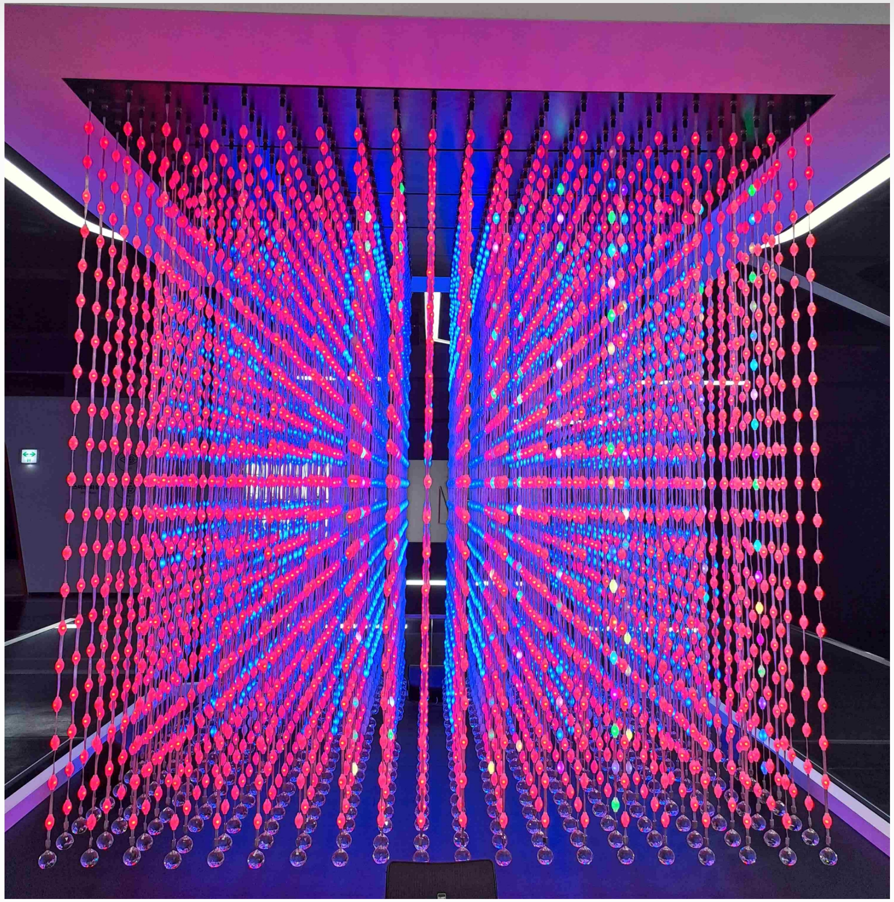
New Geant4 simulation model of X- and gamma-rays production by electron and positron beam in oriented crystals

A. Sytov, L. Bandiera, K. Cho*, G.A.P. Cirrone, S. Guatelli, V. Haurylavets, S. Hwang, V. Ivanchenko, L. Pandola, G. Paternò, A. Rosenfeld, V. Tikhomirov

