Istituto Nazionale di Fisica Nucleare

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Trillion

Overview of applications of oriented crystals in accelerator physics

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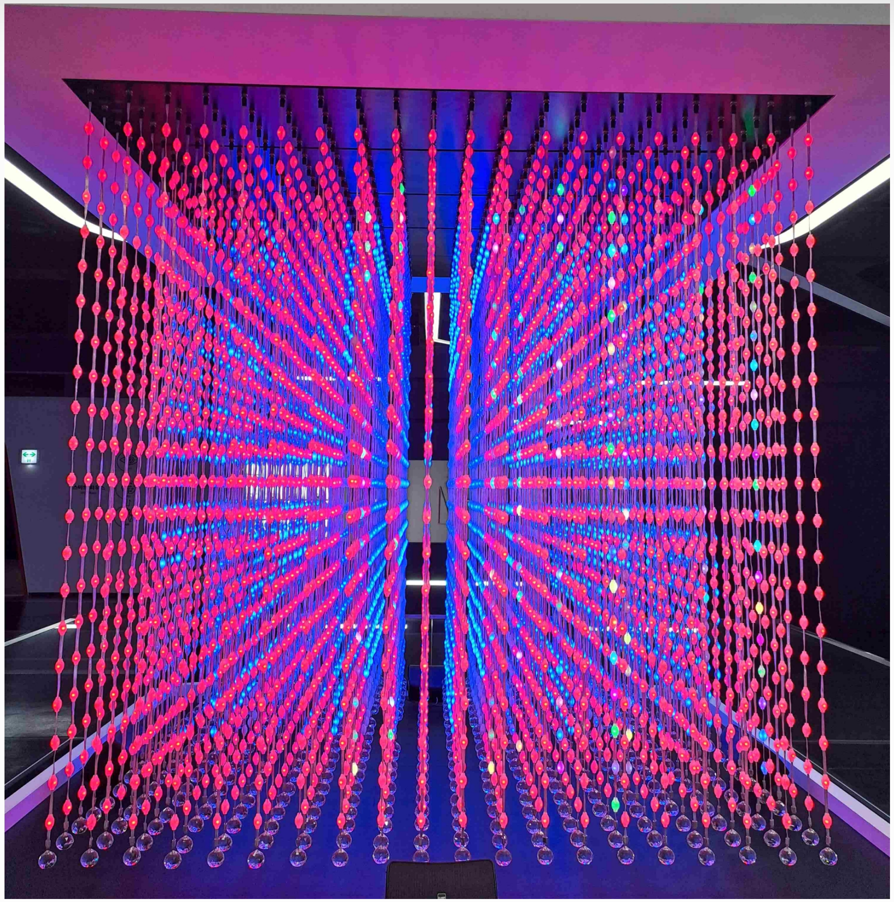
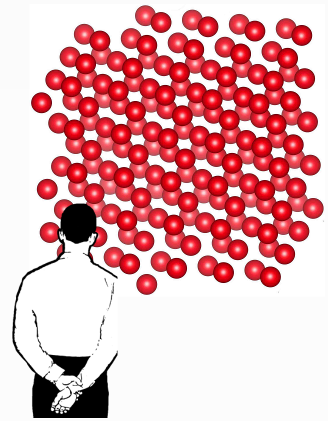
PAL Public Seminar, 23/11/15

How an oriented crystal looks like

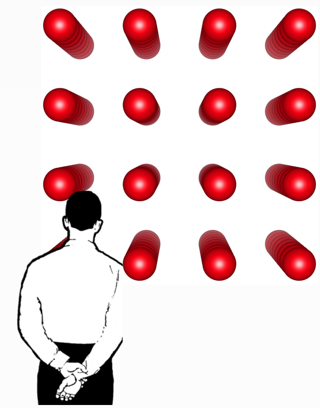


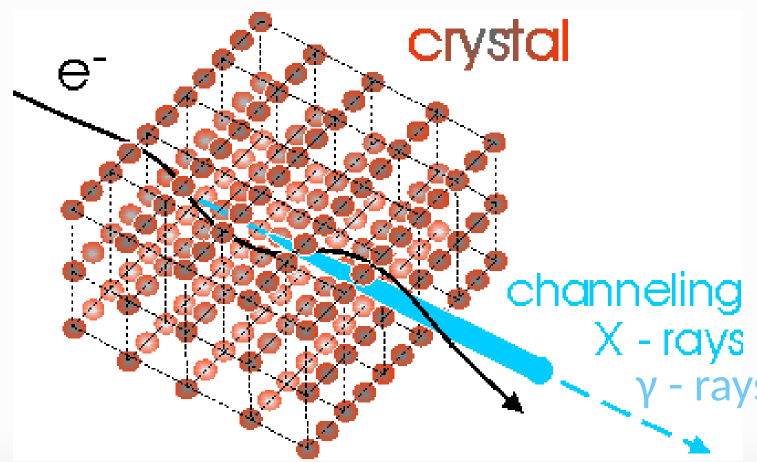
from National Science Museum, Daejeon, Korea

Non-oriented crystal

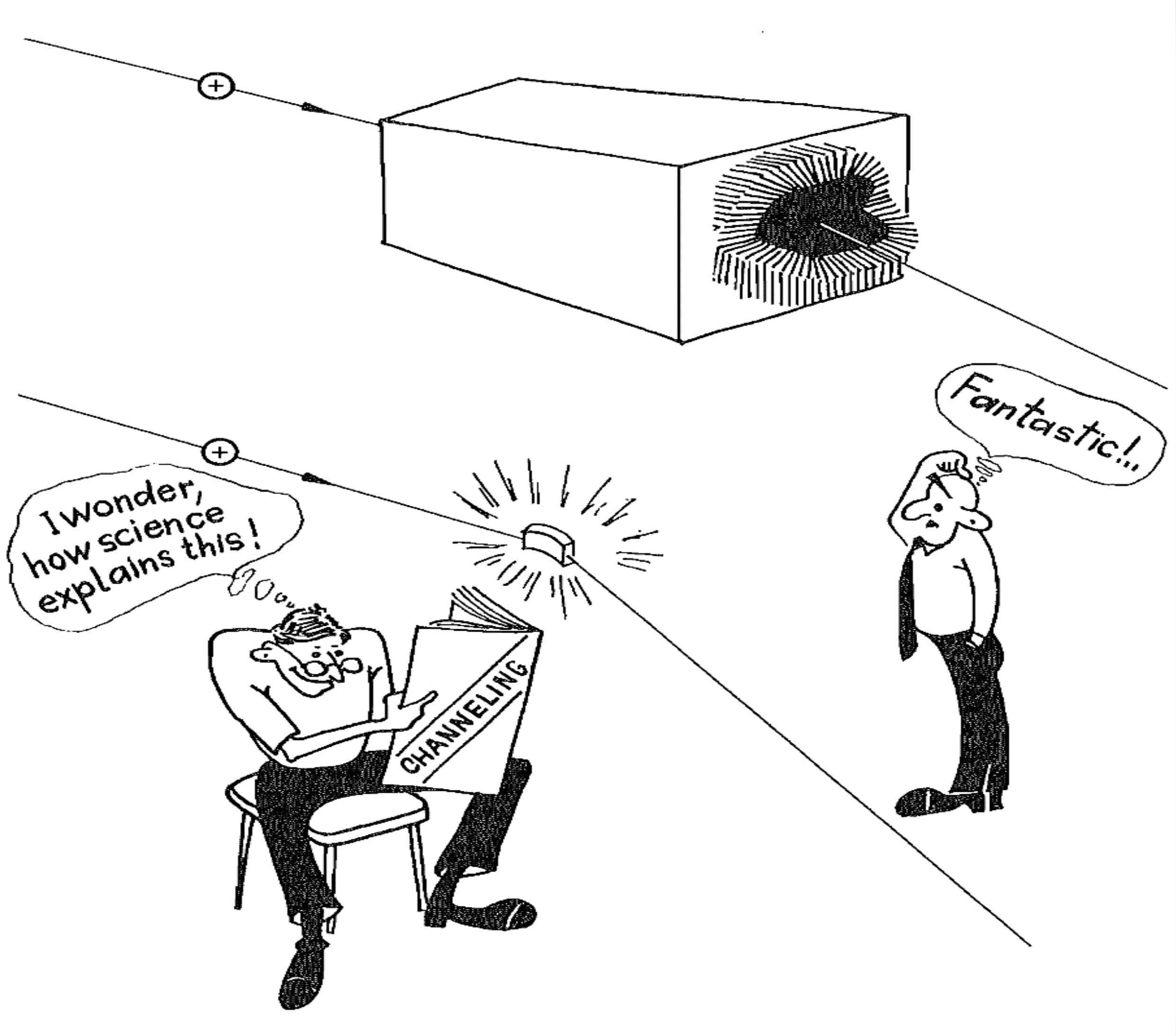


Oriented crystal



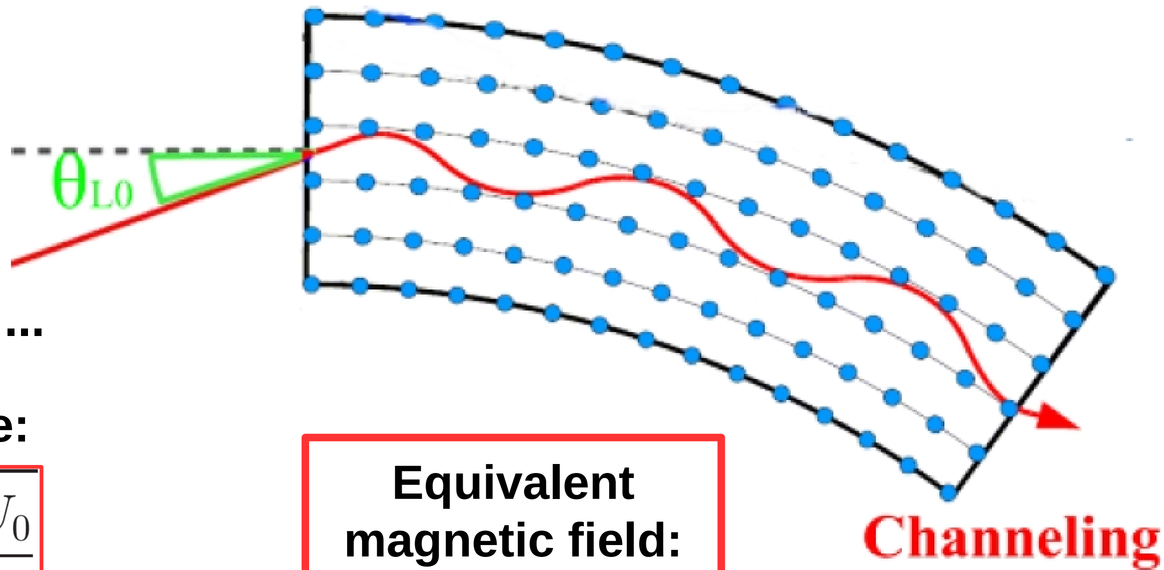


The world of the channeling effect



Channeling effect* of charged particles

Enegies:
MeV - TeV



e–, e+, proton ...

Lindhard angle:

$$\theta < \theta_L = \sqrt{\frac{2U_0}{pv}}$$

Equivalent magnetic field: more than 100 T

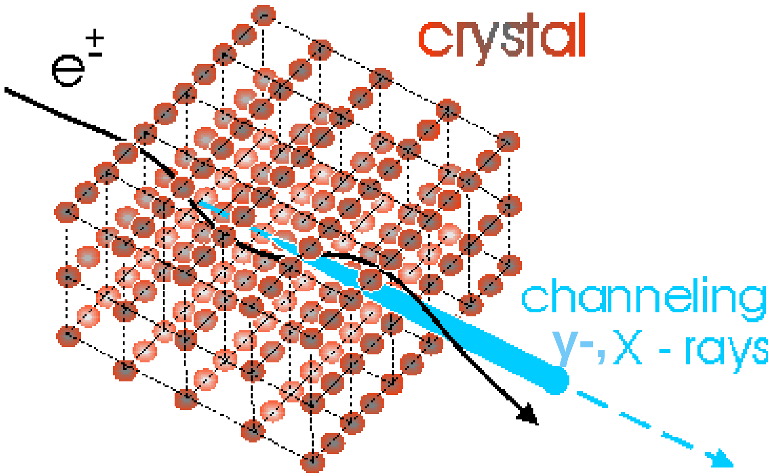
Channeling* **is the effect of the penetration of charged particles through a monocrystal quasi parallel to its atomic axes or planes.**

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

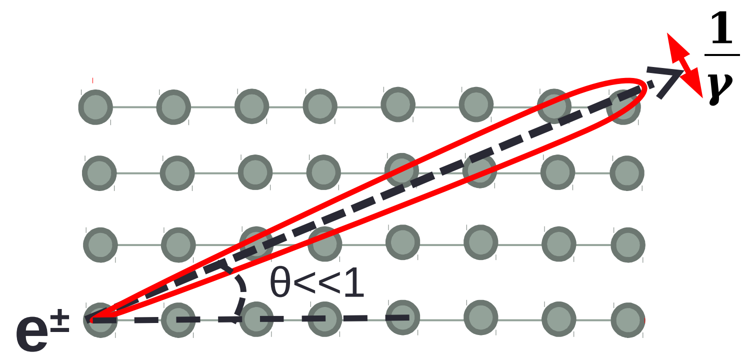
*J. Stark, Zs. Phys. 13, 973–977 (1912)
J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
M. T. Robinson, O. S. Oen, Appl. Phys. Lett. 2, 30–32 (1963)
J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)

Coherent effects in a crystal

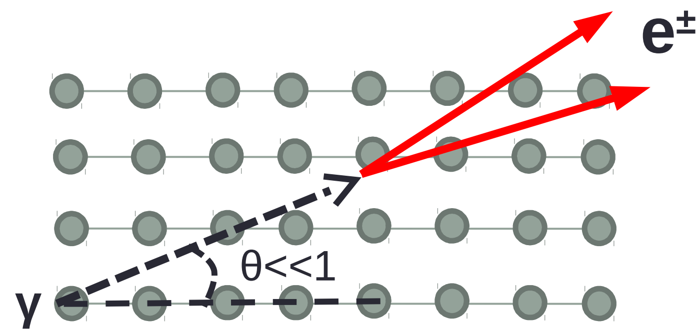
Channeling radiation*



Coherent bremsstrahlung**



Coherent pair production***



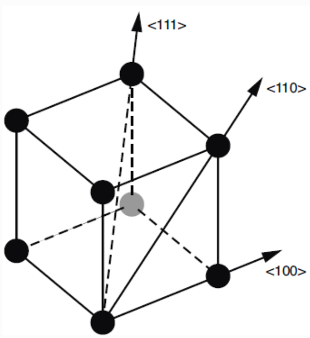
Coherent effects preserve **up to few mrad** of particle direction vs the crystal axis

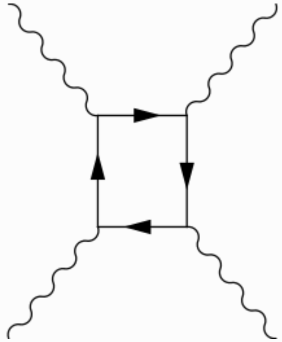
*M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
**B. Ferretti, Nuovo Cimento 7, 118 (1950).
**M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).
*** H. Überall, Phys. Rev. 103, 1055 (1956).

