Bando PRIN 2022

Funded by the European Union NextGenerationEU

INFN FERRARA Istituto Nazionale di Fisica Nucleare Sezione di Ferrara

Intense positron source Based On Oriented crySTals - e+BOOST

E+BOOST team
L. Bandiera, P.I. INFN
A.O.M. Iorio, Naple University
M. Prest, Insubria University

Non Italian partners:
IJCLab (Orsay, France): leader I. Chaikovska
Mainz University (Germany): leader W. Lauth

Speaker: **L. Bandiera** - INFN Ferrara
bandiera@fe.infn.it

E+BOOST meeting
Ferrara
11/01/2024

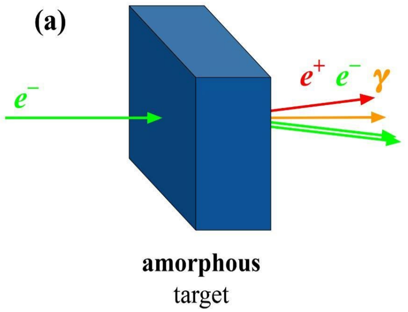
Hybrid crystal-based positron source for future e+e- colliders

Main advantages of the hybrid source:

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

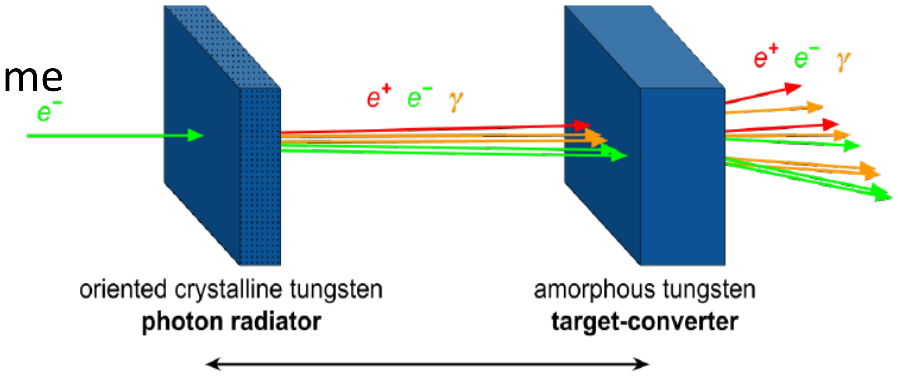
- **Enhancement of photon generation** in crystals in channeling conditions ➔ **enhancement of pair production in the converter target!**
- **High rate of soft photons** ➔ creation of **soft e^+ easily captured** in matching systems
- **Decrease of the deposited energy and Peak Energy Deposition Density (PEDD) in the converter target!**

Conventional



Choice of crystal:
W <111> provides the strongest axial potential V_0 ~ 1 keV

Hybrid scheme



Thin radiator **Thick converter**

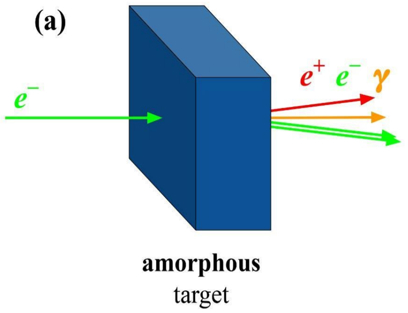
→ total energy deposit shared between the two stages ⇒ overall lower energy density

→ very low energy deposit and PEDD in **thin radiator ($< X_0$)** ⇒ very low heating and thermo-mechanical stress

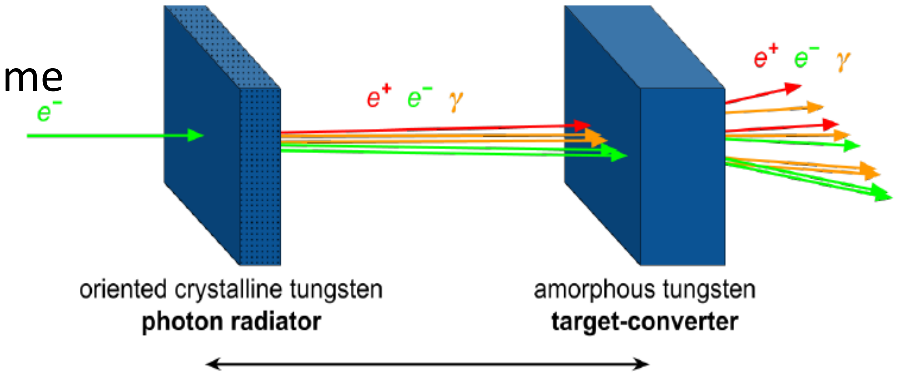
Hybrid crystal-based positron source for the FCC-ee

- The **FCC-ee Compact Design Report** of the **injector complex** foresees **a 6 GeV linac**.
- Currently **the conventional and hybrid scheme are under study!**

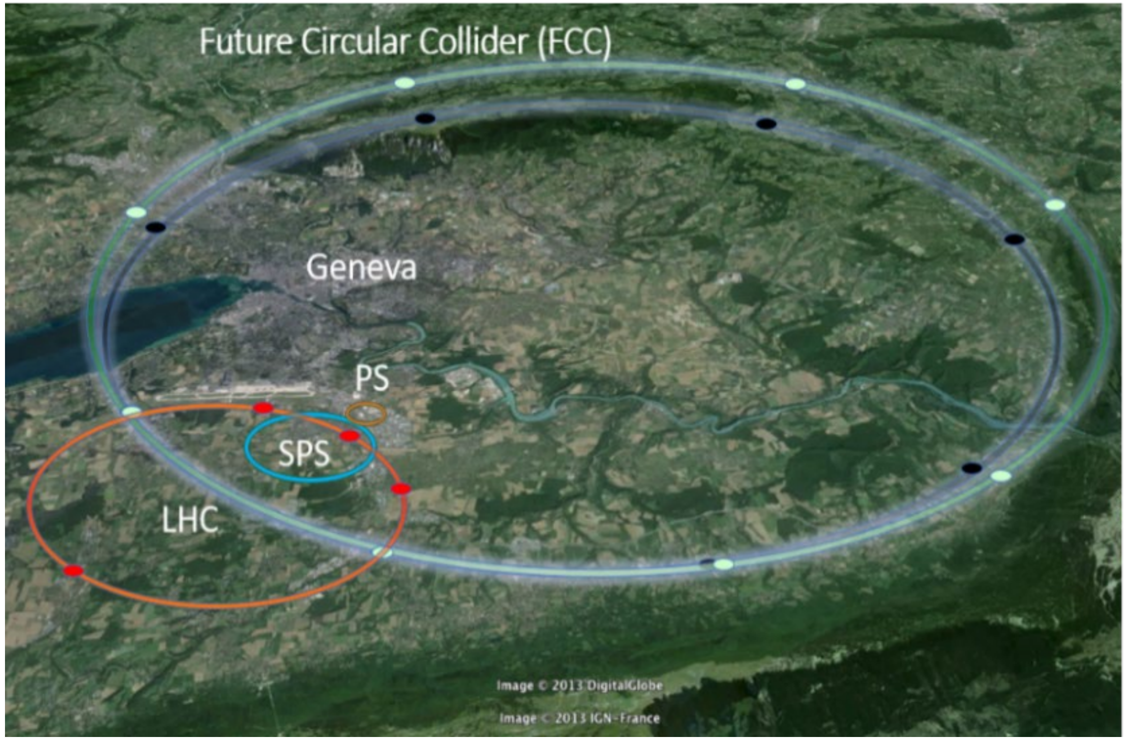
Conventional



Hybrid scheme



Thin radiator **Thick converter**



I. Chaikovska *et al.,* **JINST 17 (2022) P05015.**

Leader I. Chaikovska - IJCLab

An hybrid source can be advantageous to future colliders (FCC-ee, CLIC, ILC or CEPC) as well as for current ones (SuperKEK B).