*cho@kisti.re.kr

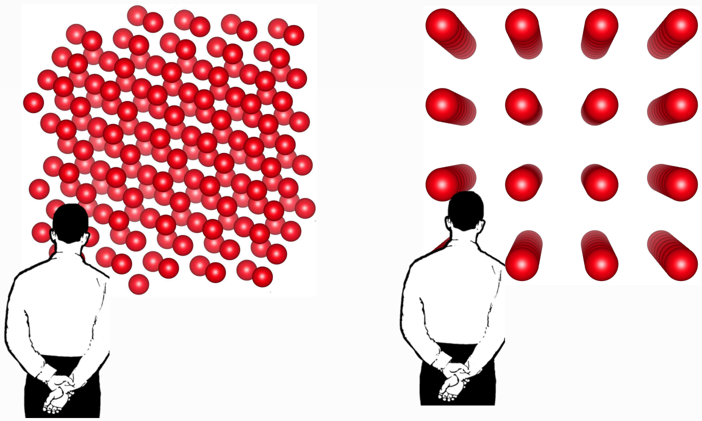
ICABU 2023, Daejeon, 23/11/09

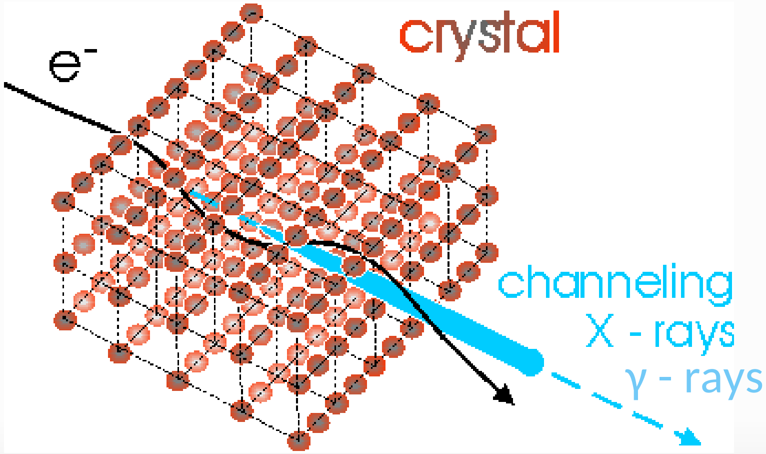
How an oriented crystal looks like



from National Science Museum, Daejeon, Korea

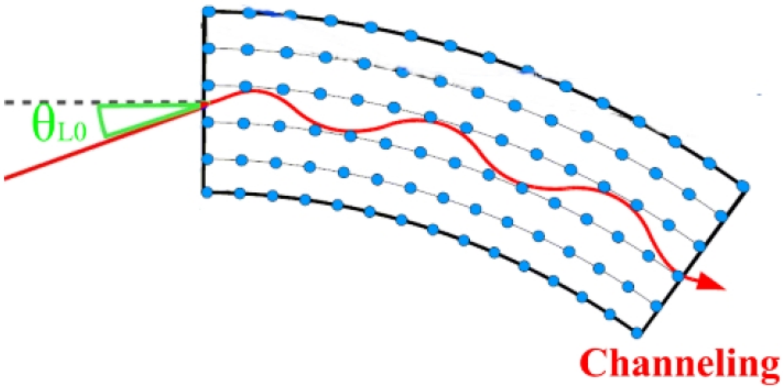
Non-oriented crystal | **Oriented crystal**