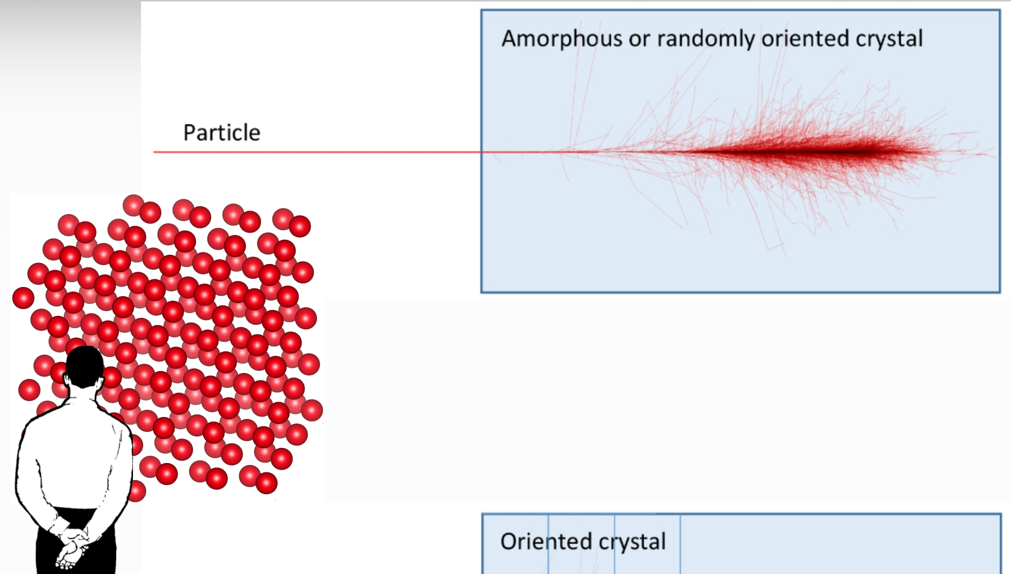
Electromagnetic shower acceleration

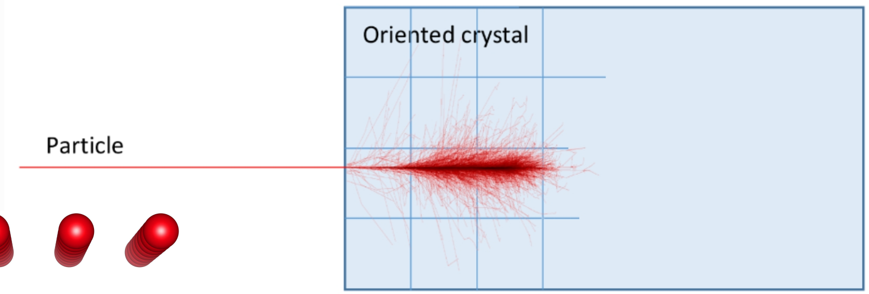
Axial field 10^{11} V/cm

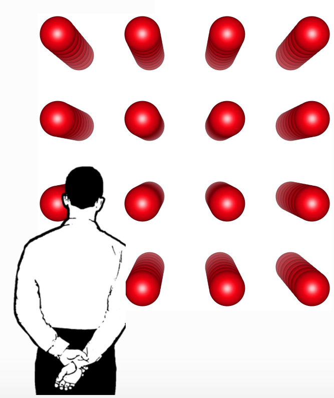
Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**









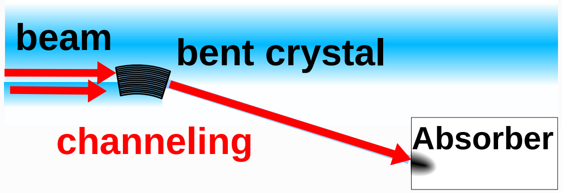


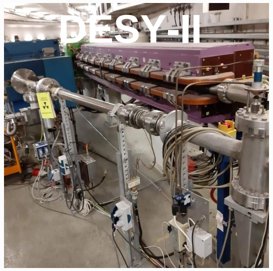
The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

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

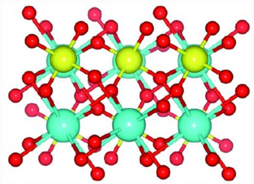
Applications*

Crystal-based collimation or beam extraction from an accelerator



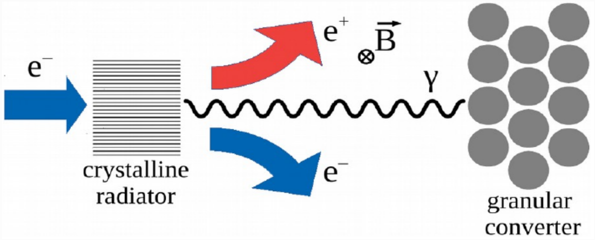


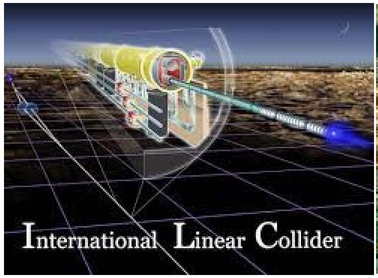
Ultrashort crystalline calorimeter

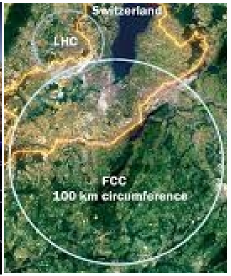


Gamma-ray Space Telescope

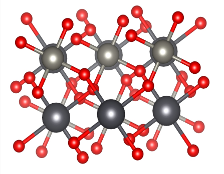
Positron source for future e+/e- and muon colliders



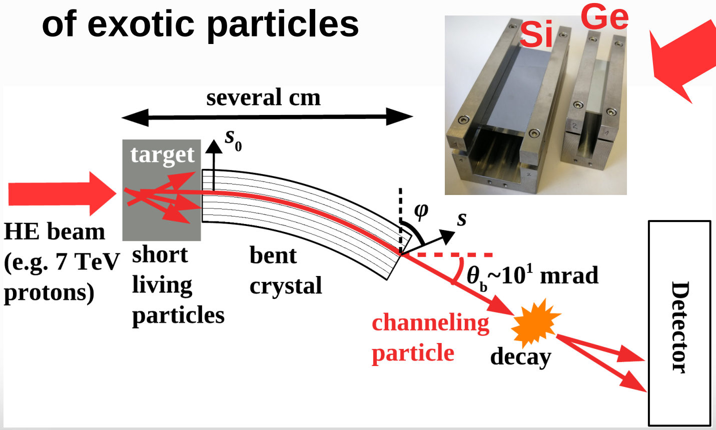




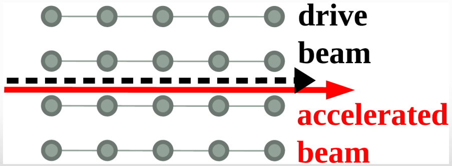
Oriented crystals



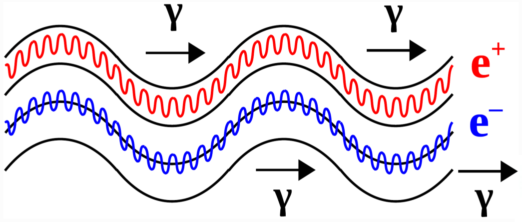
Measurement of dipole magnetic and electric moments of exotic particles

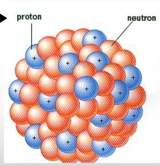


Plasma acceleration



X and γ-ray source for nuclear and medical physics





*A. Sytov et al. arXiv: 2303.04385, Accepted for publication in JKPS

Marie Sklodowska-Curie Action Global Individual Fellowships by A. Sytov in 2021-2025, 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.

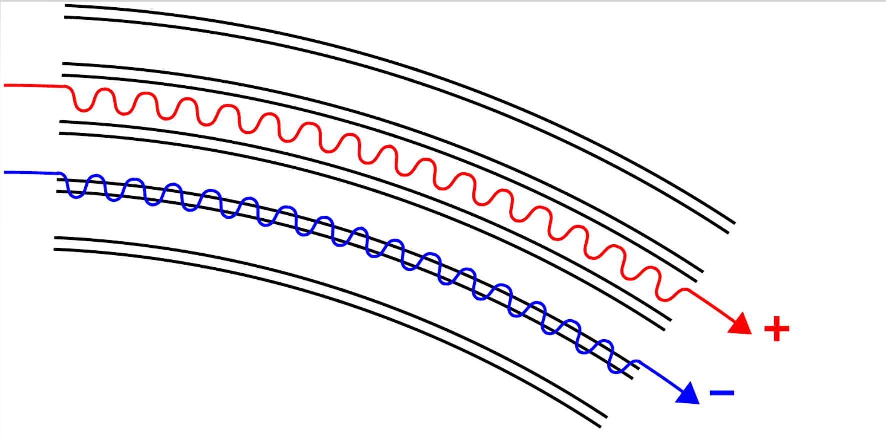
Group:

- **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)

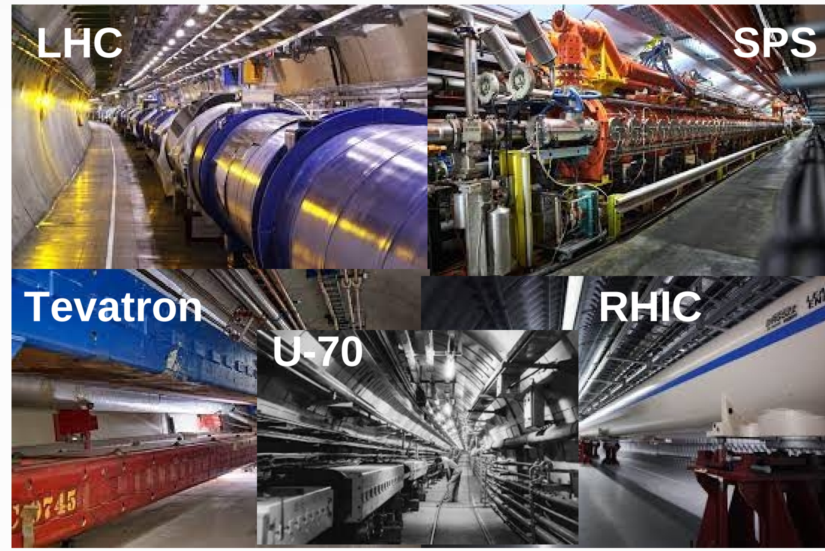
Crystal-based extraction



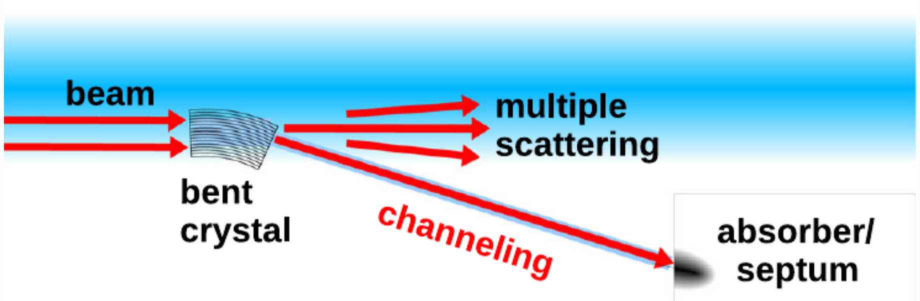
Planar channeling*:

- Charge particle penetration through a monocrystal along its atomic planes

Crystal-based collimation and **extraction have been used at hadron machines**



Crystal-based extraction/collimation

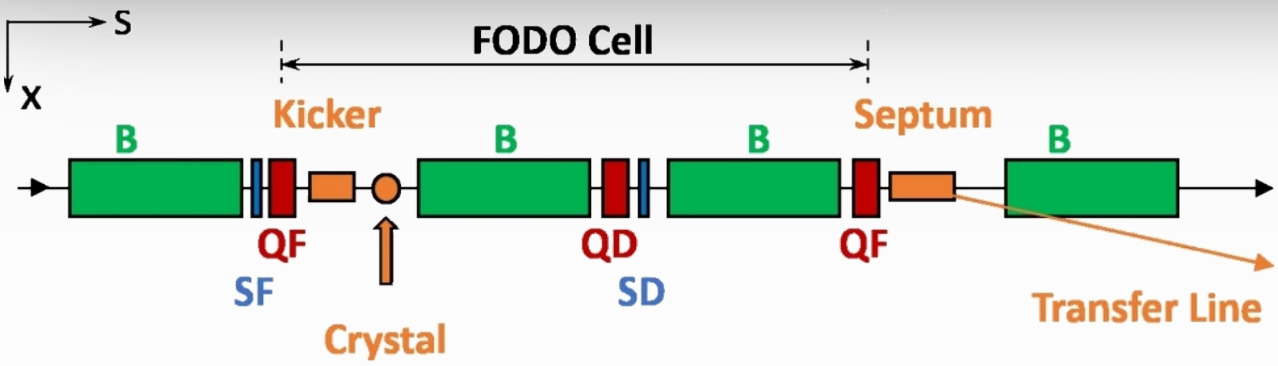


Crystal-based extraction/collimation: applied only for hadrons, not yet for e-

Interesting for tens of electron synchrotrons

***J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)**
E.N. Tsyganov, Fermilab TM-682 (1976)
A. Sytov et al. Eur. Phys. J. C 82, 197 (2022)

Crystal-based extraction: possible setup at DESY-II



B->dipoles
QF/QD->focusing/ defocusing quadrupoles

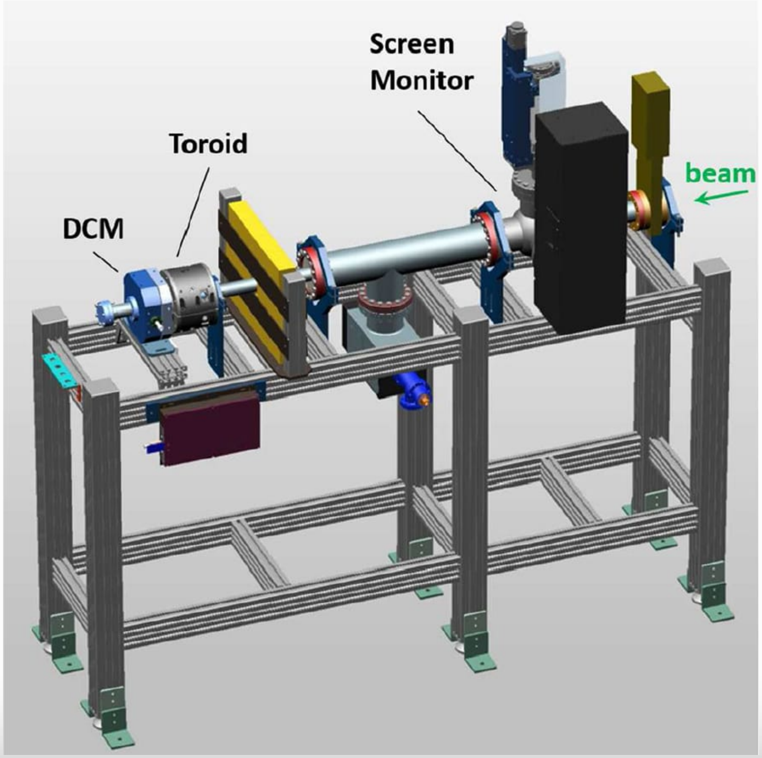
6 GeV electrons

Advantages:

- Extraction of **primary** low-emittance and very **intense electron beam** in a **parasitic mode**.
- The **extraction line** including septum magnets already **exists => ideal for prove-of-principle**
- **Few GeV** electron beam, **typical for synchrotron light sources** existing in the world.

