New extended examples to explore Channeling effects in oriented crystals and their applications

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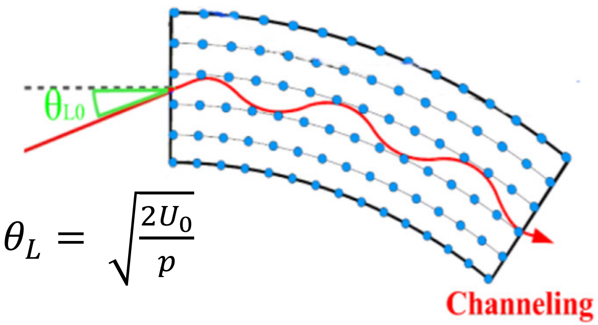
Outlook

- Short description of coherent interactions of charged particles in oriented crystals and their potential applications
- Approach used to simulate those processes in Geant4
- Description of interesting applications included/proposed as official extended/advanced examples

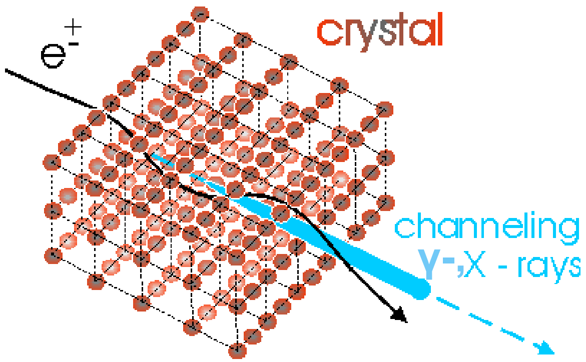
Coherent effects in crystals

Channeling*



$$\theta_L = \sqrt{\frac{2U_0}{p}}$$

Channeling radiation**

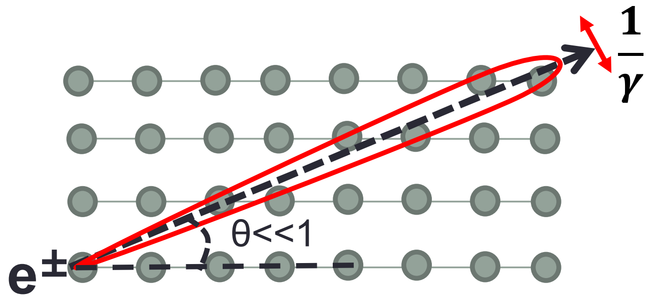


Enegies: MeV - TeV

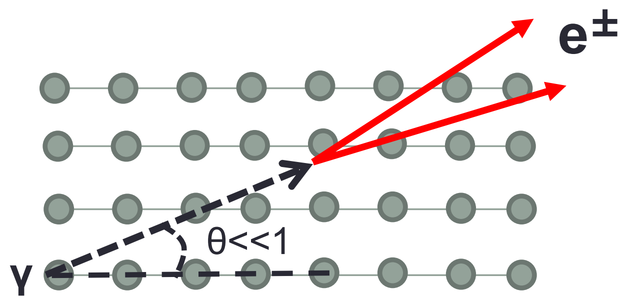
Planar/ Axial field $10^9/10^{11}$ V/cm

Equivalent magnetic field: more than 100 T

Coherent bremsstrahlung***



Coherent pair production****

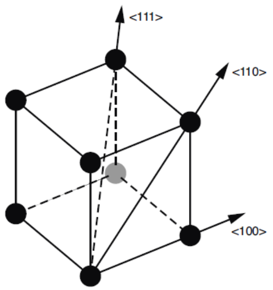


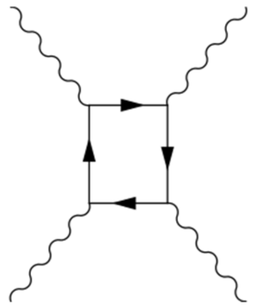
**J. Stark, Zs. Phys. 13, 973–977 (1912); J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)*
***M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)*
****B. Ferretti, Nuovo Cimento 7, 118 (1950); M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).*
***** H. Überall, Phys. Rev. 103, 1055 (1956).*

Coherent effects in crystals

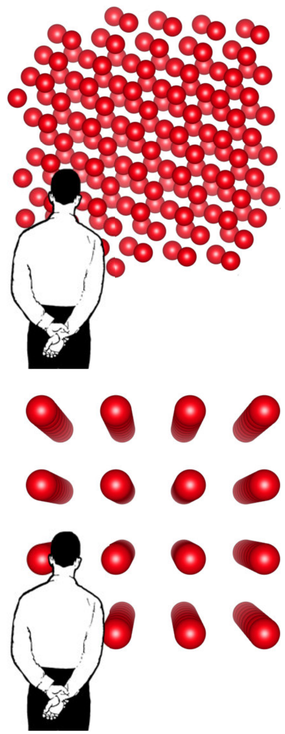
Axial field
10^{11} **V/cm**

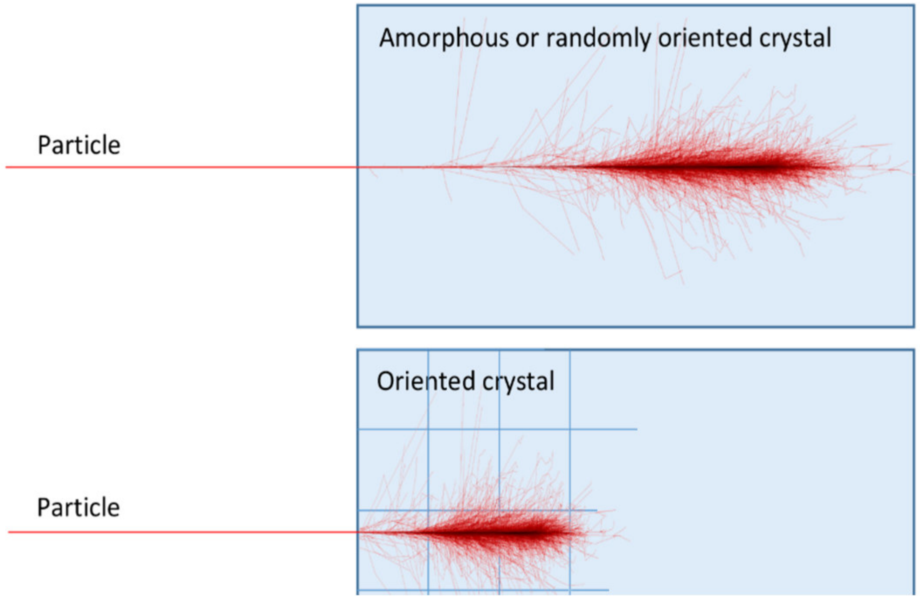
Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**





