UPDATE ON HYBRID TARGET SIMULATIONS

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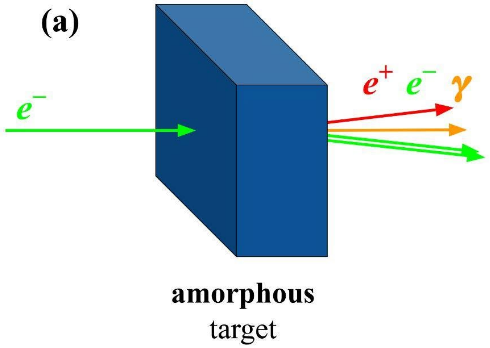
The FCC-ee Pre-Injector: CHART collaboration meeting
INFN Frascati 20-21 April 2023

21/04/2023

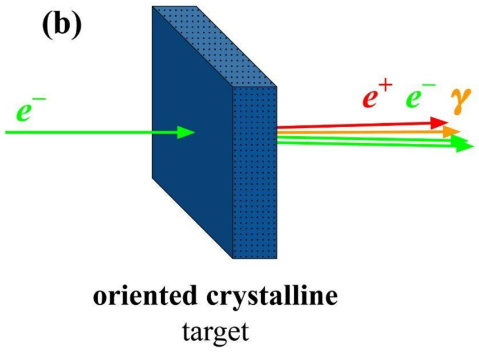
Hybrid crystal based positron source for future colliders

UNPOLARIZED POSITRON SOURCES

1. Conventional

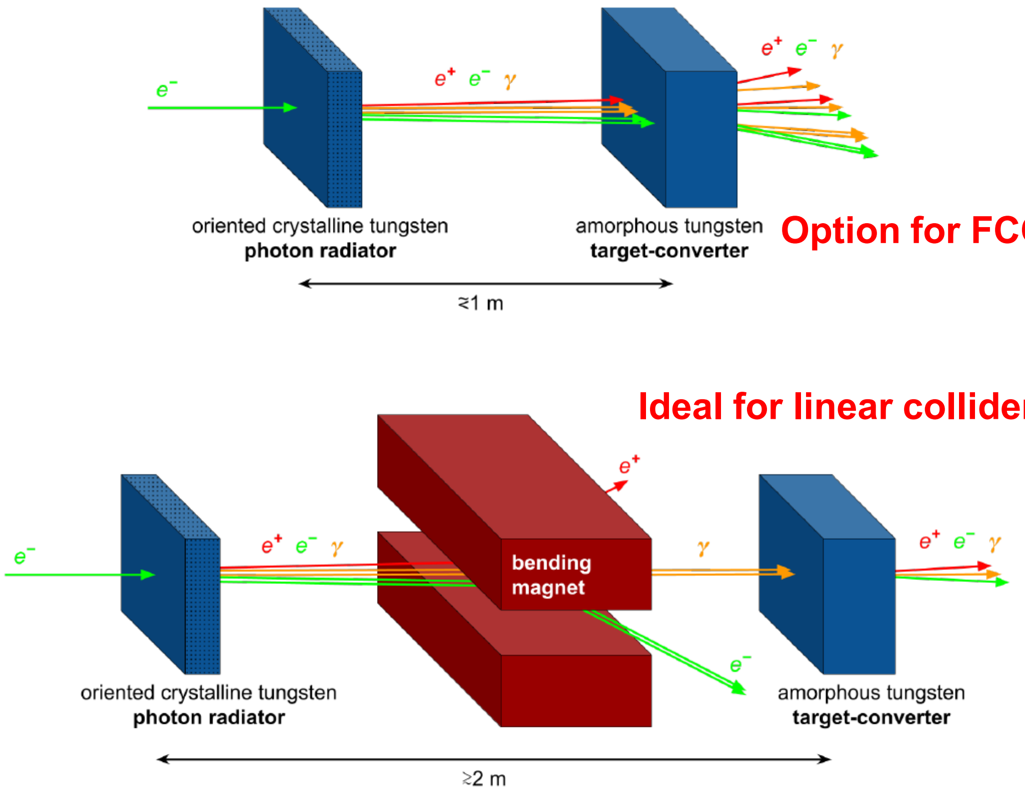


2. e+ from channeling radiation



Tests performed at CERN (WA 103) and at KEK

3. Hybrid crystal based positron source



Option for FCCee

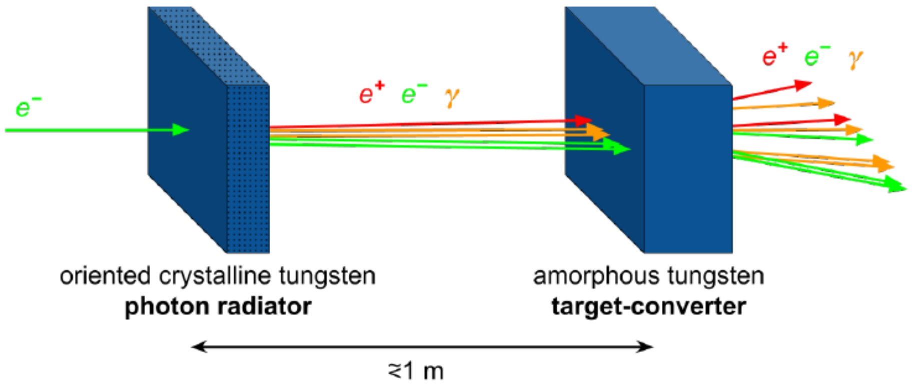
Ideal for linear colliders

Idea of R. Chehab, V. Strakhovenko and A. Variola, NIM B 266 (2008) 3868

Hybrid crystal based positron source advantages

Main advantages of the hybrid source:

- Enhancement of photon generation in crystals in channeling conditions ➔ enhanchement of pair production in the converter target
- High rate of soft photons ➔ creation of soft e^+ easily captured in matching systems
- Decrease of the PEDD in the converter target



→ total energy deposit shared between the two stages ⇒ overall lower energy density

→ very low energy deposit and PEDD in radiator ⇒ very low heating and thermo-mechanical stress

A Monte Carlo for computation of photon emission in the CRYSTAL RADIATOR

The electromagnetic radiated energy is evaluated with the Baier Katkov formula:

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1-x_2)}$$

where the integration is made over the classical trajectory.