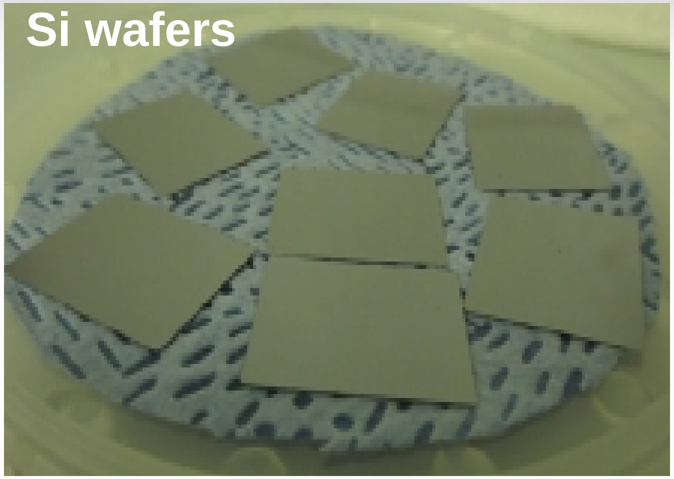
Applications:

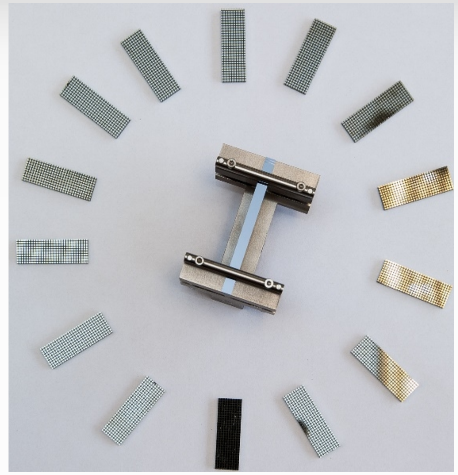
- Nuclear and particle physics detectors and generic **detector R&D**
- Fixed-target experiments in **high-energy physics** including future **lepton colliders**
- Also: **crystal-based collimation** (**synchrotron light sources**, **colliders**)



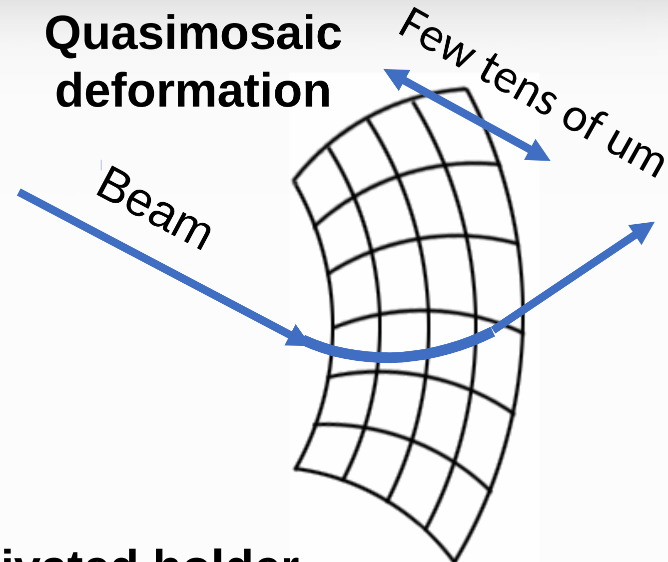
A. Sytov, G. Kube et al. Eur. Phys. J. C 82, 197 (2022)

Manufacturing and characterization of bent silicon crystals @INFN Ferrara

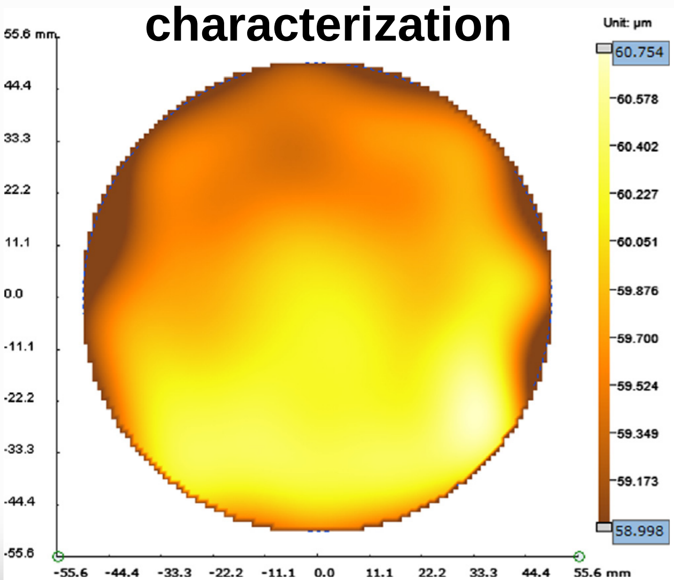




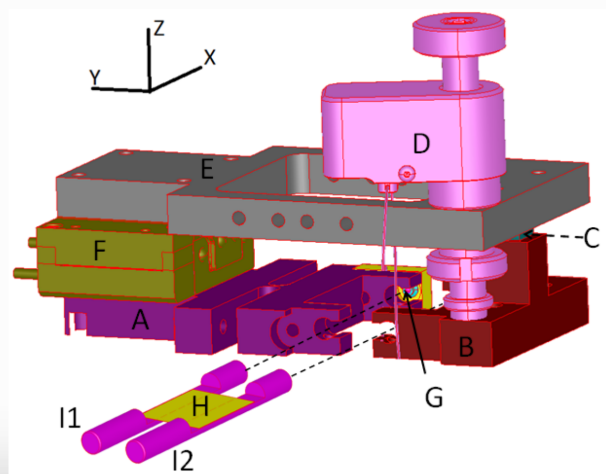
Quasimosaic deformation

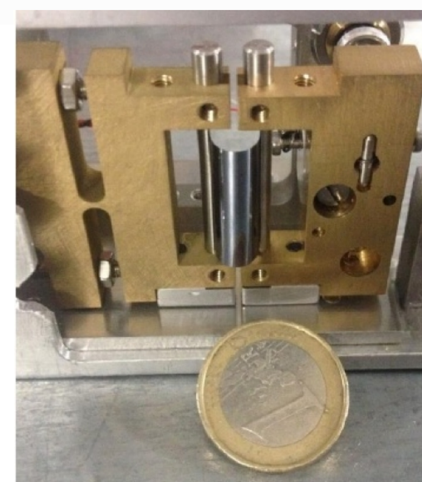


characterization

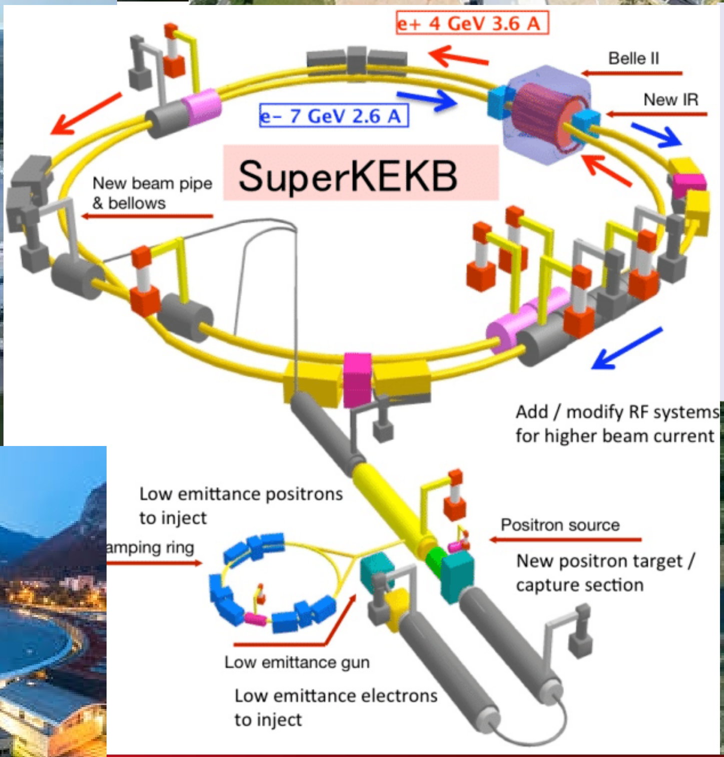


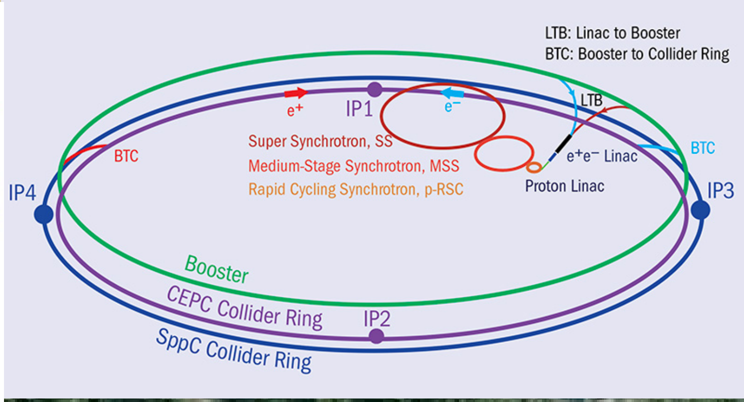
Piezo-activated holder





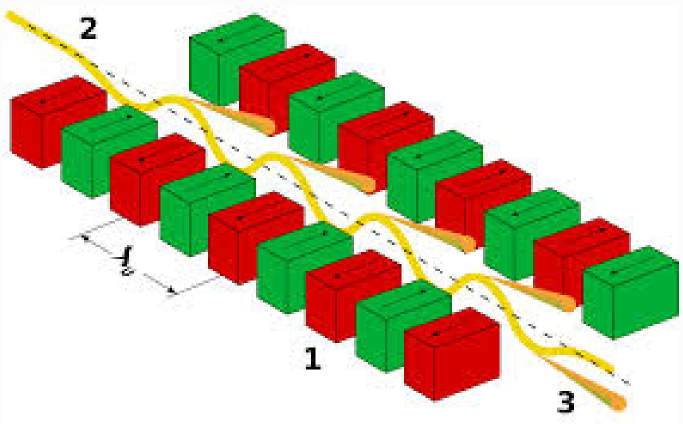
Where the crystal-based extraction of electrons can be applied?



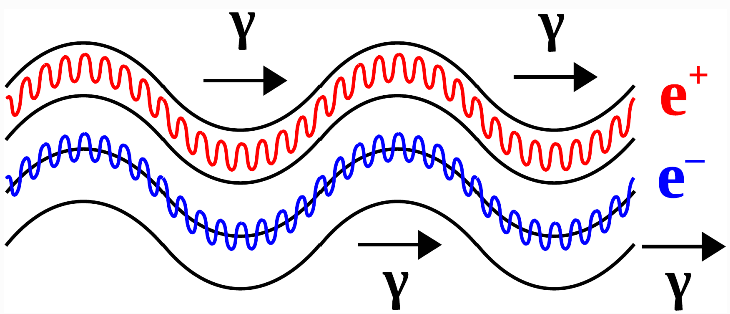


Channeling radiation in a bent crystal: Crystalline undulator

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



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



Advantage:

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

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

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

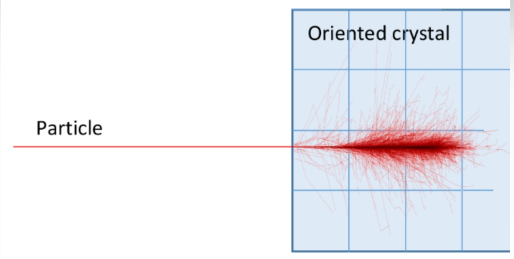
EU project MSCA RISE N-LIGHT G. A. 872196
Coordinator MBN RESEARCH CENTER (Germany)

R. Camattari et al., Phys. Rev. Acc. and Beams 22, 044701 (2019)

Crystal-based ultrashort electromagnetic calorimeter* (The INFN OREO experiment ORiEnted calOrimeter)

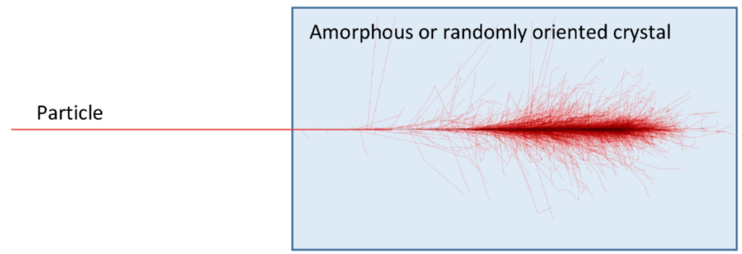
Advantage:

- Considerably shorter thickness
- More transparent for other particles (hadrons)
- Potentially lower time resolution



Crystalline calorimeter can be applied at:

- Fixed-target experiments including **dark matter search**
- **Space gamma telescopes => GRB** observation



CERN North Area

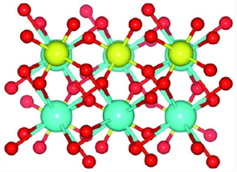
HIKE
High Intensity Kaon Experiments

$$K_L \to \pi^0 \nu\nu$$

+ dark photon search

Gamma-ray Space Telescope (like Fermi)

