Dr. Alexei Sytov

on behalf

F. Alharthi, L. Bandiera, L. Bomben, R. Camattari, G. Cavoto, I. Chaikovska, R. Chehab, K. Cho, D. De Salvador, V. Guidi, V. Haurylavets, E. Lutsenko, V. Mascagna, A. Mazzolari, M. Prest, M. Romagnoni, F. Ronchetti, F. Sgarbossa, M. Soldani, A. Sytov, M. Tamisari, V. Tikhomirov and E. Vallazza

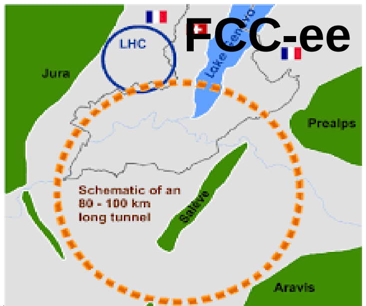
Crystal-based positron source for future lepton colliders

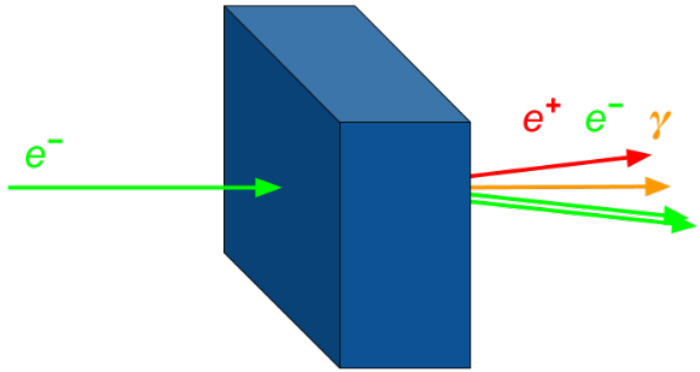
The 24th International Conference on Accelerators and Beam Utilizations

ICABU2022

Gyeongju, 2022/11/10

Positron source for future lepton colliders





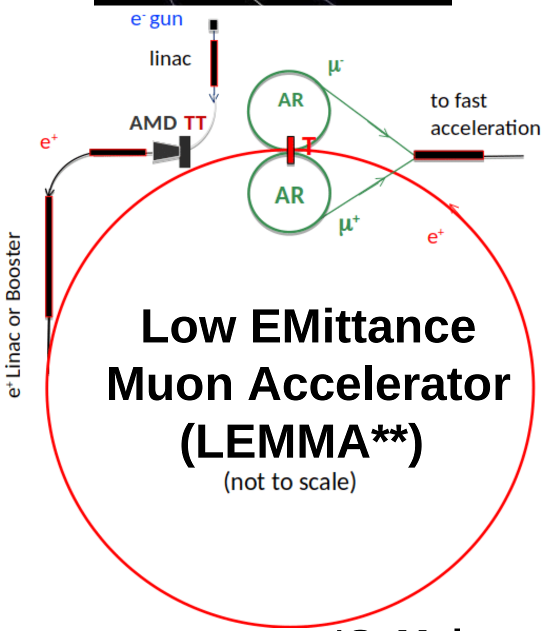
amorphous tungsten

All the future **e+e- colliders** will need an **intense positron source**

Potential challenges:
Target overheating/melting

Peak Energy Deposition Density (**PEDD**) limit:
35 J/g for **W***

The main **challenge**:
to **increase positron yield** and to **decrease PEDD**



LEMMA: **muon production by 45 GeV e+** beam annihilating with the e- of target

*S. Maloy et al., Slc target analysis. LANL LA UR-01-1913 72 (2001)

**M. Antonelli et al., Nucl. Instr. Meth. A807 101-107 (2016)

Future collider project challenge: positron flux

Demonstrated (**a world record** for existing accelerators): **e+ flux**: ~**6e12 e+/s** (SLC e+ source)

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	1312 (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
Polarization	No/Yes***	Yes/(No*)	Yes	No	No	No

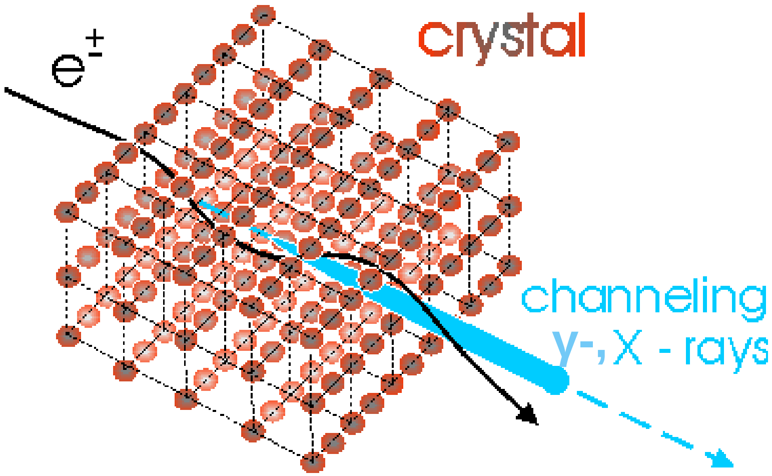
* The parameters are given for the electron-driven positron source being under consideration.
** Electron beam energy at the end of the main electron linac taking into account the looses in the undulator.
*** Polarization is considered as an upgrade option.

Strong need for a novel positron source

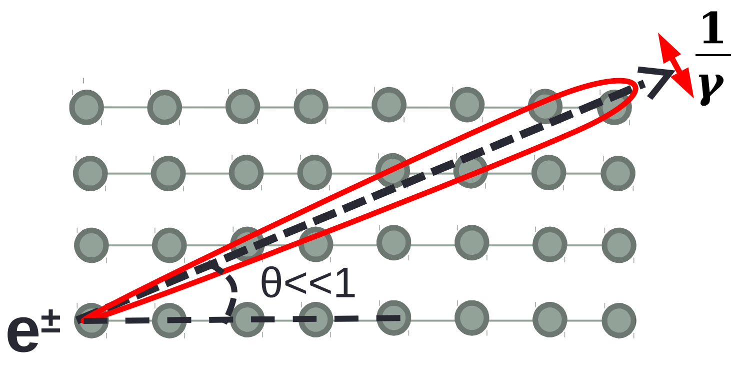
* I. Chaikovska et al. JINST 17, P05015 (2022)

What about coherent effects in crystals?

