TOWARD INTENSE POSITRON SOURCES FOR FUTURE COLLIDERS

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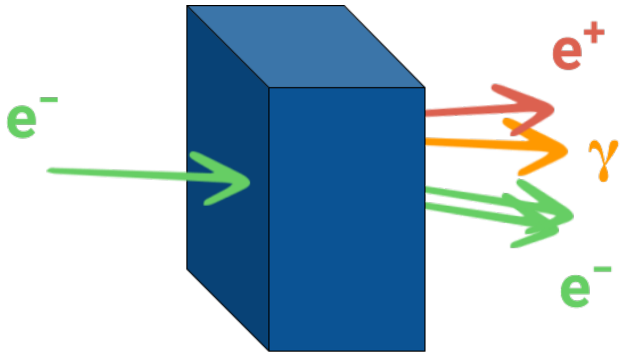
INFN Acceleratori
17/09/2024

e^+ sources are critical of the future high luminosity colliders

Conventional scheme



Thick amorphous
target

Current (Limited by the target)

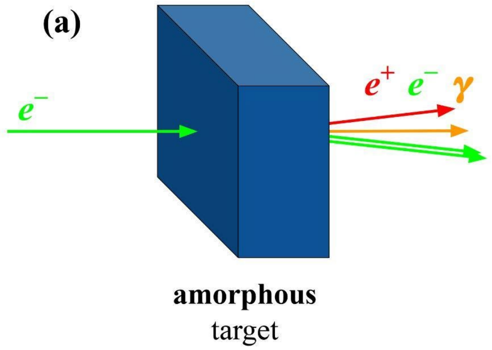
- Average energy deposition
  → target heating/melting
- Peak Energy Deposition Density (**PEDD**)
  → Inhomogeneous and instantaneous energy deposition, that cause thermomechanical stresses due to temperature gradient

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

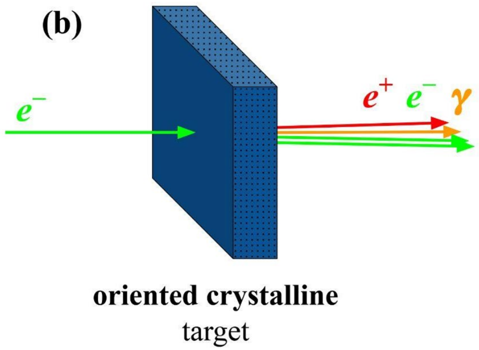
Hybrid crystal based positron source for future colliders

UNPOLARIZED POSITRON SOURCES

1. Conventional

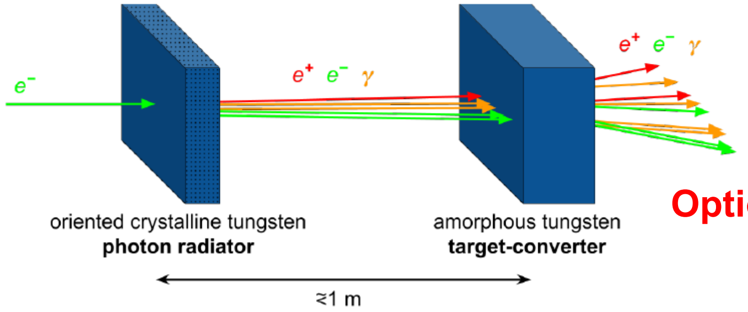


2. e+ from channeling radiation



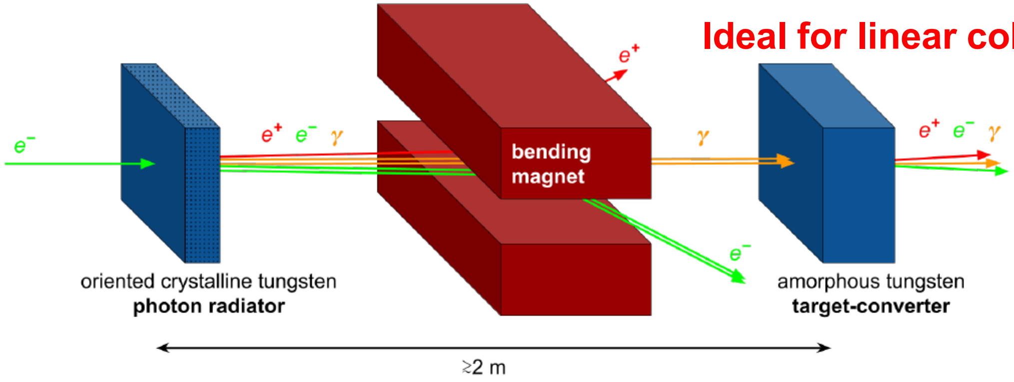
Tests performed at CERN (WA 103) and at KEK