PWO

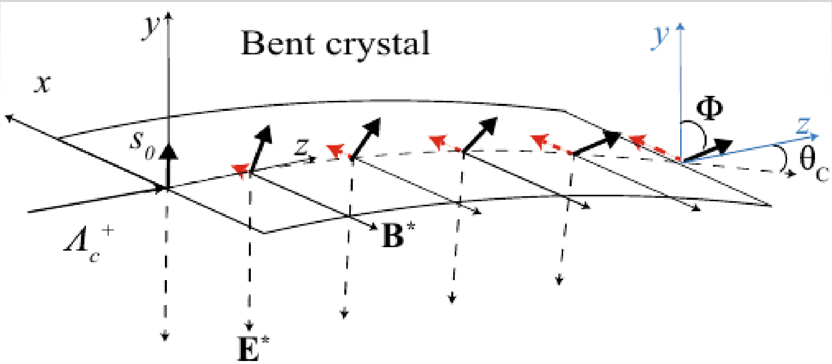


Cristalline calorimeter extends observation γ **energy range** up to **TeV**

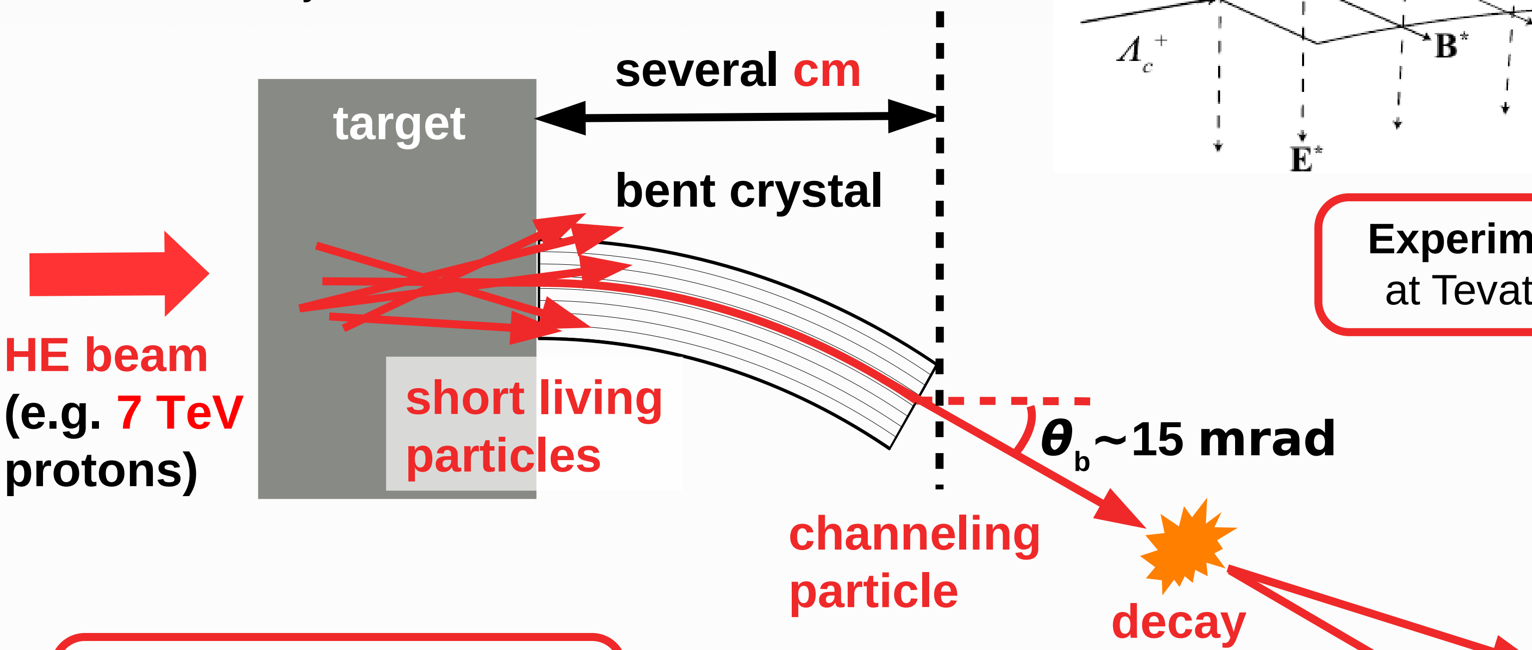
Search of MDM&EDM of short living particles using the effect of spin rotation in oriented crystals*

What we want:

- To measure **MDM** and **EDM** of exotic baryons



Experimental proof at Tevatron for Σ^+**



Detector (e.g. LHCb)

polarization measurement

Crystal thickness must be **comparable** with the **life distance** of the particle

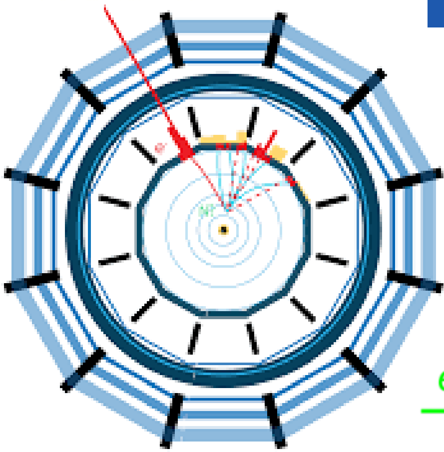
Possible particles: Λ_c^+, Ξ_c^+, ..., τ

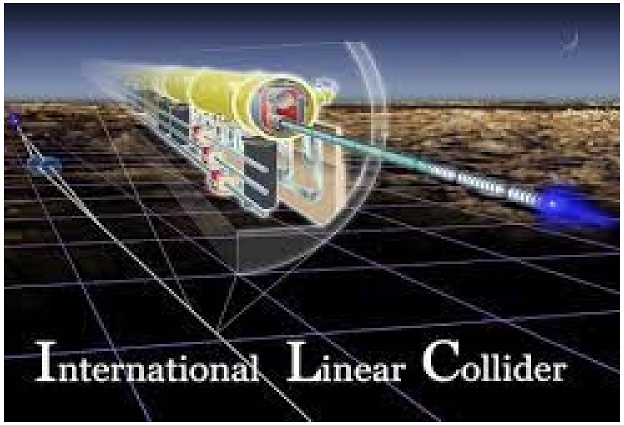
* V. G. Baryshevskii, Pis'ma Zh. Tekh. Fiz. 5, 182 (1979)

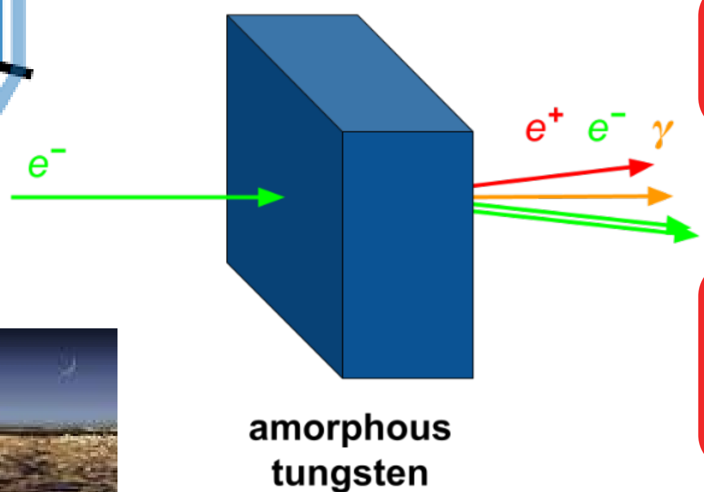
**D. Chen et al. (E761 Collaboration) Phys. Rev. Lett. 69, 23 (1992)

Positron source for future lepton colliders

FUTURE CIRCULAR COLLIDER







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

Potential challenges:
Target overheating/melting

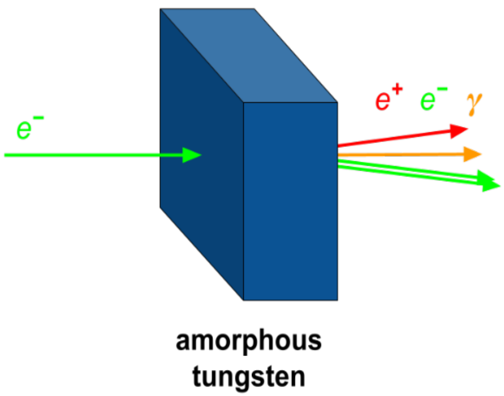
Peak Energy Deposition Density (**PEDD**) limit: **35 J/g** for **W***

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

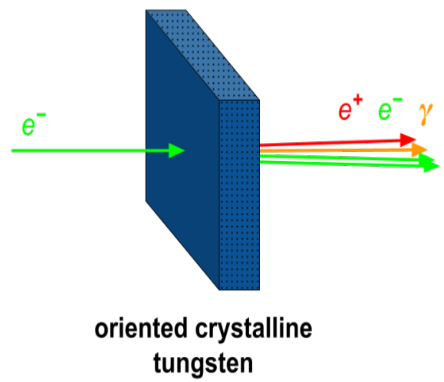
***S. Maloy et al., Slc target analysis. LANL LA UR-01-1913 72 (2001)**

Different types of crystal-based positron source*

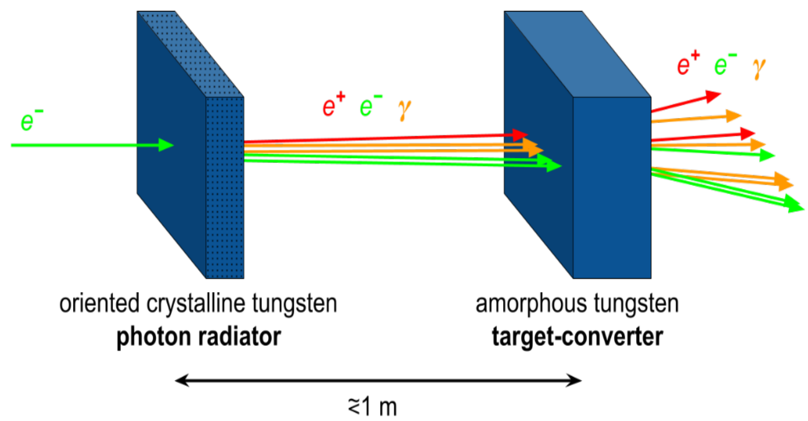
Conventional target



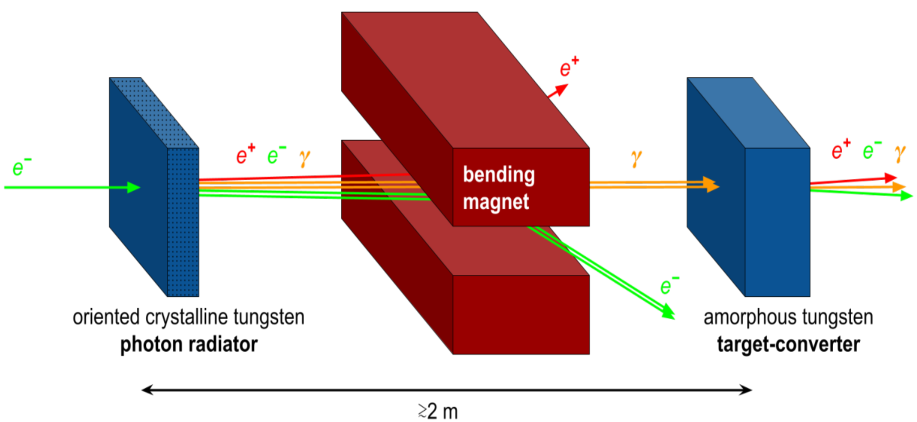
Crystal target



Hybrid scheme



Hybrid scheme with magnetic field



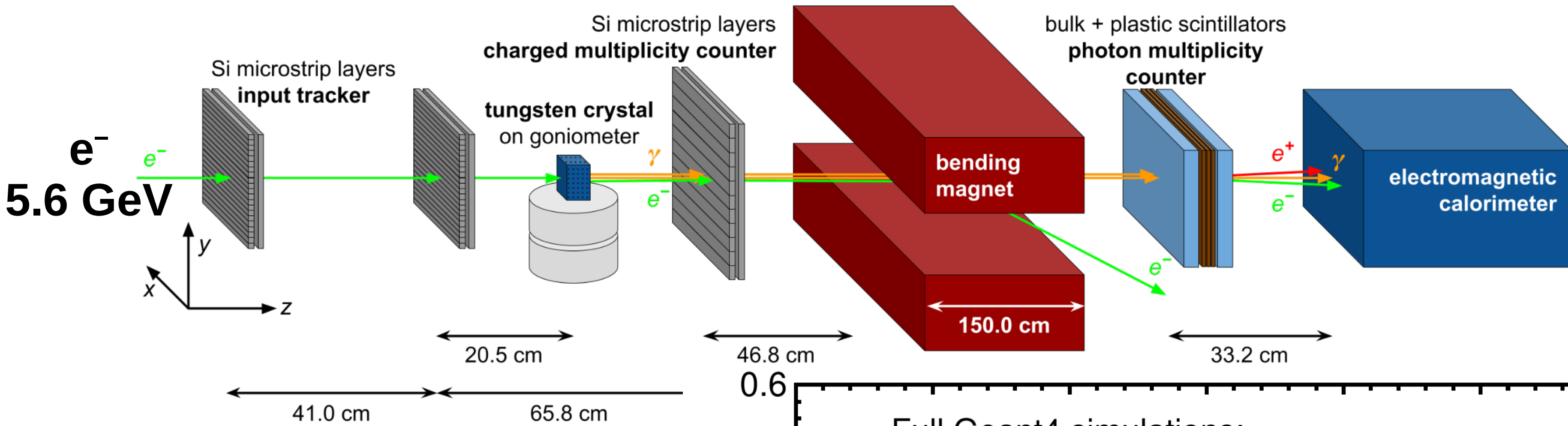
Hybrid positron source: two stages

- **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

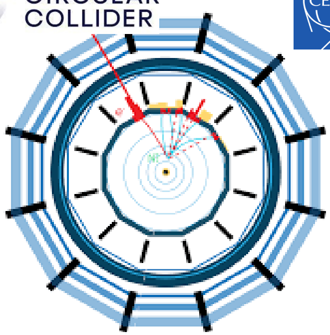
R. Chehab et al., in Proc. of the 1989 IEEE Particle Accelerator Conf., 1989, pp. 283–285

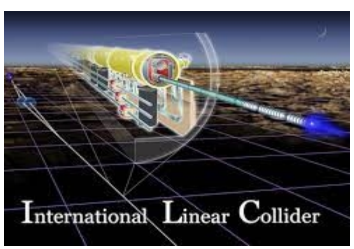
Full Geant4 simulations of the DESY experiment* for the FCC-ee positron source project

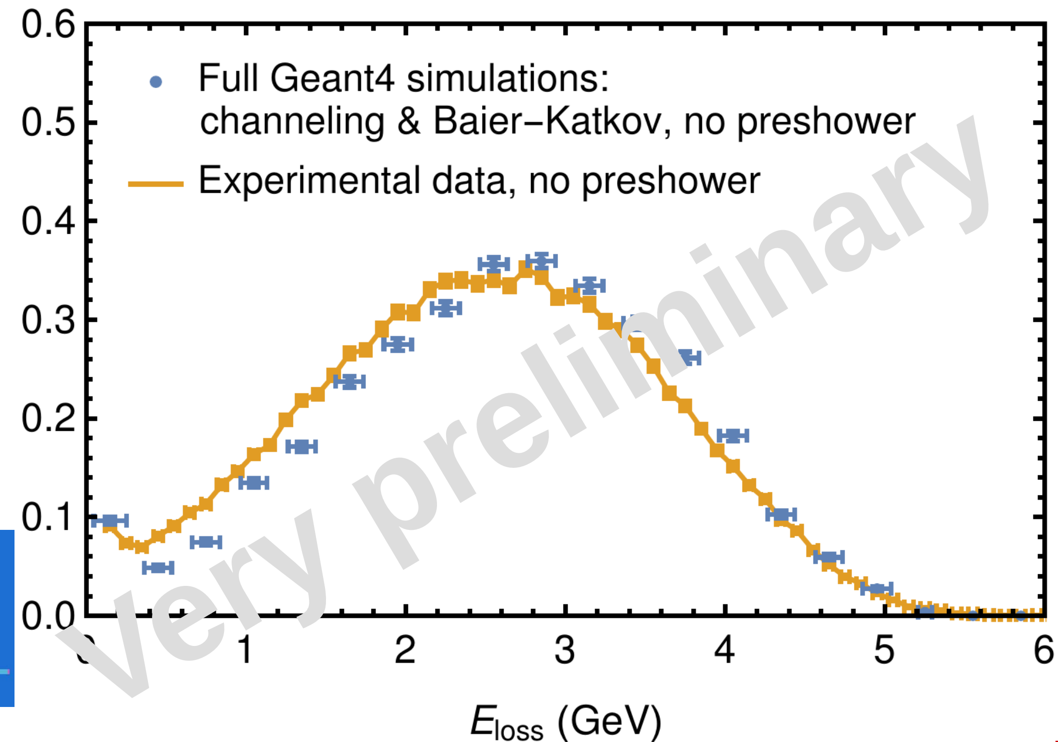


FUTURE CIRCULAR COLLIDER

CERN







Intense positron source Based On Oriented crySTals - e+BOOST

(PI L. Bandiera)

PRIN2022-2022Y87K7X

Financed by Italian Ministry of University and Research - PRIN project

Ministero dell'Università e della Ricerca

Bando PRIN 2022

UNIVERSITÀ RICERCA

Progress of channeling physics implementation into Geant4

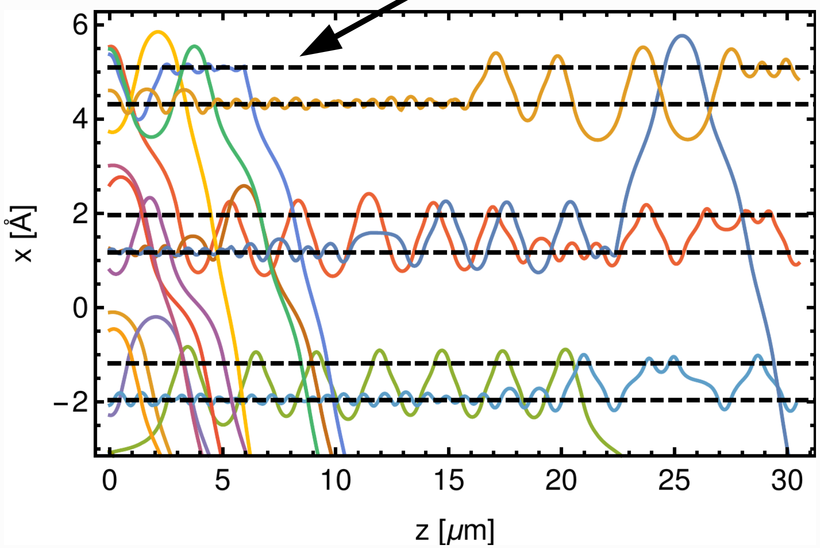
Geant4 is a toolkit for the simulation of the **passage** of particles **through matter**. Its areas of application include **high energy**, **nuclear** and **accelerator physics**, as well as studies in **medical** and **space science**.