Coherent effects in a crystal

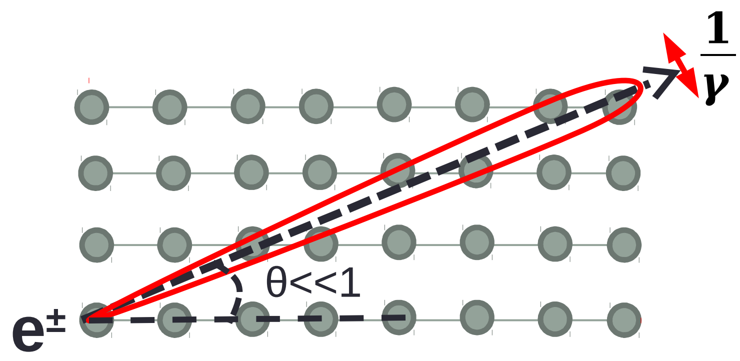
Channeling*



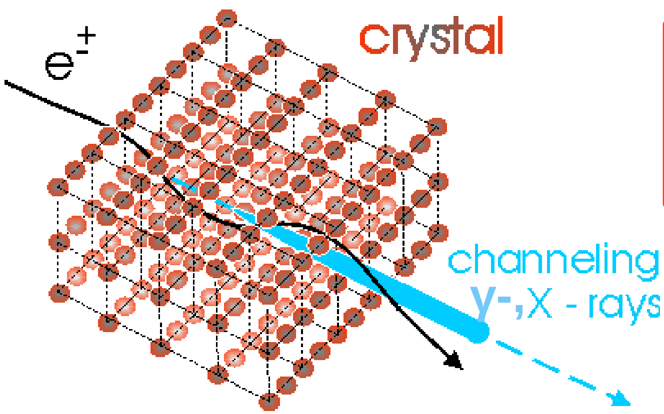
Enegies: MeV - TeV

Equivalent magnetic field: more than 100 T

Coherent bremsstrahlung***

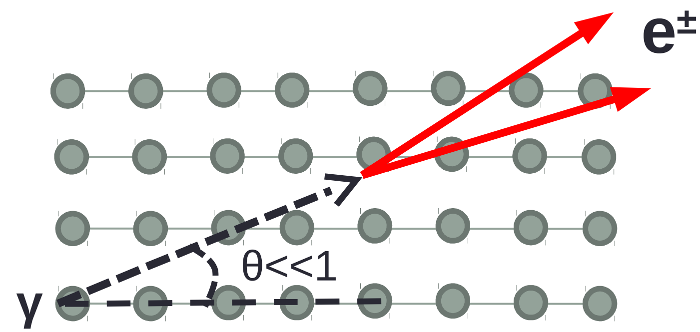


Channeling radiation**



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

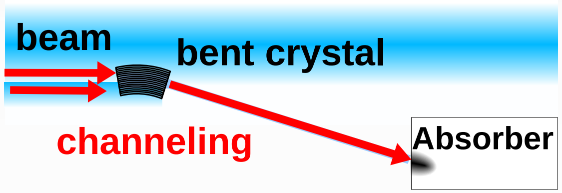
Coherent pair production****



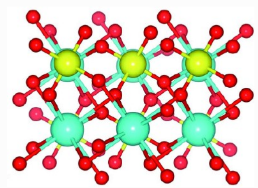
*J. Stark, Zs. Phys. 13, 973–977 (1912); J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
**M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
***B. Ferretti, Nuovo Cimento 7, 118 (1950); M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).
**** H. Überall, Phys. Rev. 103, 1055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

Applications*

Crystal-based collimation or beam extraction from an accelerator

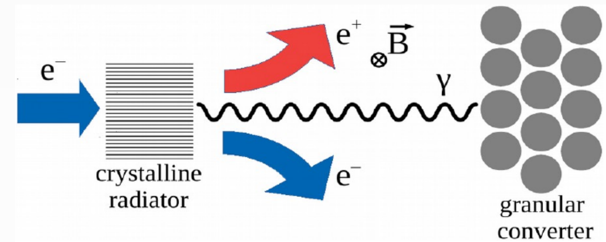


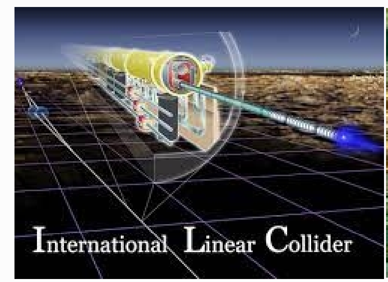
Ultrashort crystalline calorimeter



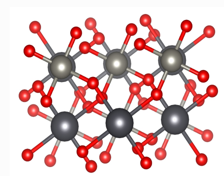
Gamma-ray Space Telescope

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

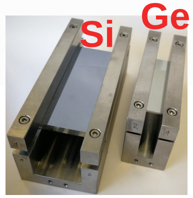


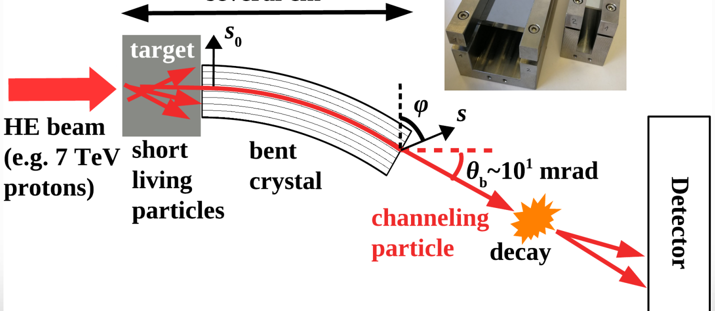


Oriented crystals

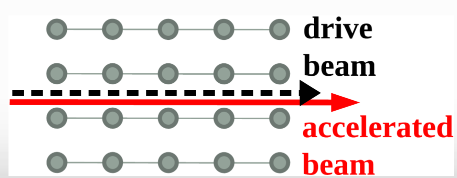


Measurement of dipole magnetic and electric moments of exotic particles

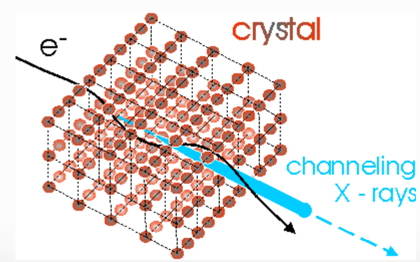


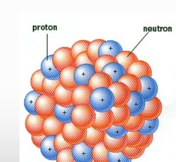


Plasma acceleration



X and γ-ray source for nuclear and medical physics





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

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:

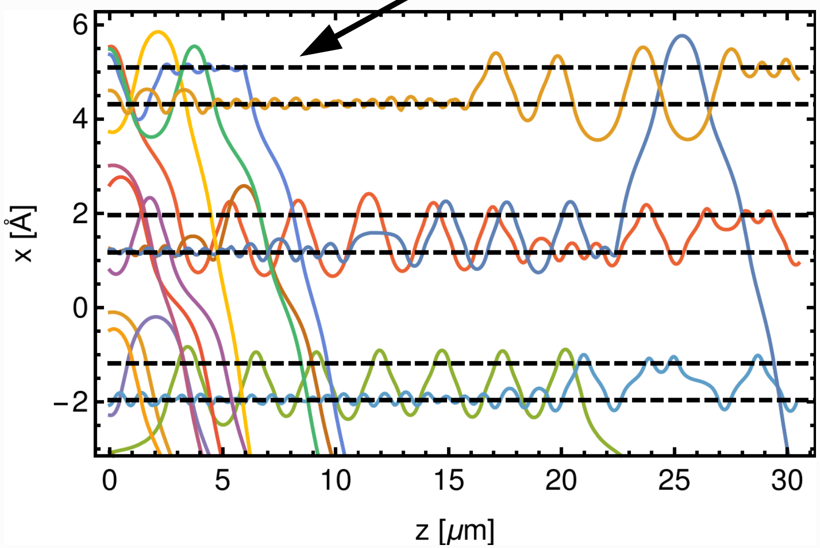
- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

Channeling simulation technique: Geant4 ChannelingFastSimModel

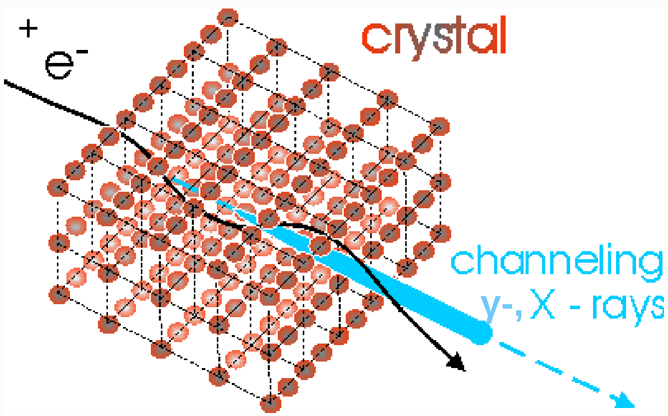
Main conception – simulation of classical trajectories of charged particles in a crystal

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

Crystal planes



channeling*



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

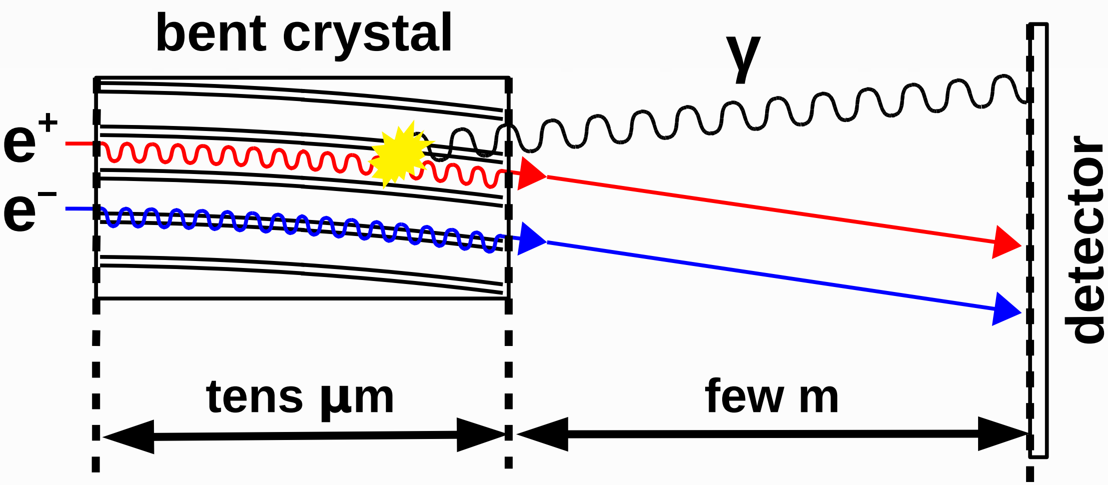
$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} \frac{\alpha}{4\pi^2} \iint dt_1 dt_2 \frac{\left[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1-x_2)}$$