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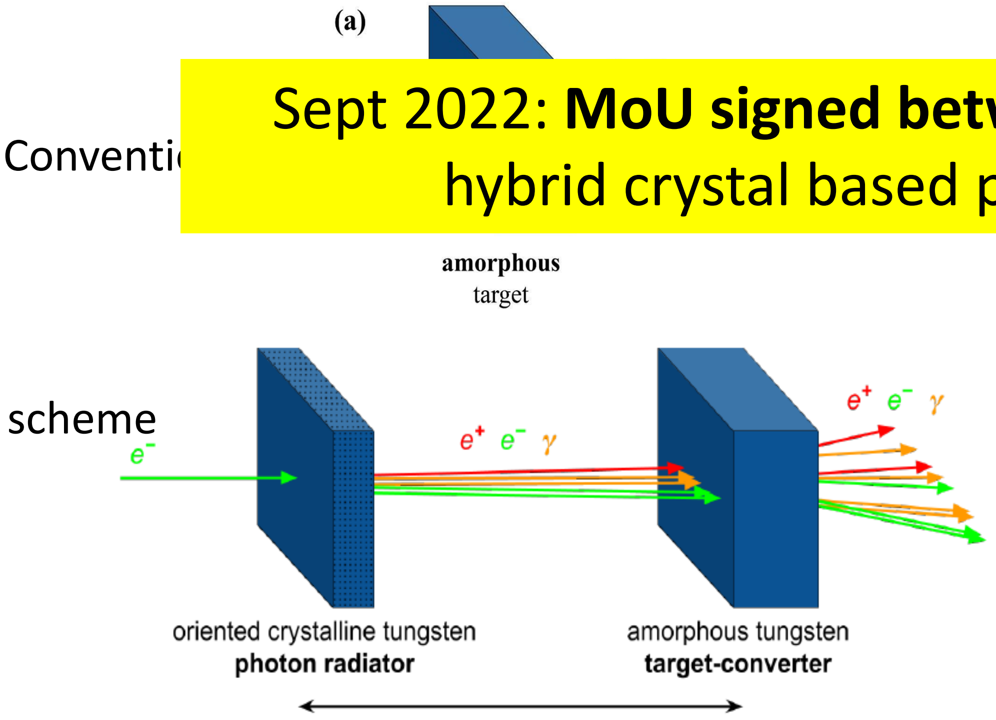
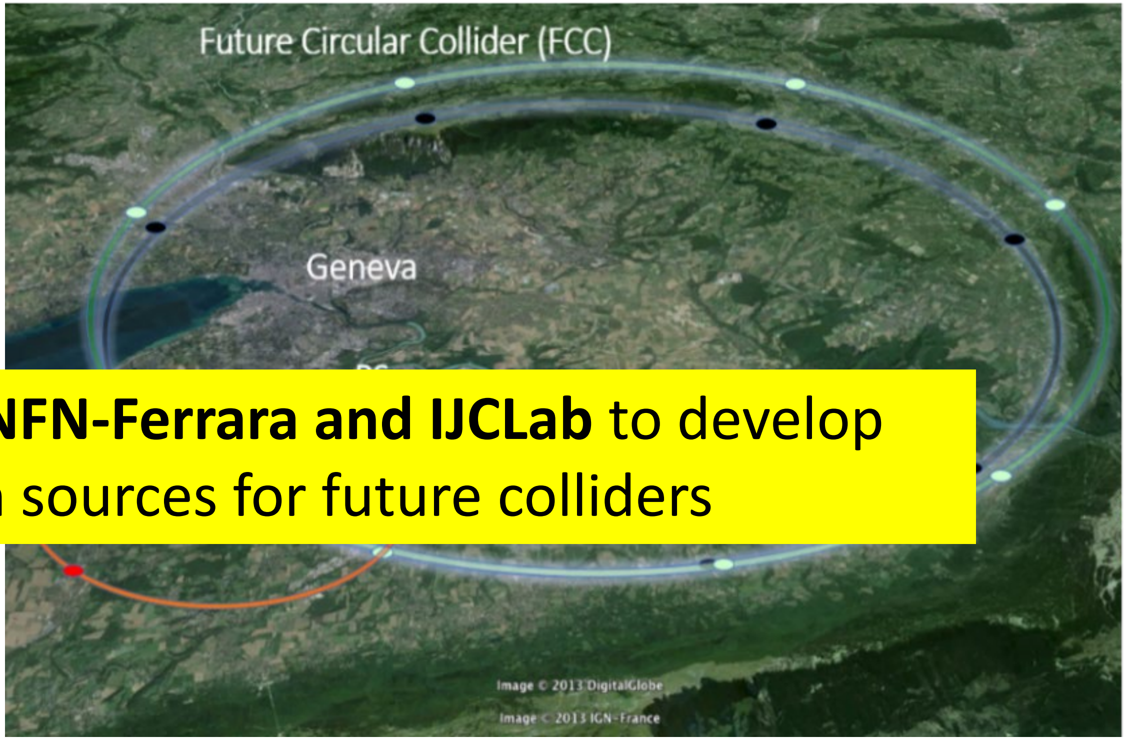
Sept 2022: MoU signed between INFN-Ferrara and IJCLab to develop hybrid crystal based positron sources for future colliders





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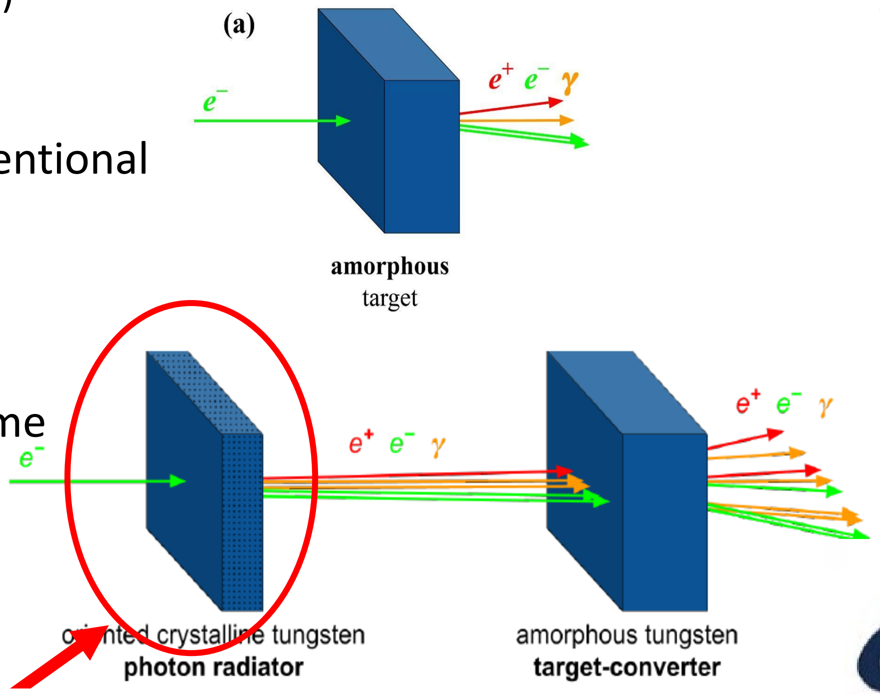
Hybrid crystal-based positron source for the FCC-ee

CHART project at PSI

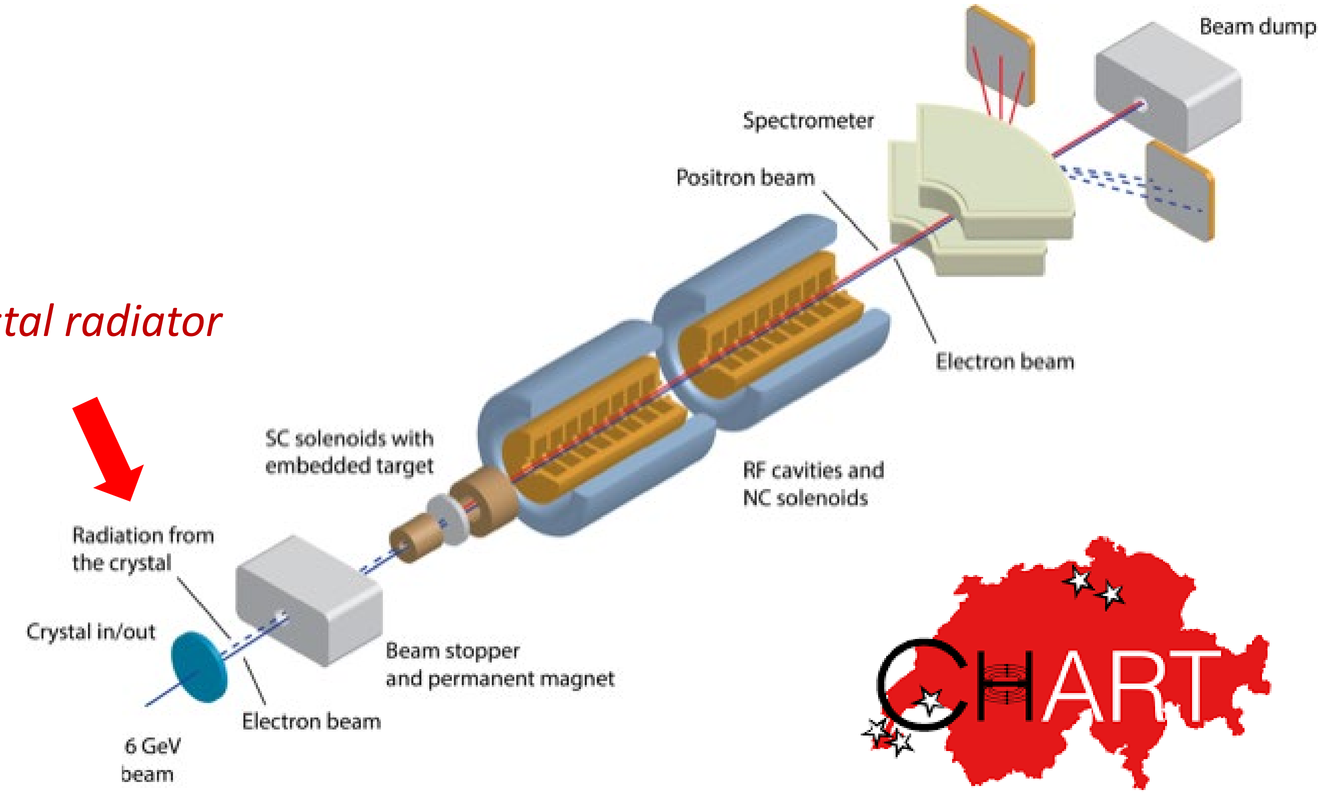
CHART project on the FCCee Injection System: Collaboration between PSI and CERN with external partners: CNRS-IJCLab (Orsay), INFN-LNF, **INFN-Ferrara**, KEK (Japan)