Simulation of crystal radiator for positron source

Simulation of different physical processes:

- Multiple and single **Coulomb scattering** on nuclei and electrons.

Simulation of radiation:

- Baier-Katkov for the energies of e^+/e^- above 200 MeV.
- Bremsstrahlung by Bethe-Heitler formula for the energies of e^+/e^- below 200 MeV.

[1] V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903
[2] L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res. B 355, 44 (2015).
[3] A. I. Sytov, V. V. Tikhomirov, and L. Bandiera, Phys. Rev. Accel. Beams 22, 064601 (2019).
[4] L. Bandiera, V.V.Haurylavets, V. Tikhomirov Nucl. Instrum. Methods Phys. Res. A 936 (2019) 124.

Simulation of pair production:

- Probabilities of pair-production pre-calculated by Baier-Katkov.
- Simulation of energies and angular distribution of e^+/e^- using the approach analogous to Geant4.

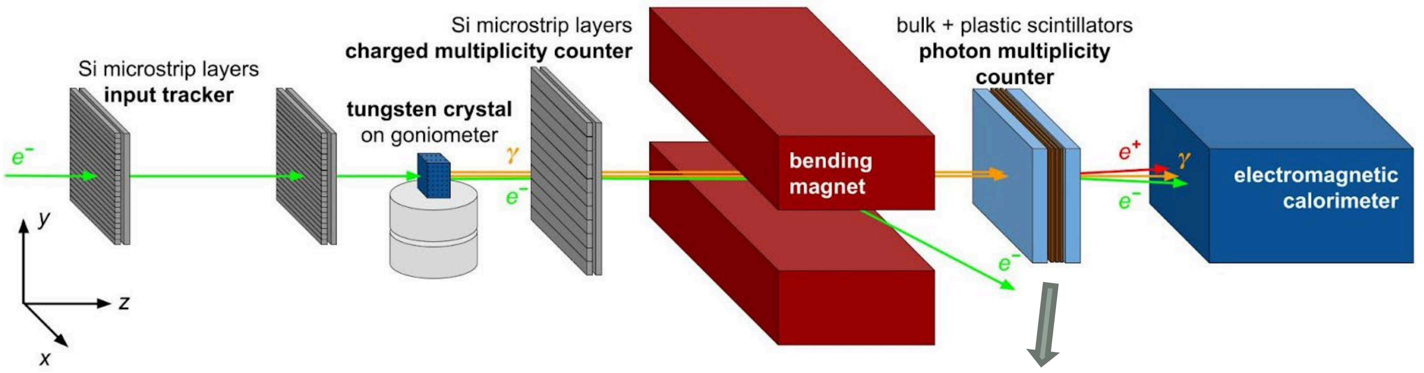
Simulation output compatible with the Geant4 toolkit

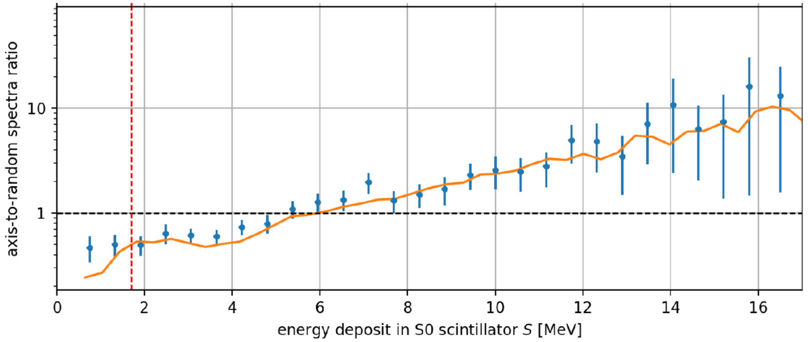
- **Both primary and secondary particles (e^+/e^- and gamma) at the crystal exit, namely coordinates and momenta**

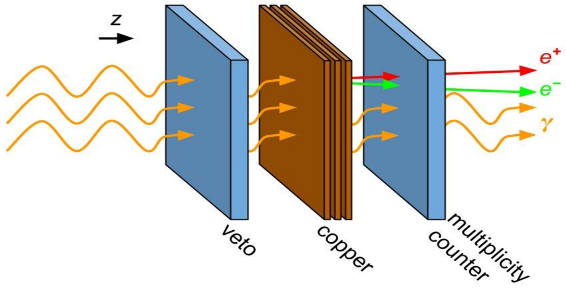
A. Sytov, V. Tikhomirov and L. Bandiera

Validation of Monte Carlo with experimental data

Setup @DESY TB beamline

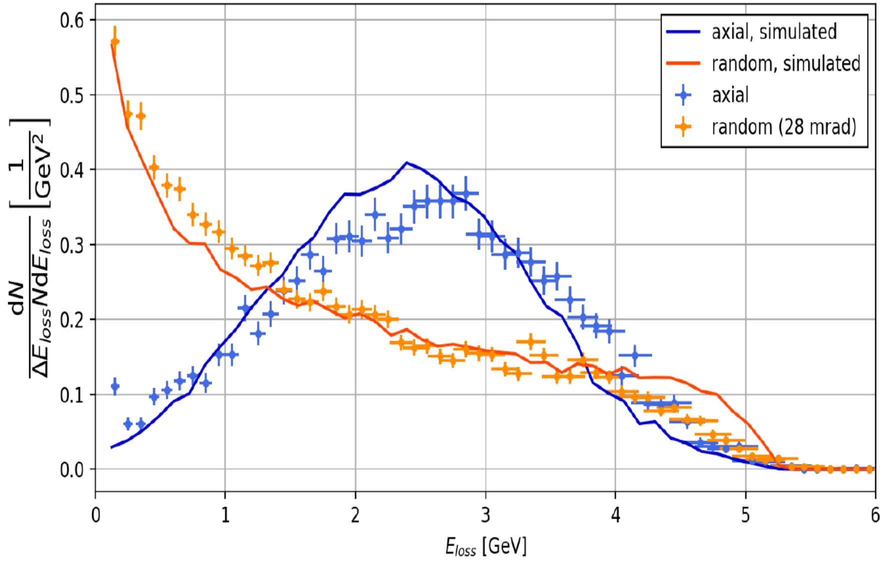






electromagnetic radiation in the BGO calorimeter at different angular configurations