3. Hybrid crystal based positron source



Option for FCCee

Ideal for linear colliders



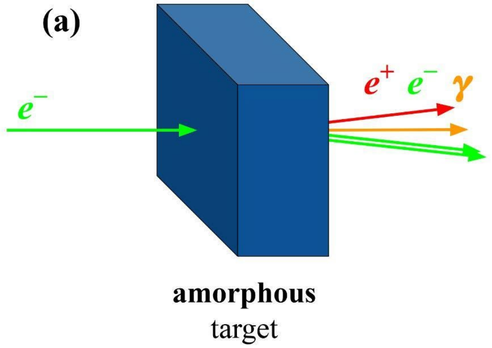
Idea of R. Chehab, V. Strakhovenko and A. Variola, NIM B 266 (2008) 3868

What investigated so far…

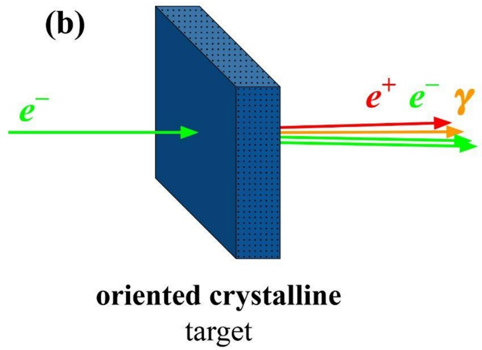
Activity born in the past CSN5 STORM project (2021-22) and CSN1 RD-MUCOL (for LEMMA), currently in CSN1 RD-FCC

UNPOLARIZED POSITRON SOURCES

1. Conventional



2. e+ from channeling radiation



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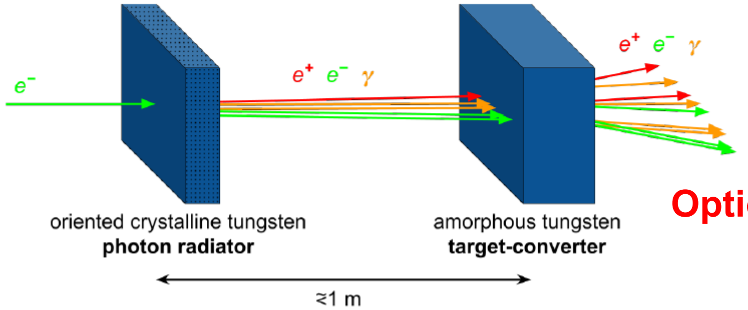
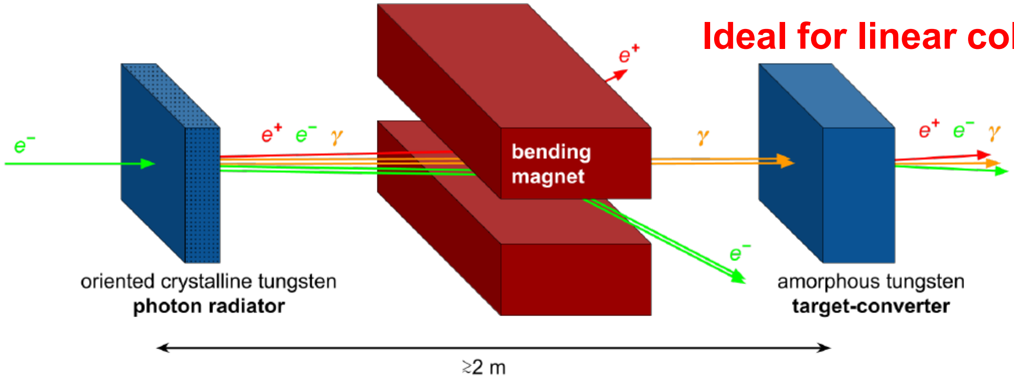