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)**

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

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**

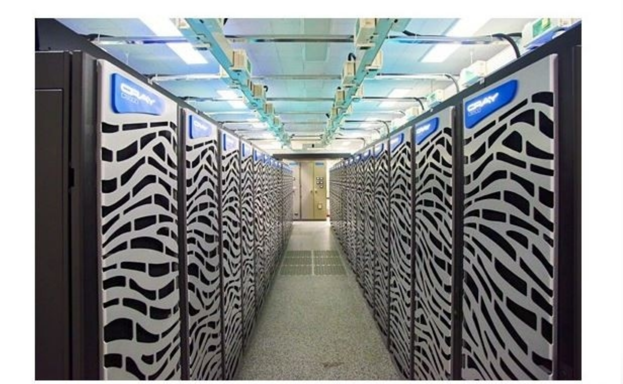


Beam setup in **run.mac** using **GPS** commands; all the **geometry** in **DetectorConstruction**

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



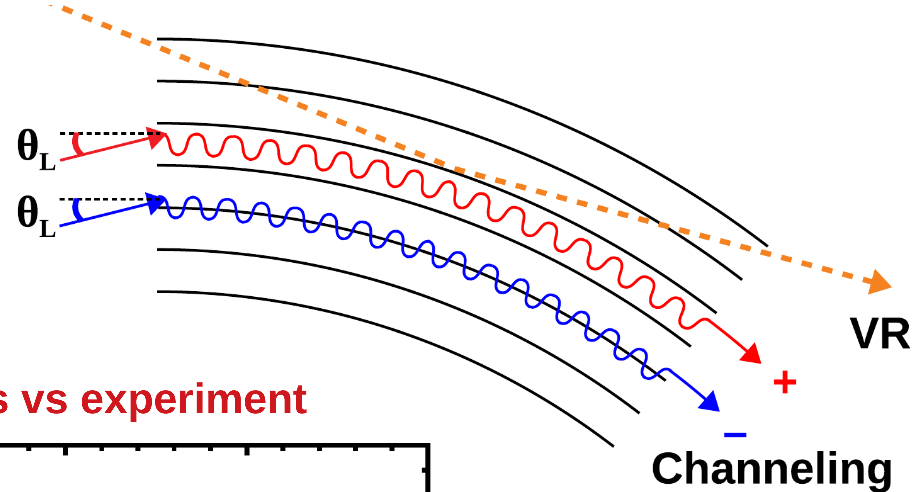
***A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)**