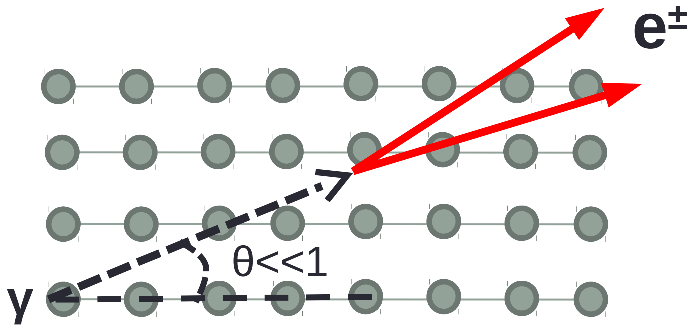
Channeling radiation*



Coherent bremsstrahlung**



Coherent pair production***



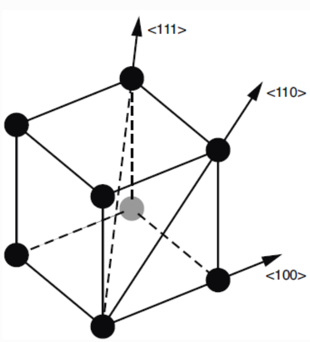
Coherent effects preserve **up to few mrad** of particle direction vs the crystal axis

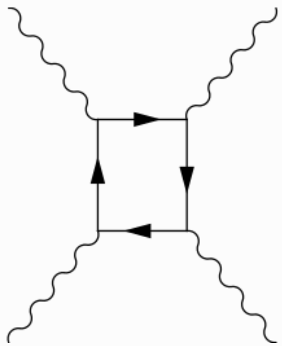
*M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
**B. Ferretti, Nuovo Cimento 7, 118 (1950).
**M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).
*** H. Überall, Phys. Rev. 103, 1055 (1956).

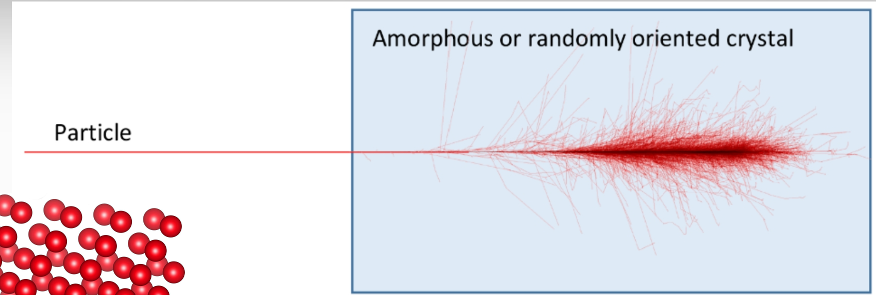
Electromagnetic shower acceleration

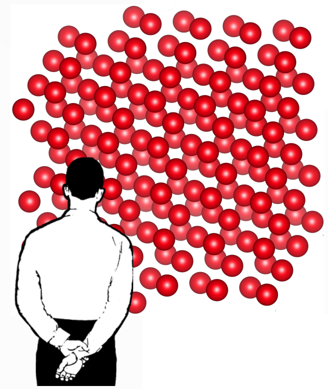
Axial field
10^{11} V/cm

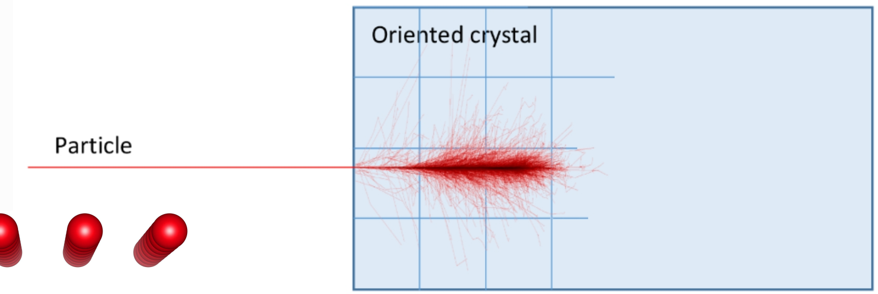
Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**

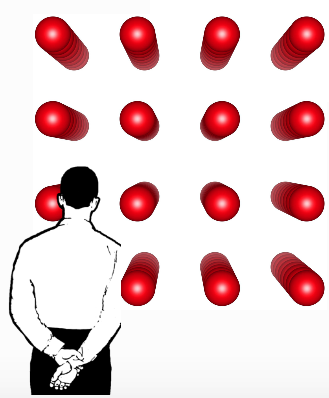










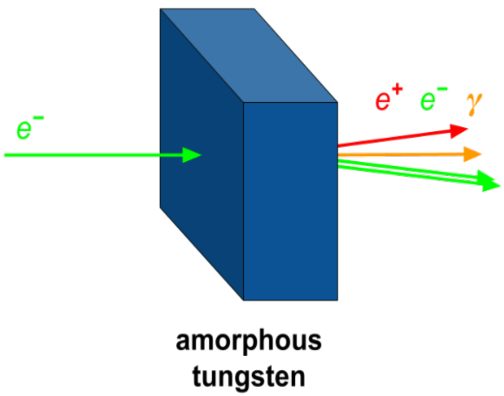


The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

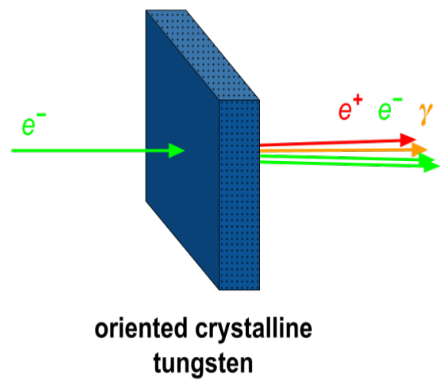
Shower development in the field of axes is **accelerated**. The radiation length is considerably reduced*.