Channeling simulation technique: Geant4 ChannelingFastSimModel

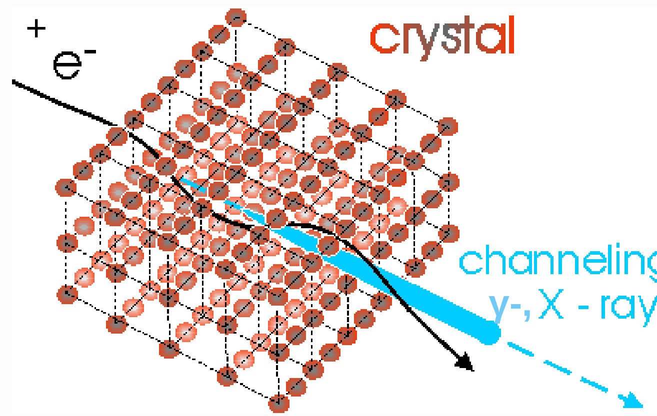
Main conception – simulation of classical trajectories of charged particles in a crystal

Multiple and single **scattering simulation** at every step

Crystal planes



channeling*



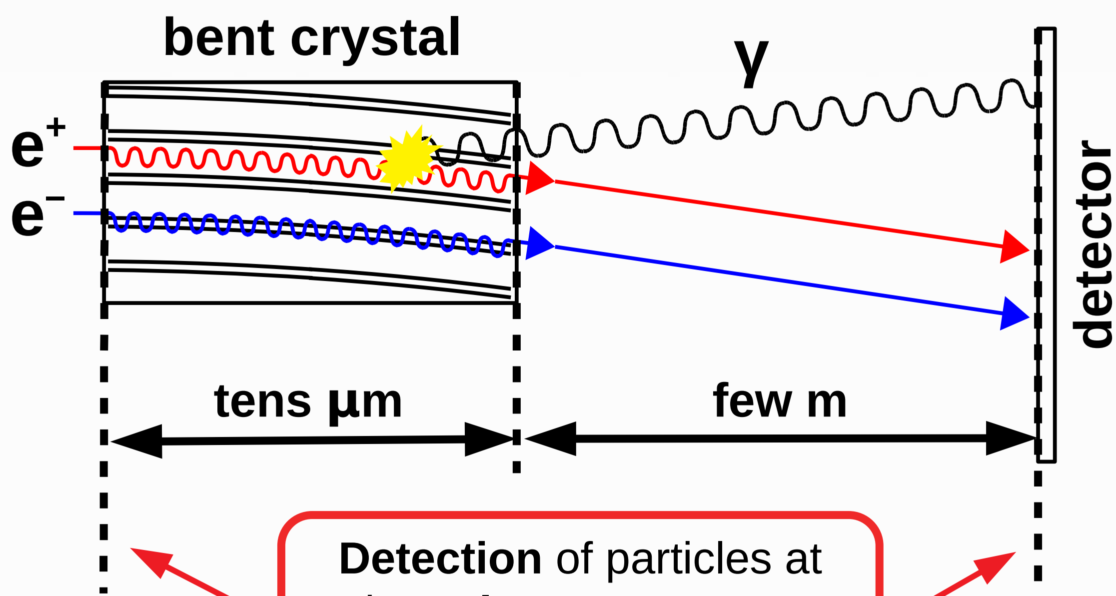
Baier-Katkov formula:
integration is made over the classical trajectory

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

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. Sytov et al. JKPS 83, 132–139 (2023)**

First Geant4 channeling example for electrons/positrons

- **Inspired by** our experiments* of **855 MeV electron** beam deflection by an ultrashort **bent crystal** at **Mainz Mikrotron MAMI**



Beam setup in **run.mac** using **GPS** commands; all the **geometry** in **DetectorConstruction**

Multithreading works! Checked at the supercomputer **Galileo100@CINECA** (Italy) **NURION@KISTI** (Korea)

Detection of particles at the **volumes entrance** using **SteppingAction**

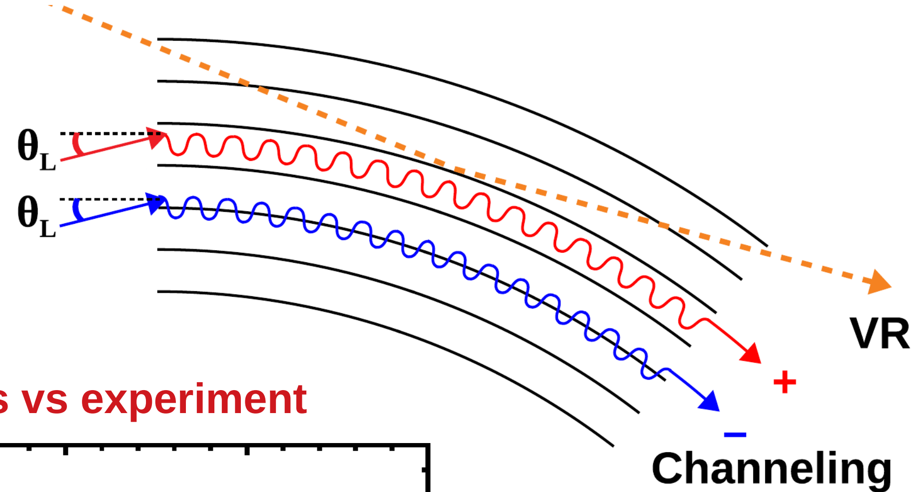
Output both in **root** (only primary particles) and in **textfile** (all the particles) format

***A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)**

First simulations with Geant4 channeling model: beam deflection by a bent crystal

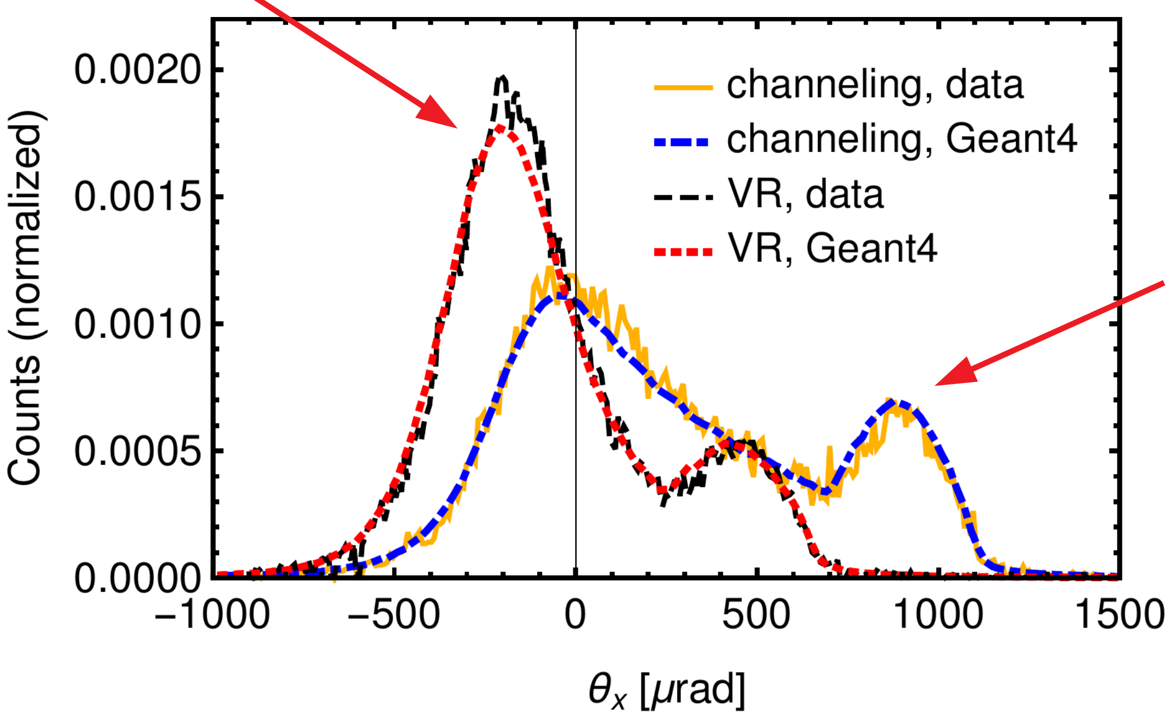
855 MeV electrons

15 µm thick bent crystal



volume reflection (VR)

Geant simulations vs experiment



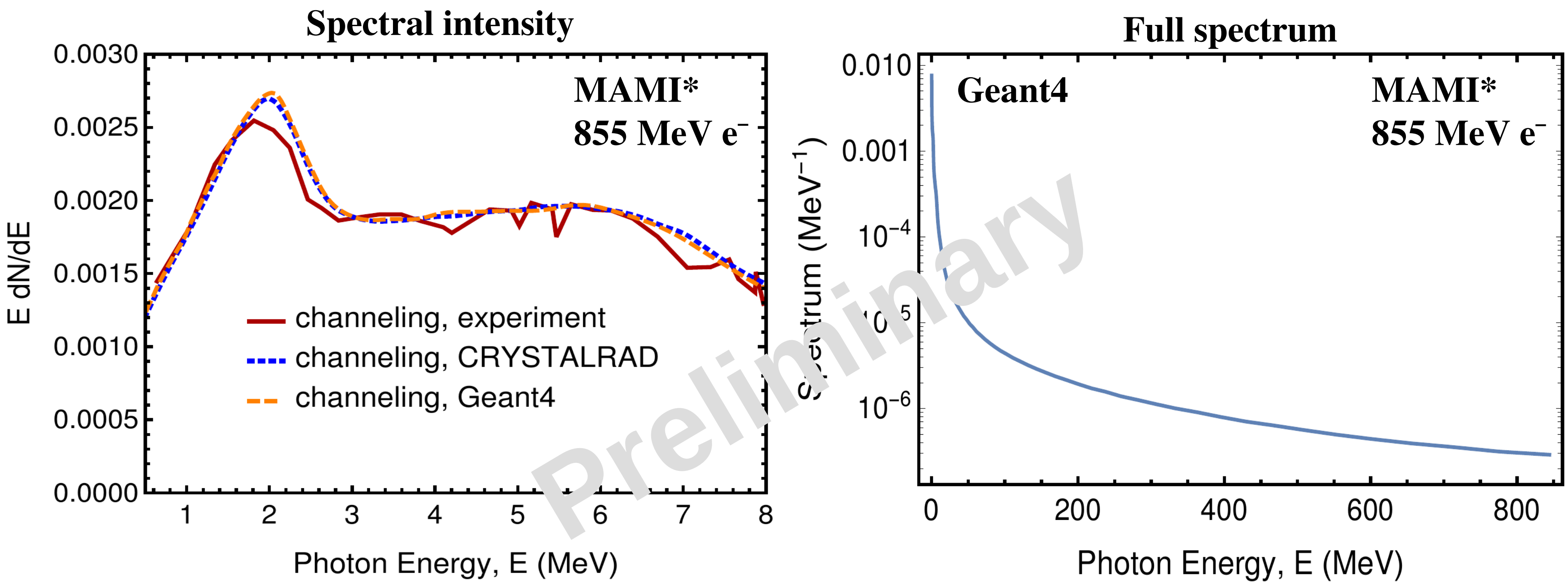
channeling

First Geant4 Baier-Katkov radiation model: radiation by 855 MeV electrons at Mainz Mikrotron MAMI*

G4BaierKatkov:

- **Physics list independent**
- Activated in the **DetectorConstruction** and used in **ChannelingFastSimModel**
- Can be used **outside channeling model** within other FastSim model
- Provides **radiation spectrum** for single-photon radiation mode
- Provides generation of **secondary photons**

Geant simulations vs experiment and CRYSTALRAD simulations



How to use the Geant4 channeling model in your example?