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



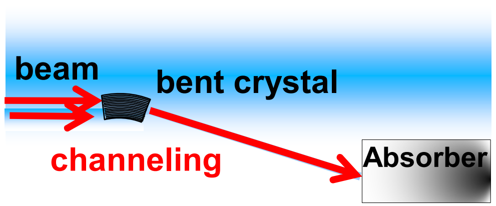


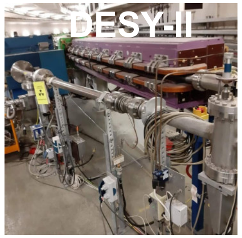
Shower development in the field of axes is **accelerated**. The radiation length is considerably reduced*.

**L. Bandiera et al., Phys. Rev. Lett. 121, 021603 (2018)*

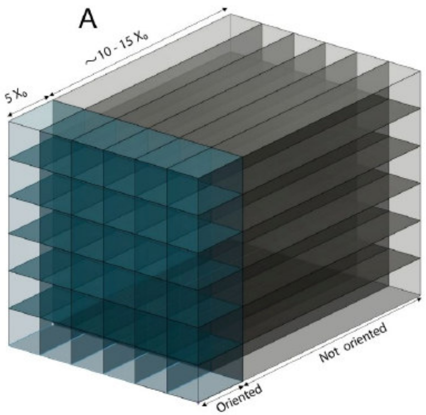
Some of the possible applications of oriented crystals

Crystal-based **collimation** or beam **extraction** from an accelerator

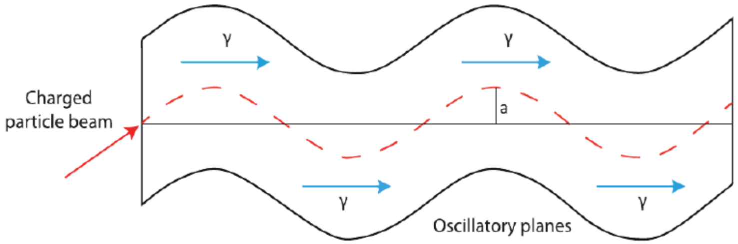




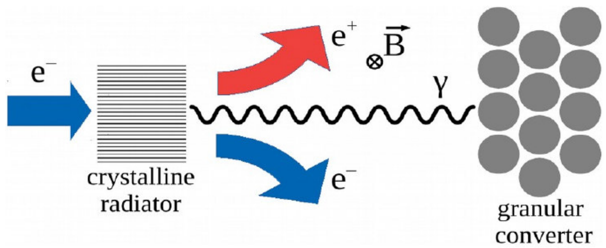
Compact Oriented Calorimeter for Gamma-ray Space Telescopes

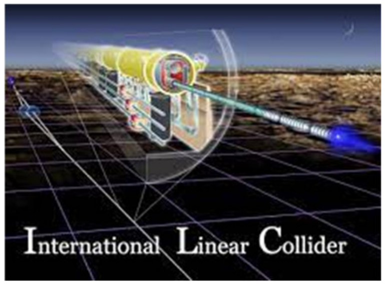


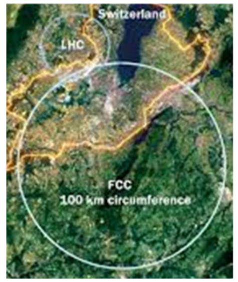
Crystalline source of hard X-ray and gamma radiation, **crystalline undulator (CU)**



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







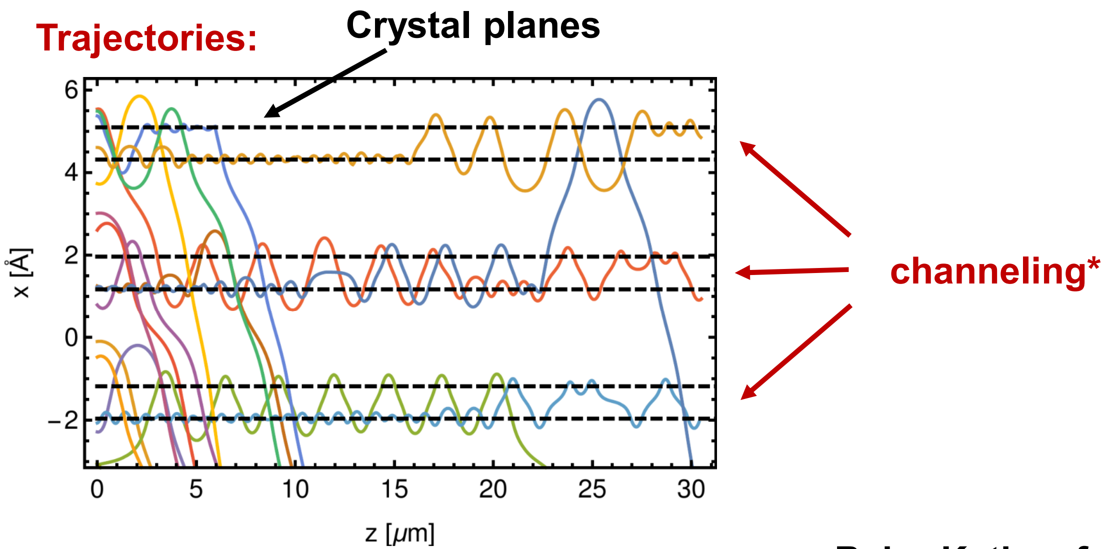
It is important to have a reliable tool to simulate particle interactions in oriented crystals.