e- @5.6 GeV



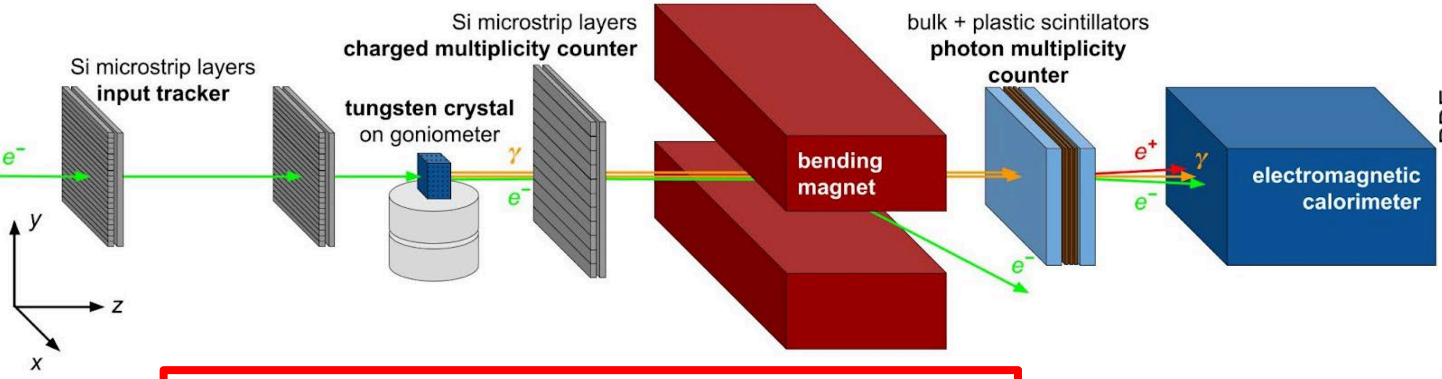
Electron beam energy: 5.6 GeV
Crystal target: W <100>, 2.24 mm long

The **active photoconverter** gives the average information on the number of radiated photons

⇒ clear pattern in the ratios between signal spectra at different lattice angles and in random orientation!

Validation of Monte Carlo with experimental data

Setup @CERN PS T9 beamline

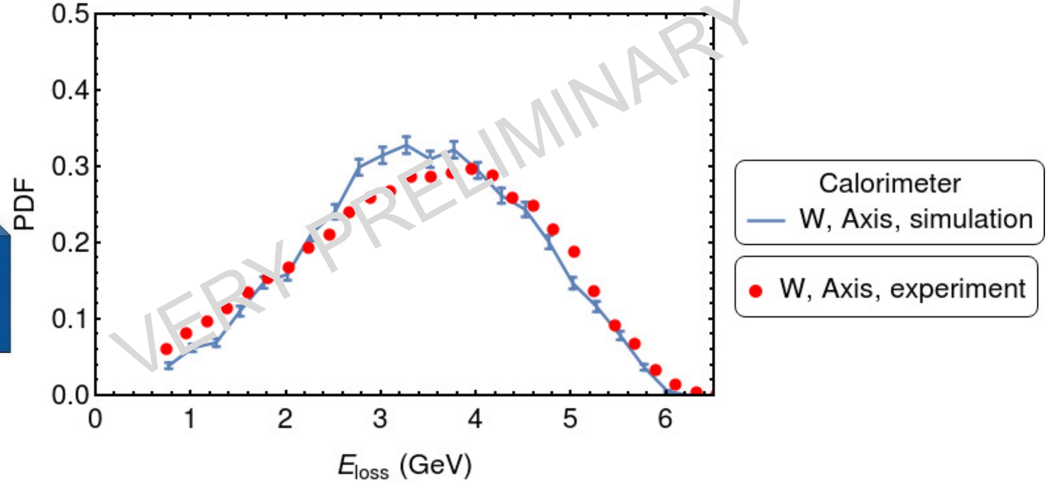


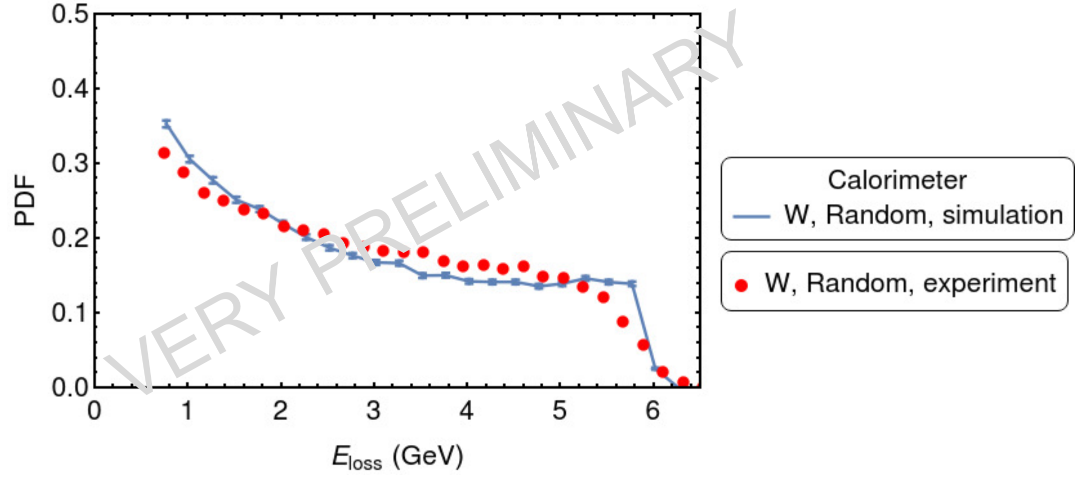
Electron beam energy: 6 GeV
Crystal target: W <111>, 2 mm long

Parameters chosen in agreement with the Geant4 optimization: *L. Bandiera et al., Eur. Phys. J. C 82, 699 (2022), Crystal-based pair production for a lepton collider positron source. https://doi.org/10.1140/epjc/s10052-022-10666-6*

We also tested a Iridium crystal and a diamond with 6 GeV and a W target with 20 GeV – analysis ongoing