Option for FCCee

Ideal for linear colliders

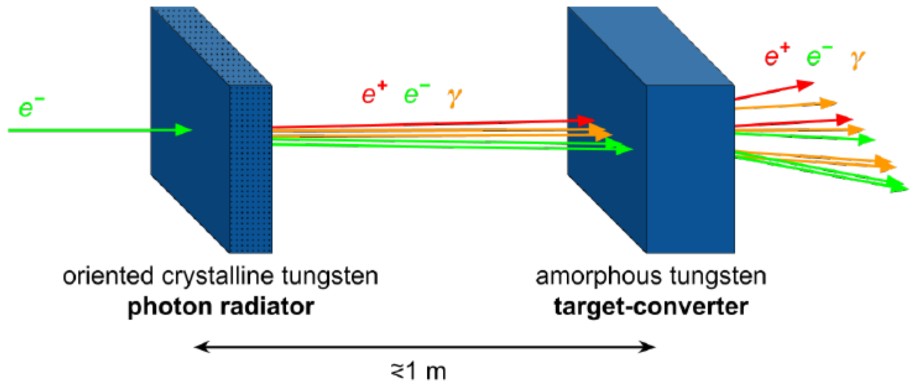


Idea of R. Chehab, V. Strakhovenko and A. Variola, NIM B 266 (2008) 3868

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

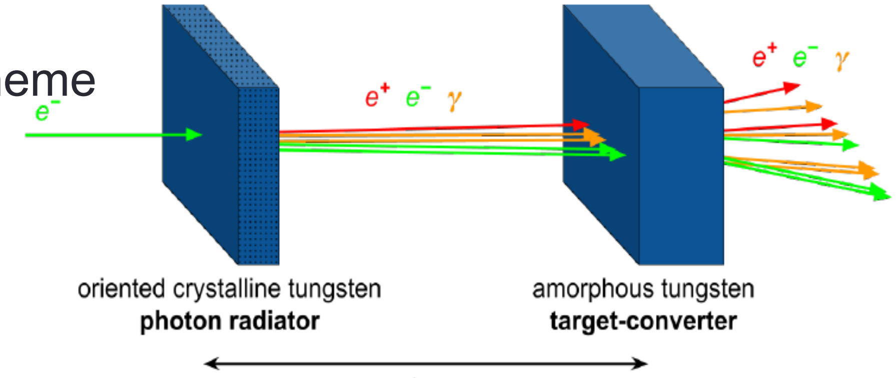
→ very low energy deposit and PEDD in radiator ⇒ very low heating and thermo-mechanical stress

I. Chaikovska, …, L. Bandiera,… et al., *Positron sources: from conventional to advanced accelerator concepts-based colliders* 2022 JINST 17 P05015

Ongoing activity: the FCC-ee e+ source

High luminosity: up to $230 \times 10^{34} cm^{-2} s^{-1}$

Hybrid scheme



Thin radiator **Thick converter**

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

Most demaning for the positron source

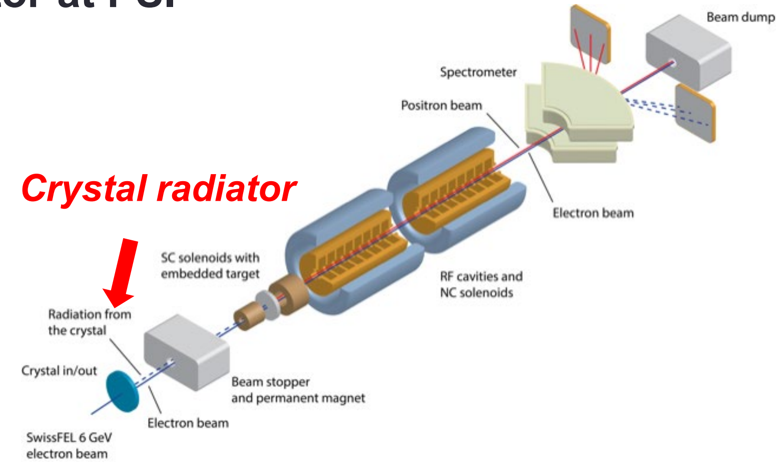
L. Bandiera et al., Eur. Phys. J. C 82 (2022) 699