Experimental tests to validate MC

Thick converter

Crystal radiator



Swiss Accelerator Research and Technology

Hybrid crystal-based positron source for the FCC-ee

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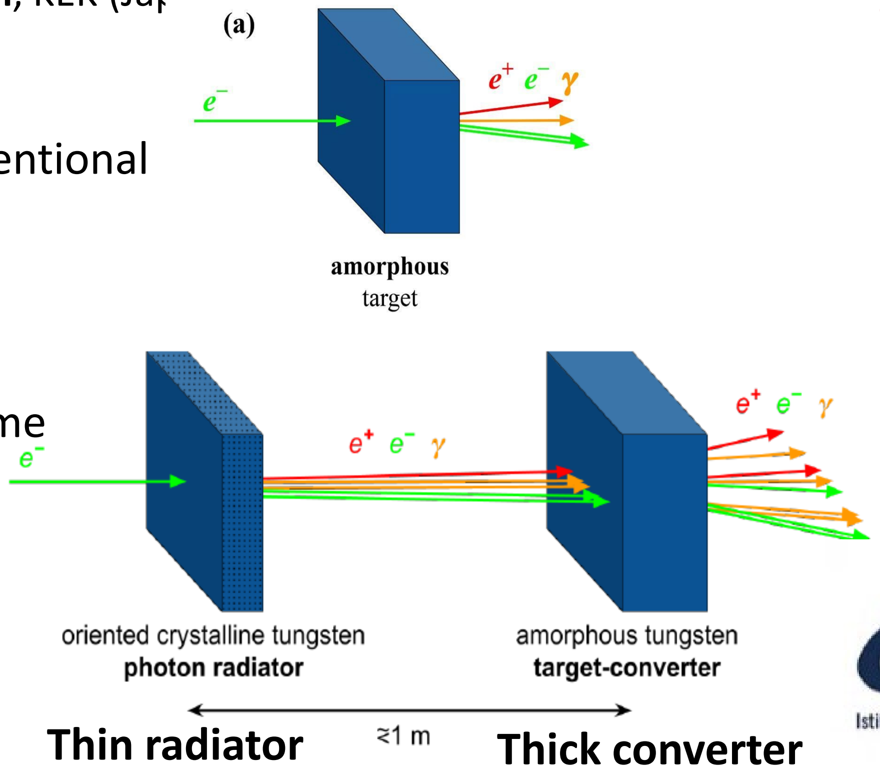
CHART project on the FCCee Injection System: Collaboration between PSI and CERN with external partners: **CNRS-IJCLab (Orsay),** INFN-LNF, **INFN-Ferrara**, **INFN Milan**, KEK (Jap

Conventional

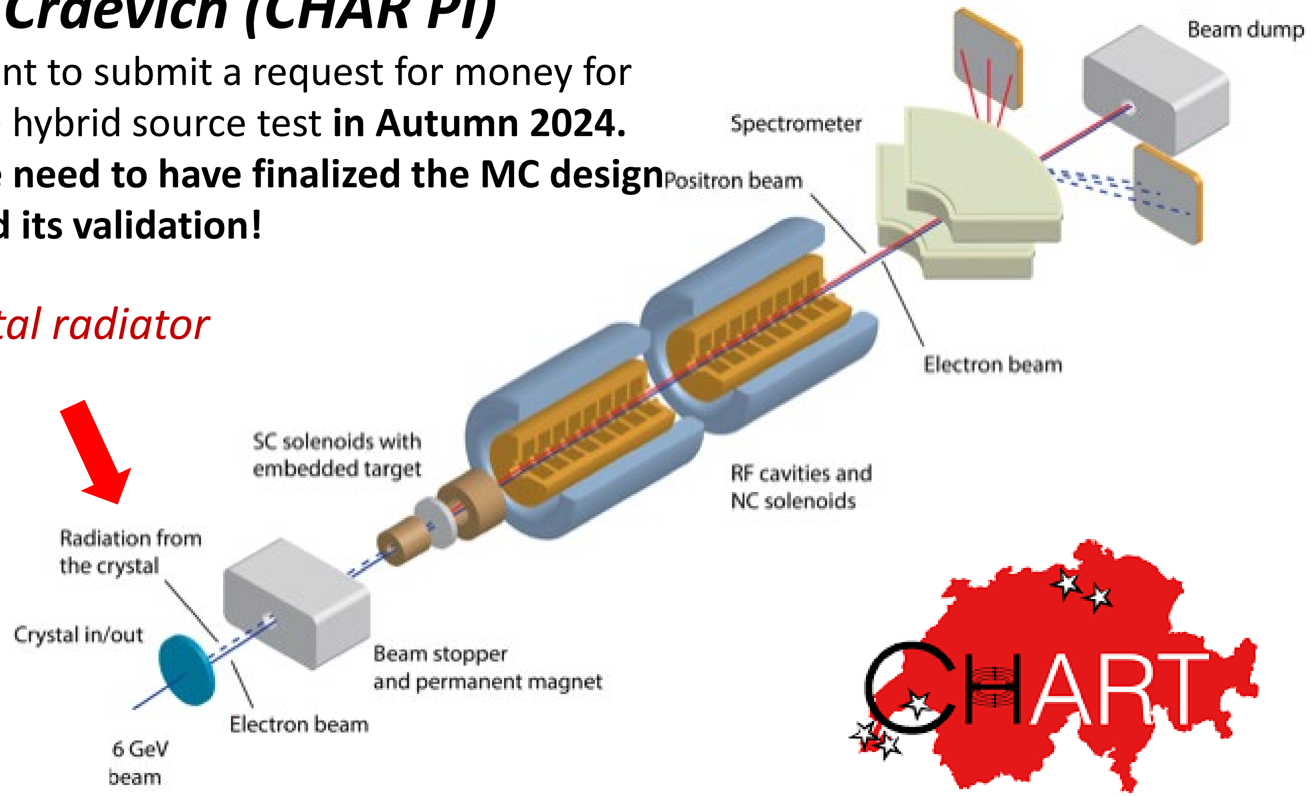
Hybrid scheme



P. Craevich (CHAR PI)

Want to submit a request for money for the hybrid source test **in Autumn 2024.**
We need to have finalized the MC design and its validation!

Crystal radiator



INFN Istituto Nazionale di Fisica Nucleare

cnrs

université PARIS-SACLAY

CHART

Swiss Accelerator Research and Technology

E+ BOOST Objectives

Main Objective: the e+BOOST project proposes to fully demonstrate that a crystal-based hybrid scheme could realistically become the baseline for intense e+ sources in high-energy accelerators in place of the conventional ones based on bremsstrahlung

Tasks:

1. Optimization of the targets parameters to maximize the positron yield and minimize the PEDD vs. electron beam energy;
2. Demonstration of the targets resistance to irradiation;
3. Development of a full Geant4 simulation including the positron yield enhancement and deposited energy inside the targets;
4. Design of a crystal-based positron source for future circular colliders, in particular for FCC-ee.

E+ BOOST WPs

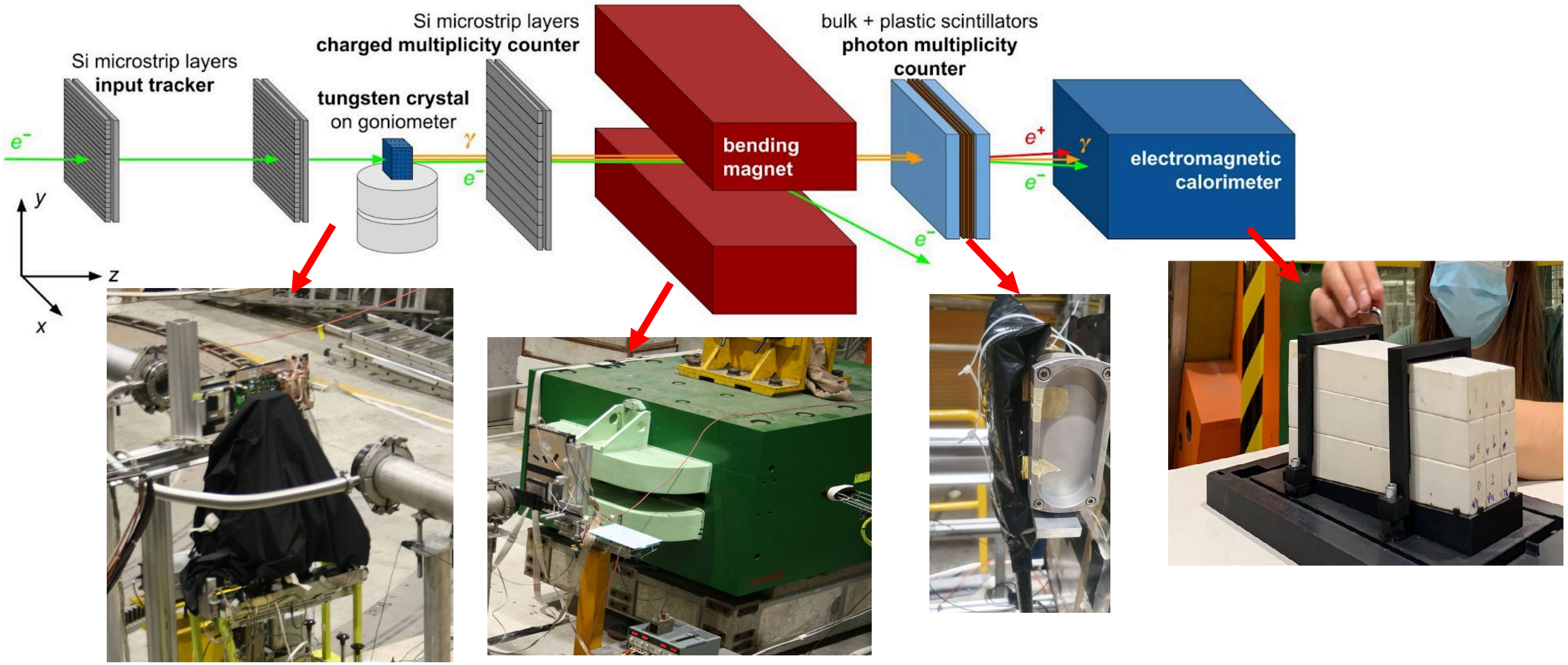
Main Objective: the e+BOOST project proposes to fully demonstrate that a crystal-based hybrid scheme could realistically become the baseline for intense e+ sources in high-energy accelerators in place of the conventional ones based on bremsstrahlung