Radiative energy loss measured by the Ecal





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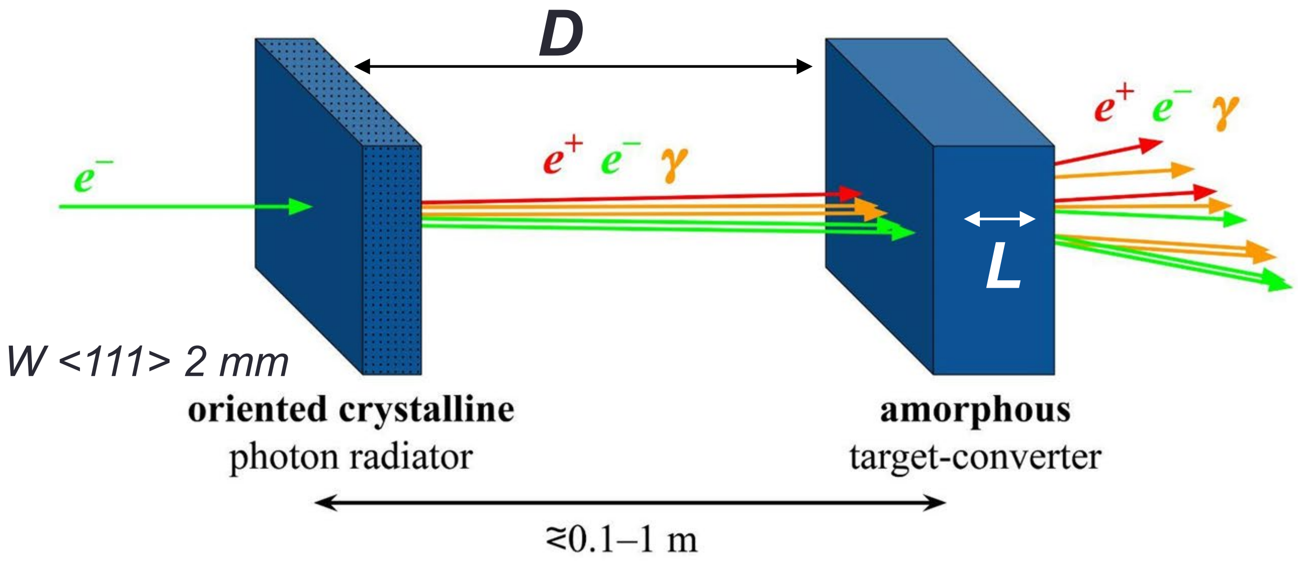
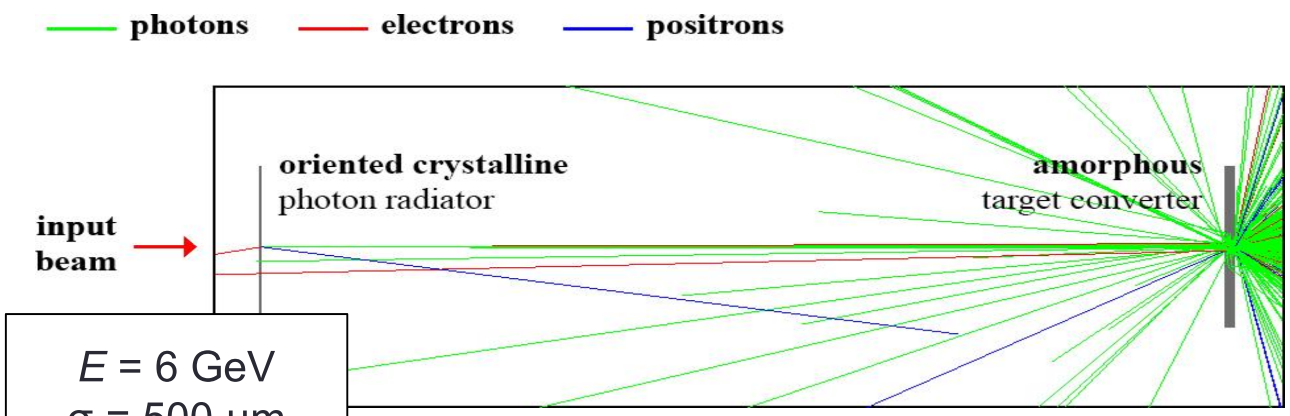
Hybrid source optimization for FCC-ee





E = 6 GeV
σ = 500 µm
σ' = 100 µrad

energy deposit and PEDD in amorphous converter can be reduced by tuning ***L*** (while keeping the radiator thickness fixed to maximise EM enhancement) and ***D***

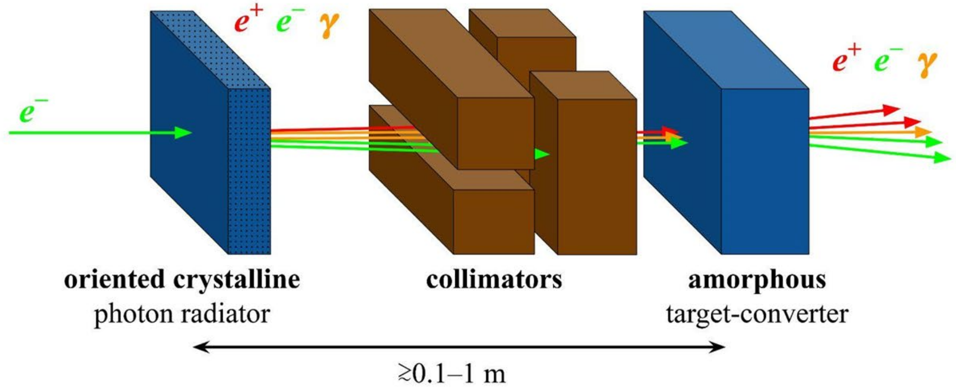
Geant4 simulation of the downstream stage…

(***upstream stage already optimised with dedicated code and experimental data→ dedicated input files***)