Different types of crystal-based positron source*

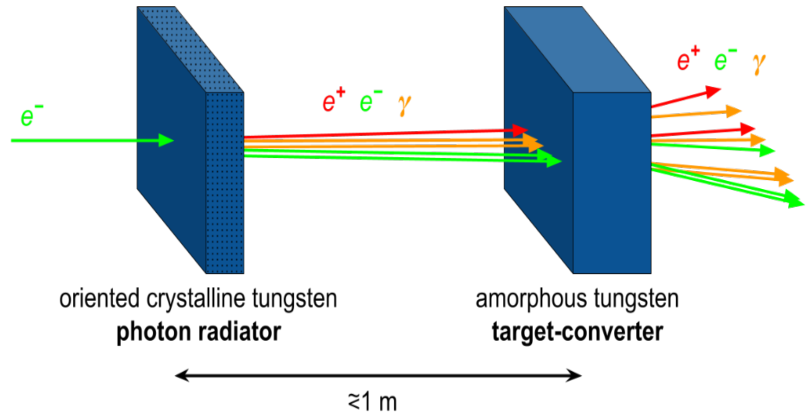
Conventional target



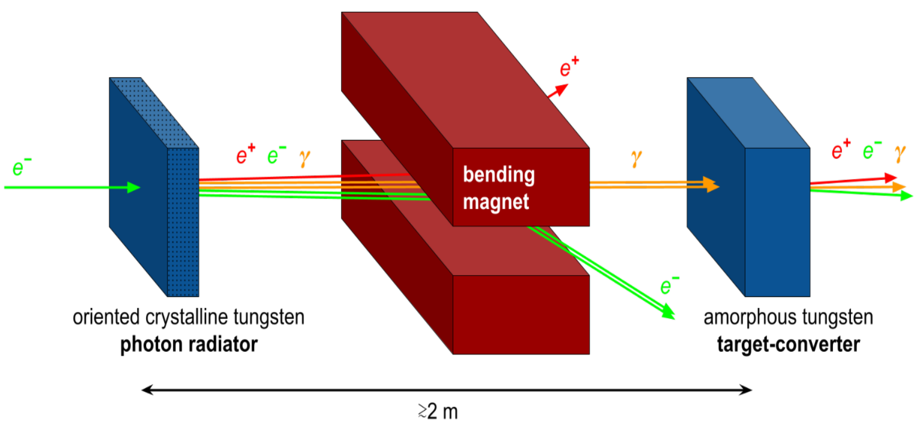
Crystal target



Hybrid scheme



Hybrid scheme with magnetic field

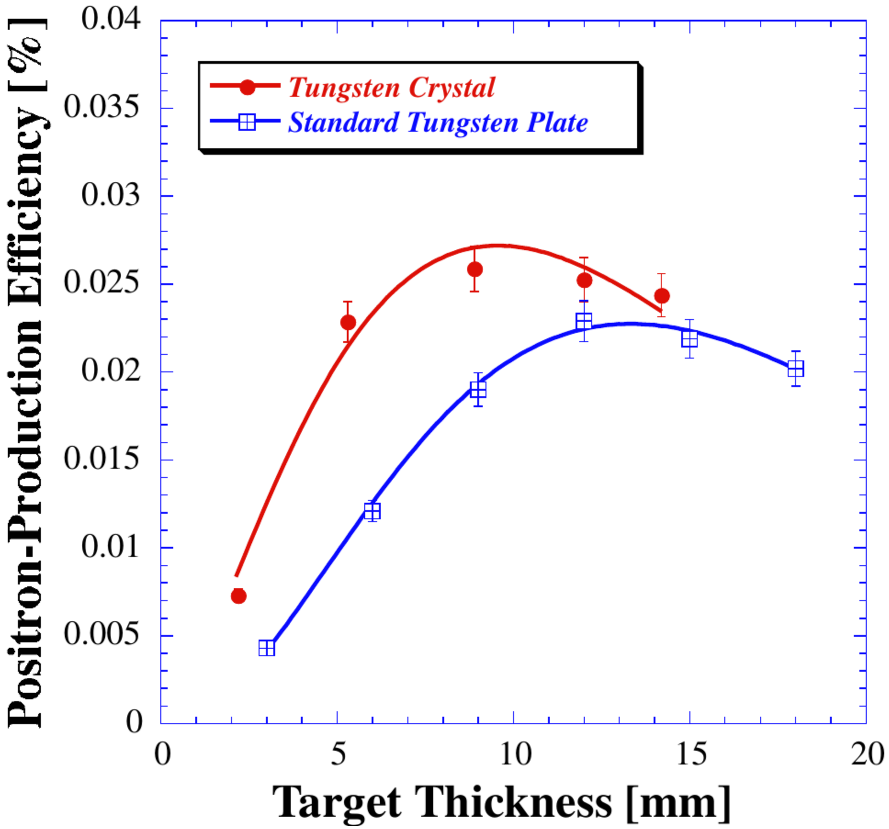


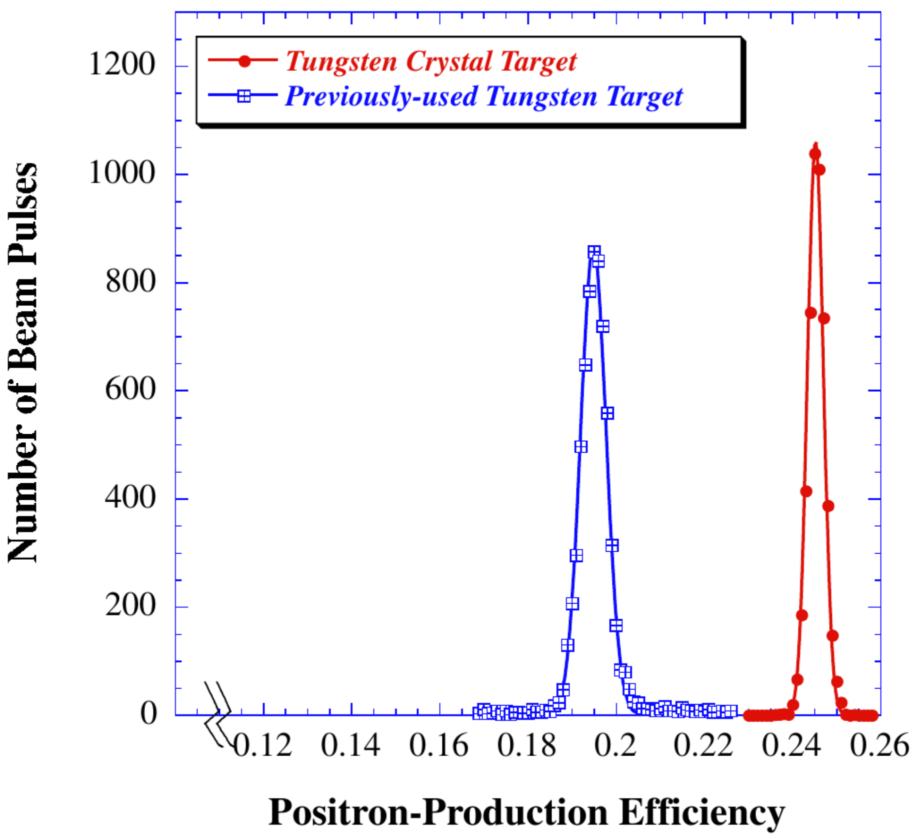
Hybrid positron source: two stages

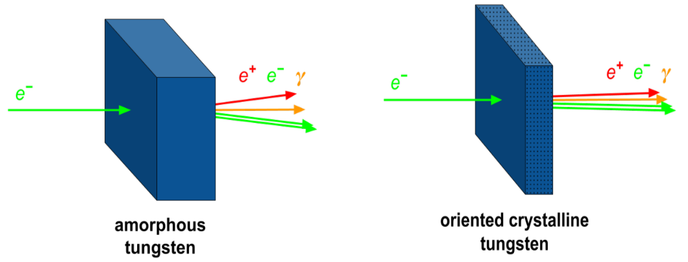
- **1. Radiation production** and **beam scattering** at the first target
- **2. pair production** in the second target
- Optional magnetic field between 2 targets to reduce PEDD at the second target

positron yield increase
PEDD reduction

First application of a tungsten single-crystal positron source at the KEK B factory (2006)*







An **oriented W crystal**:
gives **rise** to the **positron yield** up to **25 %**
reduces heat load by **20 %**

These results were published in the following paper:

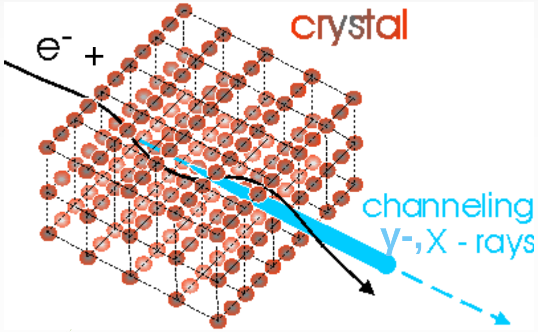