Channeling simulation in Geant4: novel ***G4ChannelingFastSimModel*** and ***G4BaierKatkov*** classes were developed and embedded in Geant4 (since 11.2.0 version). These models are based on CRYSTALRAD code

Main conception: simulation of classical trajectories of charged particles in a crystal in averaged atomic potential of planes or axes. Multiple and single scattering, as well as ionization, simulation at every step. Photon emission simulated through MC integration of Baier-Katkov formula (follow A. Sytov's talk on Thursday).

This model together with standard or pre-calculated (through B-K) pair-production model, allows us to simulate a wide **variety of applications**

coherent pair production model (from Geant4.11.3?)



European Commission

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GEANT4 A SIMULATION TOOLKIT

Baier-Katkov formula:

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

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. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)*

A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

Geant4 applications useful to simulate coherent interactions of charged particles in oriented crystals

- **FastSimChannelingRad**: it allows us to test *G4ChannelingFastSimModel* (both deflection and radiation) for different crystalline materials and orientations. It will be included in Geant4.11.3 as the new ch2 extended example (as anticipated in A. Sytov's talk on tuesday).

- **PositronSource**: a simple application for the optimization of a positron source based on oriented crystals. We aim to include it among the official extended examples in 2025.

- **OCalo4Sat**: it can be used to simulate electromagnetic calorimeters composed of oriented crystals. It can take advantage both of *G4ChannelingFastSimModel* model and a simplified model based on *cross-section modification*. We could propose it as an extended/advanced example.

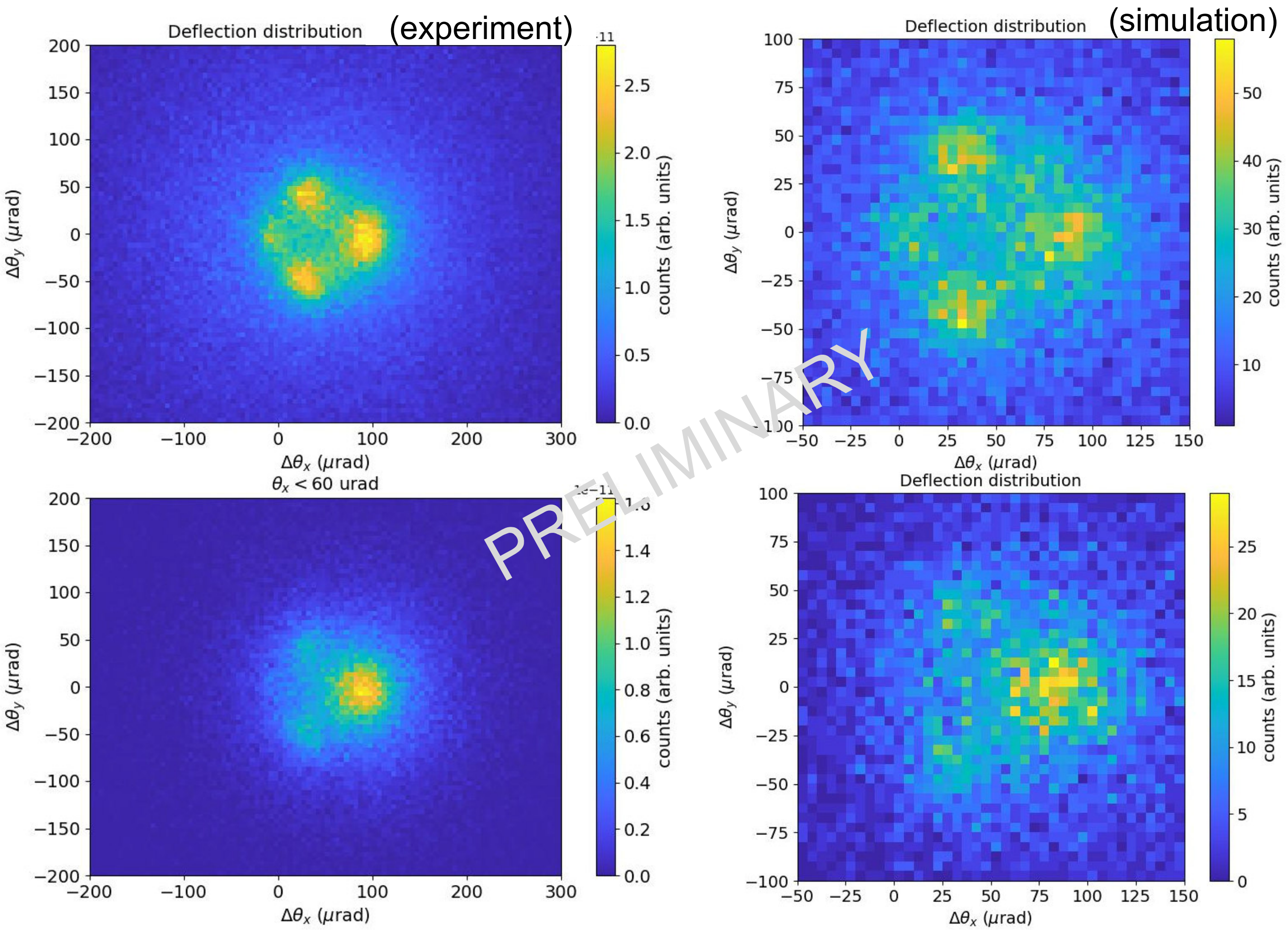
- **TestBeamOC**: it is conceived to simulate typical experiments carried out at different facilities and involving oriented crystals for various purposes. We could propose it as an advanced example.

