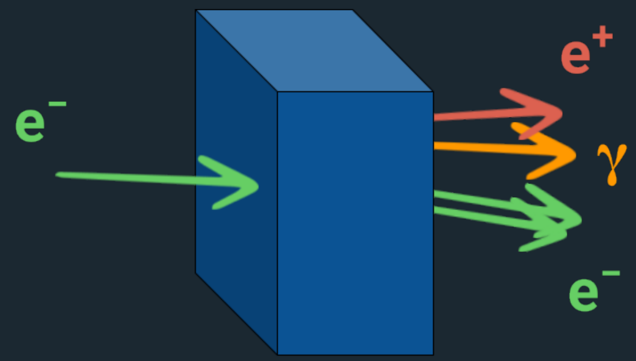

Thick amorphous
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Current (Limited by the target)

- Average energy deposition
  → target heating/melting

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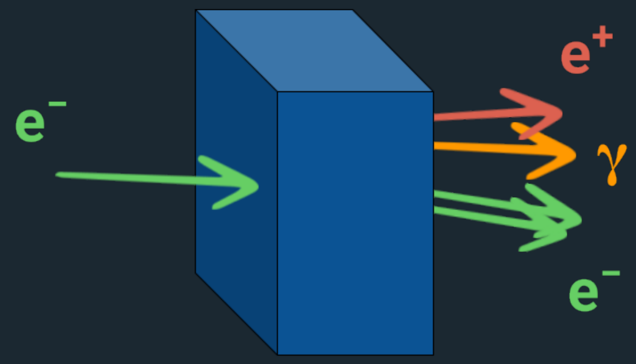

Thick amorphous target

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- Peak Energy Deposition Density (**PEDD**)
  → Inhomogeneous and instantaneous energy deposition, that cause thermomechanical stresses due to temperature gradient

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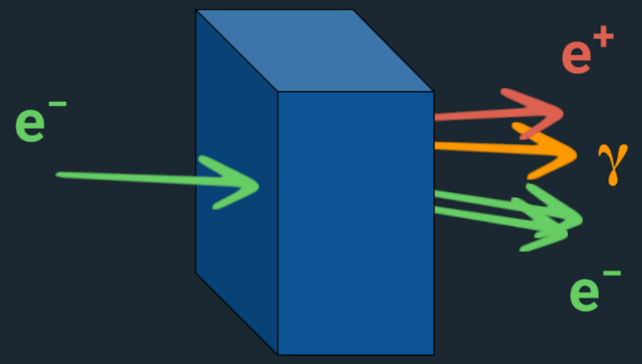

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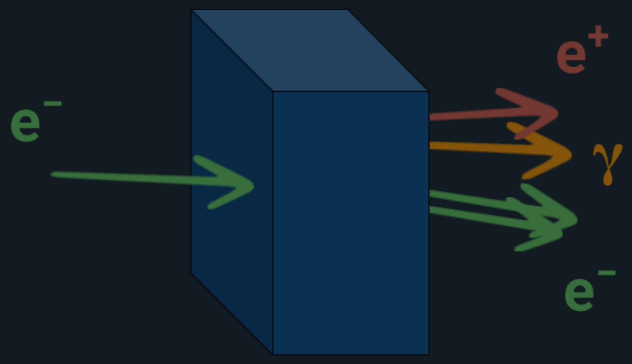
  → Inhomogeneous and instantaneous energy deposition, that cause thermomechanical stresses due to temperature gradient

e^+ source set a critical constraint for the peak and average current → **Luminosity Constraint!**
Expecially for future Linacs

Hybrid crystal based positron source for e^-e^+colliders

Idea of R. Chehab, A. Variola, V. Strakhovenko and X. Artru [3]

Conventional scheme



Thick amorphous target

Problem in future Linacs

Hybrid positron source

"Thin" oriented crystalline target ($< X_0$)
photon radiator

Amorphous
target-converter

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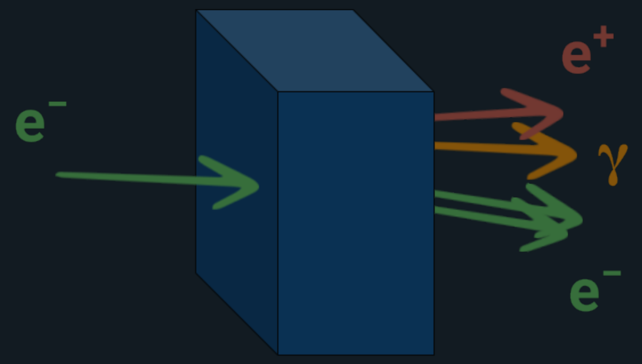

Thick amorphous target

Problem in future Linacs

Hybrid positron source

"Thin" oriented crystalline target (< X_0) **photon radiator**

Amorphous **target-converter**

"Thin" crystal radiator, with thickness < X_0 will limit the heating, enhance the radiation and thus increase the target reliability

Hybrid crystal based positron source for e^-e^+colliders

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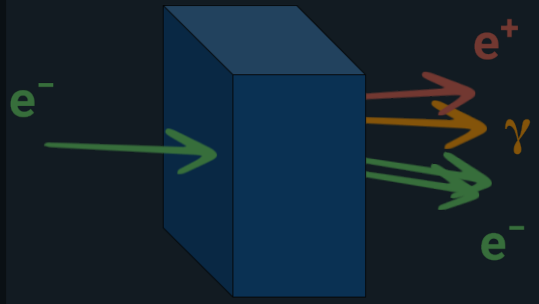
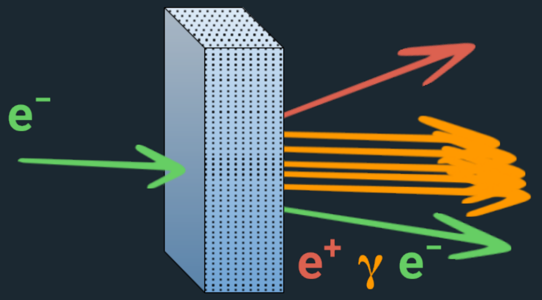