***T. Suwada et al. Phys. Rev. ST Acc. and Beams 10, 073501 (2007)**

Baseline simulation code

Main conception – tracking of charged particles in a crystal in averaged atomic potential

Simulation of the different physical processes:

- Multiple and single **Coulomb scattering** on nuclei and electrons.
- **Radiation**
- **Pair Production**



Baier-Katkov formula:
integration is made over the classical trajectory

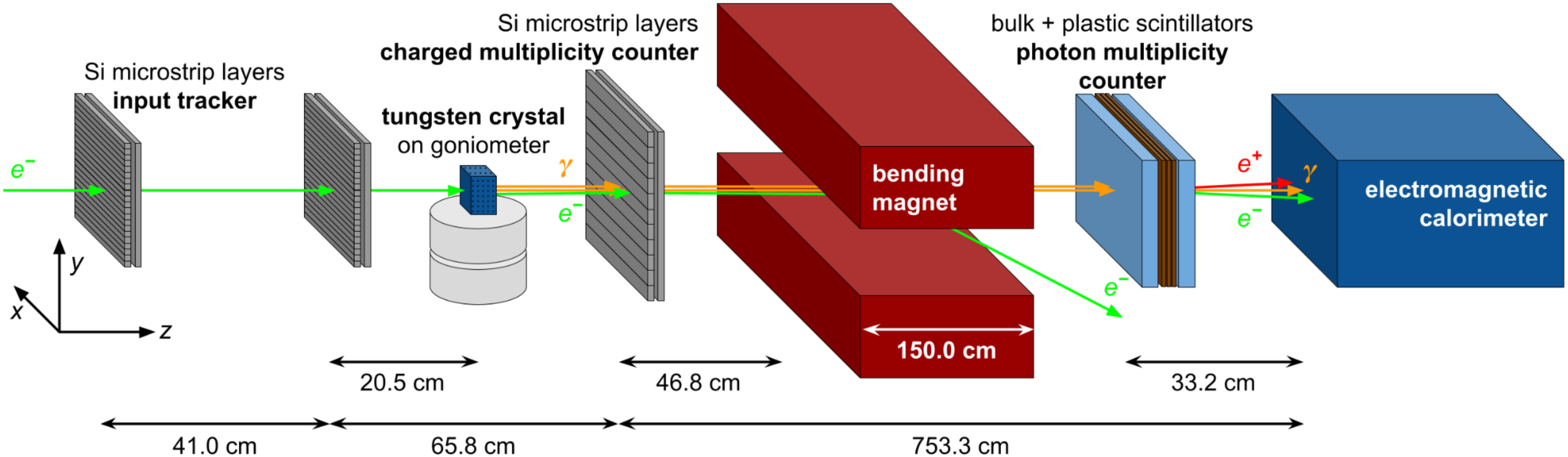
$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2]}{2E'^2} e^{-ik'(x_1 - x_2)}$$

Simulation of **physics** in a **crystal** with **our code** and **experimental setup** with **Geant4**

Supercomputing resources:
We acknowledge the CINECA award under the ISCRA initiative, for the availability of high performance computing resources and support. This work is also supported by the KISTI National Supercomputing Center with supercomputing resources including technical support (KSC-2022-CHA-0003).