*Currently, we have **private GitHub repositories** for these applications, but we can share them.*

FastSimChannelingRad (ch2 extended example)

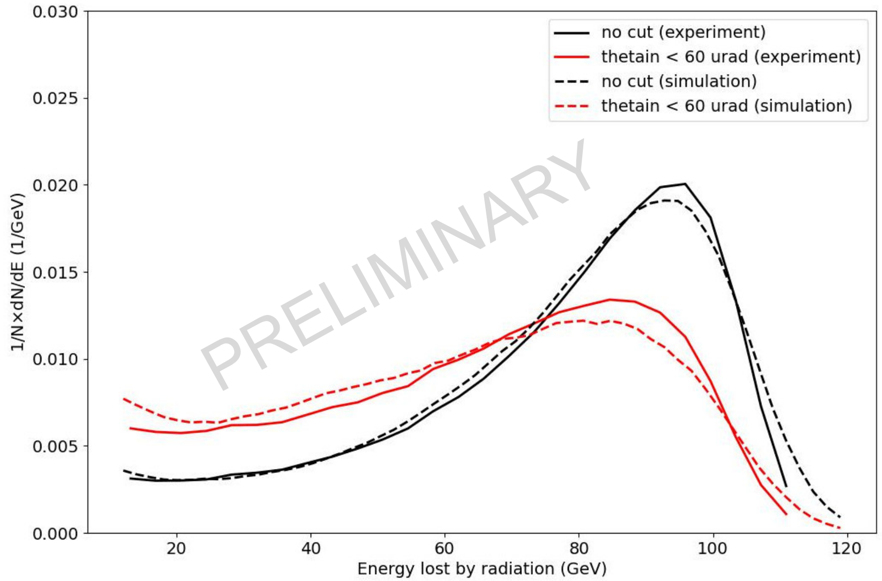
- It shows how to simulate the **deflection/radiation** of charged particles in oriented (flat, bent and periodically bent) crystals through the *G4ChannelingFastSimModel* and *G4BaierKatkov*. We can also **store trajectories inside the crystals** useful for “particle tagging” (currently in R&D version only, but we will include this feature also in ch2).
- The potentials for **many different crystalline materials in planar/axial orientation** are available (currently **Si**, and **W**. Ge, C, Ir, BGO, and PWO will be added).
- The **setup is simplified at its minimum**, since it includes only the **crystal** and a **scoring screen** used as virtual detector. Recently, a calorimeter to score the radiation in a way closer to experiments has been introduced (only in R&D version). An ideal magnet has been also introduced to remove the charged particles downstream of the virtual scoring screen.
- Through a set of custom **macro commands**, the user has the **full control** of all aspects of the simulation. In particular, some important parameters of our models can be set, depending on the particular case (energy range of interest, simulation purpose, …).
- Deflection and radiation are stored in dedicated ntuples and saved in a root file.
- Ch2 comes with a **simple python script to analyse the output**. In the R&D version, **more advanced analysis tools are available**.

FastSimChannelingRad: simulations of beam deflection by a bent crystal and related radiation

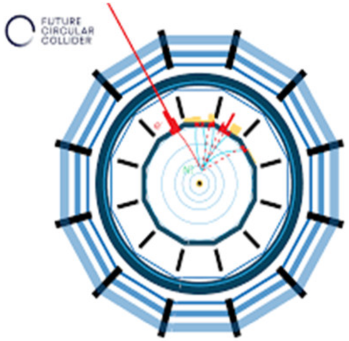


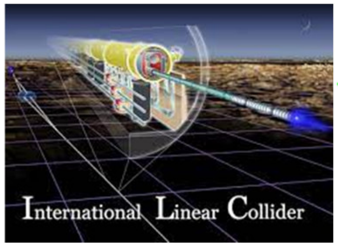
2.7 mm thick, bent (~ 100 μrad) Ge crystal, aligned along <110> axis

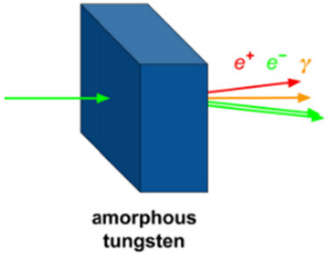
120 GeV e+ beam @ CERN SPS (H4)

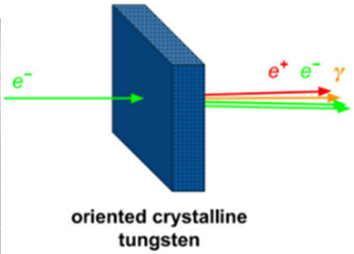


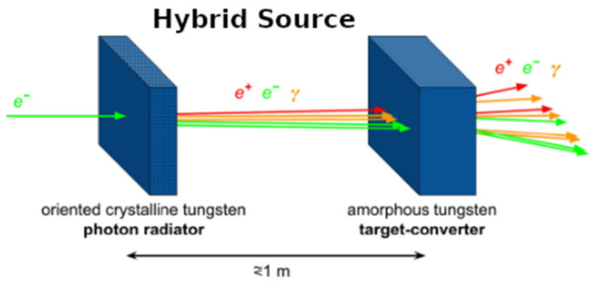
Positron source for future lepton colliders

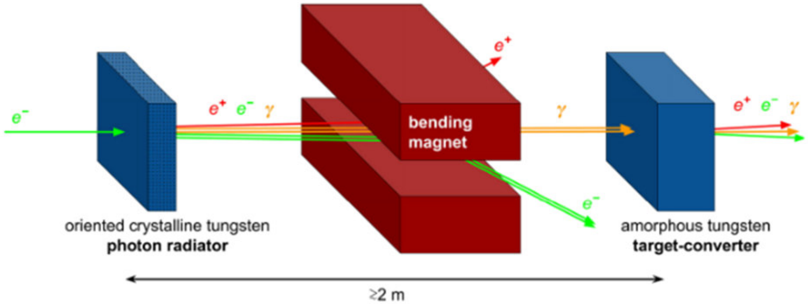












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Use of coherent effects in high-Z oriented crystals: **channeling** and **over barrier motion** (and **photon generation**) → Enhancement of (soft) photon generation → **enhancement of pair production.** **Lower energy deposit and PEDD (with hybrid scheme) in target.**