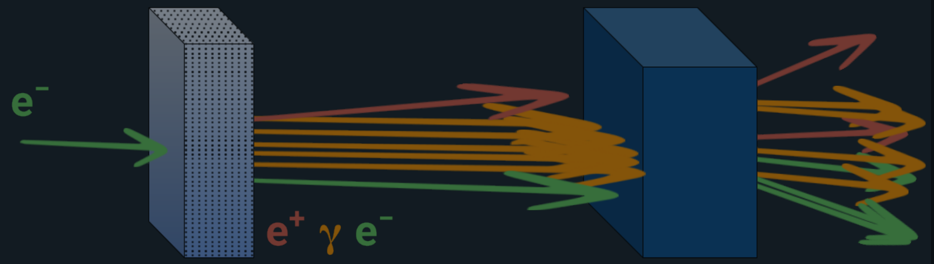
Thick amorphous target

Crystalline photon radiator



Oriented crystalline target

Hybrid positron source

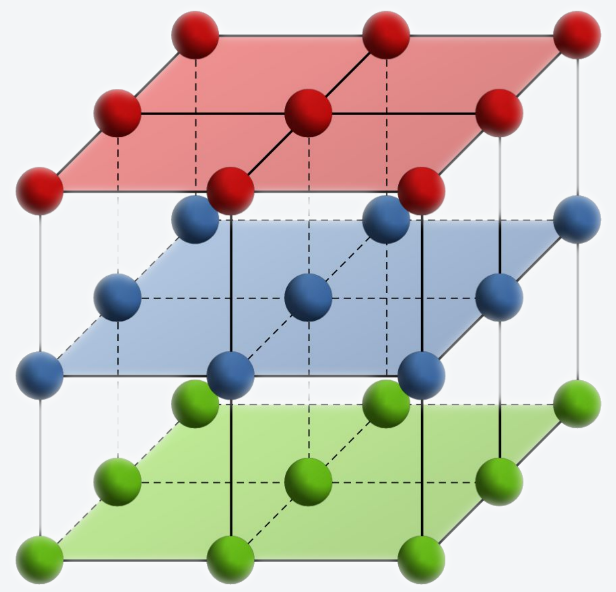


Oriented crystalline target **photon radiator**

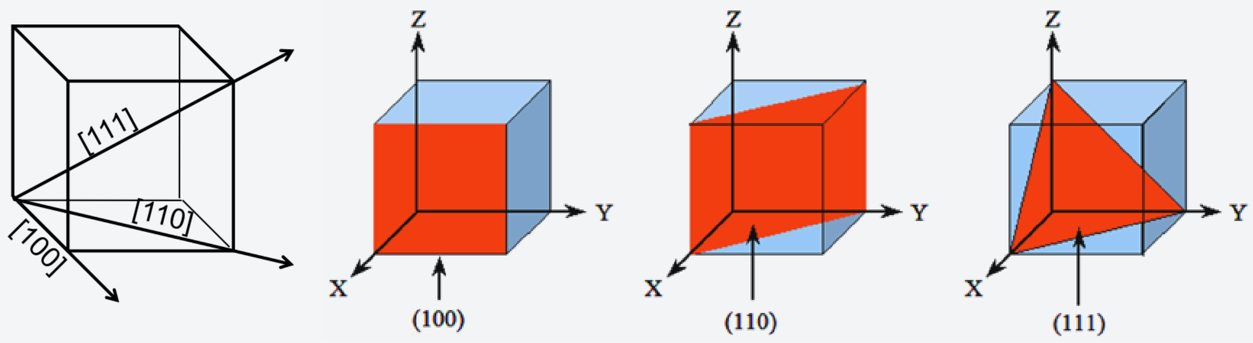
Amorphous tungsten **target-converter**

Crystalline solids

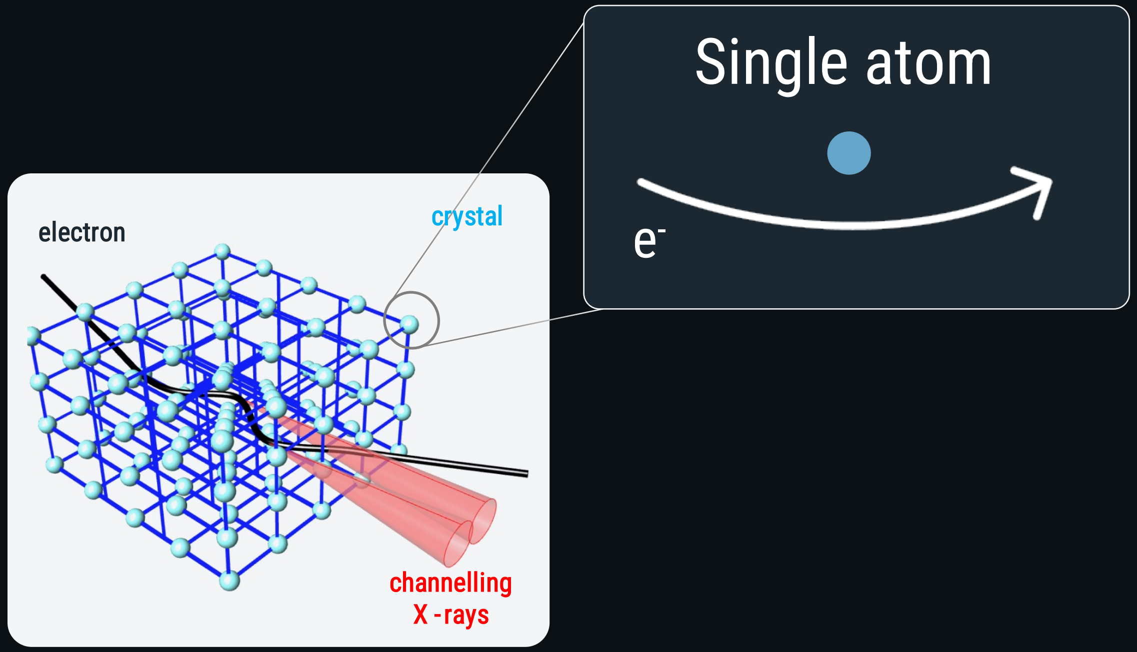
A crystal is a solid structure consisting of atoms, molecules or ions having a geometrically regular arrangement, which is repeated indefinitely in the three spatial dimensions, called the **crystal lattice**.



Simmetry: Axes and planes



Coherent effects in oriented crystals



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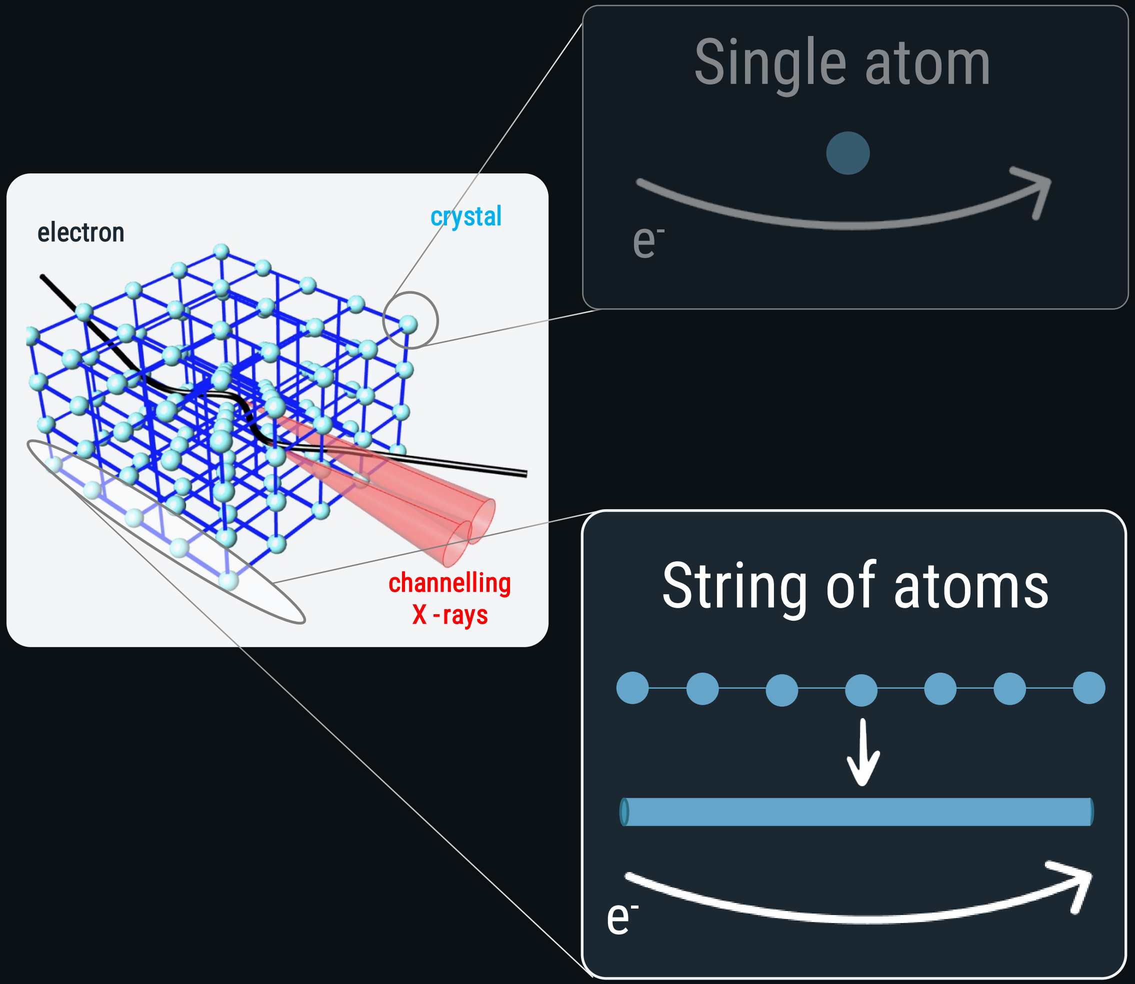
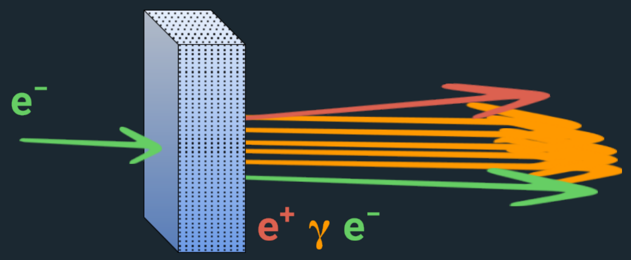
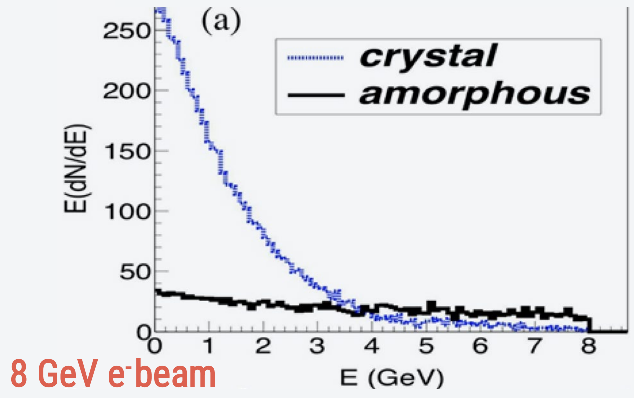