- ## Add to DetectorConstruction::Construct()

```
//crystal volume
G4Box* crystalSolid = new G4Box("Crystal",CrystalSizeX/2,CrystalSizeY/2,CrystalSizeZ/2.);
crystalLogic = new G4LogicalVolume(crystalSolid,crystalMaterial,"Crystal");
            new G4PVPlacement(xRot,posCrystal,crystalLogic,"Crystal",logicWorld,false,0);
//crystal region (necessary for the FastSim model)
fRegion = new G4Region("Crystal");
fRegion->AddRootLogicalVolume(crystalLogic);
```

Volume declaration (completely standard)

G4Region declaration

- ## Add to DetectorConstruction::ConstructSDandField()

```
void DetectorConstruction::ConstructSDandField()
{
    // --------------- fast simulation ----------------------------
    //extract the region of the crystal from the store
    G4RegionStore* regionStore = G4RegionStore::GetInstance();
    G4Region* RegionCh = regionStore->GetRegion("Crystal");

    //create the channeling model for this region
    G4ChannelingFastSimModel* ChannelingModel =
        new G4ChannelingFastSimModel("ChannelingModel", RegionCh);
    //activate the channeling model
    ChannelingModel->Input(crystalMaterial, Lattice);
    //setting bending angle of the crystal planes (default is 0)
    ChannelingModel->GetCrystalData()->
            SetBendingAngle(BendingAngle,crystalLogic);

    //activate radiation model
    if (ActivateRadiationModel) ChannelingModel->RadiationModelActivate();
}
```

Get crystal region

Channeling FastSim model declaration

Model activation and input

Optional

Radiation model activation

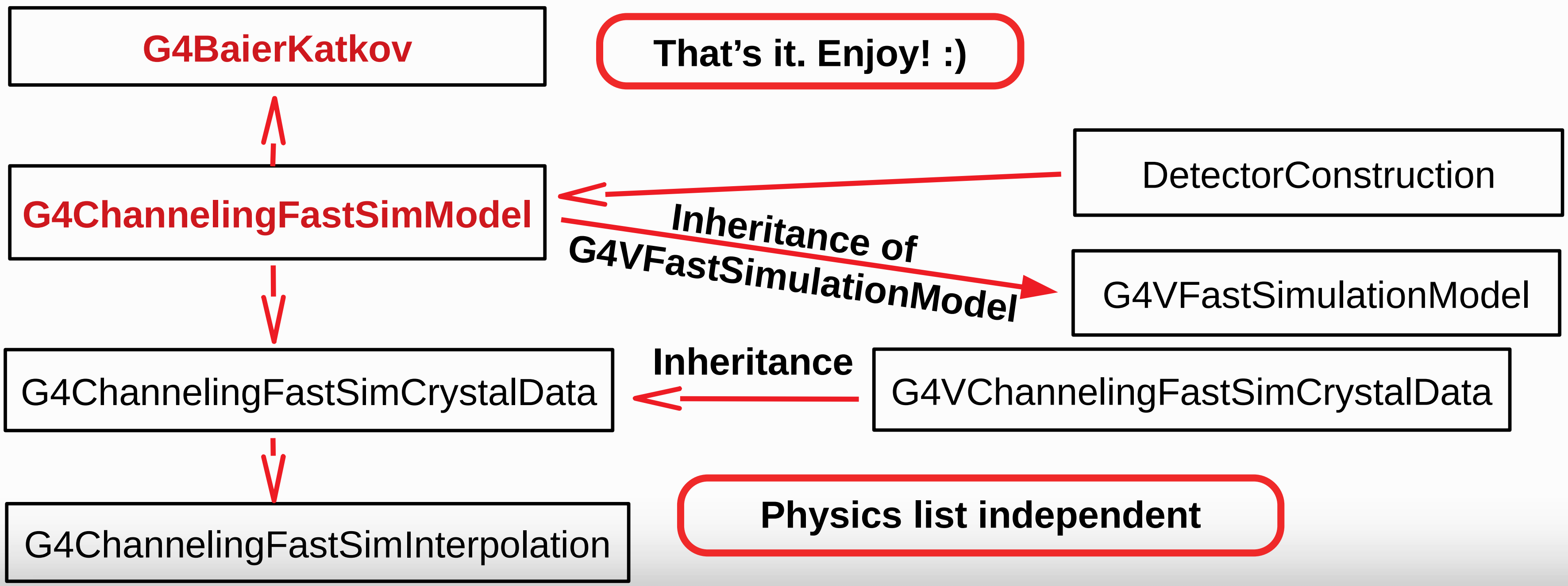
How to use the Geant4 channeling model in your example?

- **Add to main:**

Register FastSimulationPhysics

```
G4FastSimulationPhysics* fastSimulationPhysics = new G4FastSimulationPhysics();
fastSimulationPhysics->BeVerbose();
// -- activation of fast simulation for particles having fast simulation models
// -- attached in the mass geometry:
fastSimulationPhysics->ActivateFastSimulation("e-");
fastSimulationPhysics->ActivateFastSimulation("e+");
// -- Attach the fast simulation physics constructor to the physics list:
physicsList->RegisterPhysics( fastSimulationPhysics );
```

That’s it. Enjoy! :)



Physics list independent

Current status

Already in Geant4 kernel!

Geant4-11.2.0.beta
Please use it!

Don't hesitate to contact me in the case of any problems/issues/suggestions
sytov@fe.infn.it

Please cite our papers if you use our model:

1. A. Sytov et al. JKPS 83, 132–139 (2023)
2. A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)

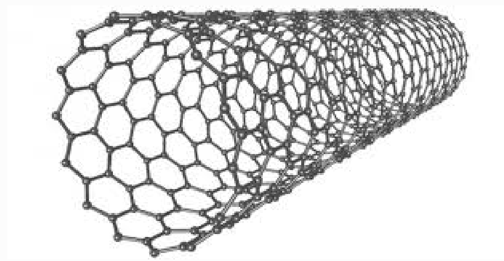
Plasma wake-field acceleration in oriented crystals/carbon nanotubes*

$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$

Acceleration gradient: $1\text{-}10\ \mathrm{TeV/m}$

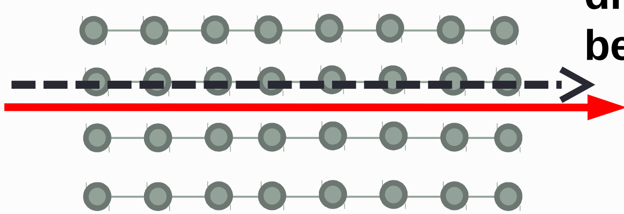
Considerably **higher electron density** in a **solid state** than in a gaseous plasma

Channeling makes **crystal** almost **transparent** both to accelerated and to drive beam



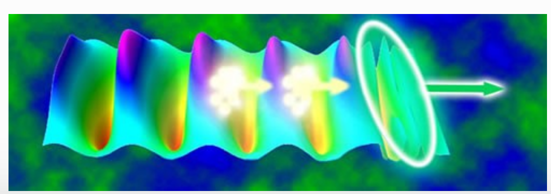
Possible drive beam:

- **X-rays**
- **electrons**
- **heavy high-Z beams**



Possible accelerated beam:

- **e+/e-**
- **muons**
- **protons**



* **R. Ariniello, …, and T. Tajima, Snowmass'2021 AF6: Advanced Acceleration Concepts, arXiv: 2203.07459**

T.Tajima, M.Cavenago, Crystal X-ray accelerator, Phys. Rev. Lett., 59(13), 1440 (1987).

SLAC NATIONAL ACCELERATOR LABORATORY

FACET-II Facility for Advanced Accelerator Experimental Tests

loa

INFN Istituto Nazionale di Fisica Nucleare

Fermilab

l'X ÉCOLE POLYTECHNIQUE UNIVERSITÉ PARIS-SACLAY

KiSTi www.kisti.re.kr Korea Institute of Science and Technology Information

European Commission

Trillion

TÉCNICO LISBOA

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cea

E336 Experiment at SLAC FACET-II on beam-driven plasma wakefield acceleration in structured solids: status and prospects

Dr. Alexei Sytov

on behalf of E336 collaboration

R. Ariniello, L. Bandiera, G. Cavoto, S. Corde, X. Davoine, H. Ekerfelt, F. Fiuza, M. F. Gilljohann, L. Gremillet, A. Knetsch, Y. Mankovska, B. Martinez, A. Matheron, H. Piekarz, I. Rago, P. San Miguel Claveria, V. Shiltsev, D. Storey, A. Sytov, P. Taborek, T. Tajima

ICABU 2023, Daejeon, 23/11/09

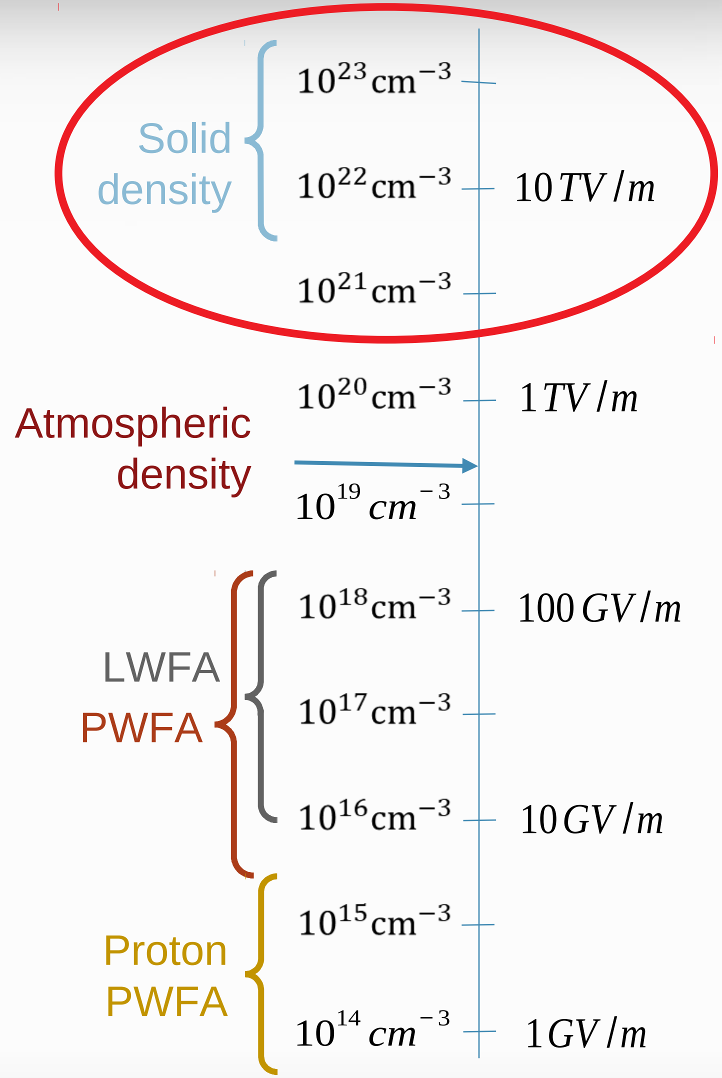
Plasma acceleration: why solid state targets?

Acceleration gradient

$$E[\mathrm{GV/m}] = m_e \omega_p c/e \approx 100\sqrt{n_0[10^{18}\mathrm{cm}^{-3}]}$$

- Most PWFA/LWFA is done in ionized gas plasma sources at densities much less than atmospheric
- Solids are 4-5 orders of magnitude more dense

Solid density wakefield accelerators could produce fields of **10 TV/m**

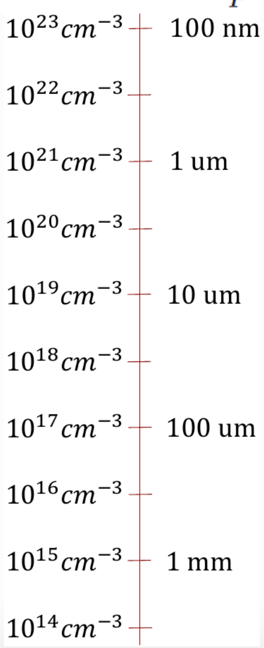


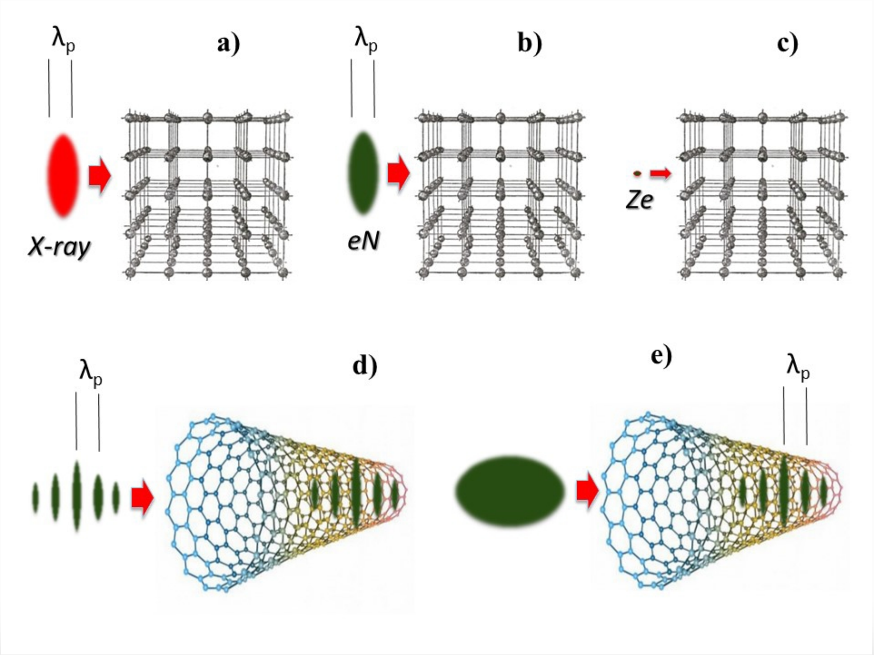
Why not amorphous targets?

Problems:

- At solid densities, scattering from plasma ions becomes significant => rapid pitch angle diffusion and particles escaping the wake
- **Transverse** and **longitudinal beam sizes** must be comparable or **smaller** than the plasma wavelength $\boldsymbol{\lambda_p}$,

$$\lambda_p = 2\pi \frac{c}{\omega_p}$$





Acceleration in a **nanostructure** (crystal or carbon nanotube) **limits scattering** off the solid's ions.

Periodic structure causes **transverse beam nanomodulation**

Additional pro:
small beam emittance

* R. Ariniello et al. arXiv:2203.07459 submitted to JINST

E336 at SLAC FACET-II
Science goals and definition of success

Science goals

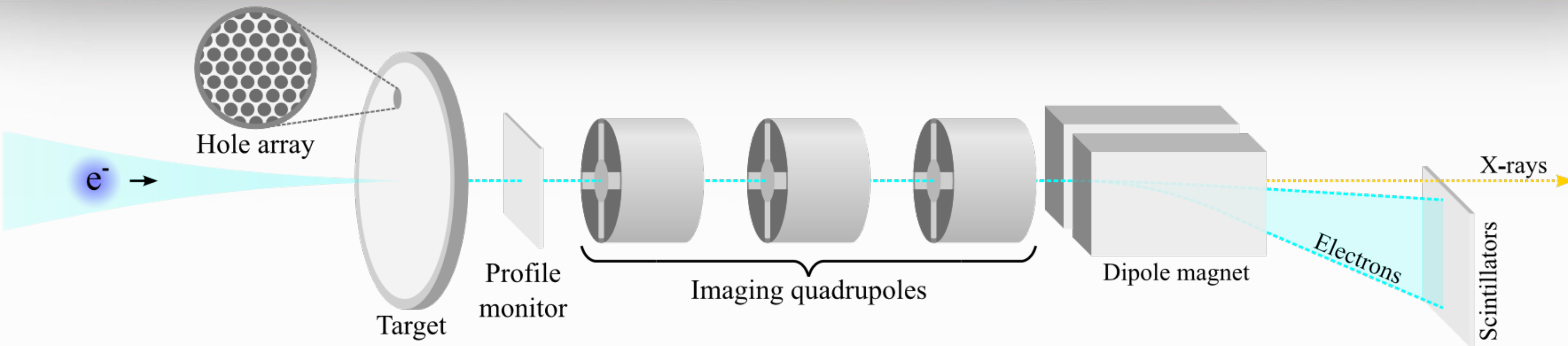
- **Proof-of-principle experiment** - demonstrate feasibility of the study of beam-nanotarget interaction and of beam-induced wakefields in nanotargets
- Observation of electron **beam nano-modulation**
- Observation of **X-ray radiation** due to transverse oscillations in wakefields
- Confirmation of **simulation models**

Definition of success:

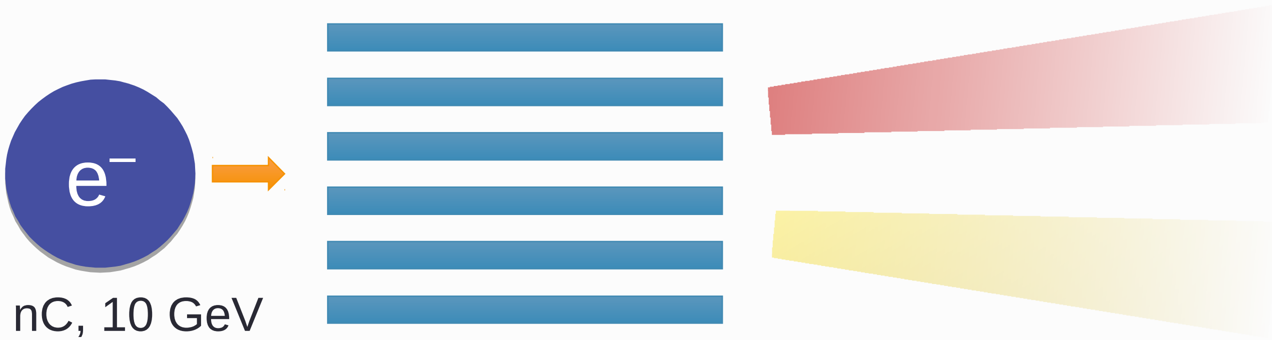
- **Evidence** for clearly distinguishable **interaction** of **FACET-II beam with structured solid targets** in comparison to amorphous targets (1.5 years)
- **Systematic parametric study** of beam-nanotarget interaction for various sample thickness, pore diameter, material type, and beam parameters, and comparison/validation against theory, to support signature and **evidence of beam nano-modulation** (3 years - dependent on beam parameters)

*** R. Ariniello et al. arXiv:2203.07459 submitted to JINST**

E336 SLAC FACET-II experimental setup



To measure:



2 nC, 10 GeV
1-10 µm

Structured target

Transverse momentum distribution & other beam parameters

X-rays
Gamma-rays

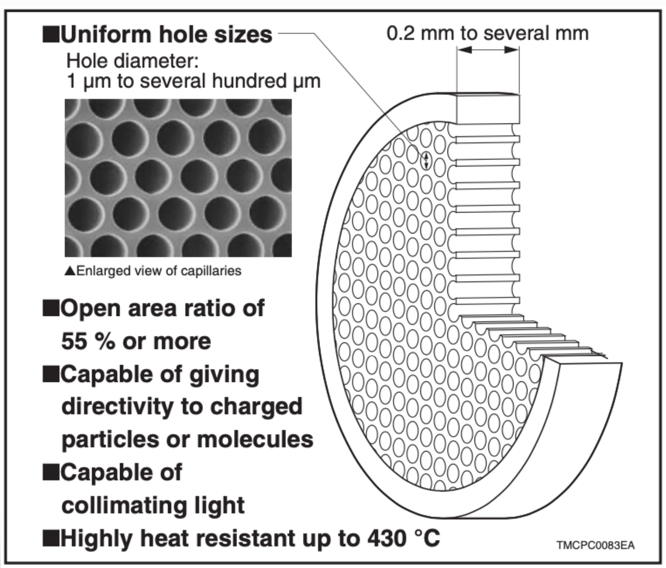
Observation of transverse plasma waves

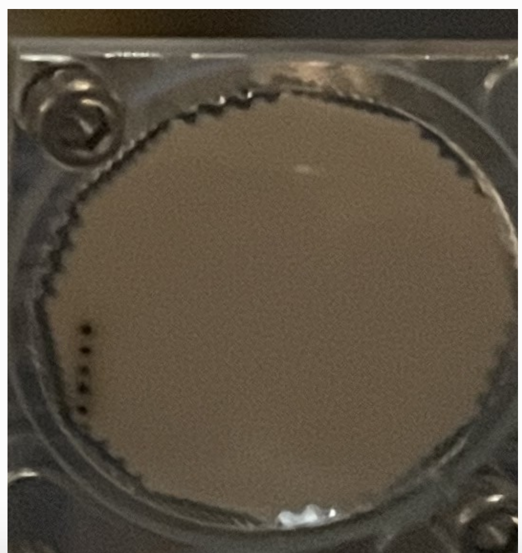
E336 SLAC FACET-II target and initial progress

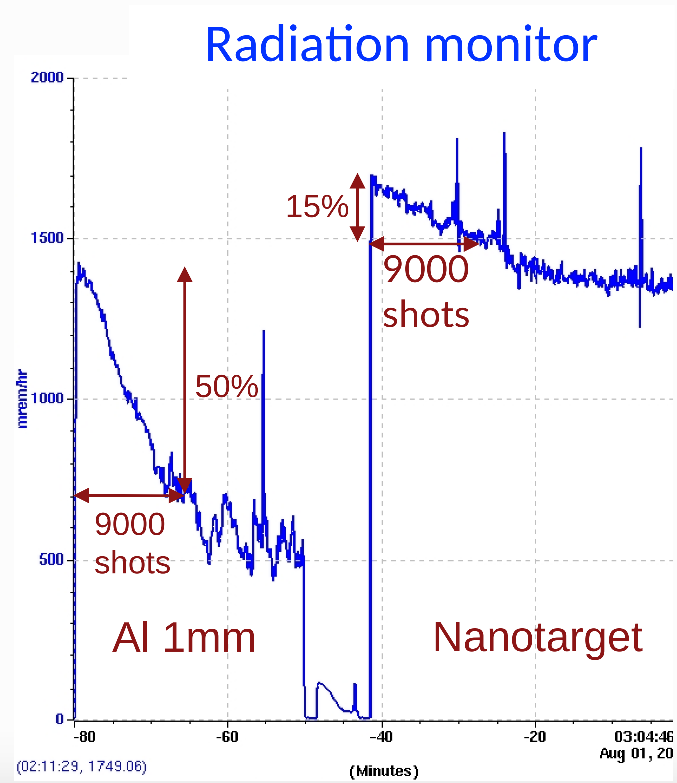
Observables

- 1 mm thick, 6 micron-diameter tubes in lead glass
- Radiation monitor downstream – drop tells how quickly the target is being damaged/drilled
- X-rays and gamma-rays

Damage observed, but targets relatively robust: 15% decrease in radiation in 9000 shots

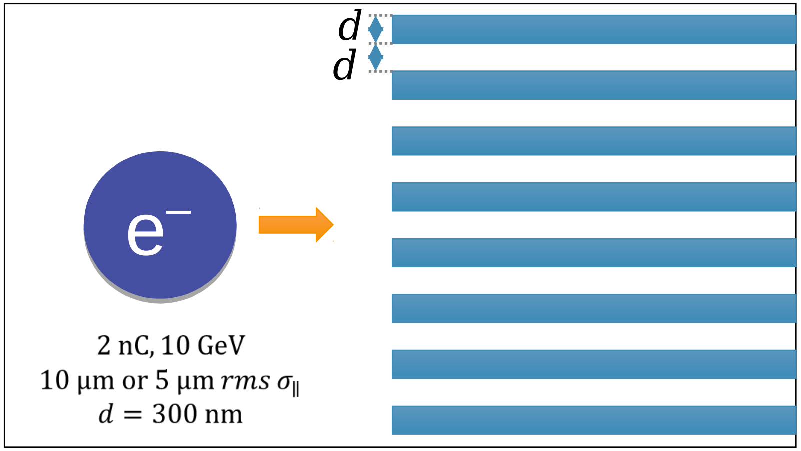




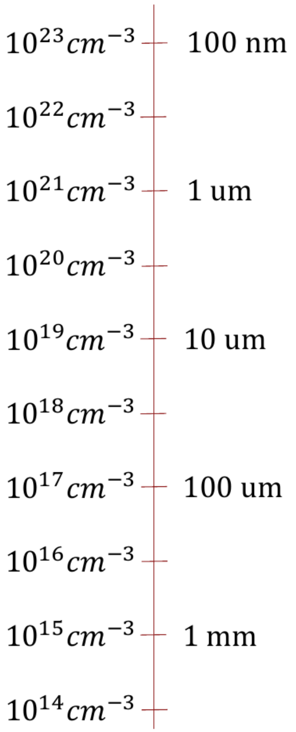


Simulation results: self-modulation of the electron beam

- **Size** of the **wake** scales as $\lambda_p = 2\pi \frac{c}{\omega_p}$

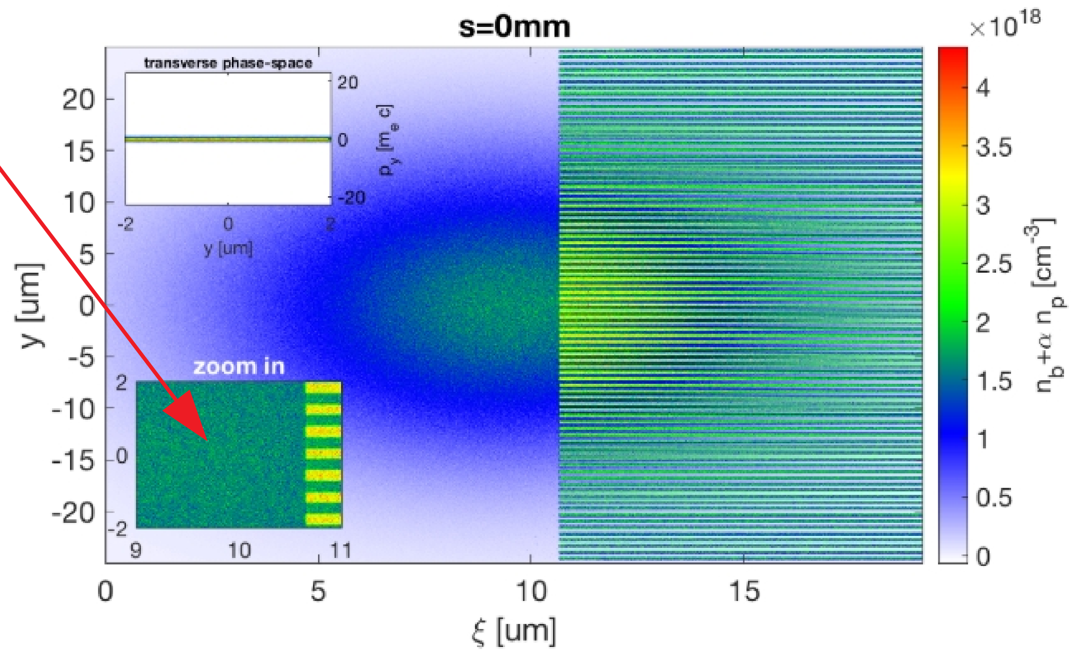


- **Driver** needs to have spatial scale on the order of the **wake scale**
- For solid densities, this is **difficult to achieve** with current facilities



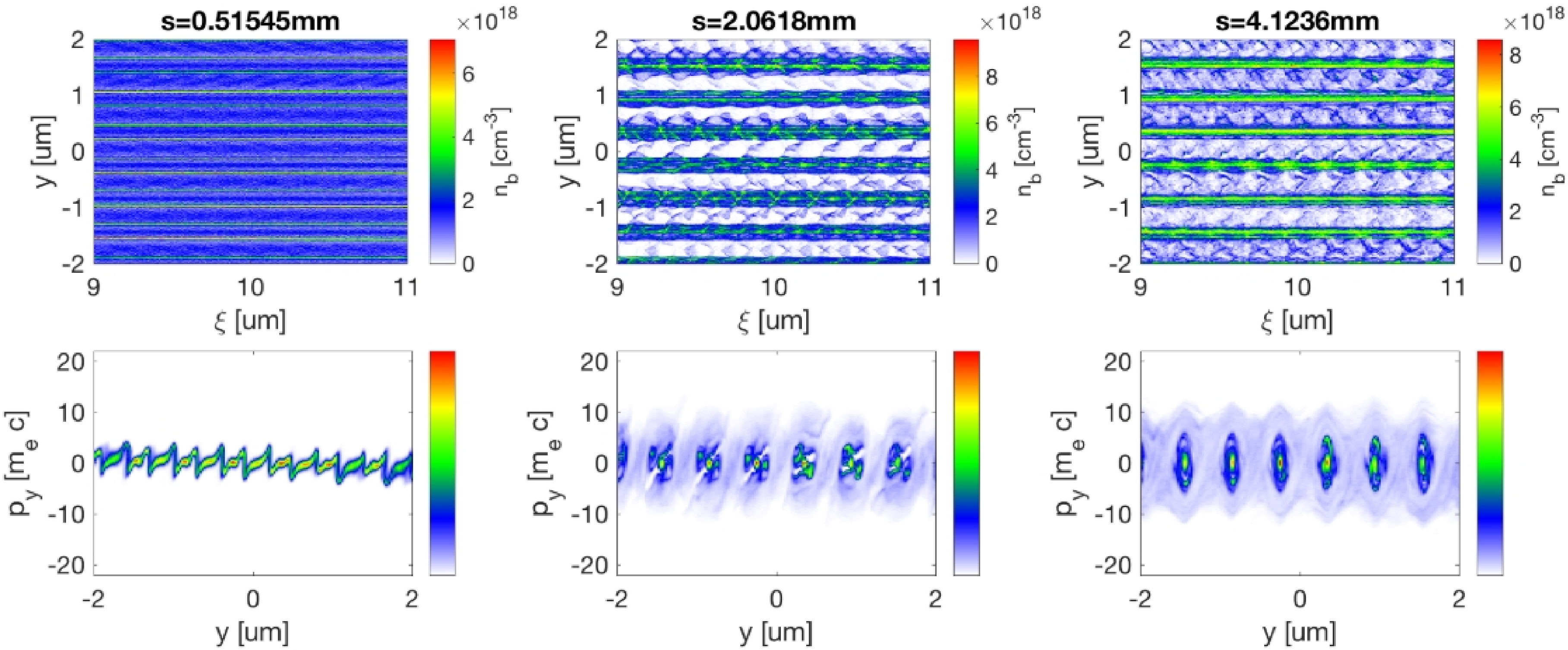
Plasma density has the same structure as the nanotarget

PIC simulations were carried out using the CALDER code



Simulation results: self-modulation of the electron beam

Transverse plasma waves

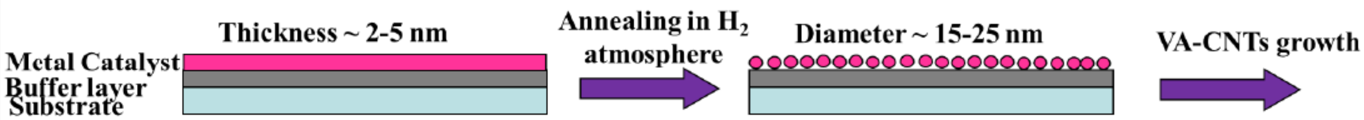


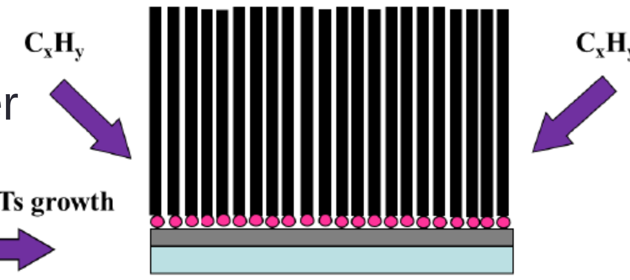
Don’t need a small driver! Imprint the target structure on the drive beam