Work Package	Description	Coordinator	Participant
WP1	Design, shaping and characterization of the targets	INFN	INFN,Napoli
WP2	Beam and Irradiation tests	INFN, Insubria	INFN, Napoli, Insubria
WP3	Detector construction	Insubria	Insubria
WP4	Monte Carlo simulation of the positron source	Napoli	INFN, Napoli
WP5	Dissemination and public engagement	INFN	INFN, Napoli, Insubria

Where are we…

Where are we… Experiment

Versatile experimental setup adaptable to CERN PS and DESY beam tests provided by UNInsubria
Electron energy of 5-6 GeV – of interest for future e+e- colliders (FCC-ee, ILC, CLIC, LEMMA, CEPC …)

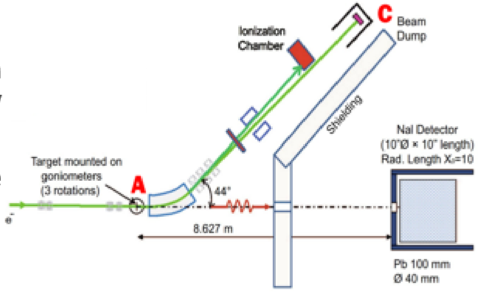


Where are we… Targets irradiation studies @MAMI done in 2021

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

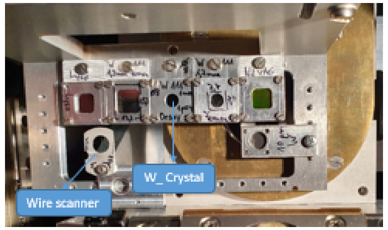
MAMI experiment layout:

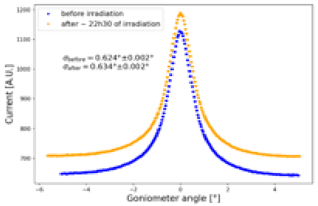
- Measurements were performed with low-emittance, high-intensity, 855 MeV electron beam on different samples.
- Two positions are chosen to place the samples: position (A) & (C).
- Samples are placed on target holders.



Preliminary results at position (A):

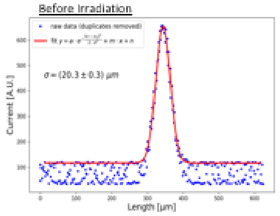
- Beam is highly focused and crystalline target is placed on a goniometer.
- **Several angular scans were performed to align the crystal <111> axis with respect to the beam direction using Ionization chamber.**





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

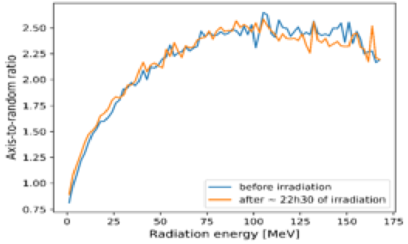
Vertical beam size



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]

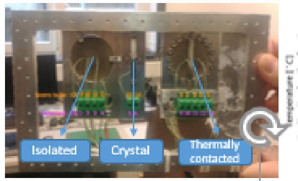


Crystalline structure of the target wasn't affected by the irradiation.

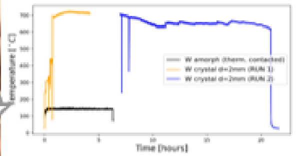
Preliminary results at position (C):

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

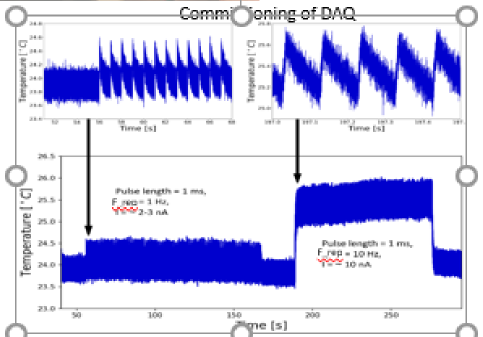
- Three W targets were installed(crystal + 2 amorphous).
- Thermocouples (K-type) were readout by DAQ (Ametek VTI Instruments EX1401).
- Observables: target steady state temperature and temperature jump per pulse.
- No beam monitoring installed at this position but an attempted was done to measure the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



Target irradiation



Commissioning of DAQ

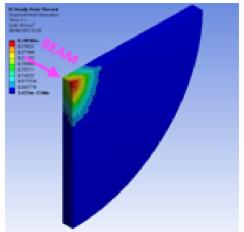


The detailed simulation studies for the PEDD are on the way

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..



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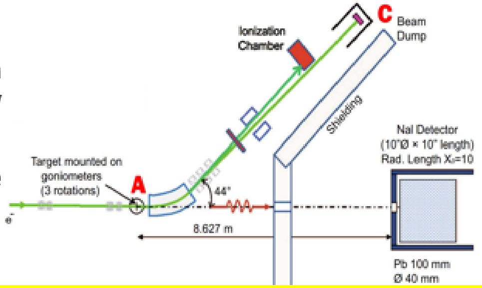

New optimized irradiation tests with a thin target foreseen this month

Preliminary

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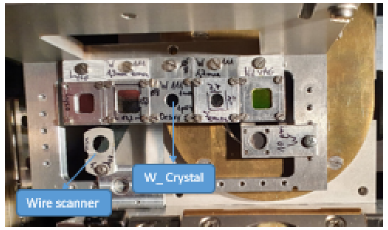

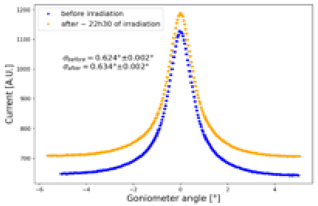

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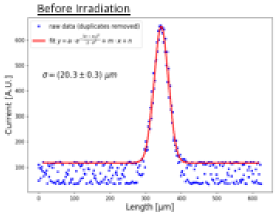

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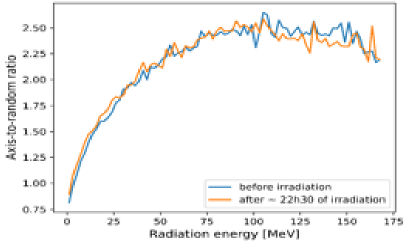

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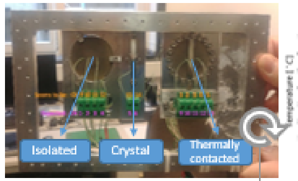

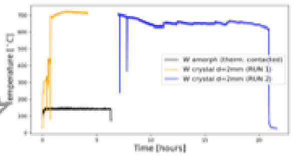

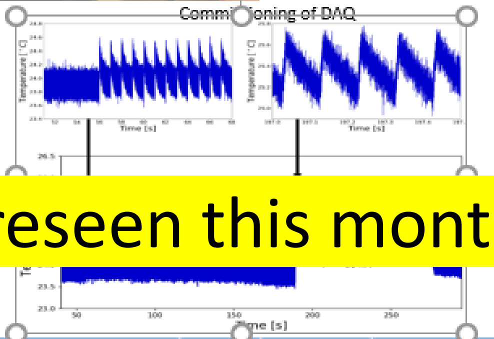

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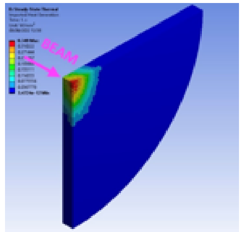

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Courtesy of F. Alharthi (IJCLab)

Where are we.. A Monte Carlo for computation of photon emission in the CRYSTAL RADIATOR

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

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

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.

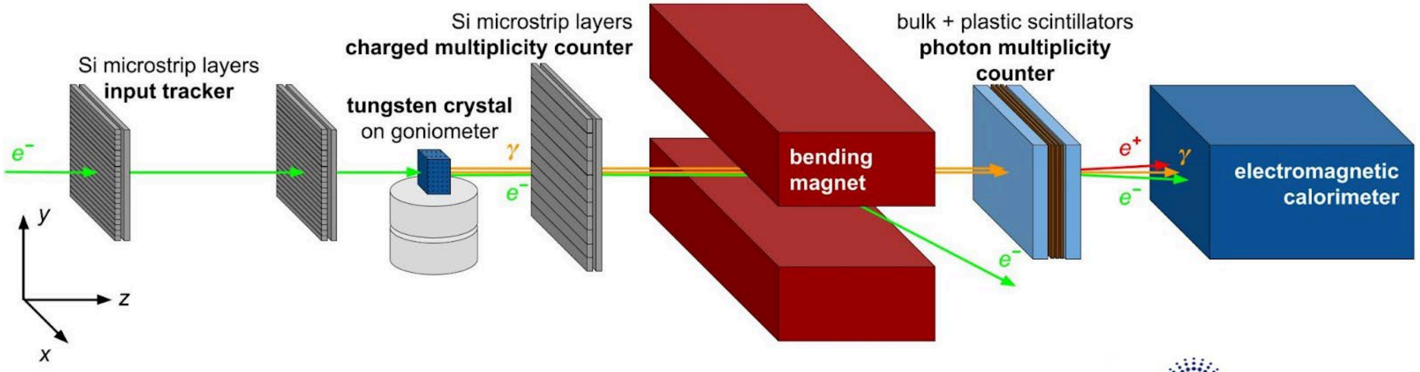
Simulation output compatible with the Geant4 toolkit