Development of the **FCC-ee full injector design with a crystal-based e+ source**

Goals: include the design in the next **FCC CDR** and test it in the **future upgrade of the CHART P3 project on the full FCC-ee injector at PSI**

PAUL SCHERRER INSTITUT

Swiss Accelerator Research and Technology

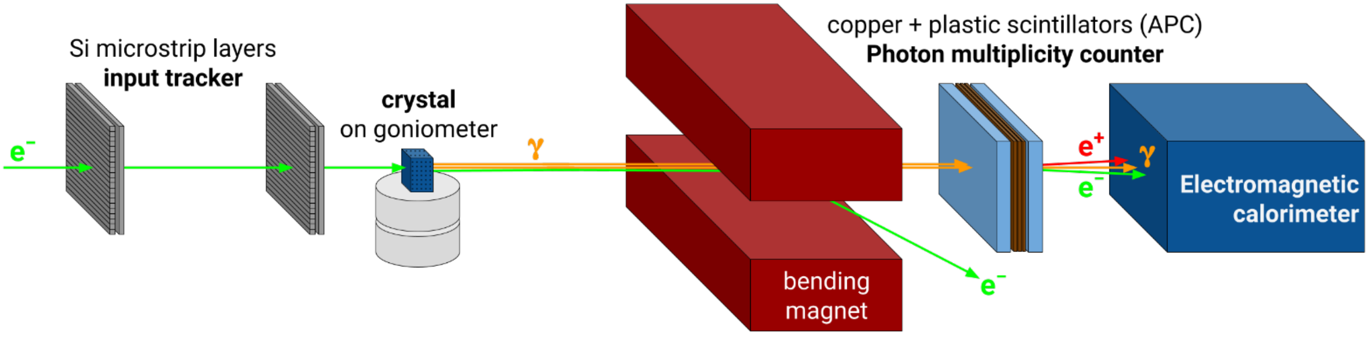


INFN Units involved: Ferrara, LNL, Milano, MiB, Naple

Collaboration with **FCC-ee Injector Studies** (I. Chaikovska, IJCLab)
MoU signed between in INFN Ferrara and IJLab in Sept. 2022

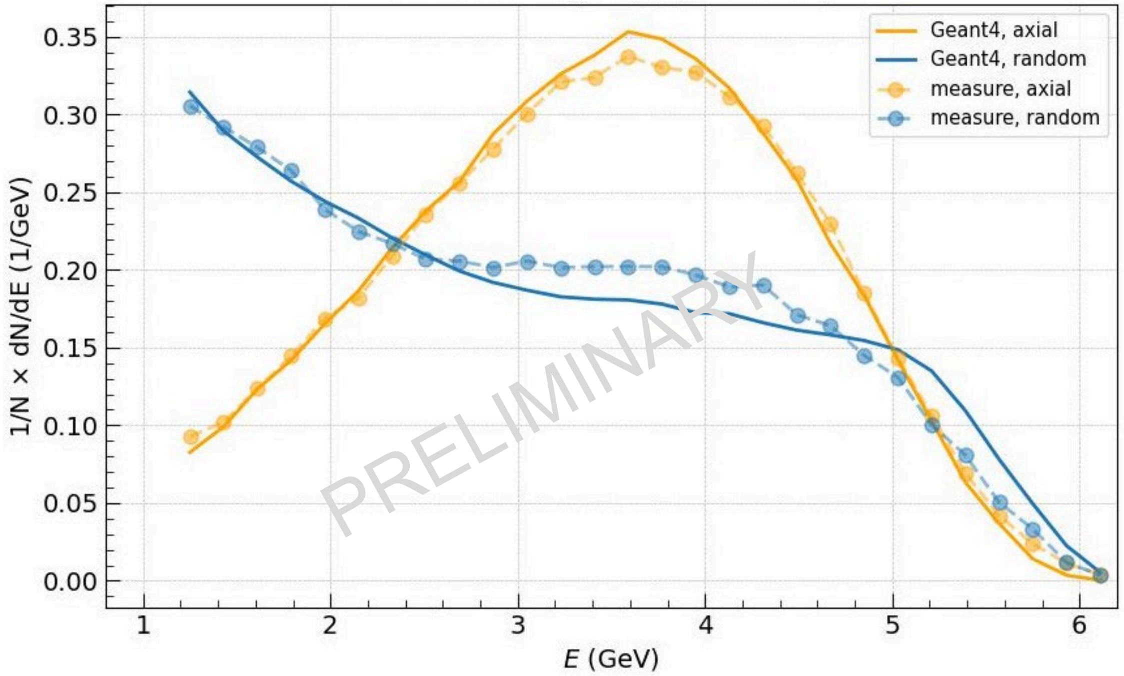
Experimental Studies on **Crystal Radiators** and Benchmarking with the Latest Geant4 Model