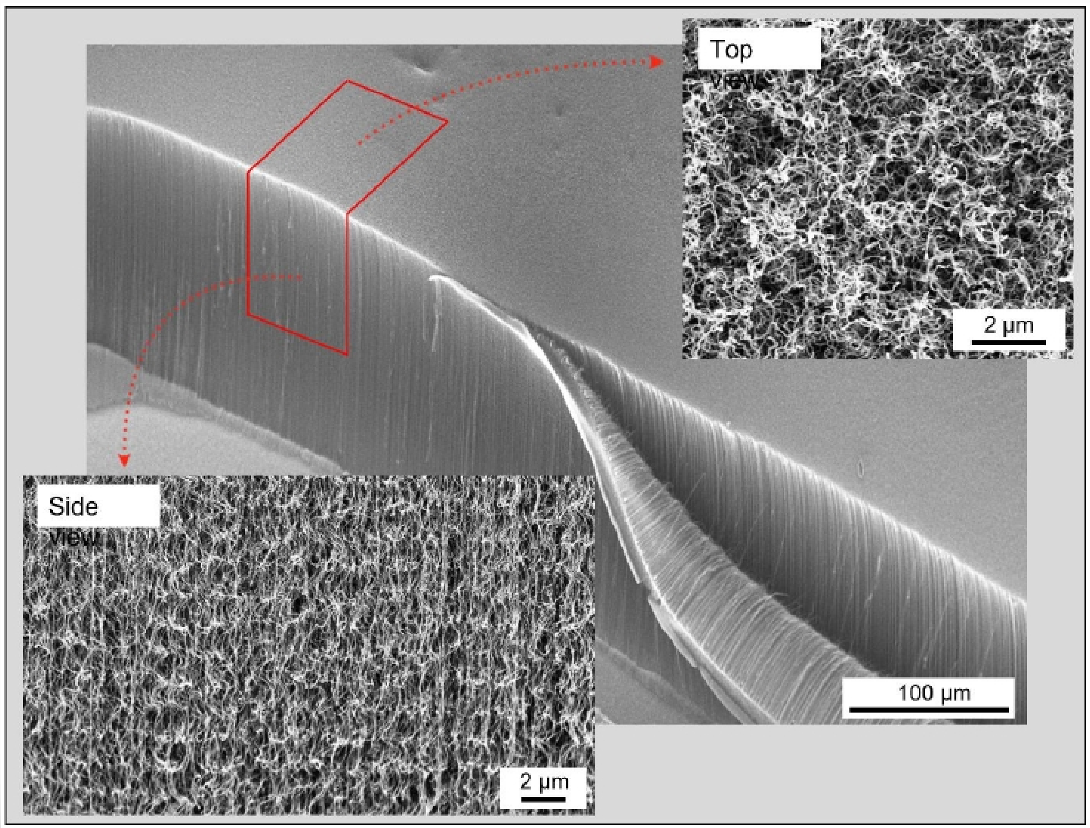
Another reason why we need nanostructures but not amorphous material

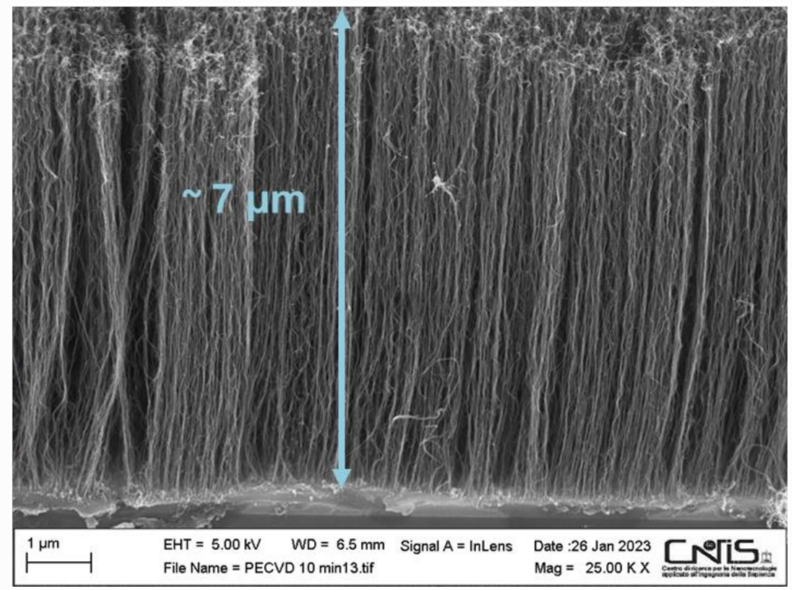
Future target: carbon nanotubes

Thermal decomposition of a gaseous precursor on catalytic nanoparticles in a high-vacuum reaction chamber







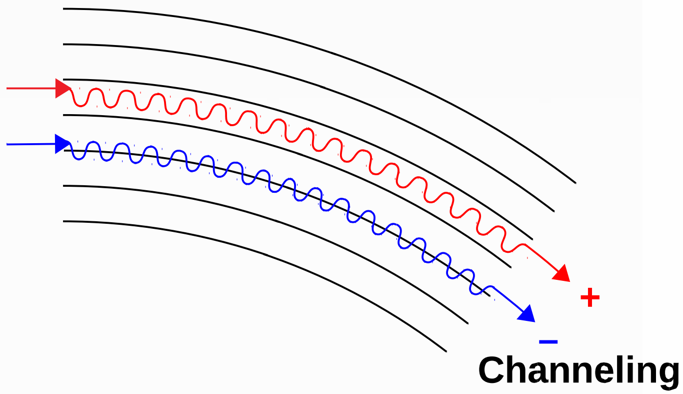


Courtesy of
Prof. Gianluca Cavoto,
Dr. Ilaria Rago

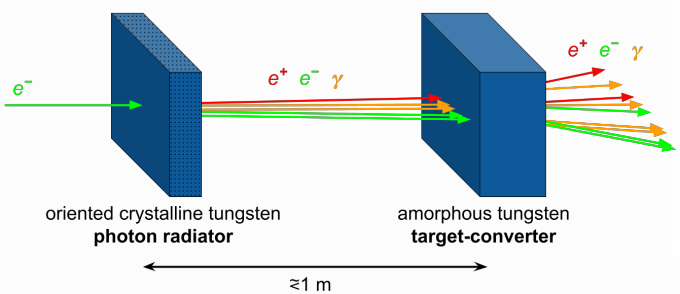
* F. Sarasini et al. Composites Part B 243 (2022) 110136

Let's dream about future lepton colliders!

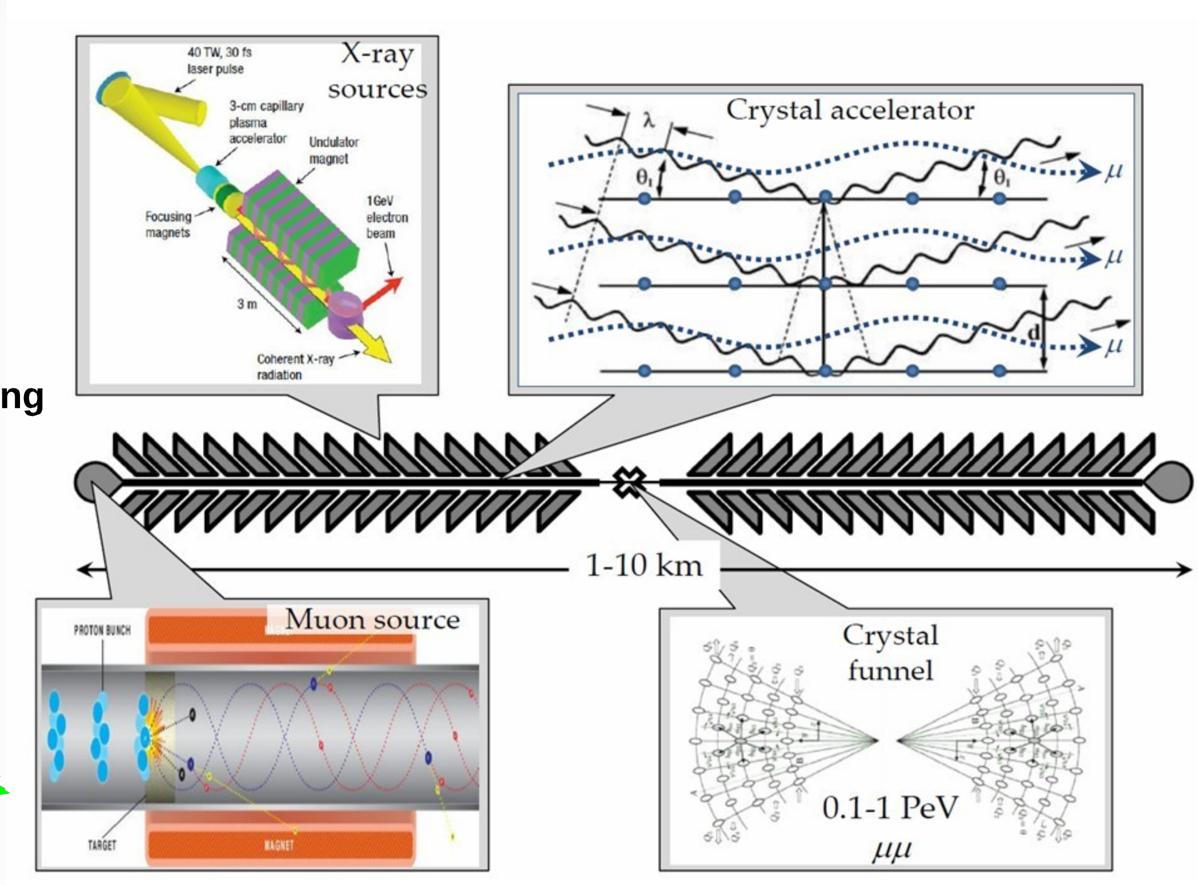
Channeling in a bent crystal



Hybrid crystal-based positron source***



Concept of a linear X-ray crystal muon collider*,**



***L. Bandiera et al. Eur. Phys. J. C 82, 699 (2022)
**V. Shiltsev, Physics-Uspekhi 55, (10), 965 (2012)
*R. Ariniello et al. arXiv:2203.07459 submitted to JINST

European Commission

List of collaborations

Trillion

TRILLION initially:

Host:

INFN
Istituto Nazionale di Fisica Nucleare

Geant4 collaboration:

Geant4 – A simulation toolkit

Planned secondments:

DESY.

IJCLab – Irène Joliot-Curie, Laboratoire de Physique des 2 Infinis

Partner for outgoing phase:

KISTI – www.kisti.re.kr
Korea Institute of Science and Technology Information

My Project MIRACLE (supercomputing time):

CINECA

TRILLION synergy with: H2020-MSCA-RISE N-LIGHT, EIC-PATHFINDER-OPEN TECHNO-CLS:

MBN Research Center

Experiments for code validation:

CERN

JG|U Johannes Gutenberg Universität Mainz

Gamma-ray space telescope for dark matter search:

Brown University

NA62:

CERN

Geant4& medical physics:

University of Wollongong Australia

MU2E:

Fermilab

Laser-driven plasma wakefield acceleration in nanostructures:

Universitat de València

University of Liverpool

Manchester 1824 – The University of Manchester

UFRGS – Universidade Federal do Rio Grande do Sul

E-336 experiment at SLAC FACET-II:

SLAC National Accelerator Laboratory

Stanford

FACET-II – Facility for Advanced Accelerator Experimental Tests

Fermilab

l'X – École Polytechnique, Université Paris-Saclay

loa

cea

Técnico Lisboa

UCI

Conclusions

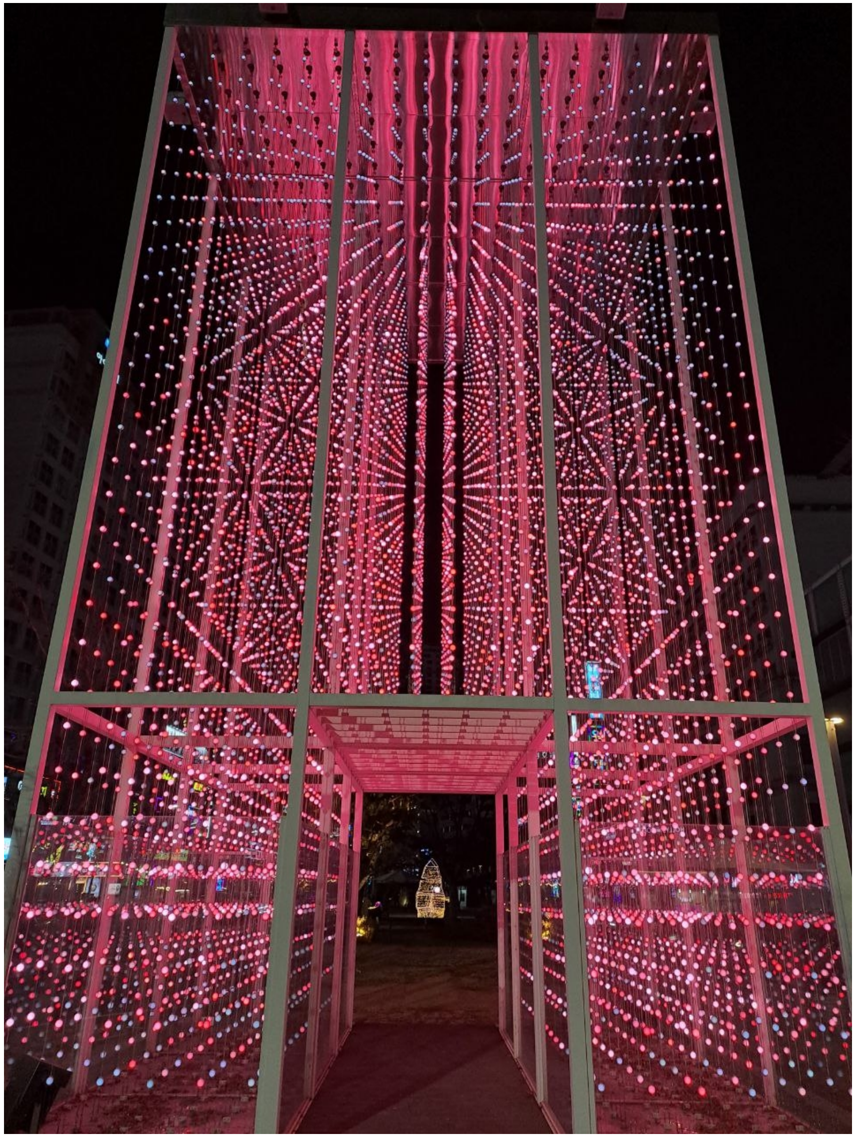
- The goal **of** **TRILLION** is to implement **electromagnetic processes in oriented crystals** into **Geant4** which will bring to a large scientific and industrial community most of possible applications of a crystal.

- **G4ChannelingFastSimModel** is our implementation of channeling physics and Baier-Katkov method into **Geant4**. We produced the **first results** on channeling and channeling radiation. We carried out these simulations at **NURION@KISTI** and **Galileo100@CINECA** supecomputers using **Geant4 multithreading**.

- **G4ChannelingFastSimModel and G4BaierKatkov** models were released in **Geant4-11.2.0.beta**.

- The Geant4 examples that will be developed can be **applied** in **nuclear** and **medical physics** (radiation source), at e-/e+ colliders – **ILC**, **FCC-ee** and **muon collider** (positron source) and at all **e-/e+ synchrotrons** existing in the world (crystal-based beam extraction).

- Additional applications are ultrashort crystalline **calorimeter**, exotic particles **MDM** and **EDM measurement**, and **plasma wakefield acceleration**.



Thank you for attention!