Coherent effects for crystal-based positron sources

Crystalline photon radiator



"Thin" oriented crystalline target (< X_0)
photon radiator



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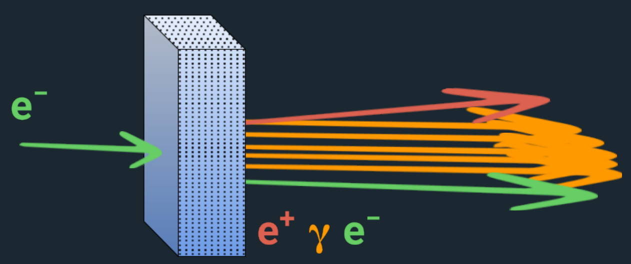

"Thin" oriented crystalline target (< X_0)
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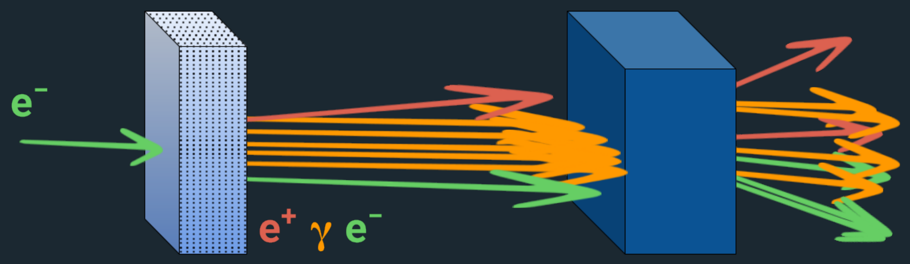
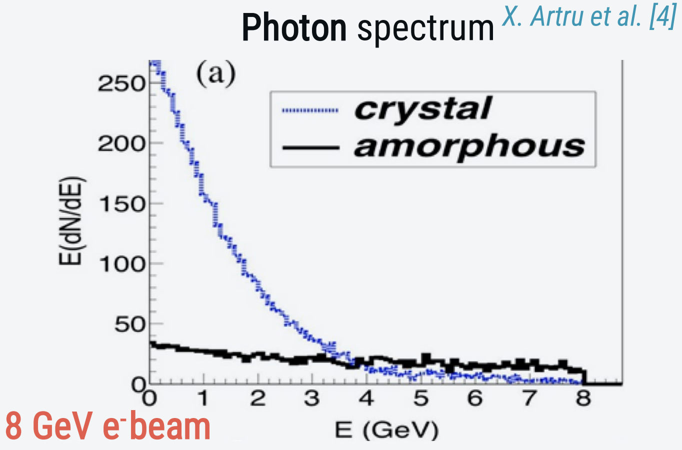
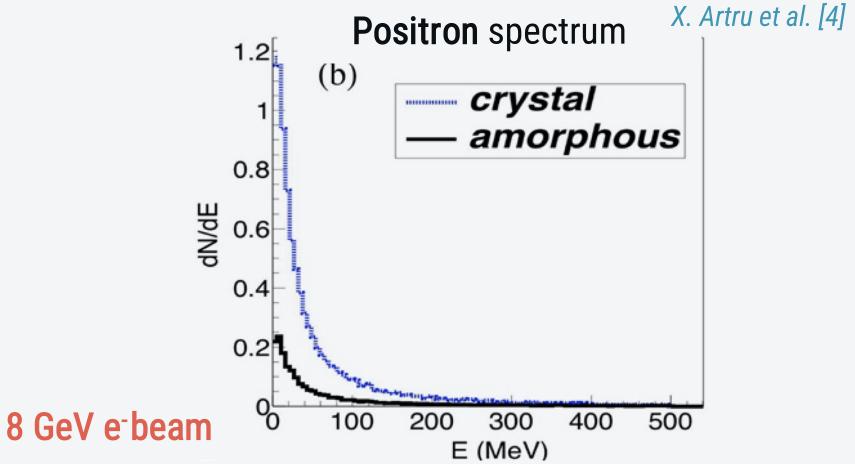
Hybrid positron source



"Thin" crystal (< X_0)
photon radiator

Amorphous
target-converter

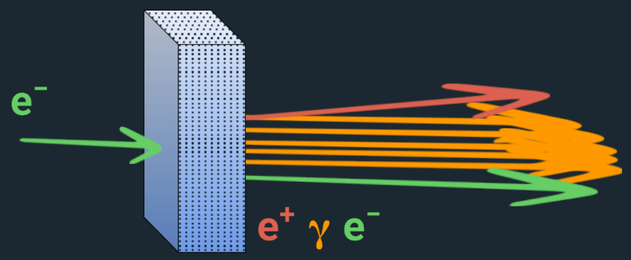




1. **Enhancement of photon generation** in crystals in coherent conditions → **enhancement of pair production** in the converter target

Coherent effects for crystal-based positron sources

Crystalline photon radiator



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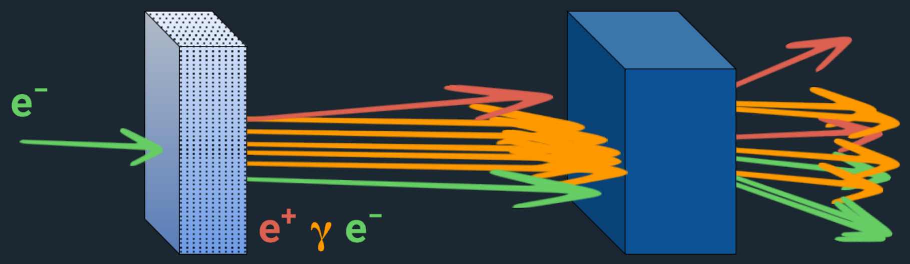

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Amorphous
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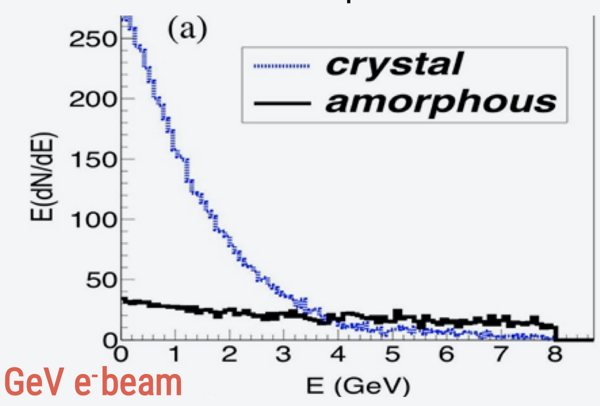
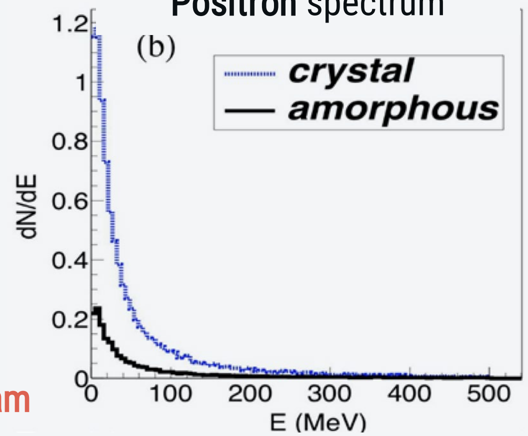
Photon spectrum *X. Artru et al. [4]*



8 GeV e⁻ beam

Positron spectrum *X. Artru et al. [4]*

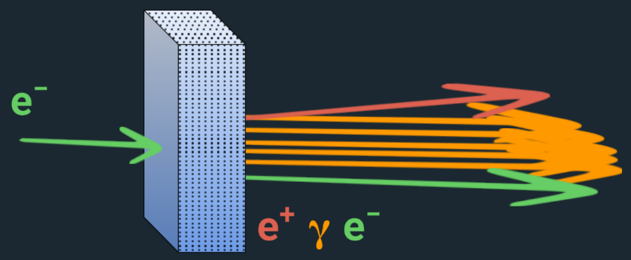


8 GeV e⁻ beam

1. **Enhancement of photon generation** in crystals in coherent conditions → **enhancement of pair production** in the converter target
2. **High rate of soft photons** → creation of soft e^+ **easily captured** in matching systems

Coherent effects for crystal-based positron sources

Crystalline photon radiator



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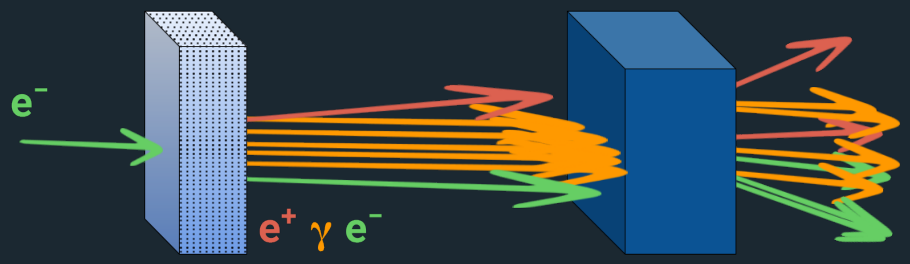