Setup @CERN PS T9/DESY TB beamlines



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

Radiative energy loss measured by the Ecal



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

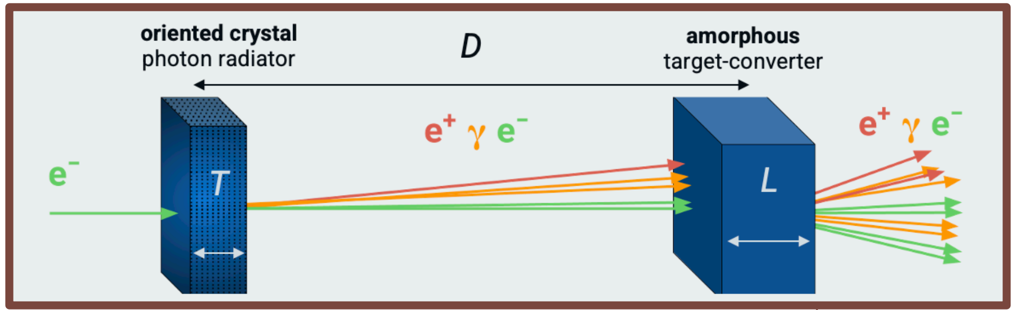
Towards conceptual design for FCC-ee

From FCC WEEK 2024

FCC-ee injector full chain simulation: e+ yield before the dumping ring

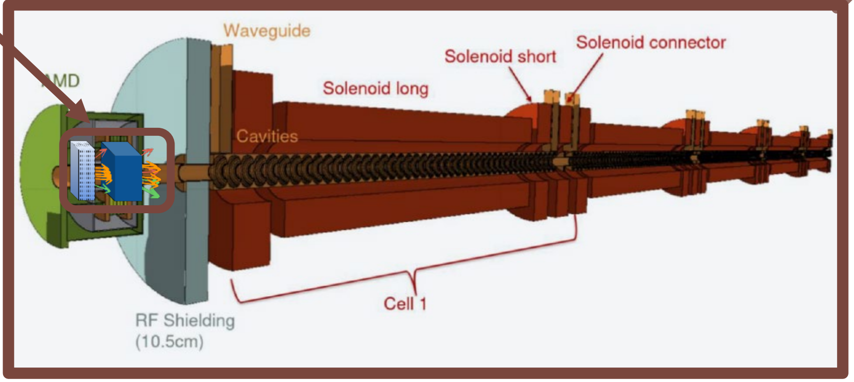
Collaboration with the **FCC-ee Injector Studies Group** (I. Chaikovska, IJCLab)

L. Bandiera et al., Eur. Phys. J. C (2022) 82:699
M. Soldani,.. L. Bandiera,. Et al., NIM A 1058 (2024)



The **whole hybrid positron source** setup was simulated through Geant4 toolkit taking advantage of **GeantG4ChannelingFastSimModel**

A. Sytov, L. Bandiera et al. JKPS 83 (2023)



After the positron source, the pair is captured in the injector system.

The simulation stages are simulated with the framwerok ***RF-Tracking*** *(IJCLab)*

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

GEANT I.N.F.N.