L. Bandiera *et al.*, **EPJC 82**, 699 (2022)

improving the hybrid scheme…

…with collimator



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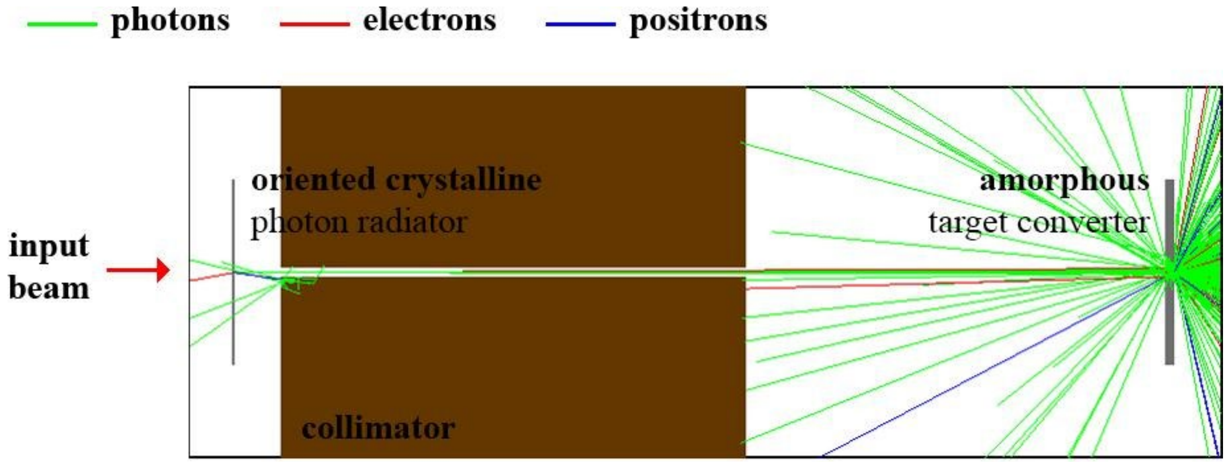
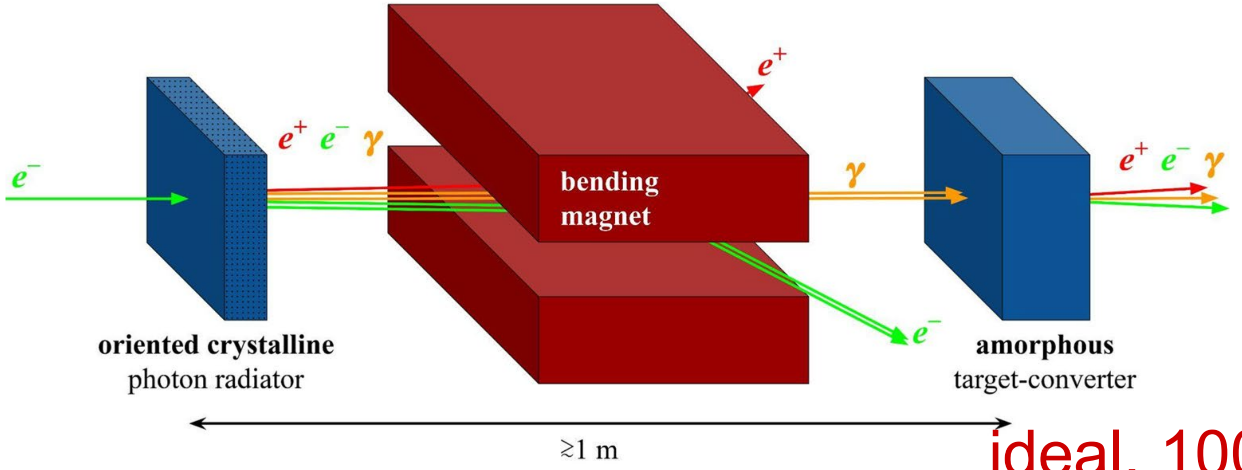
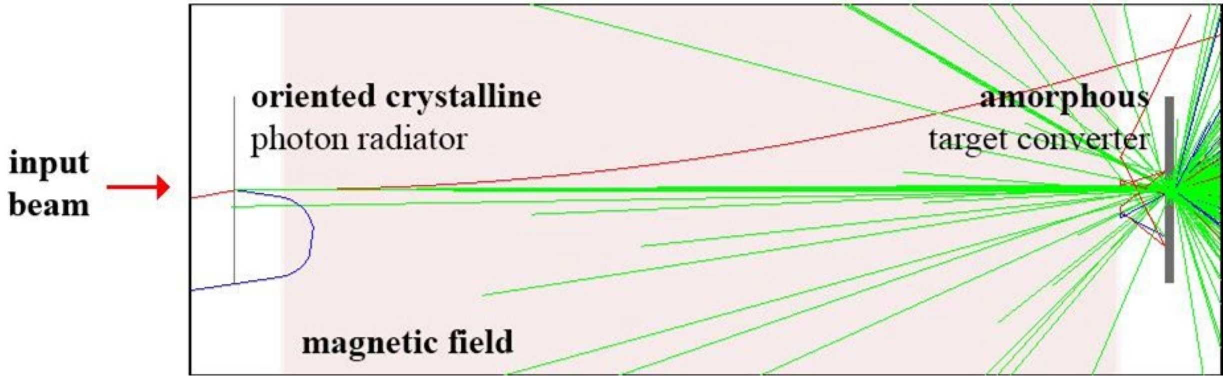
L = 11.6 D = 600, 1000, 2000 mm



tungsten block of thickness 50 cm with square hole of side ***a***

…with magnet





ideal, 100 T field to swipe all charged particles away

All together…

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a = 5.5 mm

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

conventional (amorphous)
collimator
magnet

Summarizing

Joint effort between IJCLab and INFN-FE

- The simulation environment has now been fully developed and can be used for more sophisticated studies (e.g., capture simulations), in order to arrive to the conceptual design for the hybrid scheme. In parallel, other crystals can be simulated and checked. Eventually, the performance will be compared to the conventional scheme.

Joint effort between IJCLab and INFN-FE

Summarizing

- The simulation environment has now been fully developed and can be used for more sophisticated studies (e.g., capture simulations), in order to arrive to the conceptual design for the hybrid scheme. In parallel, other crystals can be simulated and checked. Eventually, the performance will be compared to the conventional scheme.
- **The possibility to simulate the crystal radiator directly inside Geant4 will permit to modify all the parameters quite simply and very quickly.**
- The H2020 MSCA Global Individual Fellowships Project TRILLION GA n. 101032975 of A. Sytov is dedicated to this