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

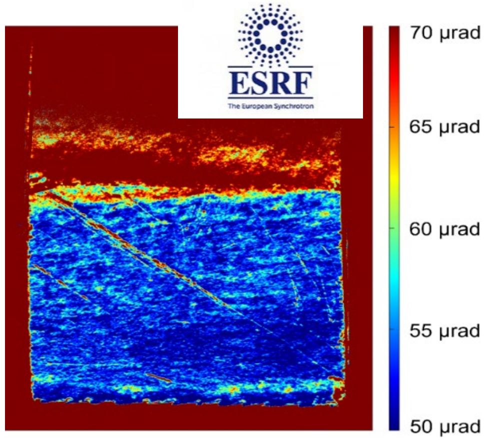
A. Sytov, V. Tikhomirov and L. Bandiera

Measurement of the γ-spectrum and MC validation

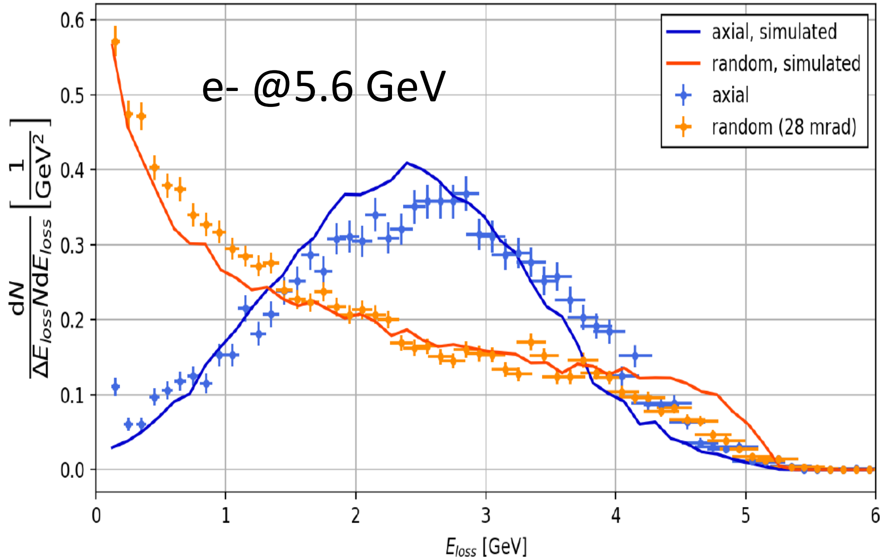
Versatile setup adaptable to CERN PS and DESY beam tests provided by INSUBRIA team



electromagnetic radiation in the BGO calorimeter at different angular configurations



W crystal X-ray topography @BM05
Courtesy of Thu Nhi Tran CALISTE



⇒ larger and peaked energy loss distribution in **axial** vs. **random** orientation!

Electron beam energy: 5.6 GeV
Crystal target: W <100>, 2.24 mm long
Channeling critical angle ≈ 1 mrad

L. Bandiera et al., Eur. Phys. J. C 82, 699 (2022)

Measurement of the γ-spectrum and MC validation

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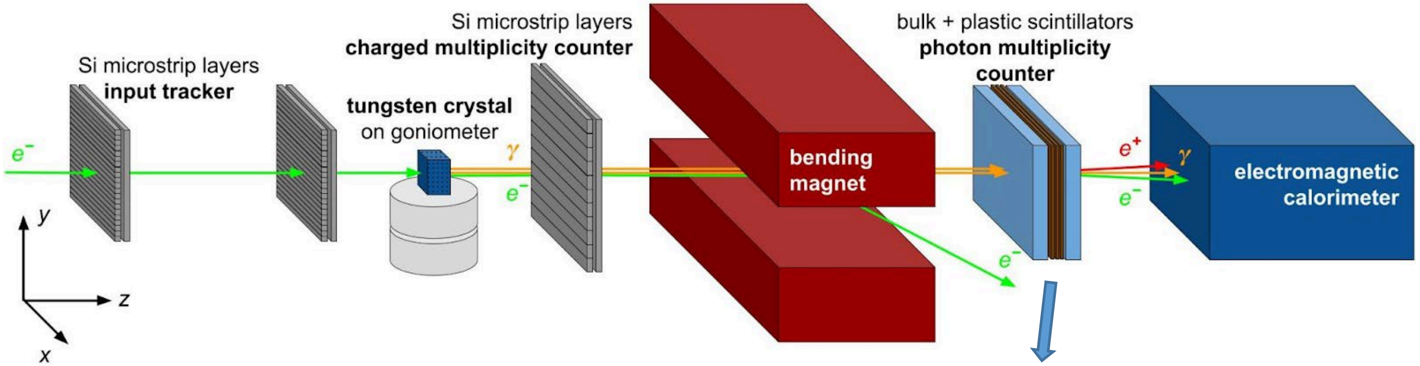
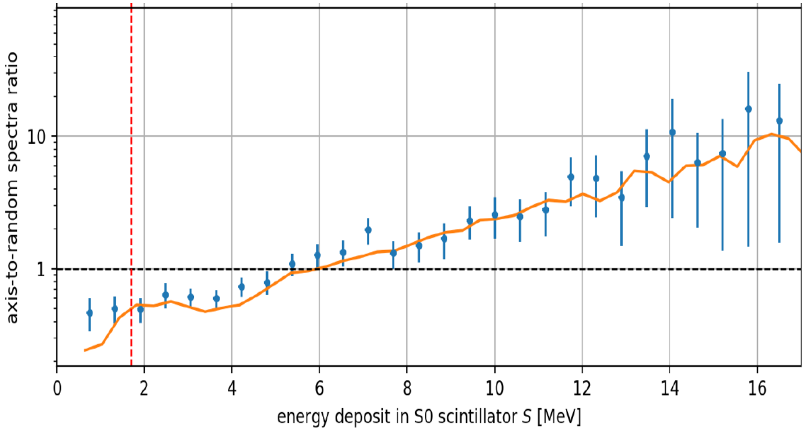
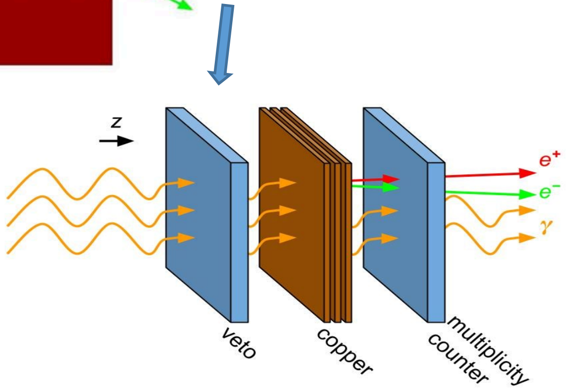


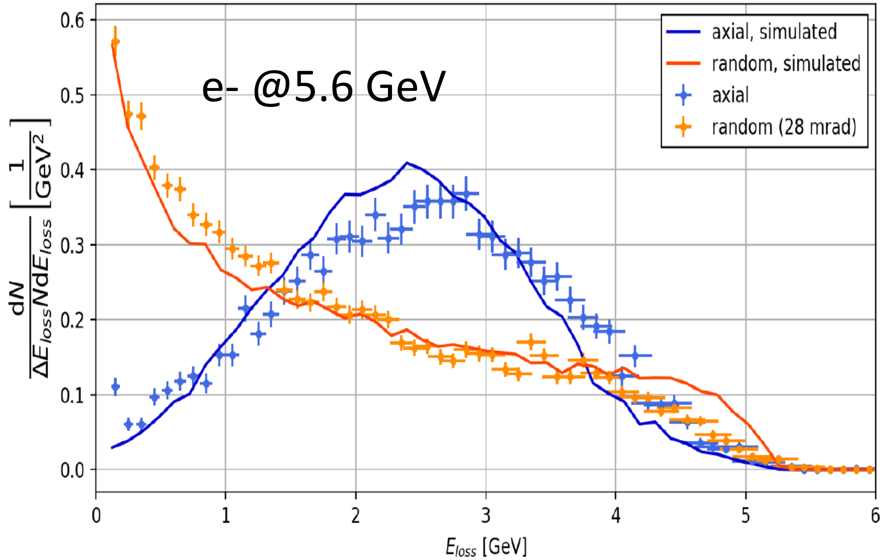


⇒ **Increase in the average number** of high-energy deposit events (i.e. in the average number **of events featuring many output photons — more than 2**) in case of axial alignment if compared to random.



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

electromagnetic radiation in the BGO calorimeter at different angular configurations