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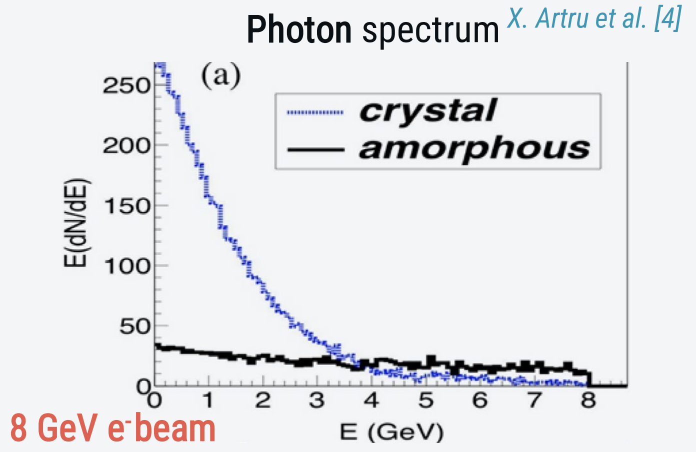
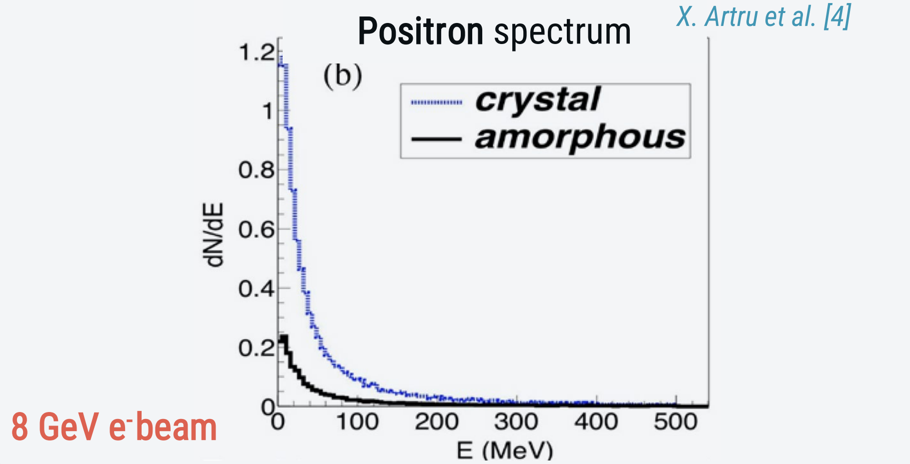


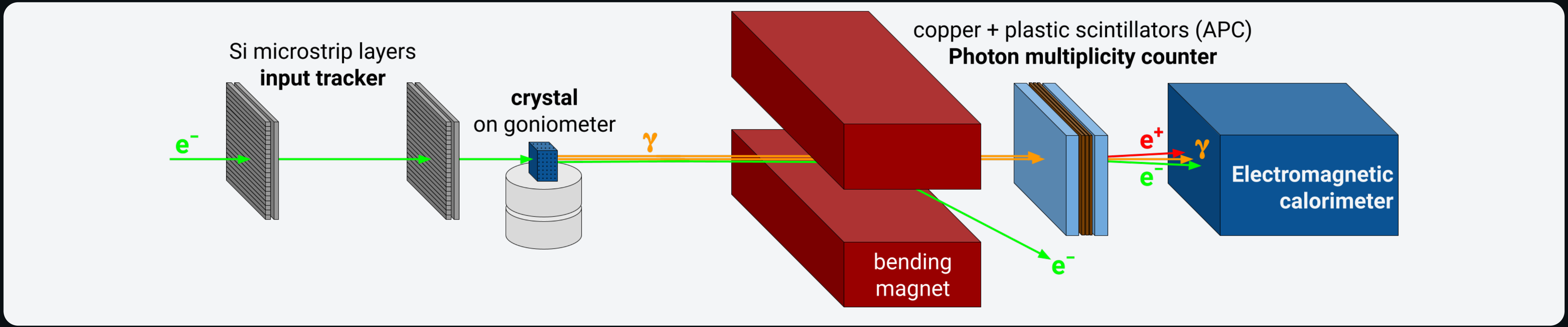


1. **Enhancement of photon generation** in crystals in coherent conditions → **enhancement of pair production** in the converter target
2. **High rate of soft photons** → creation of soft e^+ **easily captured** in matching systems
3. **Decrease of the PEDD** in the converter

Bandiera et al. [5]

FCC-ee hybrid source optimization via Geant4

Benchmark with Test Beam of crystalline radiator

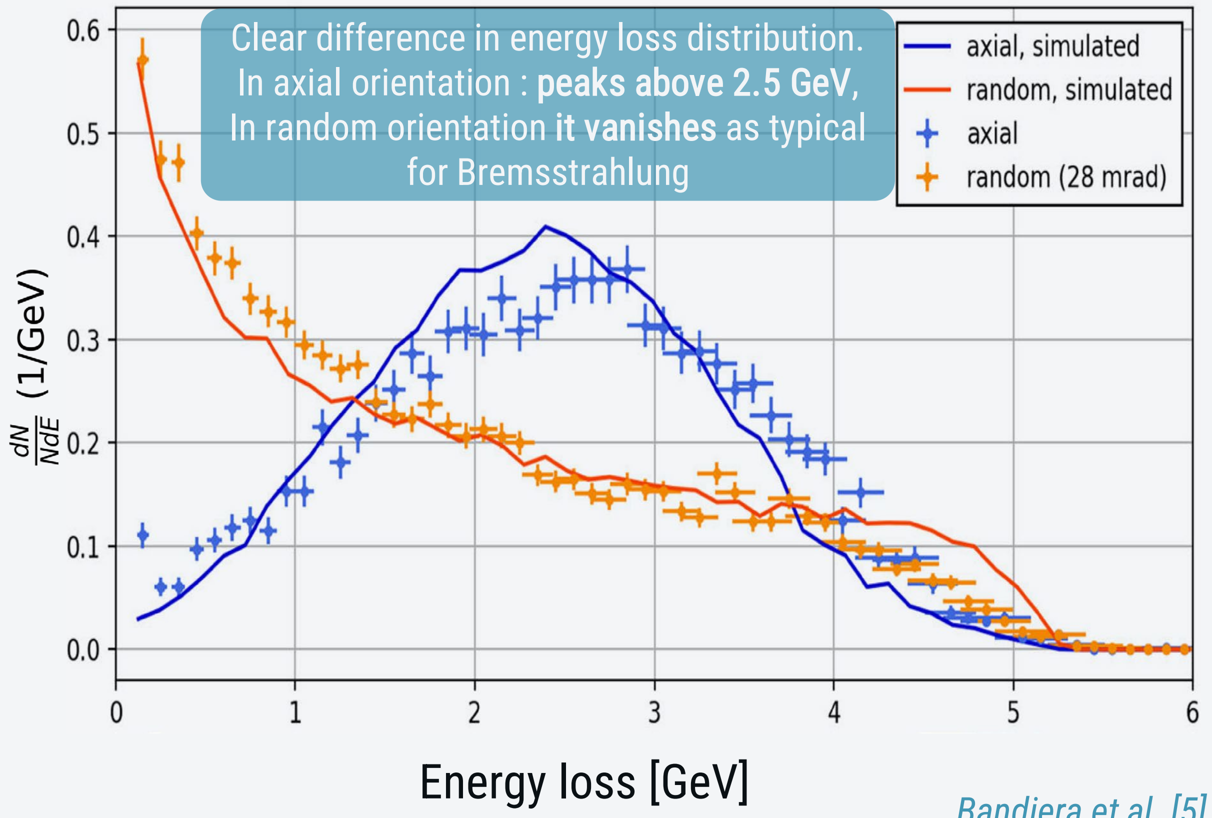


The results from beam tests conducted at DESY and CERN PS **were used to benchmark** the Monte Carlo simulation enviroment:

- The whole setup was simulated using the Geant4 toolkit with the new *G4ChannelingFastSim* library *A. Sytov et al. [6 – 7]*
- The output file encompassing all secondary γ and $e^{\pm}$ particles considers the interactions within the entire experimental setup. *Bandiera et al. [5]*