V. Tikhomirov Nucl. Instrum. Methods Phys. Res. Sect. B 82, 409 (1993)
V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86, 042903 (2012)
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)

Experiment @DESY Test Beam Facility T21 (2019)*

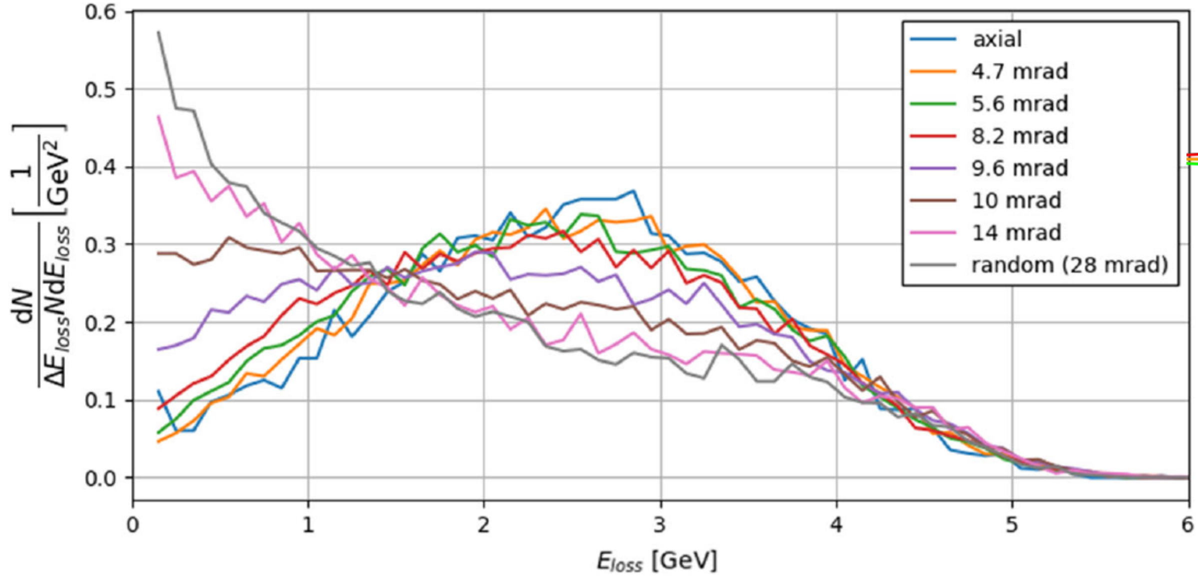


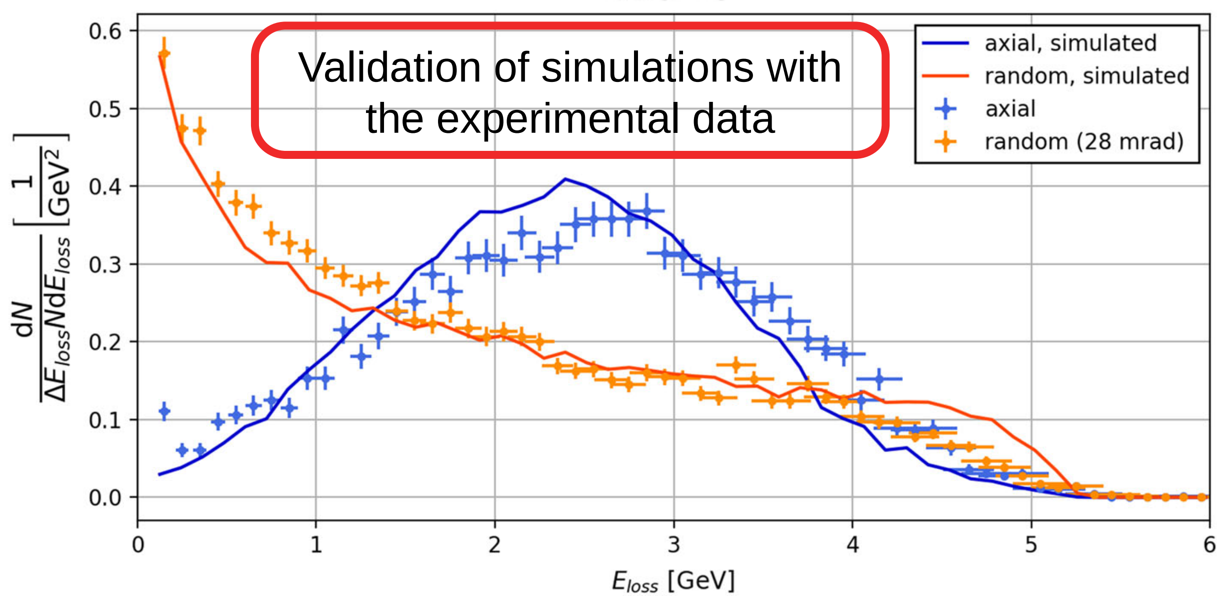
Investigation of radiation enhancement **in an axially oriented tungsten crystal**

e- beam energy = 5.6 GeV, beam divergence ≈ 0.7 mrad, W crystal, <100> oriented, 2.25 mm thick (≈0.65 X0). For this axial orientation: θc ≈ 0.52 mrad. Mosaicity < 150 μrad.

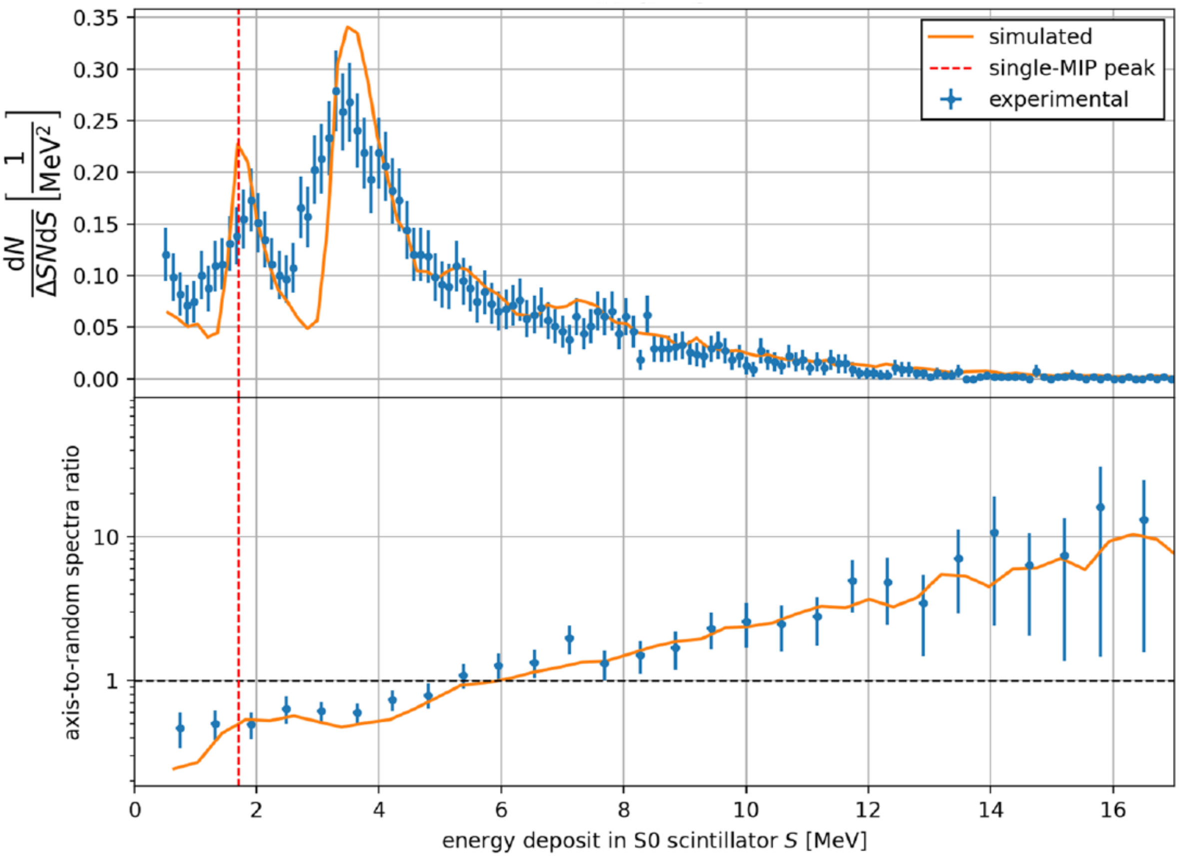
We acknowledge the DESY beamline staff for the assistance provided.
The experiment financed by STORM project of INFN.
V.Haurylavets and V.Tikhomirov acknowlegde the support by F22MC-006 Grant.