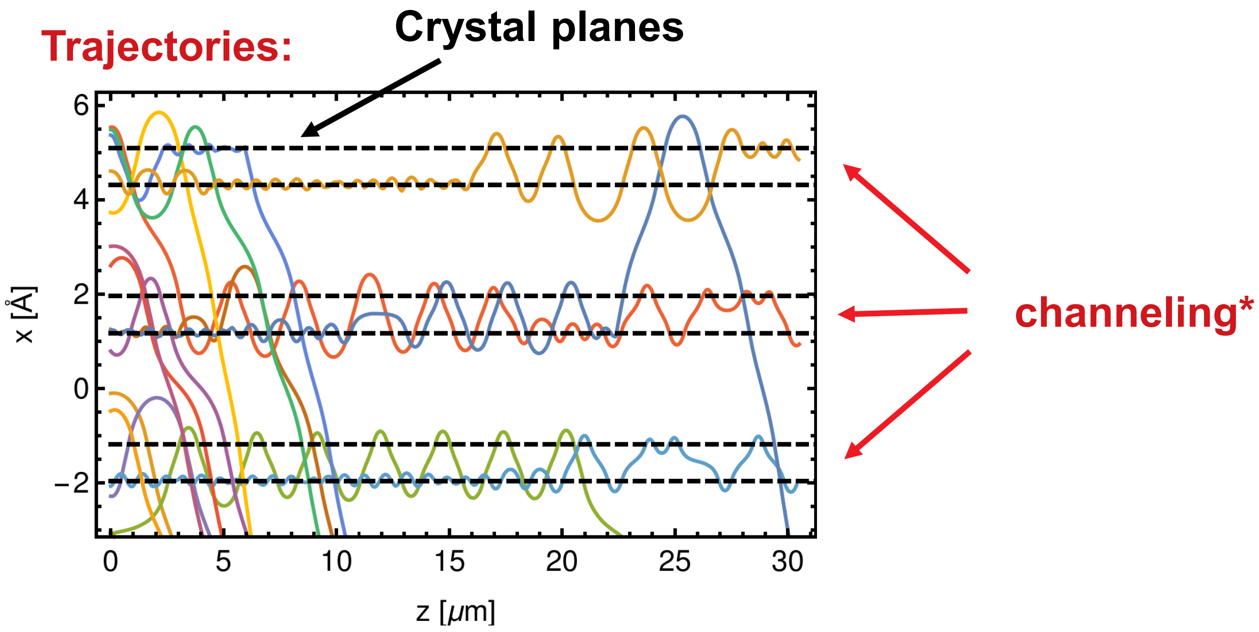
TRILLION Main goal: The **implementation** of both physics of **electromagnetic processes in oriented crystals** and the design of specific applications of crystalline effects into **Geant4** simulation toolkit as Extended Examples.

Channeling simulation technique: Geant4 ChannelingFastSimModel

- **Channeling** model using FastSim interface (trajectories): **READY**
- **Radiation** model (Baier-Katkov method) **TESTING NOW**
- **Radiation** and **positron source Geant4 examples** **END OF 2023**

A. Sytov and G. Paternò @INFN Ferrara

Trajectories:



European Commission

Trillion

GEANT4 A SIMULATION TOOLKIT

Baier-Katkov formula: $$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1 - x_2)}$$

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. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)
*A. Sytov et al. arXiv: 2303.04385, Accepted for publication in JKPS

Joint effort between IJCLab and INFN-FE

In the meantime experimental tests are going on..

Experiment in 2023

- Other crystals (W and other materials) with different thicknesses will be tested in the near future to select the final configuration for the crystal radiator and amorphous converter.
- Continue irradiation tests on crystal and converter targets at MAMI (started in 2021) or in other facilities. Evaluating the possibility to use more sophisticated targets (granular, rotating) – interesting also for the conventional source.