Benchmark with Test Beam of crystalline radiator

Calorimeter Signal – Energy loss of W 2.25mm (~0.65X_0) <001>



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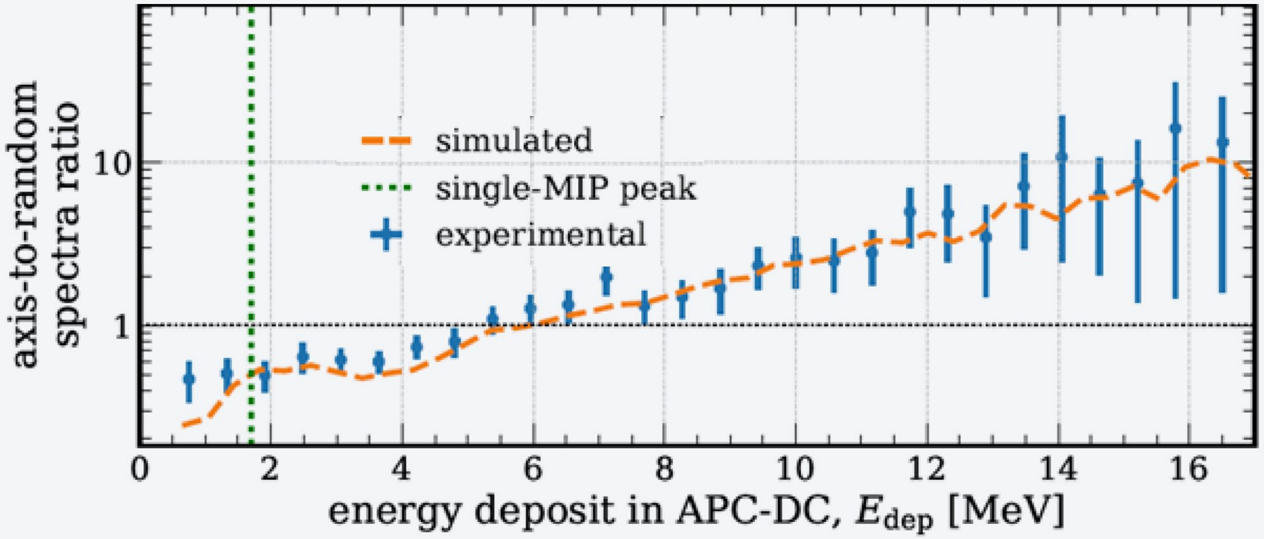
Benchmark with Test Beam of crystalline radiator

Active Photon Converter (Photon multiplicity counter)
axial to random signal of 2.25mm (~0.65X_0) <001>



Clear enhancement of photon production in axial orientation case

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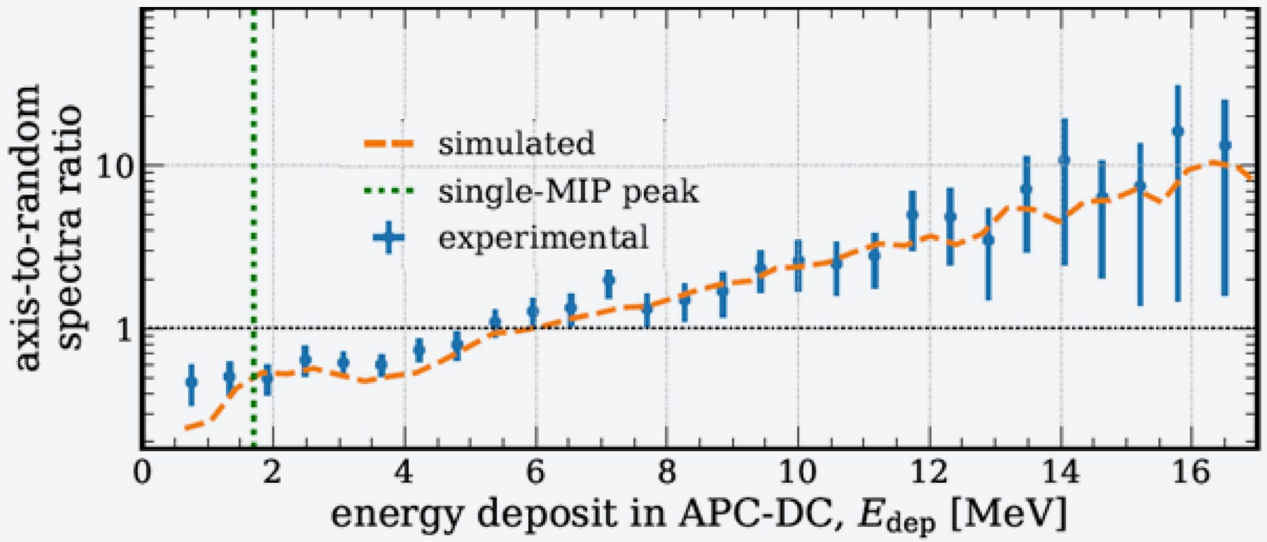

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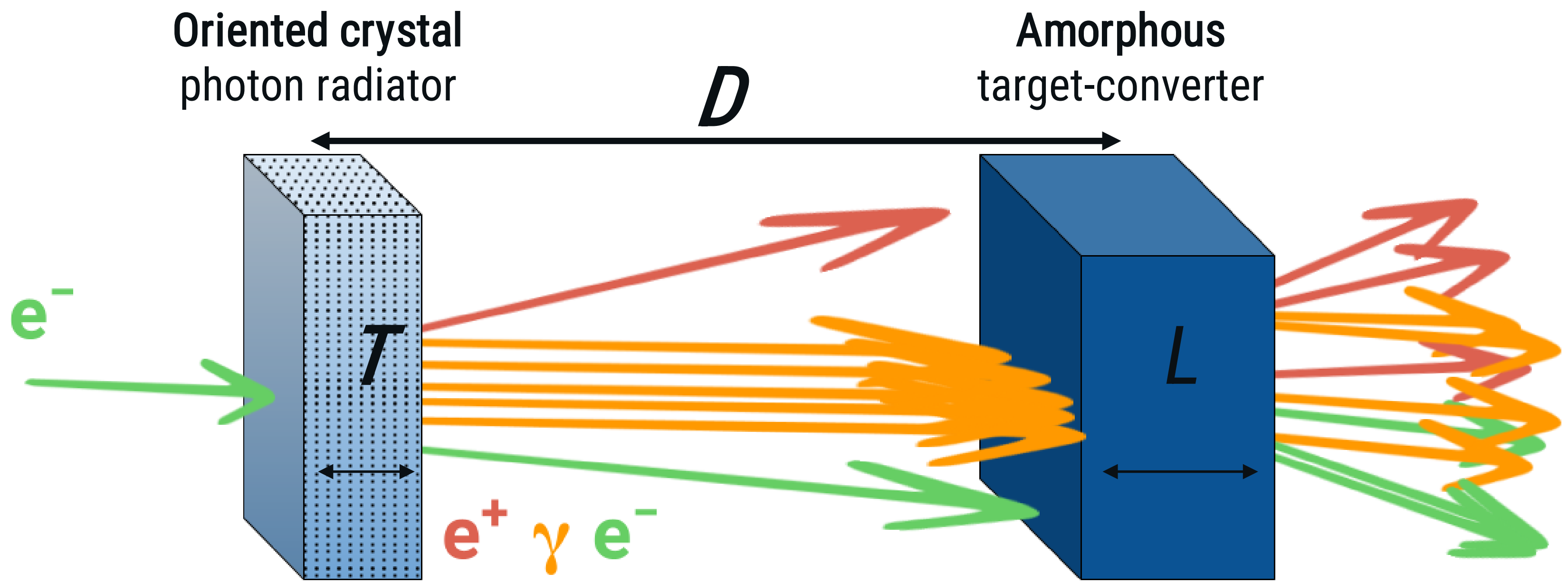
Once the **simulation environment was validated** against experimental findings, efforts were directed towards optimizing the FCC-ee hybrid scheme.