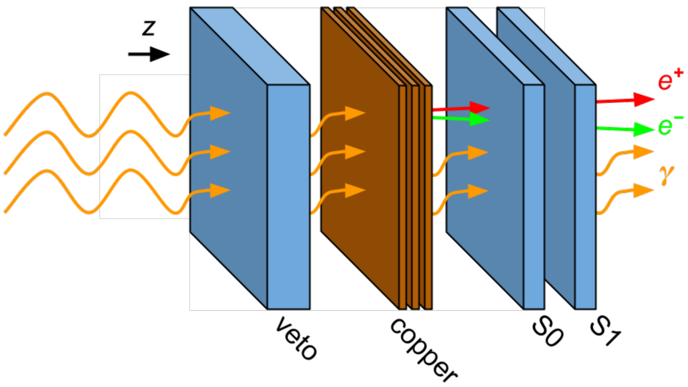
Radiation energy loss measurement (from axial to random alignment)





Experimental results on photon emission enhancement



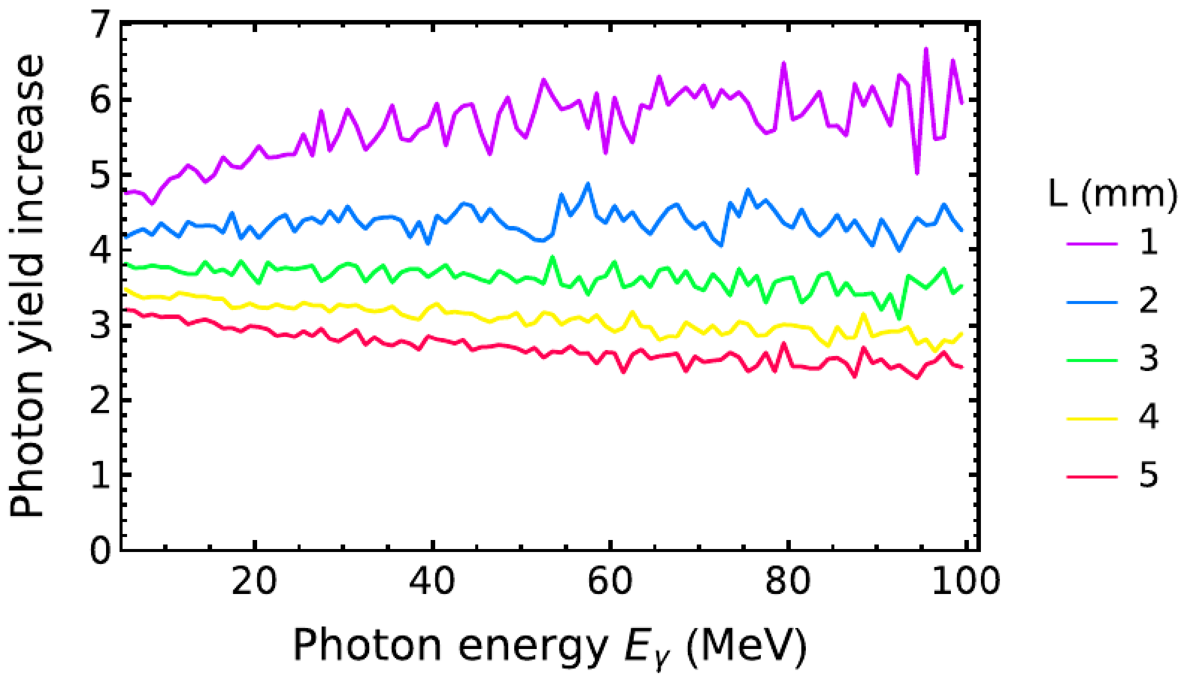


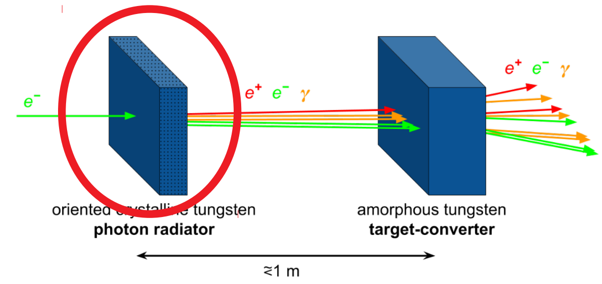
The **number of photons** produced in the crystal was **measured** by using a **preshower**

The experimental results show **photon multiplicity increase** for the **axial crystal alignment**

Agreement between **experiment** and **simulations** allows us to **use** our **simulation codes** for the **design** of crystal-based hybrid positron source