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

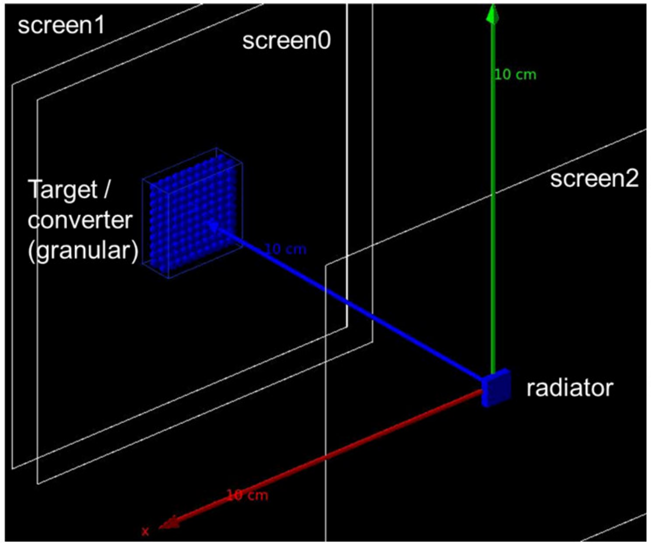
Potential challenges:
Target overheating/melting

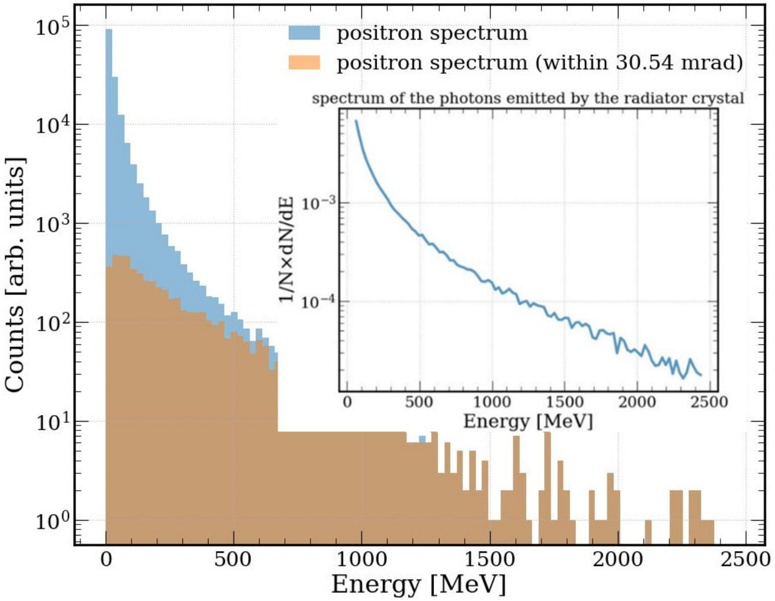
↑

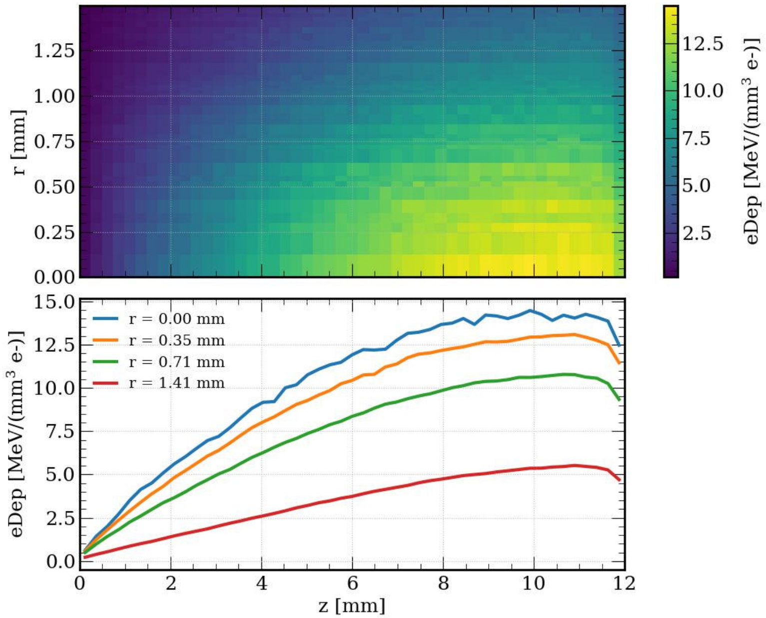
Peak Energy Deposition Density (**PEDD**) limit: **35 J/g** for **W***