Parameters chosen for the FCC-ee hybrid source optimization via Geant4

FCC-ee hybrid source optimization via Geant4

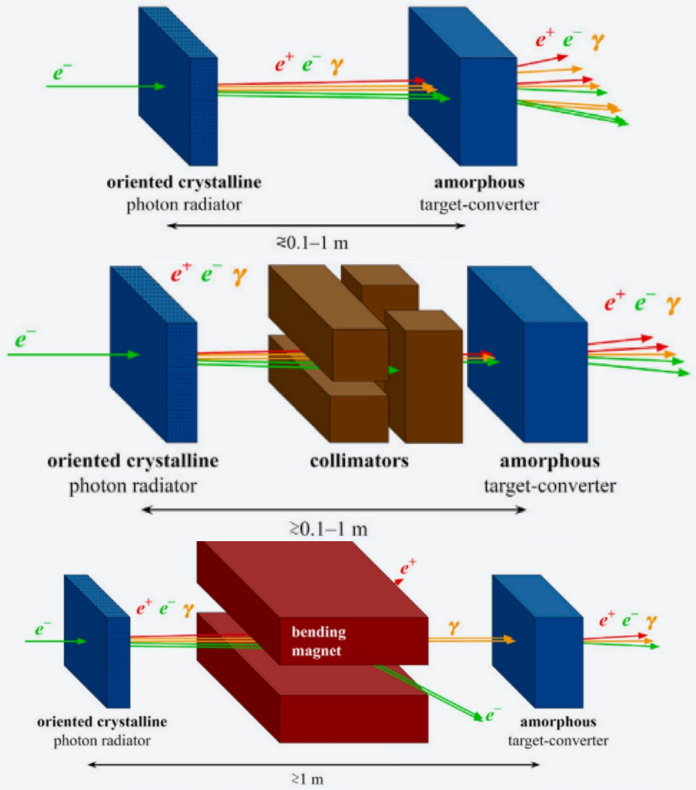


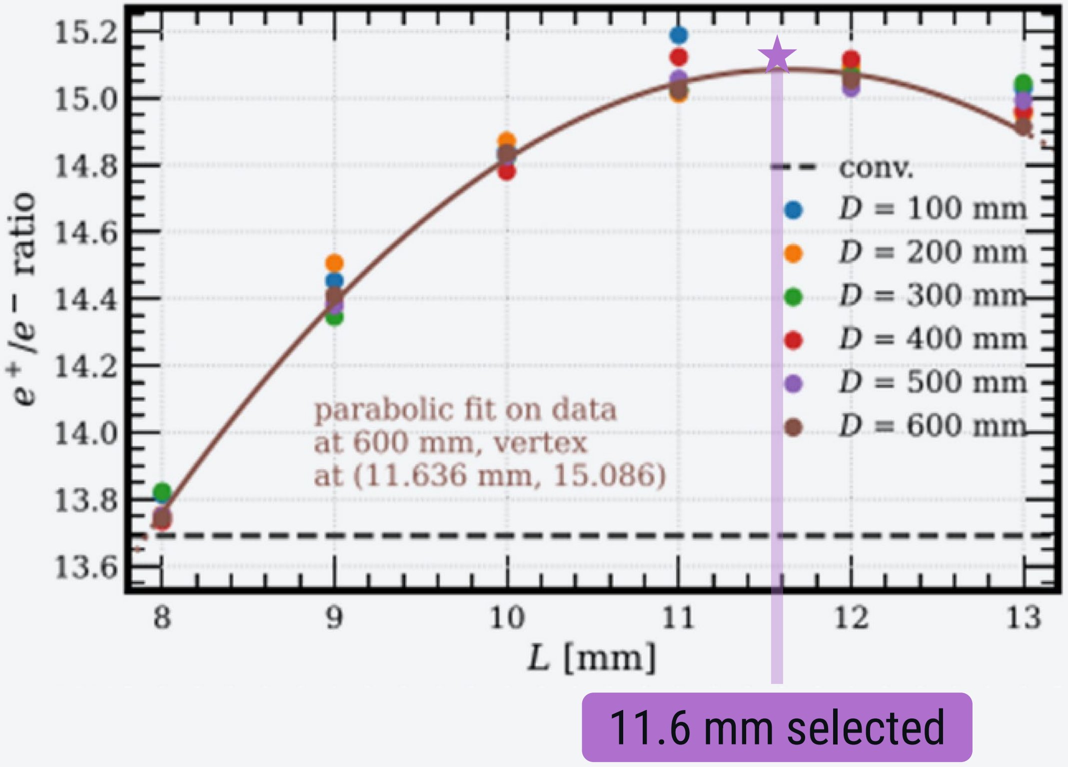
Positron yield, energy deposit and Peak Energy Deposition Density can be modified by tuning radiator *thickness (T), amorphous thickness (L)* and the distance between them (*D*).

Bandiera et al. [5]

FCC-ee hybrid source optimization via Geant4

In *M. Soldani NIM A (2024) [8]*, we focused on reducing the PEDD by changing the distance *D* and exploring the possibility of adding collimators or magnets

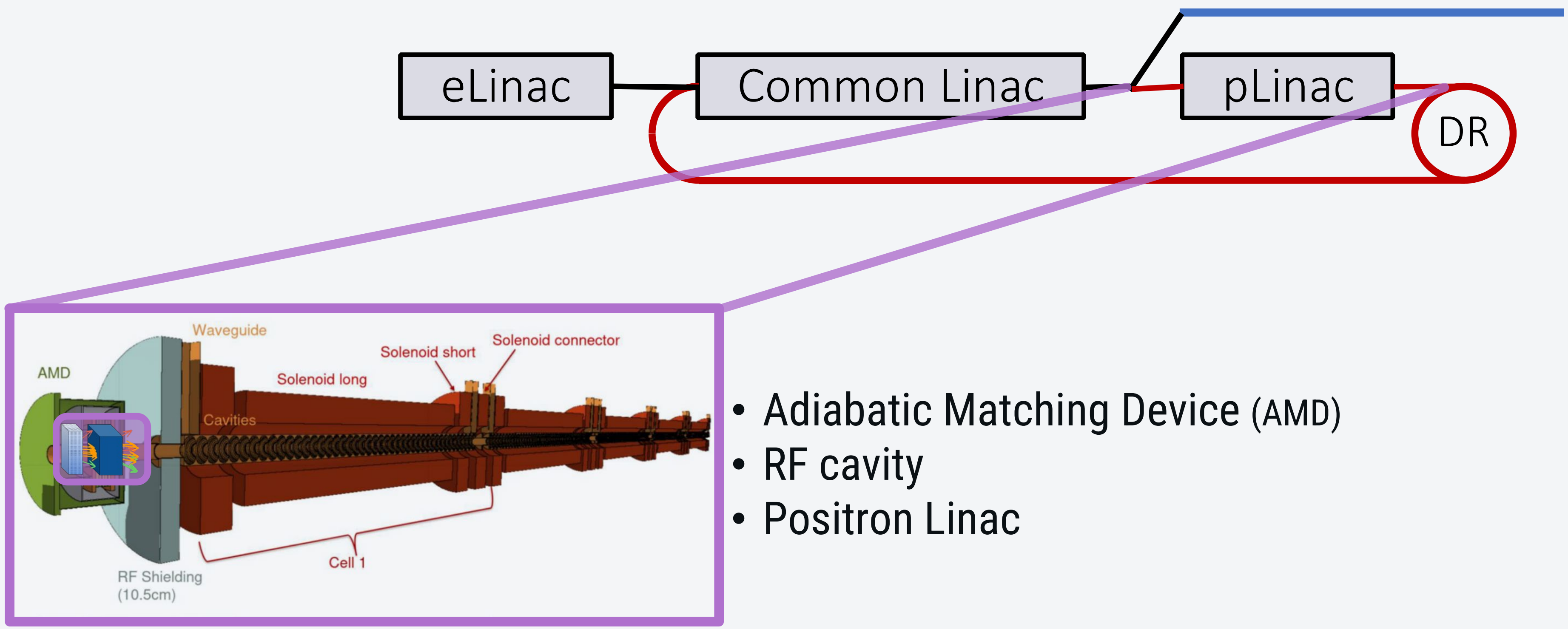




Simulate the following stages after the positron source

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

After the positron source, the pair is captured in the injector system.
The simulation stages are simulated with the framework *RF-Tracking*.



- Adiabatic Matching Device (AMD)
- RF cavity
- Positron Linac

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IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

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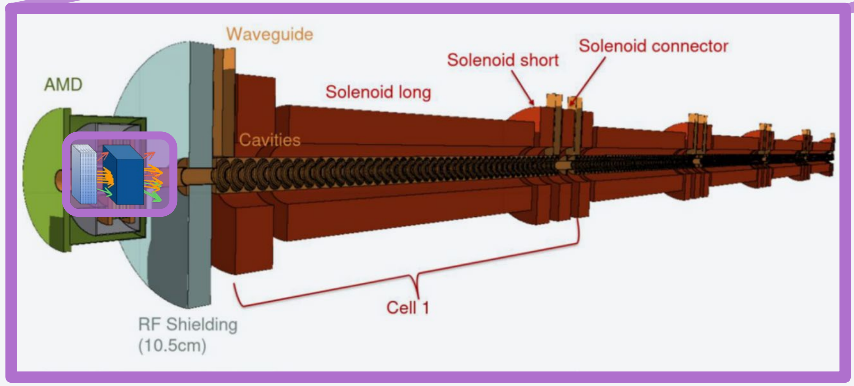