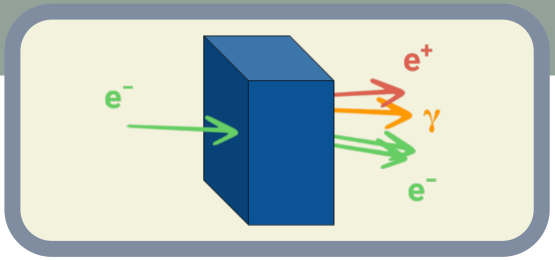
European Commission

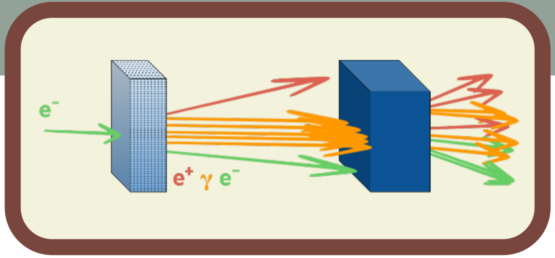
Trillion

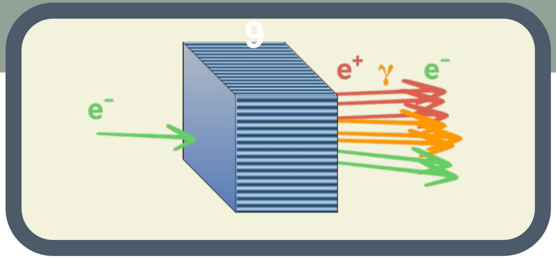
Funded by the European Union NextGenerationEU

Contribution from INFN Ferrara and Naple (people cofinanced by the e+BOOST PRIN2022-2022Y87K7X)

FCC-ee Conventional vs. crystal







To be validated

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**
- **Next steps**: **integration studies** with potential **proof-of-principle** at P^3 experiment @ PSI (and future CHART projects)
- **Missing:** test of **positron production with single crystal without goniometer** and **radiation resistance**

And what about other colliders?

Project	CLIC	ILC	LHEC (pulsed)	LEMMA	CEPC	FCC-ee
Final e^+ energy [GeV]	190	125	140	45	45	45.6
Primary e^- energy [GeV]	5	128** (3*)	10	-	4	6
Number of bunches per pulse	352	1412 (66*)	10^5	1000	1	2
Required charge [$10^{10}e^+$/bunch]	0.4	3	0.18	50	0.6	2.1
Horizontal emittance $\gamma\epsilon_x$ [μm]	0.9	5	100	-	16	24
Vertical emittance $\gamma\epsilon_y$ [μm]	0.03	0.035	100	-	0.14	0.09
Repetition rate [Hz]	50	5 (300*)	10	20	50	200
e^+ flux [$10^{14}e^+$/second]	1	2	18	10-100	0.003	0.06

* The parameters are given for the electron-driven positron source being under consideration.

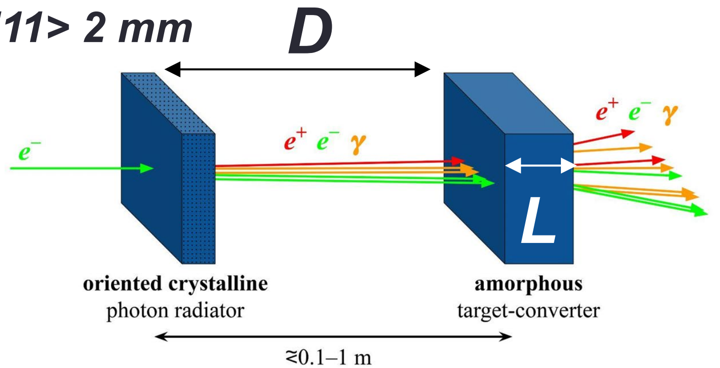
** Electron beam energy at the end of the main electron linac taking into account the looses in the undulator.

- The future Linear Colliders CLIC and ILC designs foresee a positron rate higher than FCC-ee by a factor 20 ÷ 30;
- The LHeC and LEMMA proposals aim at extremely high rates, about two order of magnitude higher than CLIC and ILC.