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

PositronSource application

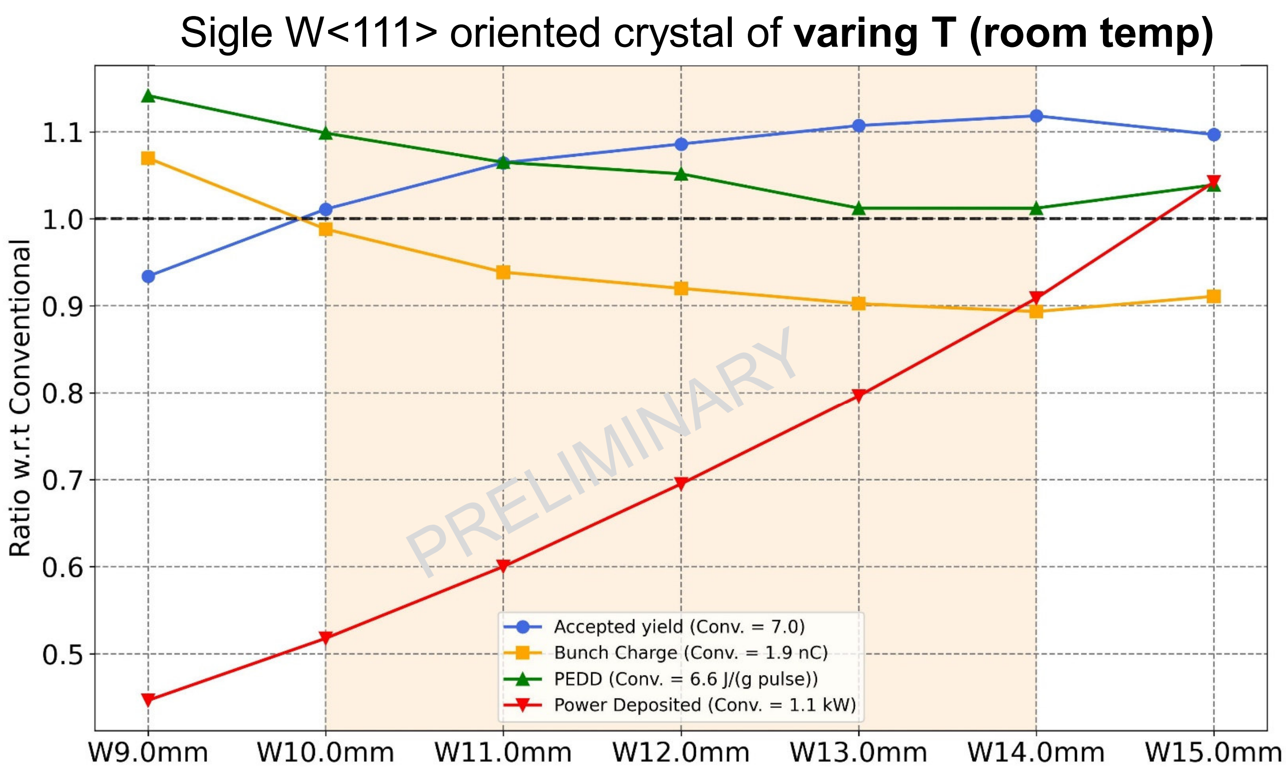


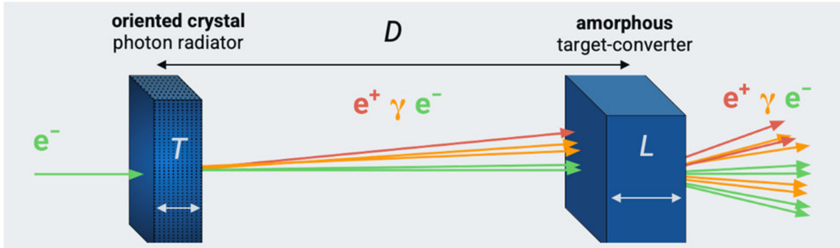




- It allow us to simulate both a conventional and a **crystal-based positron source**.
- The code relies on ***G4ChannelingFastSimModel***. Alternatively, a phase-space (e.g. from CRYSTAL code) can be imported.
- A **collimator** or a **magnetic field** can be included in the simulation (**advanced hybrid scheme**).
- Scoring of particle phase space at exit of crystals and of energy distribution inside them (**BoxMesh** or custom VoxelScorer).
- The application is fully compatible with **multi-threading** and everything can be controlled via **macro commands**.
- A set of **python scripts** are available for output **analysis** and **positron phase-space export for tracking in the pre-injector**.

PositronSource: Simulation (Geant4 + RF-Track) results for 6 GeV FCC-ee e+ source





Simulation studies converge to a **total W thickness of about 12-13 mm** (~3.4 / 3.7 X0) → need **D~0** (2 targets) or **1 thick single-crystal** for **6 GeV** source.

The Single Crystal **PEDD** is **acceptable** considering FCC-ee parameters [max 10.5 J/g/pulse].

We can use **just one device** to obtain +10% e+ yield and -20% power at «**zero cost**» for FCC-ee.