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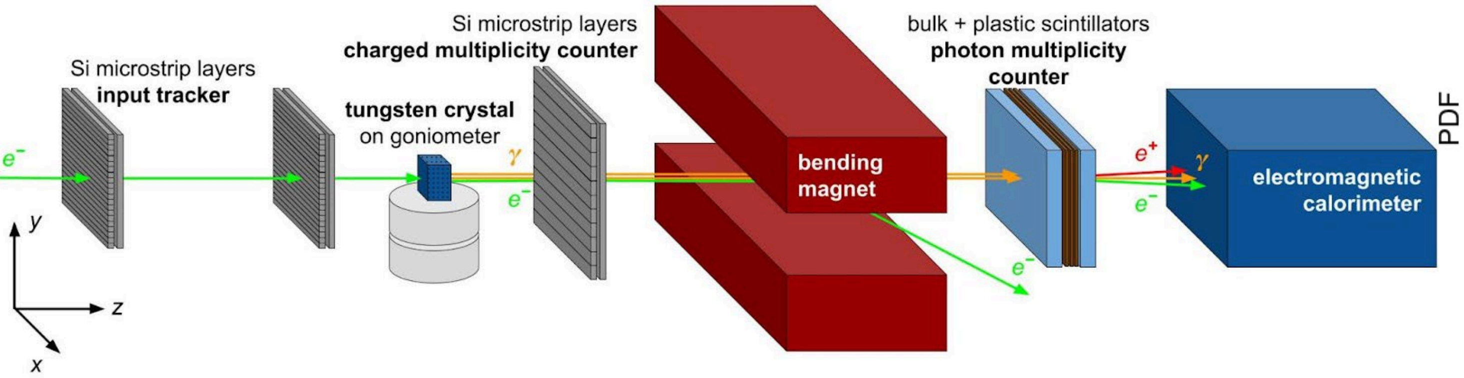
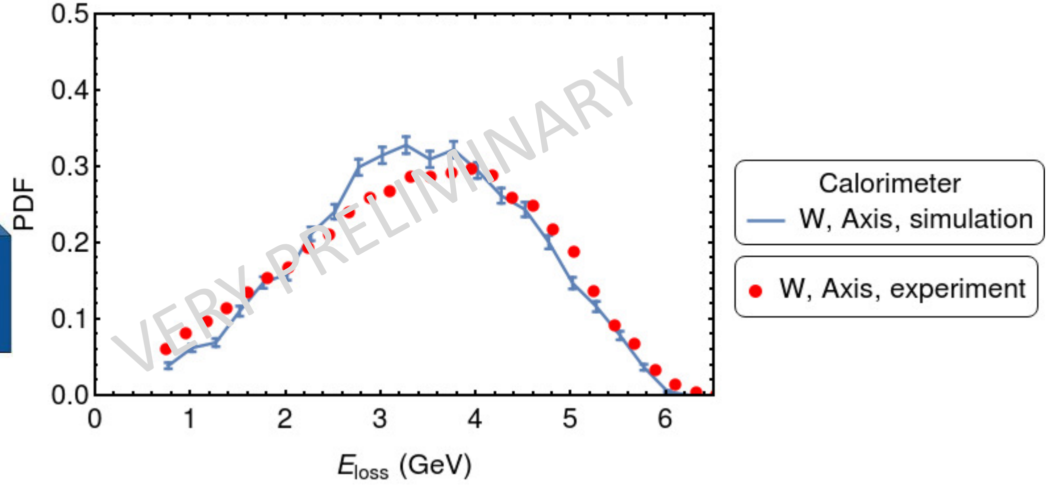
Validation of Monte Carlo with experimental data

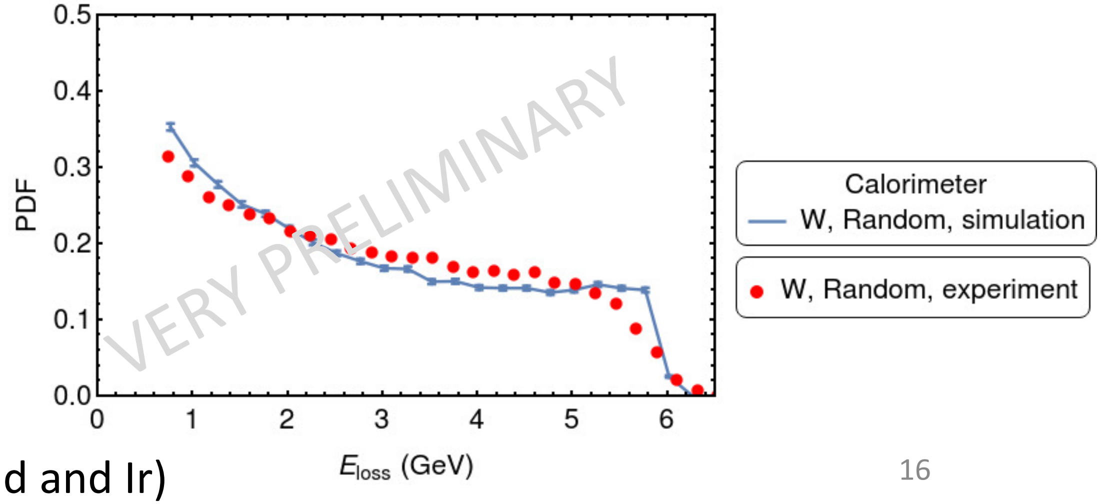
Setup @CERN PS T9 beamline



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

Radiative energy loss measured by the Ecal



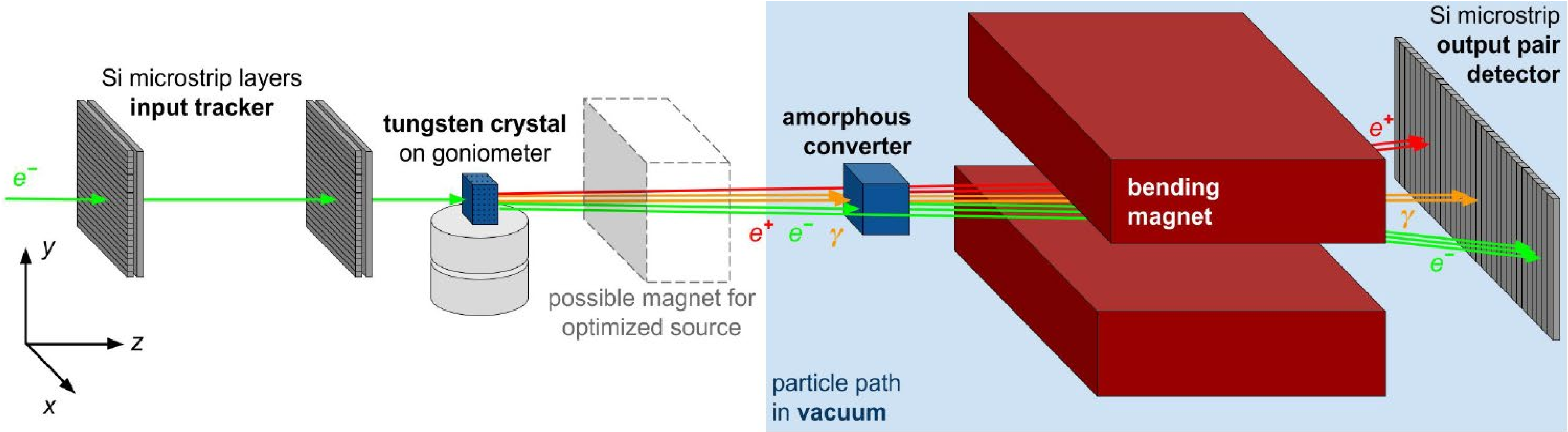


Parameters chosen in agreement with the Geant4 optimization:
L. Bandiera et al., Eur. Phys. J. C 82, 699 (2022), Crystal-based pair production for a lepton collider positron source. https://doi.org/10.1140/epjc/s10052-022-10666-6

Data analysis within E+BOOST ongoing
also with other W crystals with different thickness and materials (diamond and Ir)

E+BOOST plan for 2024 @PS

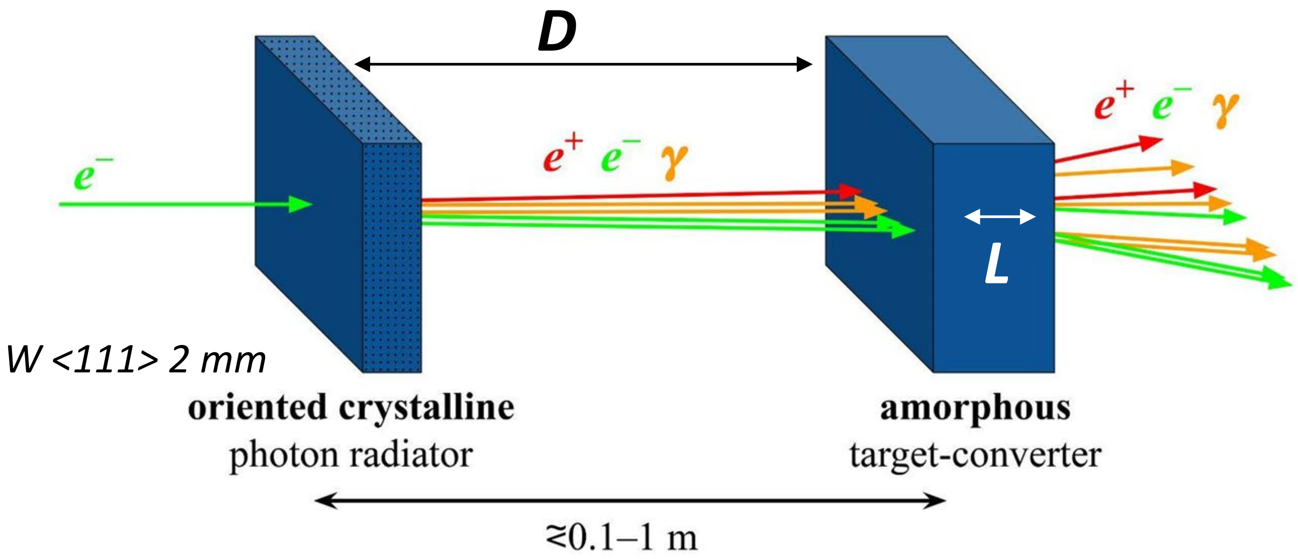
Test of crystal radiator + converter (placed immediately after the crystal target)