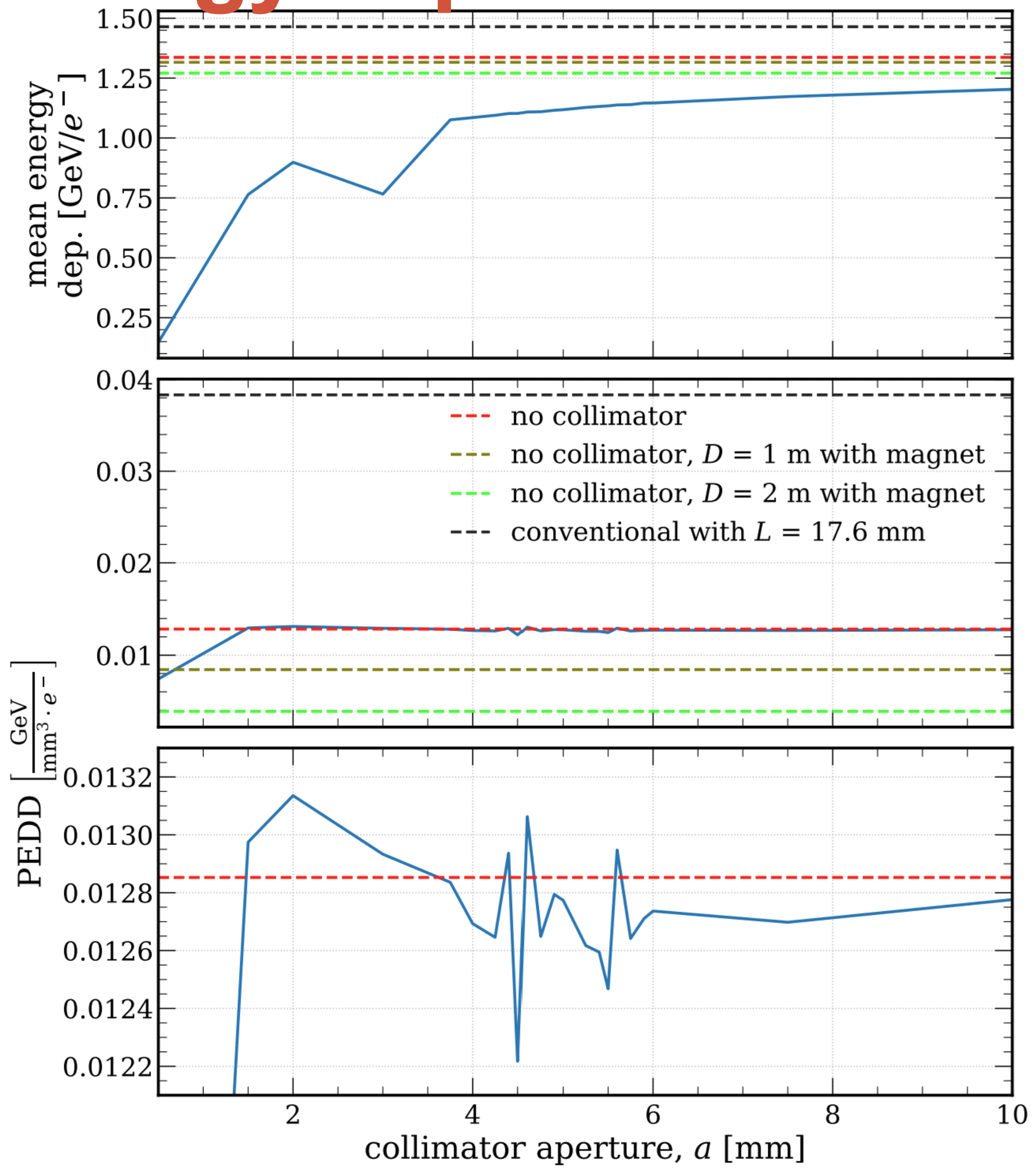
Simulation in 2023

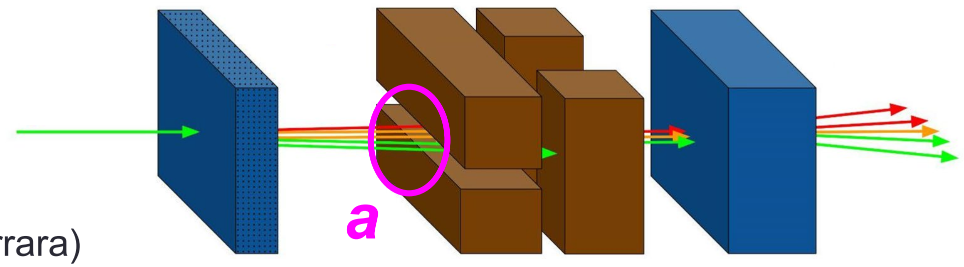
- Use the current MC setup in Geant4 for the implementation of the hybrid-source in the full pre-injector -> collaboration with people involved in this task
- Validate the new G4 model for crystal radiator simulation inside Geant4

The final goal is to be ready with a full hybrid source desing to be directly compared with the conventional one and to be tested at PSI

THANK YOU FOR THE ATTENTION!

energy deposit & PEDD





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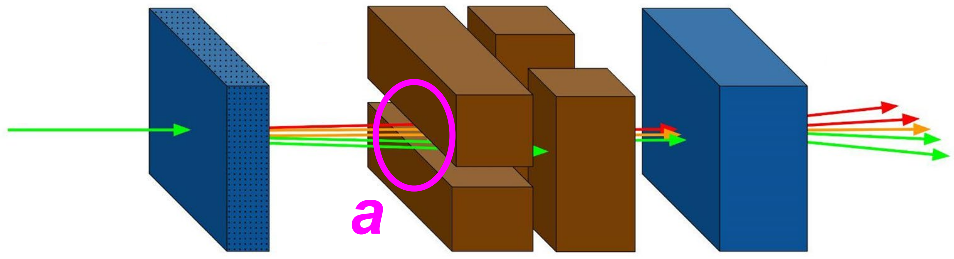
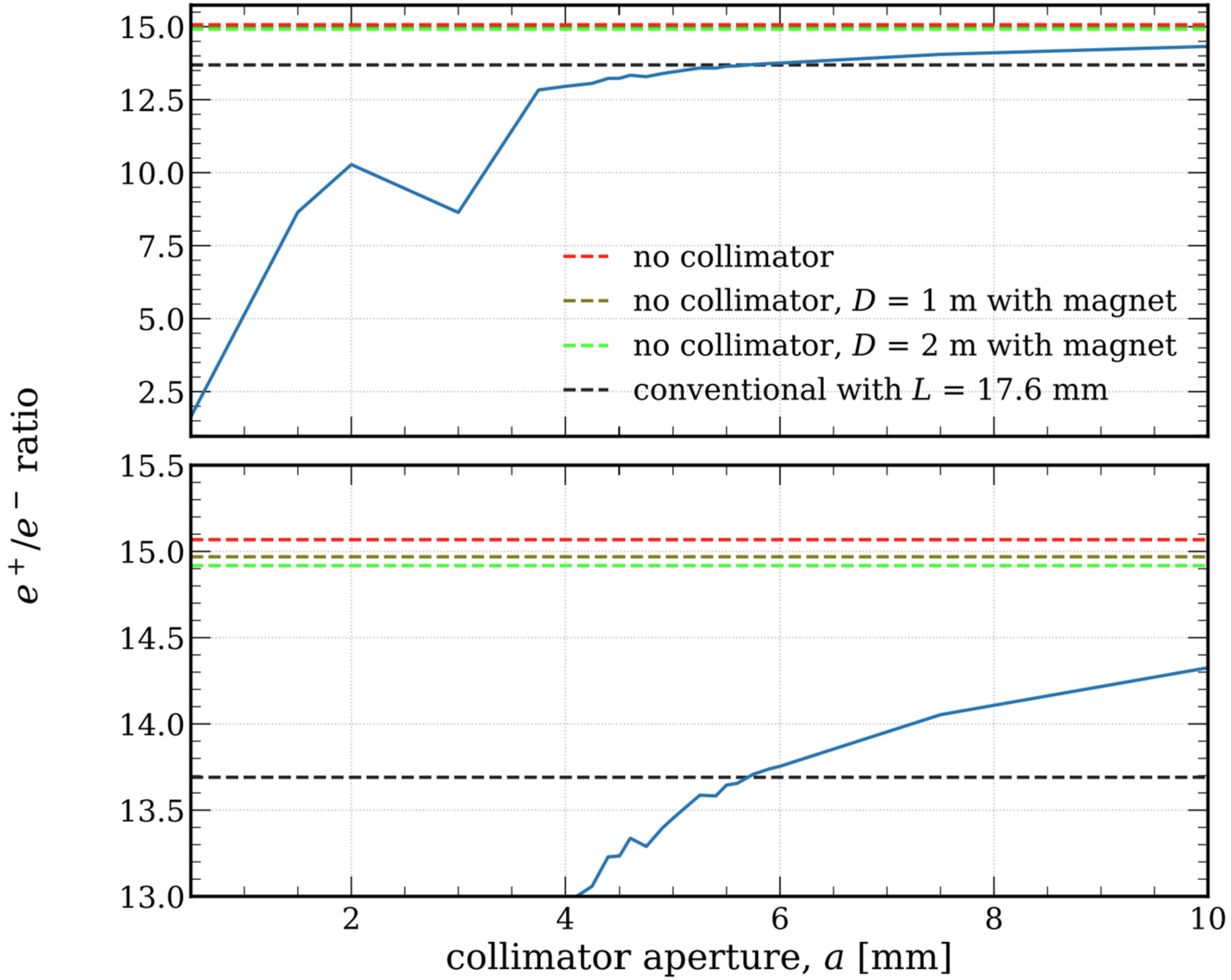
in general, **energy deposit** is lower (much lower) with magnet (collimator) wrt normal hybrid case, and it grows with *a* → better to keep *a* as low as possible