- Adiabatic Matching Device (AMD)
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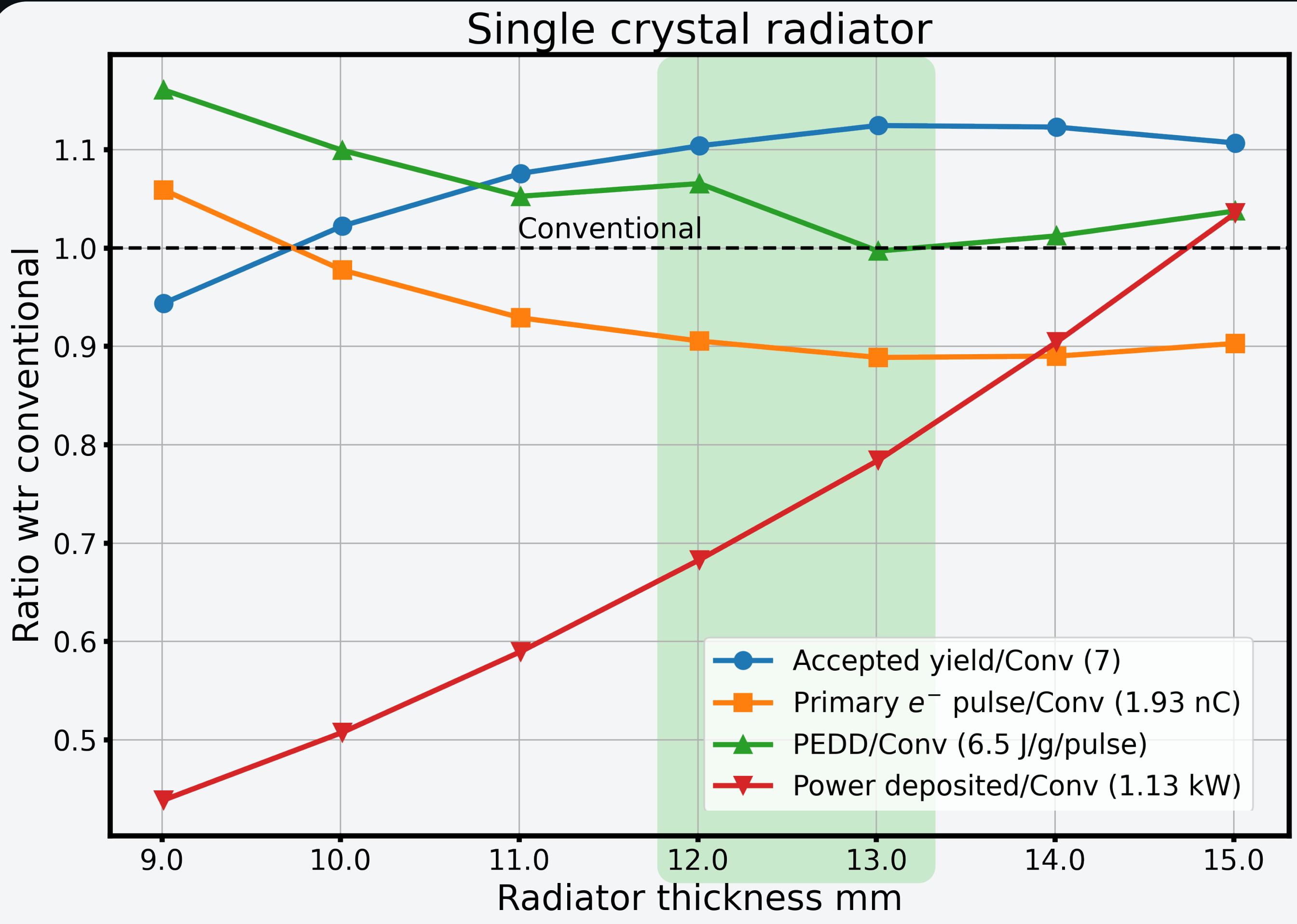
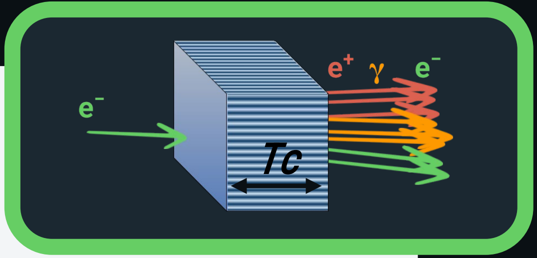
We measure the performances of e^+ sources **before the damping ring** where the cooling occurs

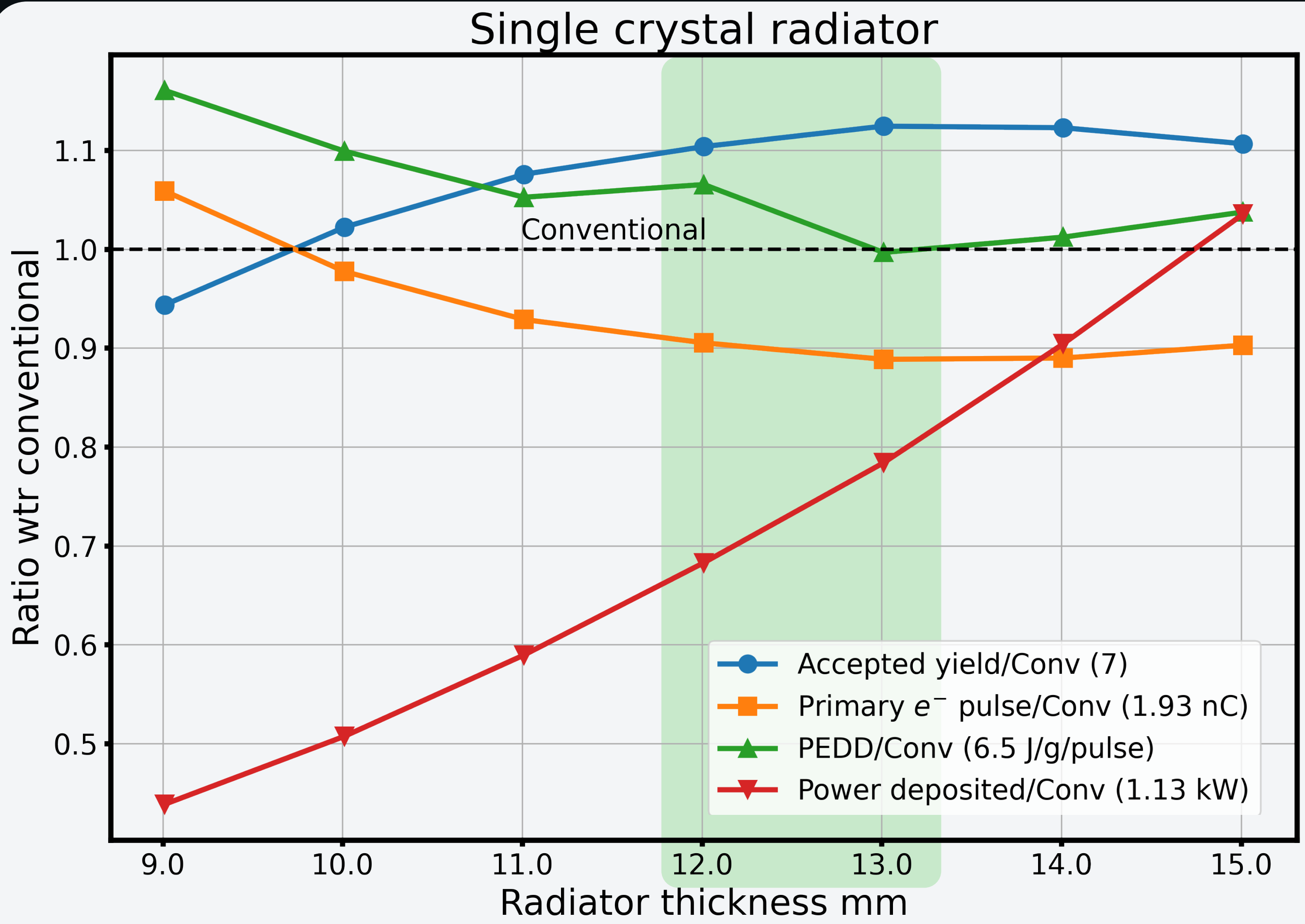
Results of Geant4 FCC-ee hybrid source optimization

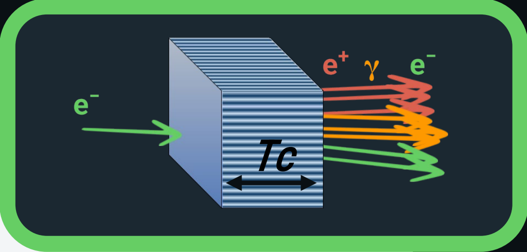




Simulation studies converge to a total W thickness of about **12-13 mm** **(~3.4 / 3.7 X_0),** performances are increasing **if D~0** (2 targets) or a single thick crystal

Results of Geant4 FCC-ee hybrid source optimization





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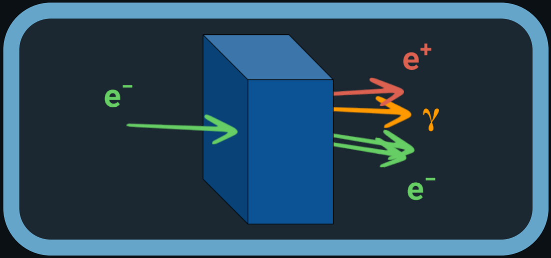
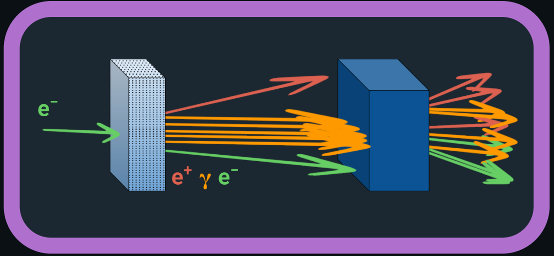
The Single Crystal **PEDD** is **acceptable** considering FCC-ee parameters.