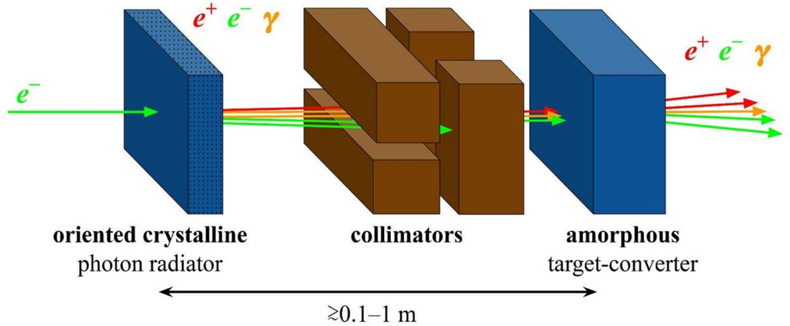
I. Chaikovska, …, L. Bandiera,… et al., *Positron sources: from conventional to advanced accelerator concepts-based colliders* 2022 JINST 17 P05015

Improved hybrid source….

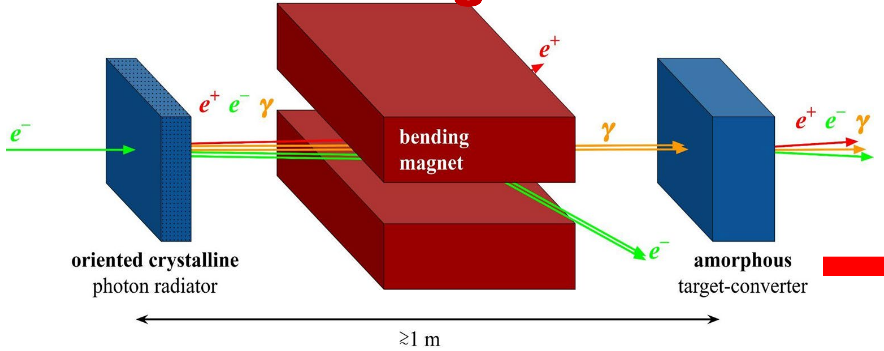
Crystal:
W <111> 2 mm



…with collimator



…with magnet



M. Soldani, A. Sytov (INFN-Ferrara)

conventional

Scheme	conv.	hybrid						
L_{crys} [mm]	–				2			
D [m]	–	0.6		1			2	
L [mm]	17.6				11.6			
Collimator? (: 5.5 mm)	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 · 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

PEDD decreased in case of hybrid vs conventional

Nearly the same or even higher positron production vs. the conventional scheme

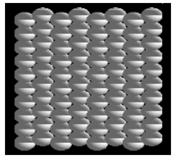
Baseline for CLIC and proposed for LHeC/LEMMA (several hybrid targets in parallel with cooled, rotating/granular converter)

Objectives

The goal of this project is to develop and test different positron source schemes to realize high-performance positron sources for future lepton colliders.

Task 1. Study of **hybrid sources not considered in the current studies** that combine the use of oriented crystals with magnets and collimators to reach the highest intensity required by **linear colliders (CLIC, ILC), LHeC or LEMMA.**

Task 2. Use of **granular and/or rotating targets** designed to distribute the thermal load over a larger area, reducing wear and increasing component lifespan. Also **cooling** will be considered..



J.Phys.G.Nucl.Part.Phys.29 (2003)1797-1800

Taks 3. Study of the **single thick crystal** option for the current **FCC-ee** CDR update, which potentially reduces the system complexity. This scheme needs further investigation to be validated (thick crystal resistance, absence of goniometer for alignment control, beamtest for MC validation, etc..)