Beamtime request submitted on December 2022

Hybrid source optimization for FCC-ee

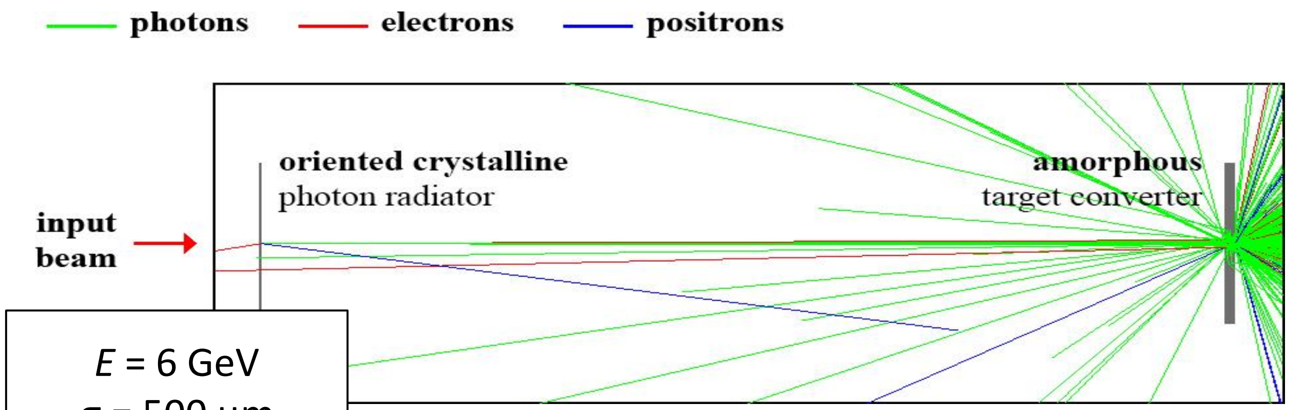
M. Soldani (INFN-Ferrara)



energy deposit and PEDD <u>in amorphous converter can be reduced by tuning</u> ***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***)



E = 6 GeV
σ = 500 μm
σ’ = 100 μrad

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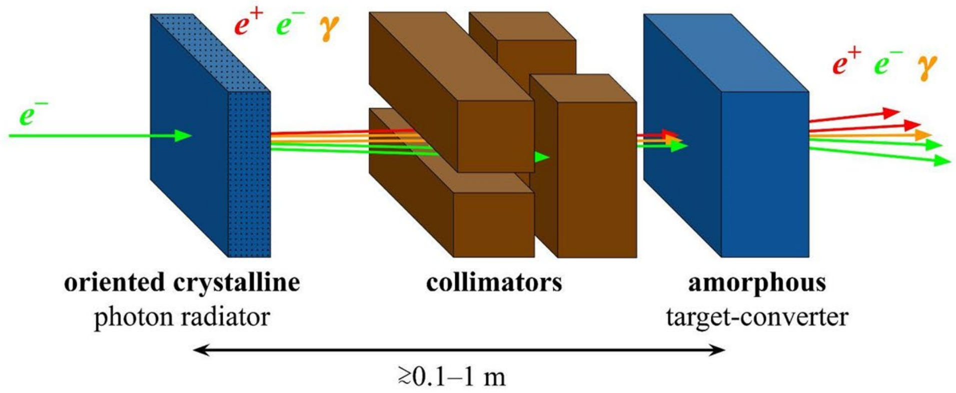
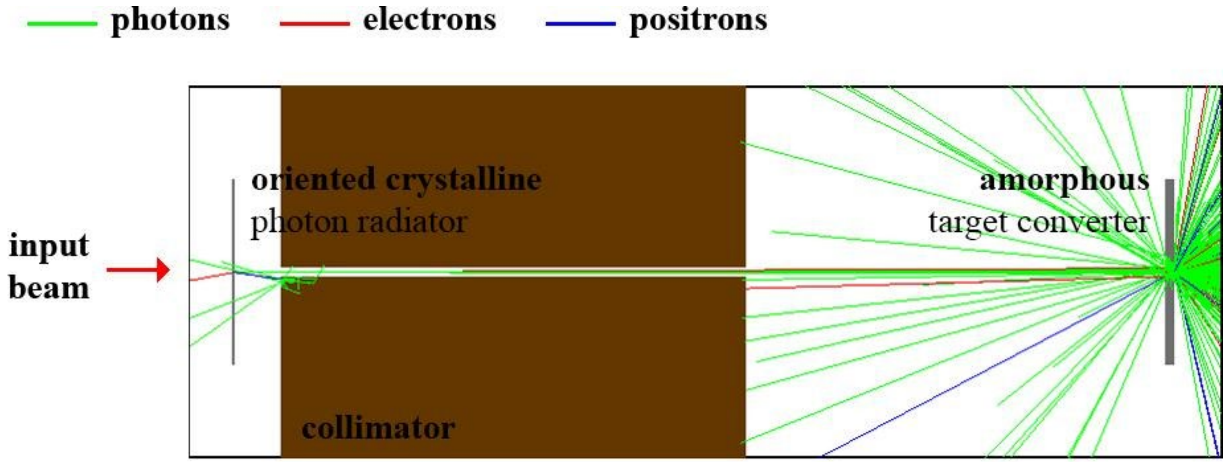
Collaboration with IJCLab (leader I. Chaikovska)

Improving the hybrid source for FCC-ee

L = 11.6 D = 600, 1000, 2000 mm

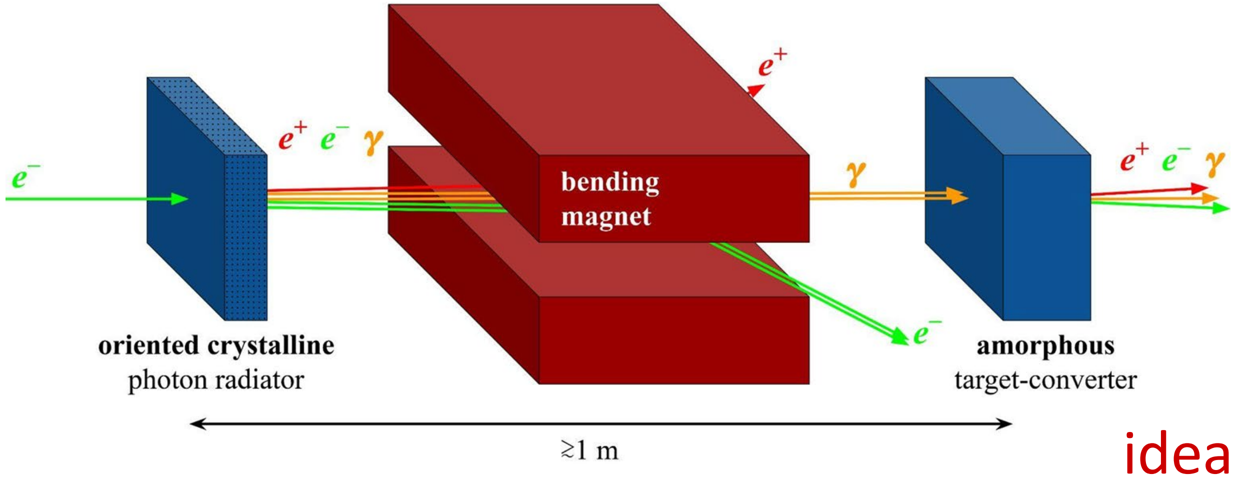
...with **collimator**

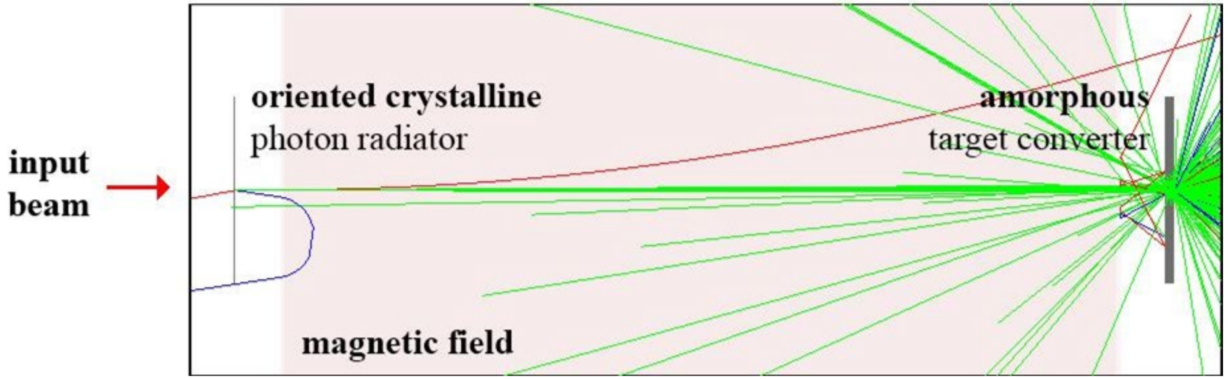




tungsten block of thickness 50 cm
with square hole of side ***a***

...with **magnet**





ideal, 100 T field to swipe all charged particles away

All together..

M. Soldani (INFN-Ferrara) in collaboration with I.Chaikovska (IJCLab)

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

a = 5.5 mm

conventional (amorphous)
collimator
magnet

Huge reduction of PEDD in the converter!
Same or even higher rate of positrons!