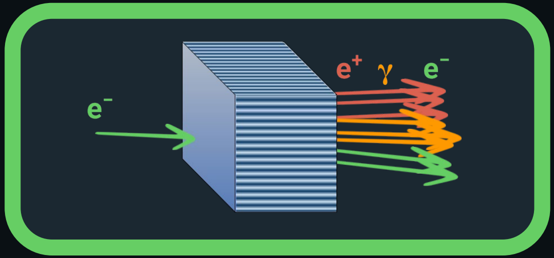
The **performances** are very **similar** to the hybrid source.

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

Summary

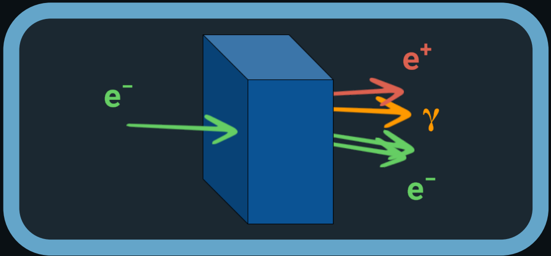


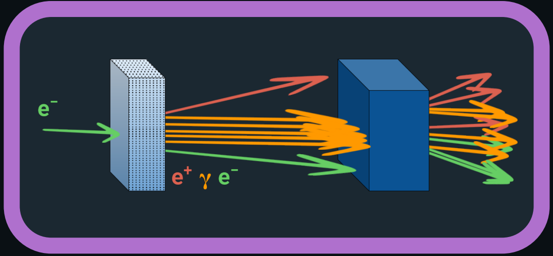


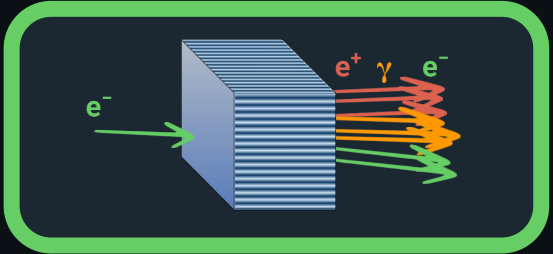


for 13.5 nC e^+ bunch charge	**Conventional source** *Iryna Chaikovska, FCC Week2024 [2]*	**Hybrid source**	**Single crystal**
e^+ beam energy	6 GeV	6 GeV	6 GeV
e^+ yield @DR	7 N_{e+}/N_{e-}	7.36 N_{e+}/N_{e-} (+5%)	7.87 N_{e+}/N_{e-} (+12%)
Target thickness	17.5 mm (5 X_0)	11.6 + 1.4 mm (~3.7 X_0)	13 mm (~3.7 X_0)
Target deposited Power	1.3 kW	0.88 kW (-32%)	0.89 kW (-31%)
Primary e^- bunch charge	1.93 nC	1.83 nC (-5%)	1.72 nC (-11%)
Target PEDD	6.5 J/g/pulse	6.41 J/g/pulse	6.48 J/g/pulse

Summary







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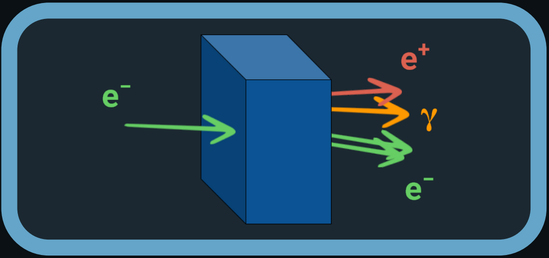
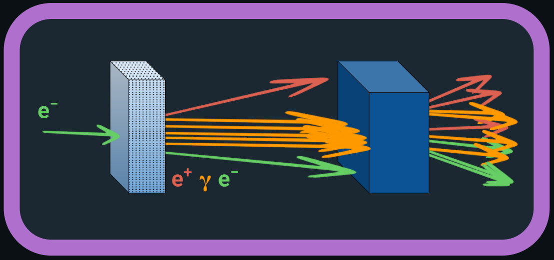
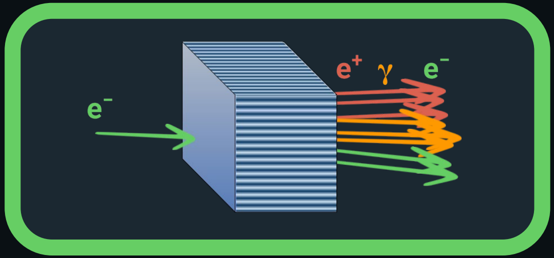
e^+ beam energy	6 GeV	6 GeV	6 GeV
e^+ yield @DR	7 N_{e+}/N_{e-}	7.36 N_{e+}/N_{e-} **(+5%)**	7.87 N_{e+}/N_{e-} **(+12%)**
Target thickness	17.5 mm (5 X_0)	11.6 + 1.4 mm (~3.7 X_0)	13 mm (~3.7 X_0)
Target deposited Power	1.3 kW	0.88 kW **(-32%)**	0.89 kW **(-31%)**
Primary e^- bunch charge	1.93 nC	1.83 nC **(-5%)**	1.72 nC **(-11%)**
Target PEDD	6.5 J/g/pulse	6.41 J/g/pulse	6.48 J/g/pulse

The design of a **crystal-based positron source** for the FCC-ee is well-advanced.

Summary





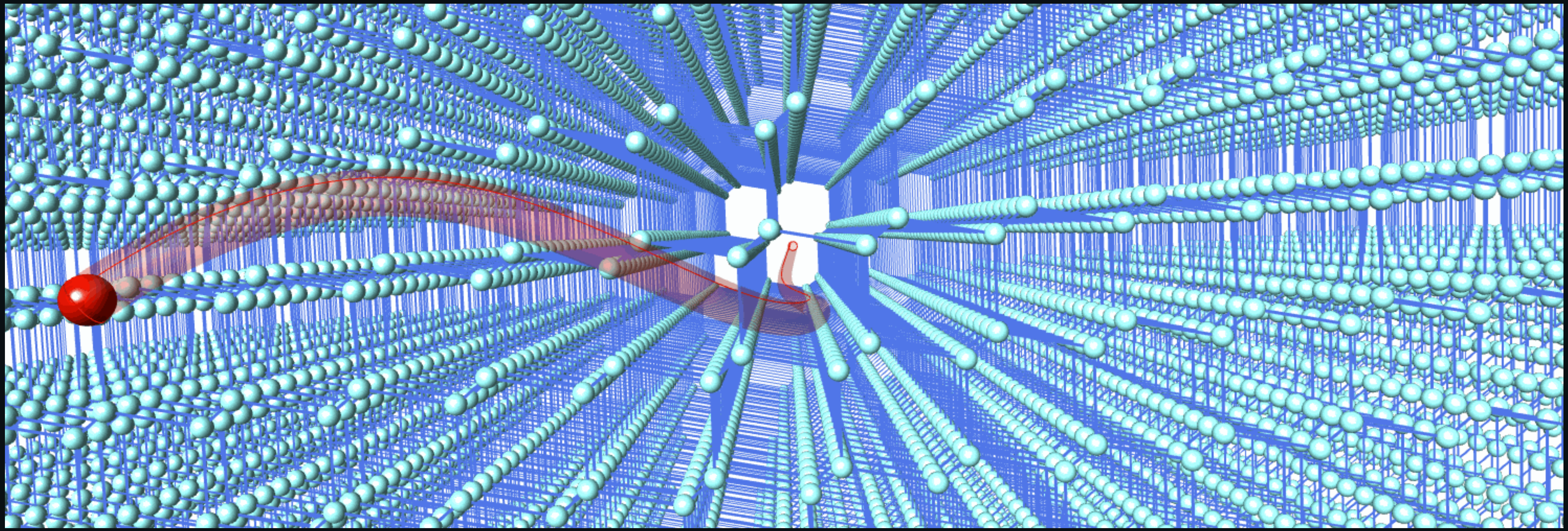


for 13.5 nC e^+ bunch charge	**Conventional source** *Iryna Chaikovska, FCC Week2024 [2]*	**Hybrid source**	**Single crystal**
e^+ beam energy	6 GeV	6 GeV	6 GeV
e^+ yield @DR	7 N_{e+}/N_{e-}	7.36 N_{e+}/N_{e-} (+5%)	7.87 N_{e+}/N_{e-} (+12%)
Target thickness	17.5 mm (5 X_0)	11.6 + 1.4 mm (~3.7 X_0)	13 mm (~3.7 X_0)
Target deposited Power	1.3 kW	0.88 kW (-32%)	0.89 kW (-31%)
Primary e^- bunch charge	1.93 nC	1.83 nC (-5%)	1.72 nC (-11%)
Target PEDD	6.5 J/g/pulse	6.41 J/g/pulse	6.48 J/g/pulse

The design of a **crystal-based positron source** for the FCC-ee is well-advanced.

NEXT STEPS: **integration studies** and **beam tests** with potential **proof-of-principle** at P^3 experiment @ PSI

Thank you



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References and Aknowledgment

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