OCalo4Sat: simulation of Oriented Calorimeters for HEP and space applications

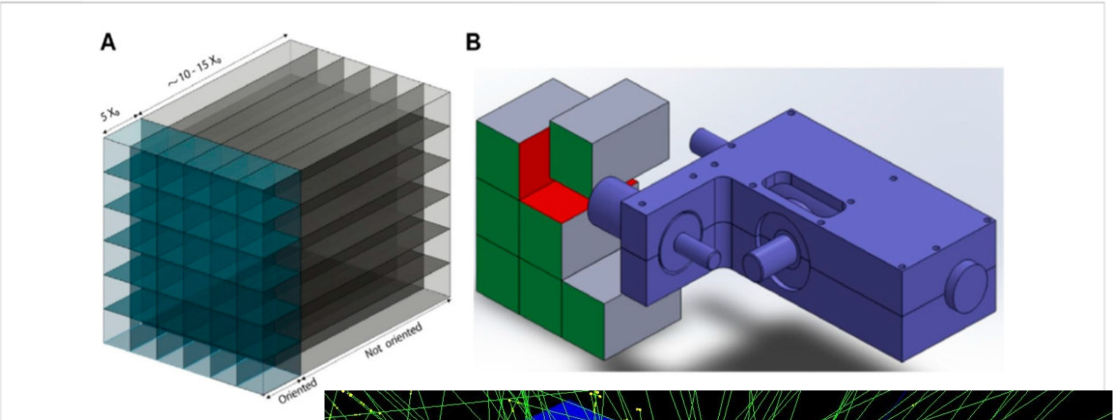


FIGURE 10
Conceptual sketch of an oriented crystal

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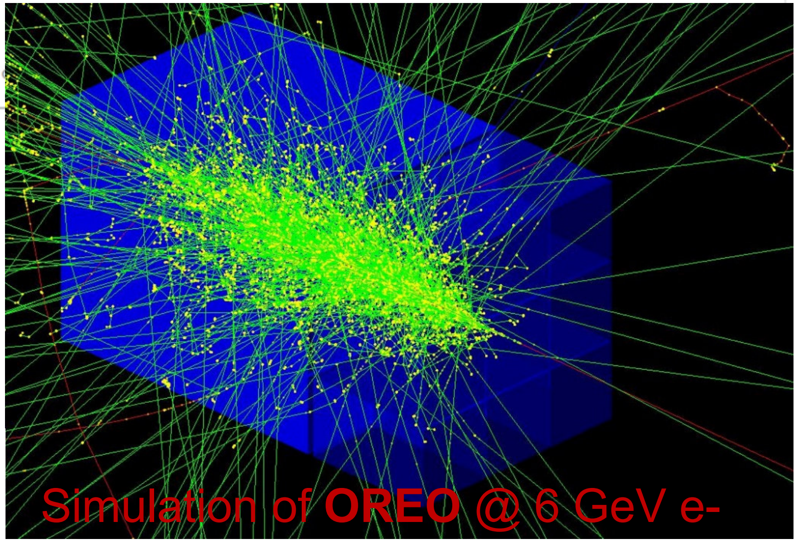
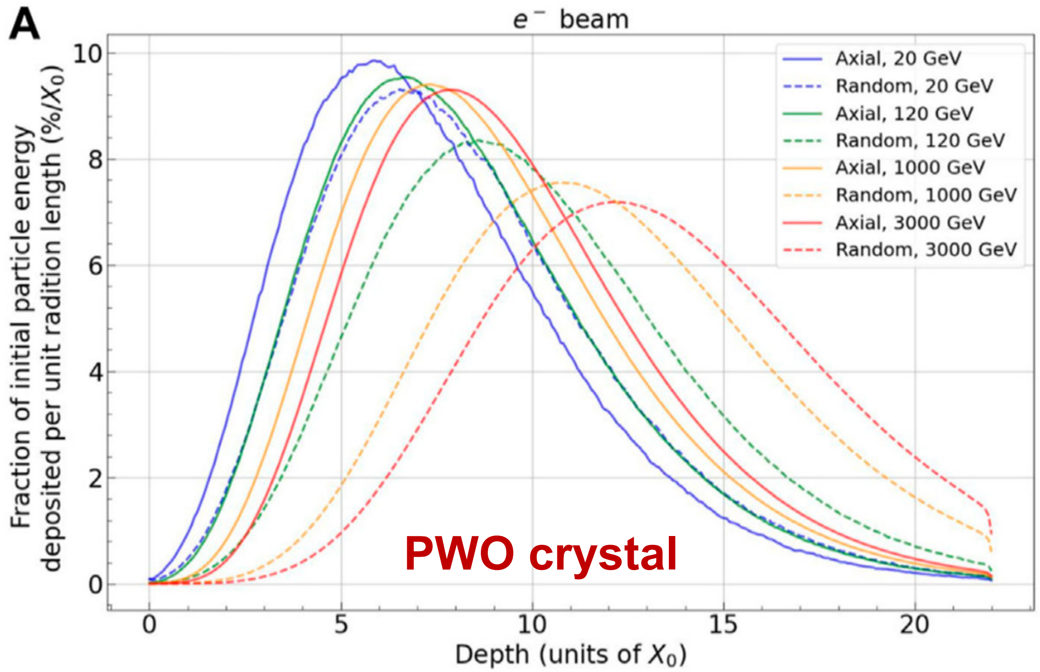


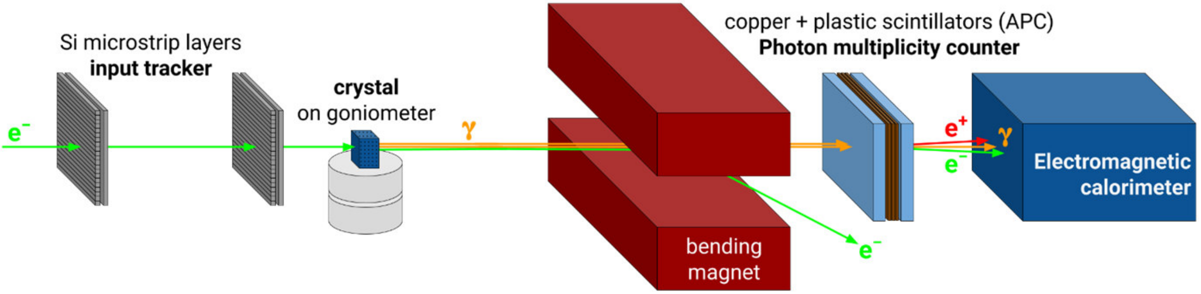
L. Bandiera et al., Frontiers, (2023), 10.3389/fphy.2023.1254020



Collaborations ongoing with different astrophysics groups on this topic

TestBeamOC: simulation of complete setup involving oriented crystals

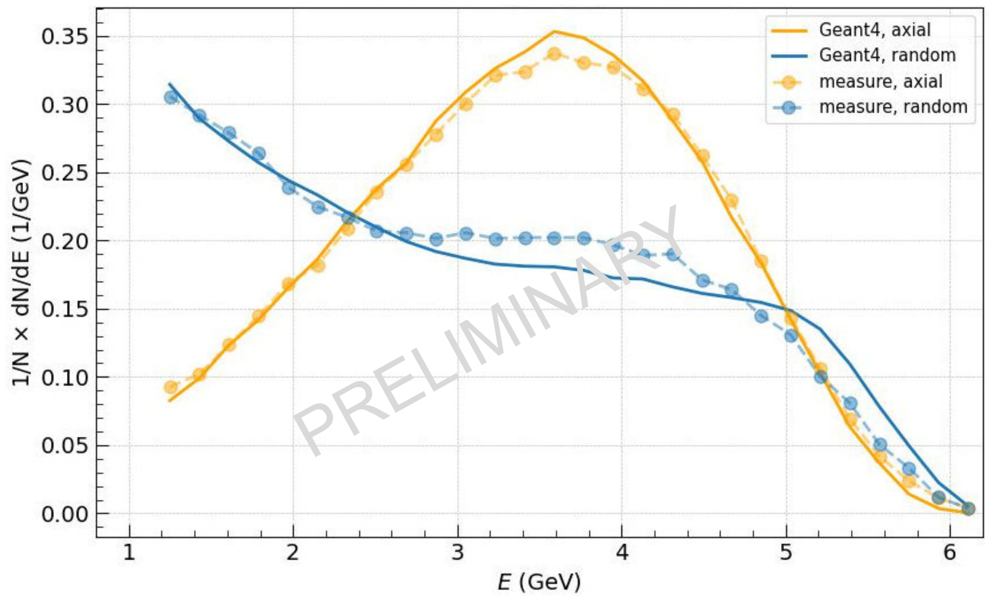
Setup @CERN PS T9 beamline



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

Set-up similar to the one desribed in*: L. Bandiera et al., Eur. Phys. J. C 82, 699 (2022), where there is a also compoarison with simulations in which coherent interactions of e- in the W crystal were* ***simulated with CRYSTAL code*** *(by V. Tikhomirov of Belarusian State University).*

Radiative energy loss measured by the Ecal



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

Validation of Geant4 channeling model against experimental data at an energy significant for FCC-ee positron source.