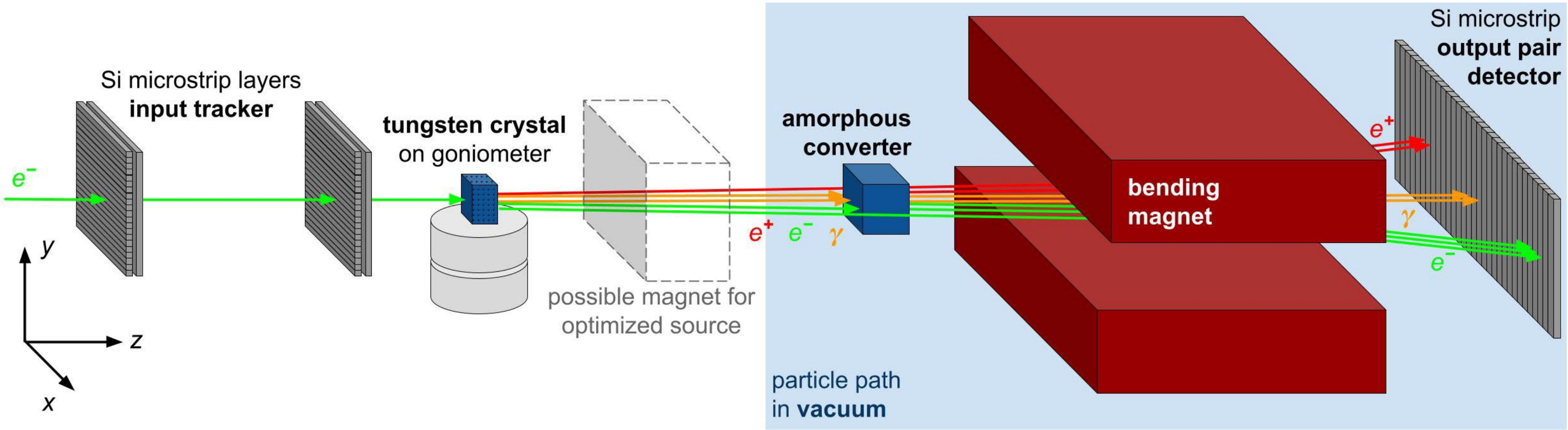
This approach not only addresses the limitations of current high-intensity conventional positron sources but also offers a more sustainable solution, even when conventional methods are still operational.

Planned Activities

WP1 MC Design: The new tool integrated into the Geant4 toolkit will enable detailed modeling and optimization of hybrid source performance. Optimization of beam properties for positron production and capture before injection into the damping ring.

WP2 Targets study: Crystallographic characterization of selected samples will be performed to ensure lattice quality. Irradiation tests, likely at CERN or MAMI, will assess the target's durability and structural resilience.

WP3 Experimental validation: The most promising designs will be tested with electrons in the few-GeV range at facilities like CERN PS or DESY TB. This will require new detectors, mechanical supports, and vacuum systems to build a spectrometer to measure the positrons produced.



Considering different solution for the spectrometer, most likely detectors will be placed inside the magnet

Preliminary Budget Estimate and Personnel

Research Budget: about 300 k for the first three years

Materials (240 k):

•Crystals and amorphous target (possibly rotating, granular, or cooled) of W (Ir or C as alternatives)
•Mechanical supports and systems dedicated to characterizations in lab and on beamlines, irradiation tests, etc.

•Trackers for positron spectrometer (to be placed inside the magnets, already available at CERN PS and DESY TB)

Missions (60 k):

•CERN PS and DESY TB for beamtest with GeV electrons
•MAMI and CERN for irradiation tests

PostDoc positions: 1 or 2 (1 simulation, 1 experimental activities)

INFN FE & UniFE (8 people); 2 FTE
INFN LNL (3 people); 0.5 FTE
INFN MI (3 people); 1 FTE
INFN MiB & UniInsubria (2 people); 0.5 FTE
INFN NA & UniNA (2 people); 1 FTE

INFN team and collaboration

INFN Units involved

- INFN **Ferrara & UNIFE** (leader Laura Bandiera): Design and characterization of targets for the positron source, expertise in channeling radiation physics (experiment and Geant4 simulation).
- INFN **LNL &UniPD** (leader Davide De Salvador): High-precision goniometer system for crystal alignment.
- INFN **Milano** (leader Alberto Bacci): Beam dynamics and modeling via AI software GIOTTO. Team already involved in CHART P3, for the conventional source.
- INFN **MiB, University of Insubria** (leader Michela Prest): Beam test design (and detector commissioning).
- INFN **Napoli and UniNA**(leader Orso Iorio): Monte Carlo simulations of the experimental setup, design of different positron source configurations for future colliders via simulations.

International Partners:

- **IJCLab** (leader Iryna Chaikovska): Expertise in positron sources, currently leader of the FCC-ee Injector Studies: WP3 "Positron source: target and capture system" and CHART FCC-ee Injector design and PSI Positron Source (PSS) project. An MoU between INFN Fe and IJCLab signed in 2022 for the development of positron sources for future colliders.
- **PSI** for the CHART P3 project (P. Craevich)
- **CERN** for the FCC-ee Injector Studies: WP3 "Positron source: target and capture system"