PEDD with collimator is similar to normal hybrid case, only a slight reduction for *a* with minimum around 7 mm is observed

PEDD with magnet (with larger *D*) is lower



positron production rate



output positron rate with collimator improves as *a* increases

⇒ conventional value is obtained at *a* ~ 5.5 mm, hybrid (without and with magnet) value is obtained asymptotically

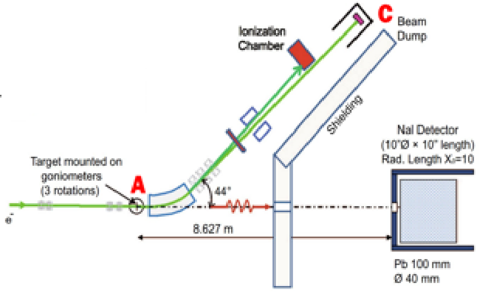
M. Soldani (INFN-Ferrara)

Targets irradiation studies @MAMI

*IPAC 2022: **F. Alharthi** ,I. Chaikovska , R. Chehab , S. Ogur , S. Wallon , , A. Ushakov , V. Mytrochenko , Y. Zhao , P. Sievers , L. Bandiera , A. Mazzolari , M. Romagnoni , A. I. Sytov , M. Soldani , W. Lauth , O. Khomyshyn , D. Klekots*

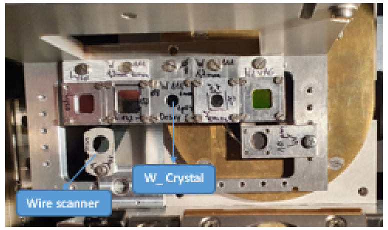
MAMI experiment layout:

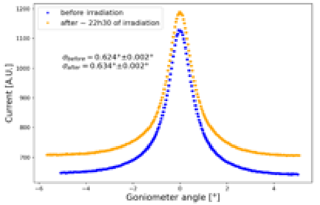
- Measurements were performed with low-emittance, high-intensity, 855 MeV electron beam on different samples.
- Two positions are chosen to place the samples: position (A) & (C).
- Samples are placed on target holders.



Preliminary results at position (A):

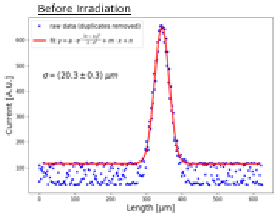
- Beam is highly focused and crystalline target is placed on a goniometer.
- **Several angular scans were performed to align the crystal <111> axis with respect to the beam direction using Ionization chamber.**





No significant variation in the width of the axial angular ranges has been observed.

Vertical beam size

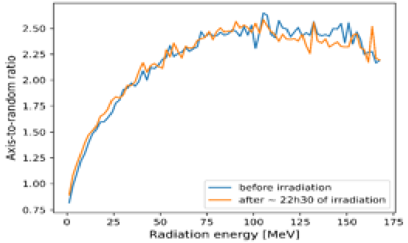


Stable beam size for the whole radiation cycle, σ_{after} =(20.4μm)

- **Measurement of the integral energy spectrum was performed by NaI detector.**

Target	Dimensions	Beam current	Irradiation time	Preliminary Fluence
W-crystal	1mm thick, 8mm diameter	8-10nA CW	~22.5h	6.11e17 [e-/mm²]

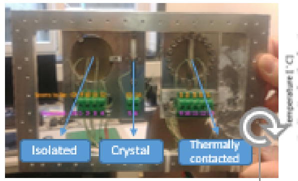
Crystalline structure of the target wasn't affected by the irradiation.



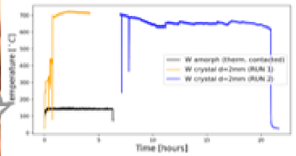
Preliminary results at position (C):

The main goal : target irradiation, under the precise temperature control.

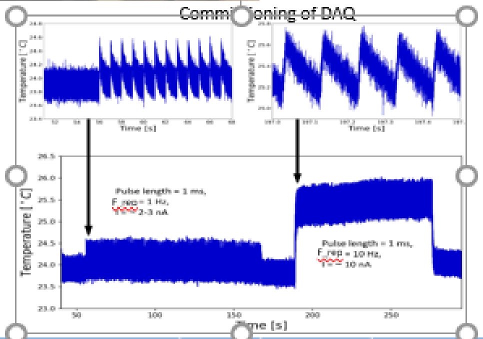
- Three W targets were installed(crystal + 2 amorphous).
- Thermocouples (K-type) were readout by DAQ (Ametek VTI Instruments EX1401).
- Observables: target steady state temperature and temperature jump per pulse.
- No beam monitoring installed at this position but an attempted was done to measure the beam size using the thermocouples.
- Crystal and amorphous thermally contacted targets were irradiated.



Target irradiation



Commissioning of DAQ

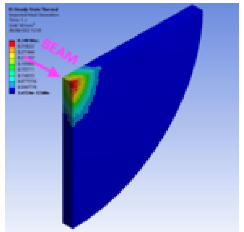


The detailed simulation studies for the PEDD are on the way

Target	Dimensions (Thickness, diameter)	Beam current	Irradiation Time	Preliminary Fluence [e-/mm²]
W-amorphous	(2mm, 50mm)	1-3μA	~23 hours	~1.3e18
W-crystal	(2mm, 8mm)		~21 hours	~1.1e18

Thermal simulation and analysis:

- ANSYS thermal simulations are under way to assess the target behavior during the beam tests
- It allows useful comparison with temperature measurements in order to:
  - check the beam power deposition and PEDD in the target, therefore giving an "overall" check of beam parameters..



The results of this work is based on the collaboration between CNRS, University of paris saclay, INFN-FERRARA and MAINZ.

Courtesy of F. Alharthi (IJCLab)

Experimental Setup

Versatile setup adaptable to CERN and DESY test beam