Conclusions

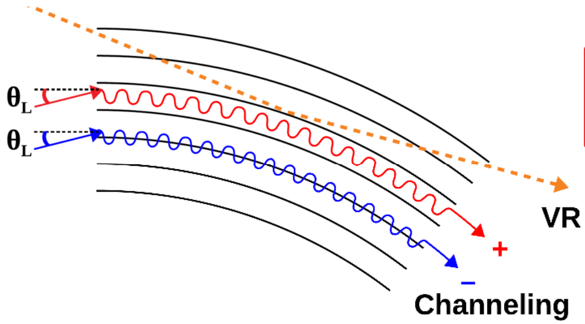
- We have now ab-initio models for coherent interactions of charged particles in oriented crystals.

- In Geant4.11.3 we will have an extended example to show how to setup a simulation of deflection/radiation in oriented crystals and test new crystalline materials/orientations.

- Other, more specific examples, could be included in the next releases.

Back-up slides

FastSimChannelingRad: simulations of beam deflection by a bent crystal and related radiation

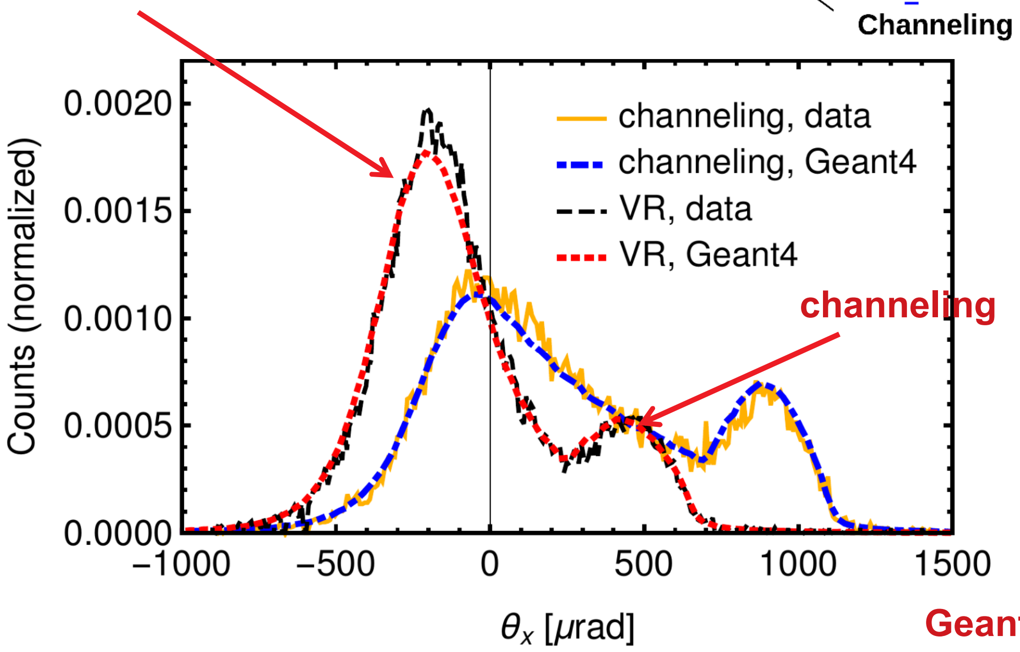


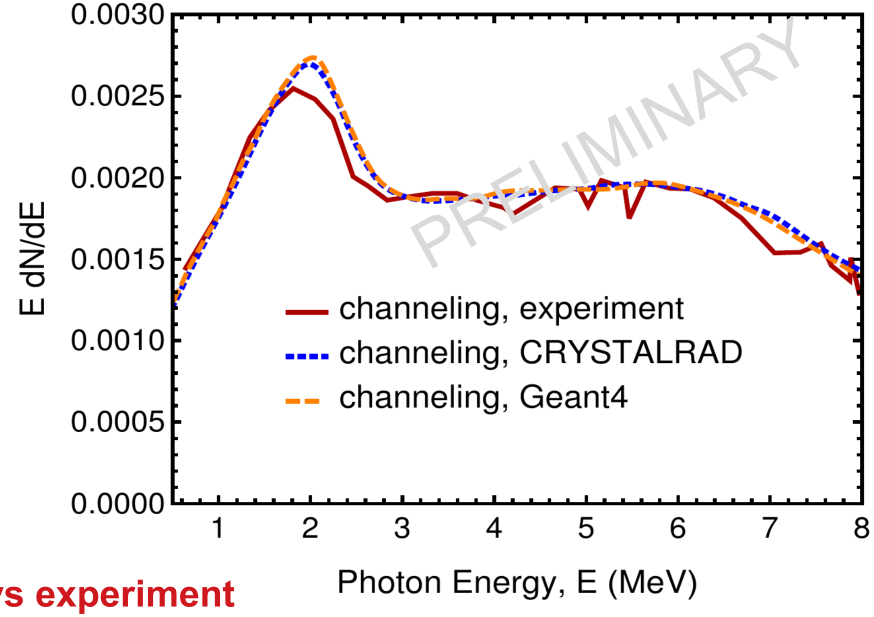
15 µm thick bent crystal

855 MeV electrons*

**L. Bandiera et al. Phys. Rev. Lett. 115, 025504 (2015)*

volume reflection (VR)





Geant4 simulations vs experiment