Simulations of photon yield increase in a crystal vs random





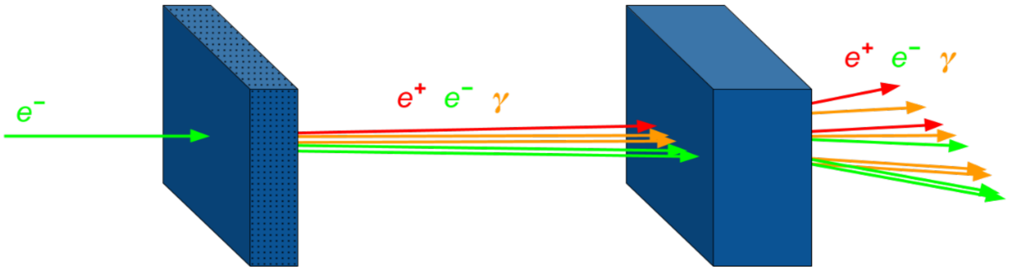
Simulation input:

- e- energy: **6 GeV**
- angular divergence: **0.1 mrad**
- r.m.s. transverse beam size: **0.5 mm**
- **W, axes <111>**

Crystal thickness (mm) N_γ	1	2	3	4	5
< 100 MeV, amorphous	1.1	2.6	4.6	7.4	10.9
< 100 MeV, ⟨111⟩ axis	6.1	11.3	17.2	24.0	31.8
Full spectrum, amorphous	2.3	4.7	7.5	11.0	15.1
Full spectrum, ⟨111⟩ axis	11.0	17.6	24.0	31.0	38.8

Mainly **soft γ photons** will be **used** for **positron** production due to requirements of the capture system

Hybrid source optimization for FCC-ee positron source using Geant4



configuration	tgt. PEDD $\left[\frac{GeV}{e^{-}*mm^3}\right]$	e+ rate [e+/e-]	e+ beam size [mm]	e+ beam divergence [mrad]	e+ mean energy [MeV]
conventional, 17.6 mm	0.038	13.7	0.67	25.915	48.7
hybrid, 2mm+1000mm+11.6 mm	0.008	15.1	1.24	26.841	45.6
hybrid, 2mm+2000mm+11.6 mm	0.004	14.9	1.55	29.208	46.1
hybrid, 2mm+600mm+11.6 mm	0.013	15.1	1.05	27.392	46.2

positron yield increase
PEDD reduction

Marie Sklodowska-Curie Action Global Individual Fellowships by A. Sytov in 2021-2024, Project TRILLION GA n. 101032975

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 to bring them to a large scientific and industrial community and under a free Geant4 license.

Group:

- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

Location:

- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

GEANT4 A SIMULATION TOOLKIT

In the future: **Crystal-based hybrid positron source** as a **Geant4 example**

More details in my poster PU-9

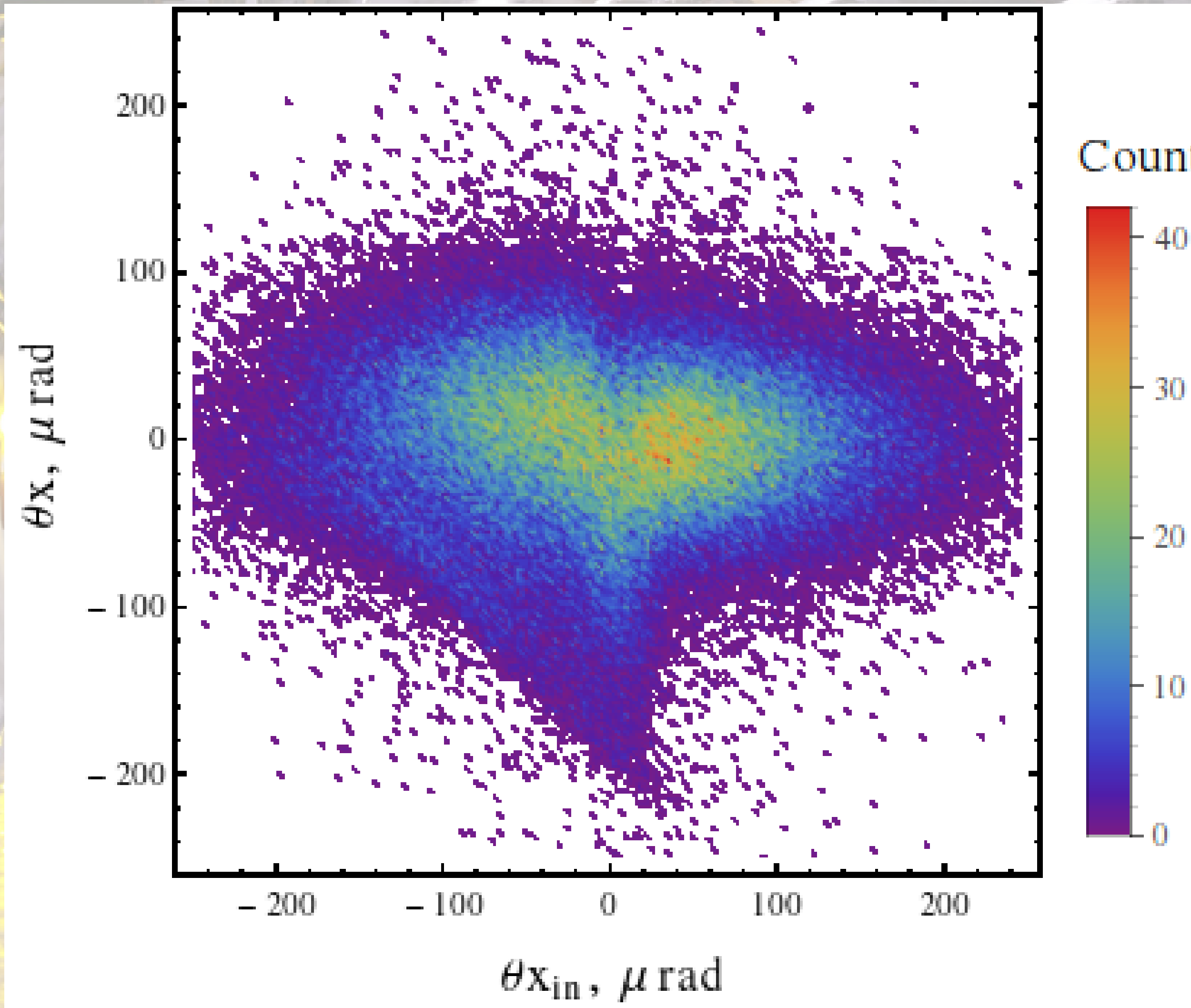
Conclusions

- **Positron sources** are a **key element** of past, present and future lepton colliders. Future projects require the development of the new types of positron sources to **reduce the Peak Energy Deposition Density** and to **increase** the **positron yield** as well.