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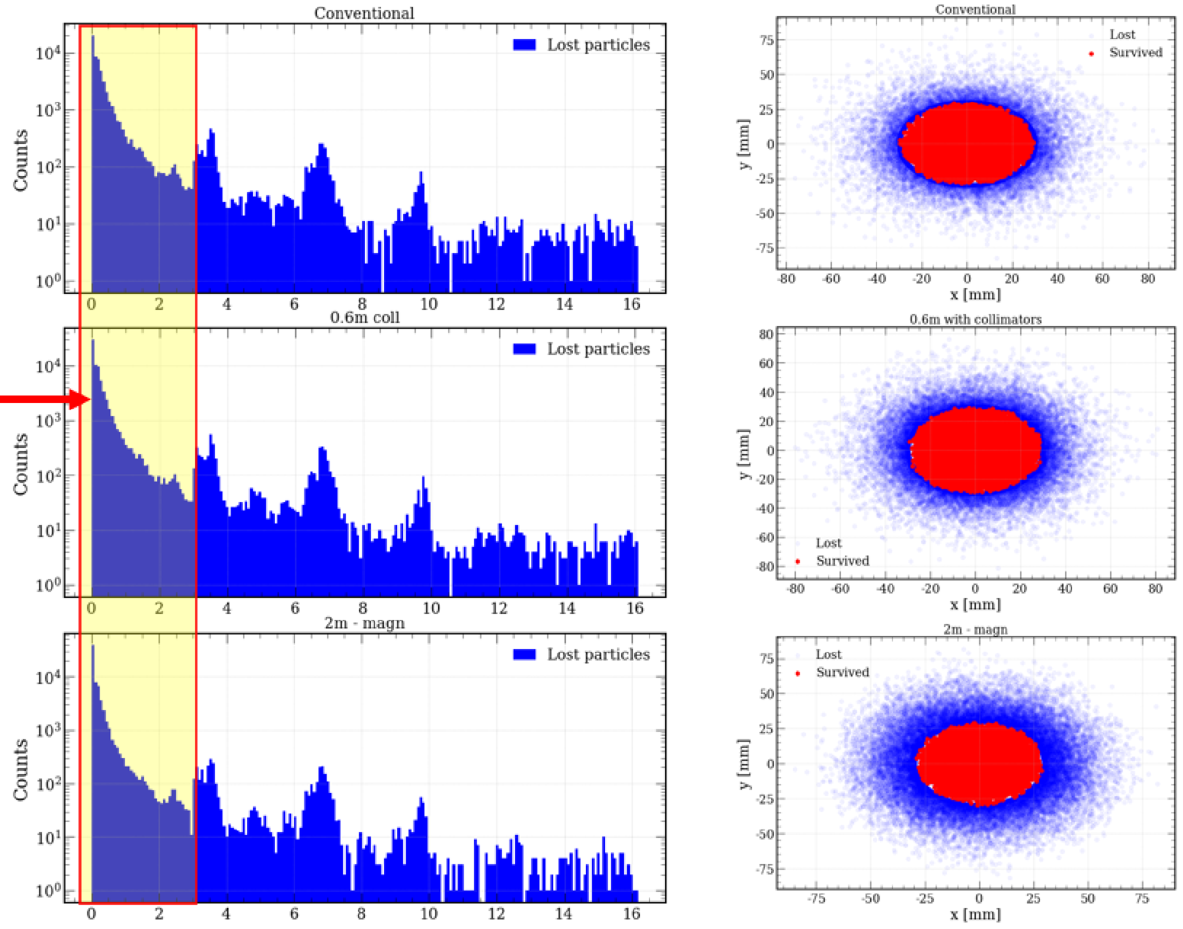
IJCLab started the Capture system simulation optimized for the Conventional source

Lost particles along the capture section

- Two cases were studied:
  best case (0.6m with collimators)
  worst case (2m with magnet)
- Both cases are compared with **Conventional**.
- Majority of the particles lost in first RF structure.
- The loss study focuses on the losses in the first RF structure.

- Possible reasons:
  - Large beam size ?
  - Large angular divergence?

Courtesy of F. Alharthi (IJCLab)



IJCLab started the Capture system simulation optimized for the Conventional source

Lost particles along the capture section

- Two cases were studied:
  best case (0.6m with collimators)
  worst case (2m with magnet)

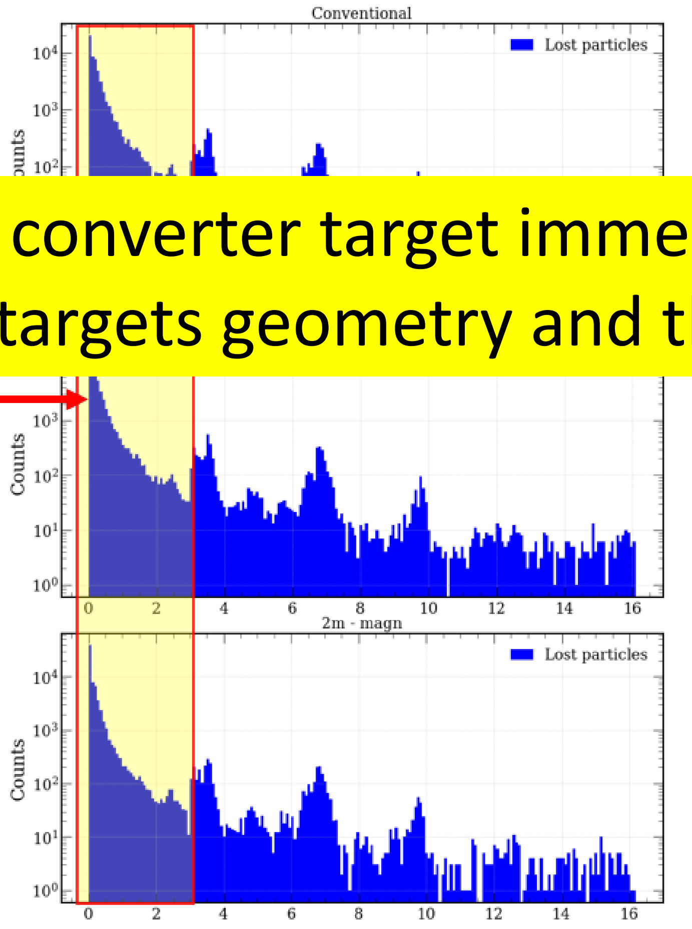
Current plan: place the converter target immediately after the crystal radiator; optimize targets geometry and the Capture system

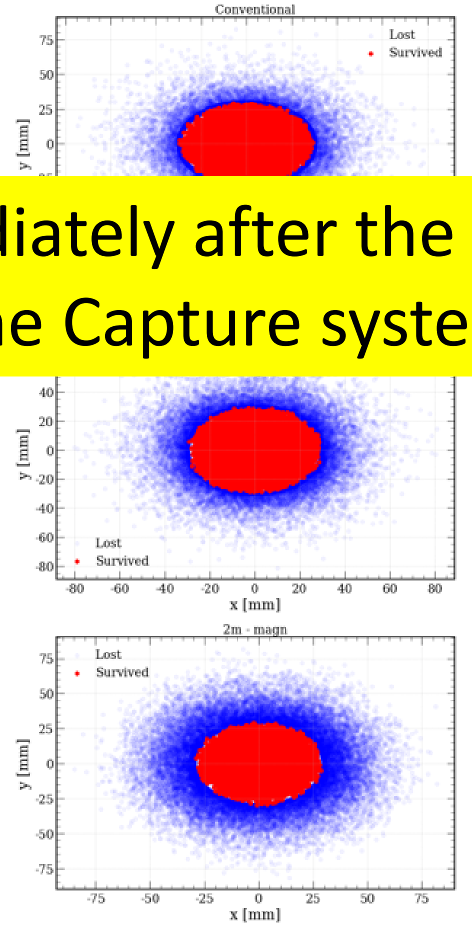
first RF structure.

- The loss study focuses on the losses in the first RF structure.

- Possible reasons:
  - Large beam size ?
  - Large angular divergence?

Courtesy of F. Alharthi (IJCLab)



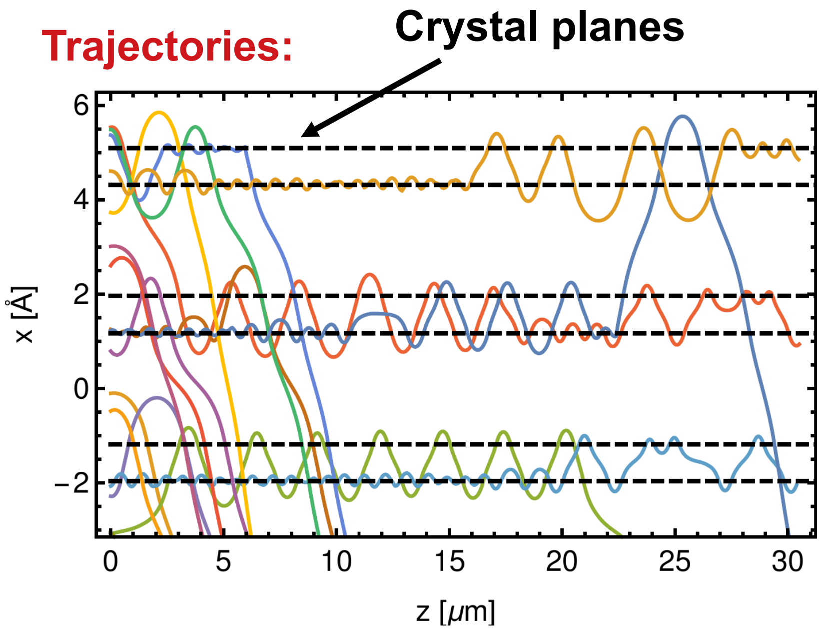


Channeling simulation technique: Geant4 ChannelingFastSimModel

- **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:



channeling*

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

Summarizing

Joint effort between IJCLab and INFN

- 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.

Joint effort between IJCLab and INFN

Activity ongoing and future plans

Experiment (coord. L.Bandiera INFN; M. Prest UNINSUBRIA)

- Crystal radiators (W and Ir) tested on e-beam at CERN PS in 2023 as a route the final configuration for the crystal radiator and amorphous converter. Data analysis ongoing @INFN Ferrara and UNIINSUBRIA.
- We applied for beamtime at CERN PS for 2024 to test the configuration crystal radiator + converter target.
- New Irradiation tests on crystal and converter targets at MAMI at the end of this month.

Simulation (coord. G. Paternò, A. Sytov INFN; AOM. Iorio Naple)

- In Autumn we started to 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 (IJCLab and INFN Milan)
- We are validating the new G4 model for crystal radiator simulation inside Geant4

Dissemination (coord. S. Bertelli – INFN LNF)

- Preparation of the website

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 in the full injector – deadline Autumn 2024 for the MC desing! -> This is the most urgent task!