- The novel schemes of **crystal-based positron sources** have been tested **experimentally** at KEK, at CERN (WA 103 experiment) and DESY. The **simulation** codes have been **validated**.

- A preliminary version of a **FCC-ee hybrid crystal-based positron source** has been **simulated**. It provides a **reduction** of **PEDD** and **positron yield increase** as well.

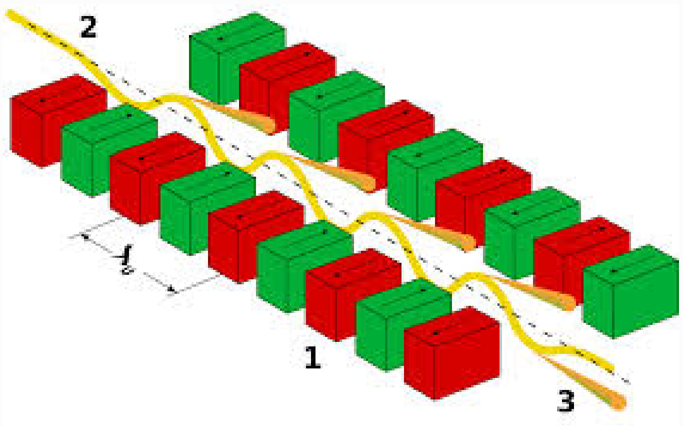
- The crystal-based positron source will be implemented as a **Geant4 example** in the frame Marie Curie IF **TRILLION** project, GA n. 101032975.



Thank you for attention!

Channeling radiation in a bent crystal: Crystalline undulator

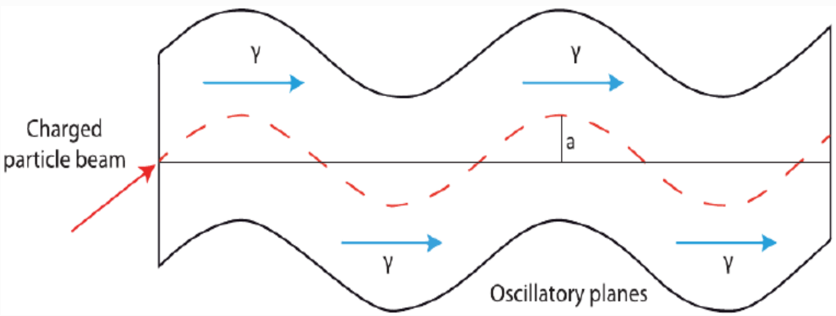
Classical scheme: magnetic undulator in a free electron laser soft X-rays $\lambda_u \sim$ cm



Advantage:

- Intense X- and gamma-rays produced in a crystal, in a compact piece of material

Innovative scheme: Crystalline undulator*-> Hard X-rays and gamma rays $\lambda_u <$ mm



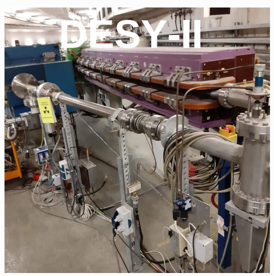
Crystalline X and gamma-ray source **can be applied** in:

- **Nuclear physics**
- **Medical physics**

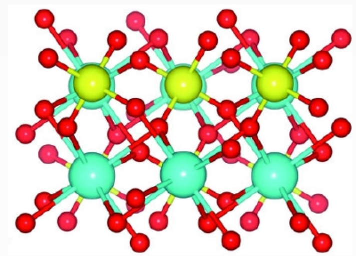
EU project MSCA RISE N-LIGHT G. A. 872196
Coordinator MBN RESEARCH CENTER (Germany)

Applications*

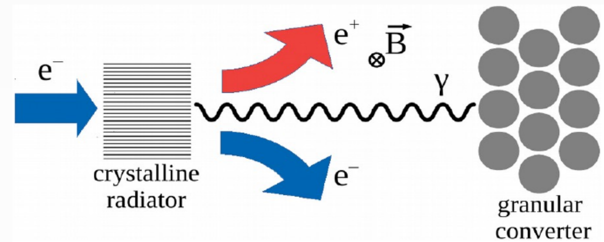
Crystal-based collimation or beam extraction from an accelerator

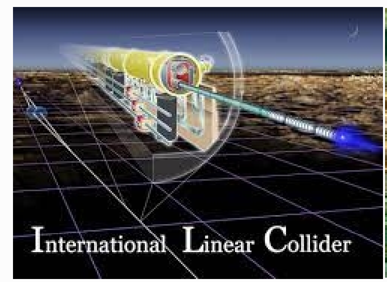


Ultrashort crystalline calorimeter

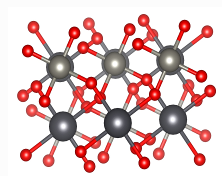


Positron source for future e+/e- and muon colliders

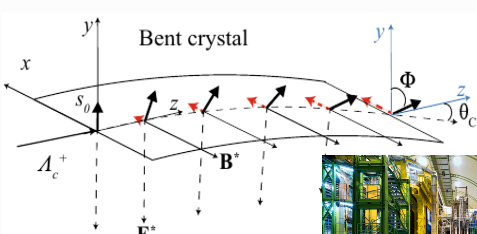




Oriented crystals

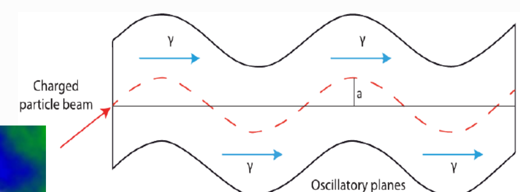


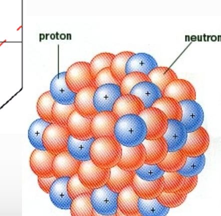
Measurement of dipole magnetic and electric moments of exotic particles



Plasma acceleration

X and γ-ray source for nuclear and medical physics





*From A. Sytov presentation at the European Researchers' Night 2021