A. Sytov et al. Eur. Phys. J. C 77, 901 (2017)

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

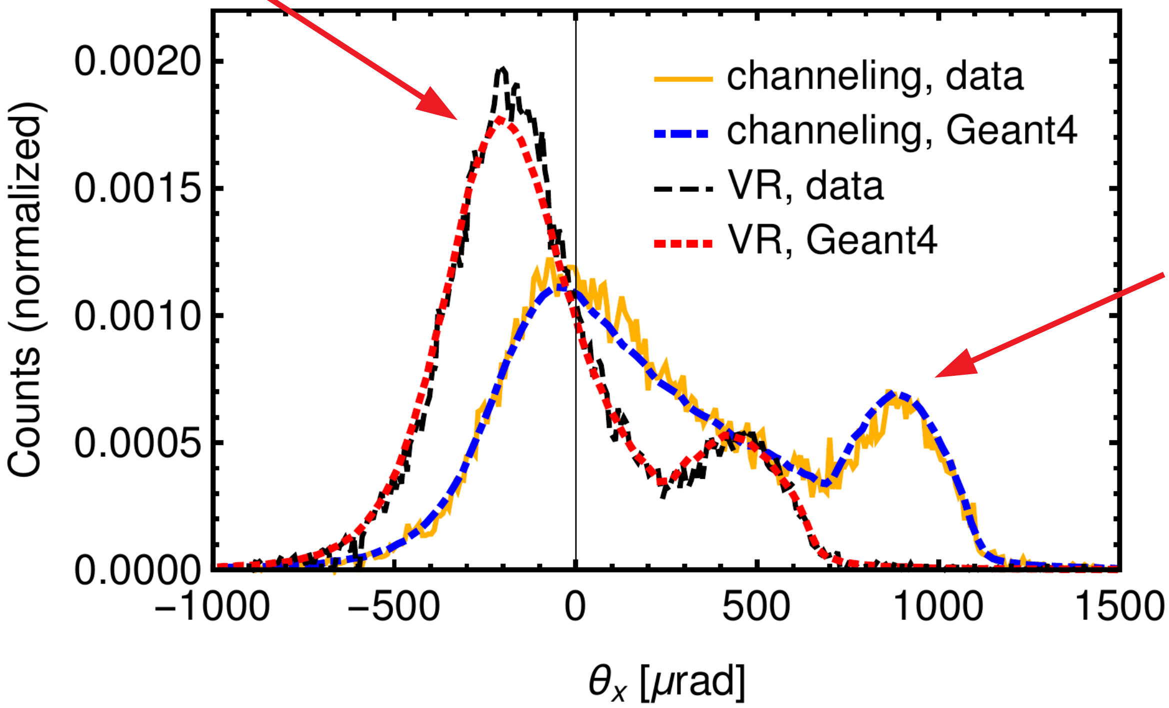
855 MeV electrons

15 µm thick bent crystal



volume reflection (VR)

Geant simulations vs experiment



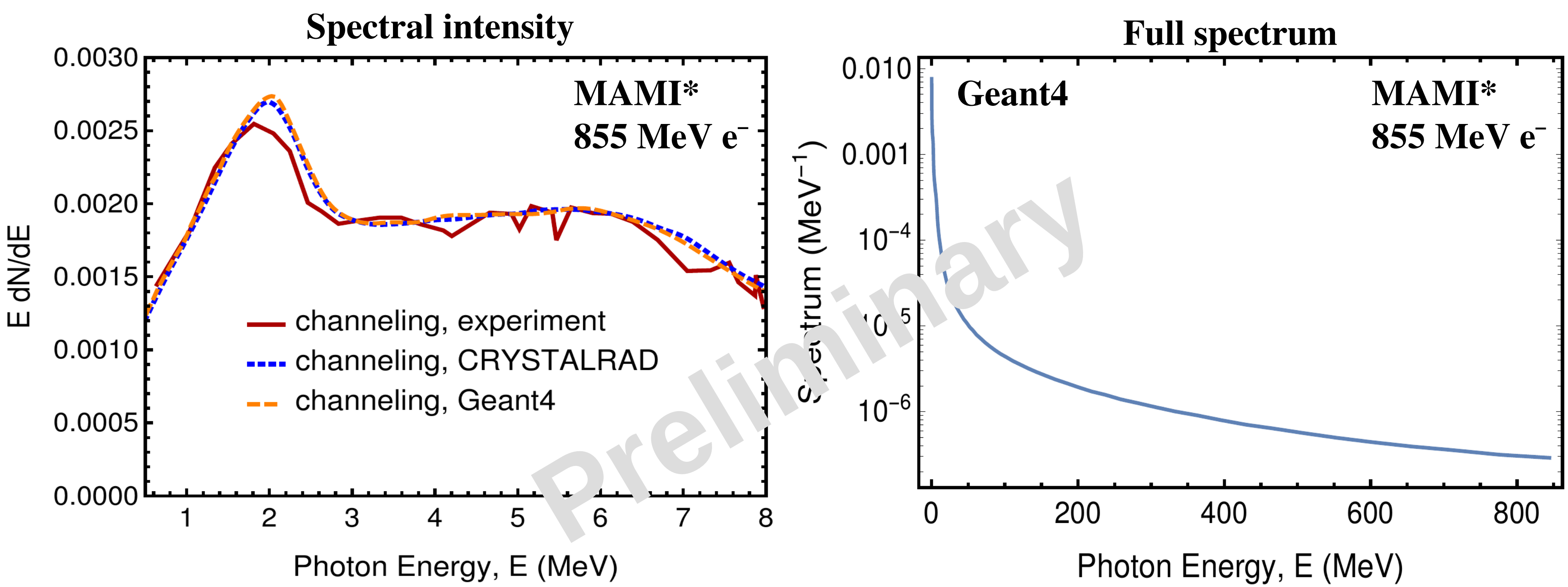
channeling

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

G4BaierKatkov:

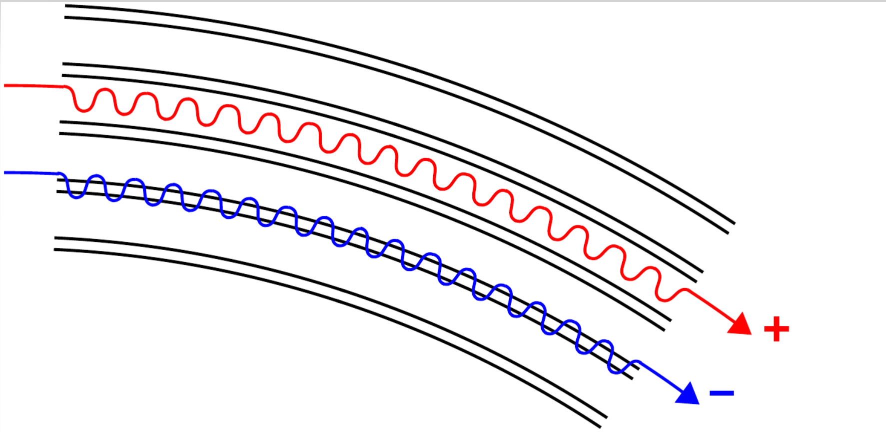
- **Physics list independent**
- Activated in the **DetectorConstruction** and used in **ChannelingFastSimModel**
- Can be used **outside channeling model** within other FastSim model
- Provides **radiation spectrum** for single-photon radiation mode
- Provides generation of **secondary photons**

Geant simulations vs experiment and CRYSTALRAD simulations



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

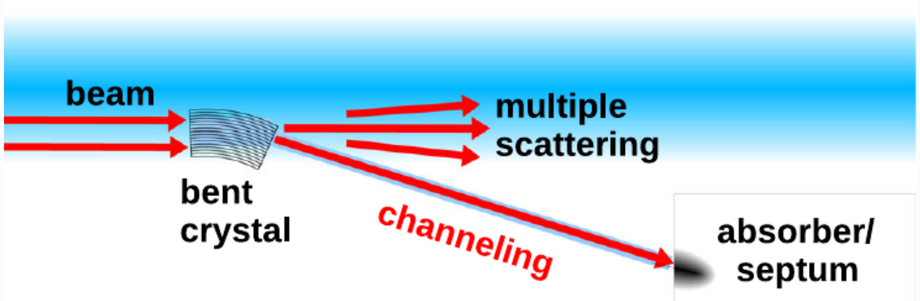
Crystal-based extraction



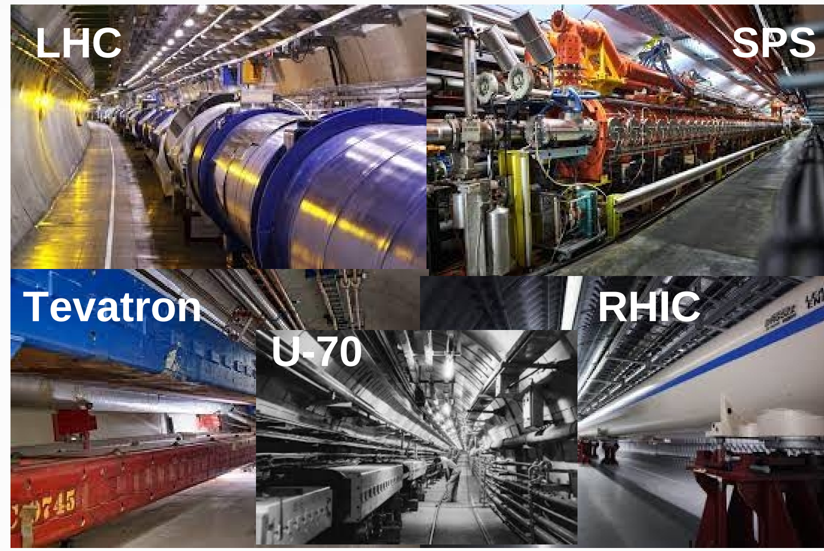
Planar channeling*:

- Charge particle penetration through a monocrystal along its atomic planes

Crystal-based extraction/collimation



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



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)

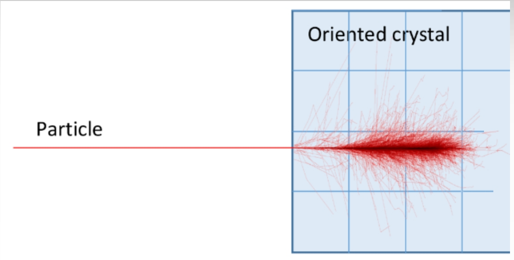
Crystal-based ultrashort electromagnetic calorimeter* (The INFN OREO experiment ORiEnted calOrimeter)

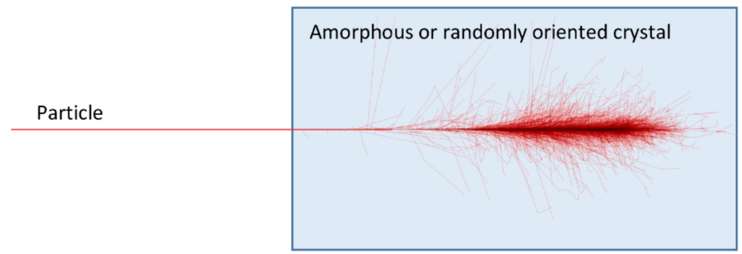
Advantage:

- 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





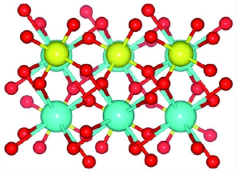
CERN North Area

$$K_L \rightarrow \pi^0 \nu\nu$$

+ dark photon search

Gamma-ray Space Telescope (like Fermi)

PWO

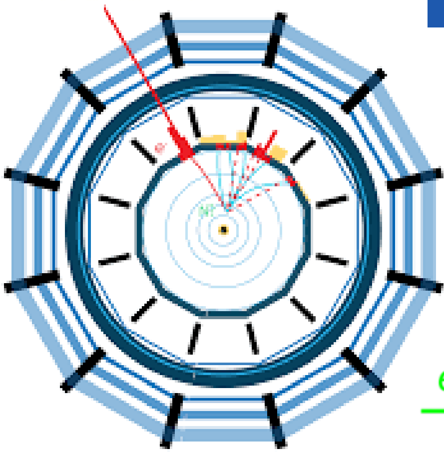


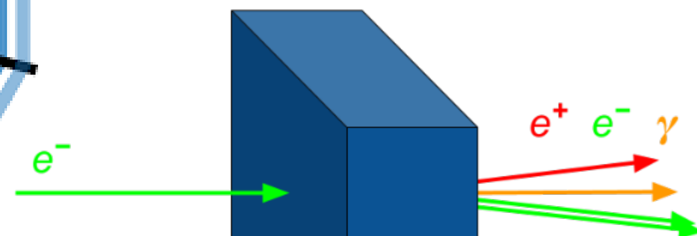
Cristalline calorimeter extends observation **γ energy range** up to **TeV**

Positron source for future lepton colliders

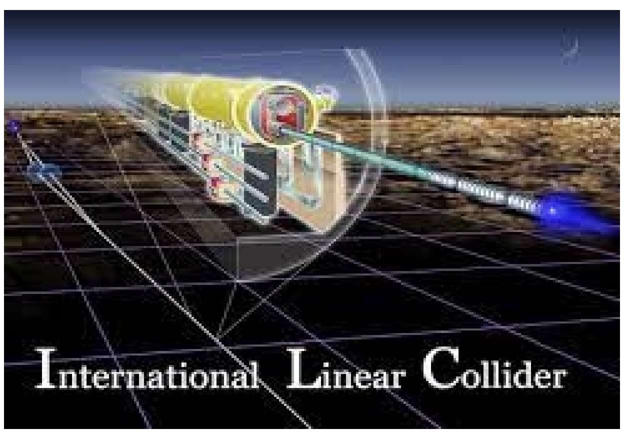
FUTURE CIRCULAR COLLIDER

CERN





amorphous tungsten



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

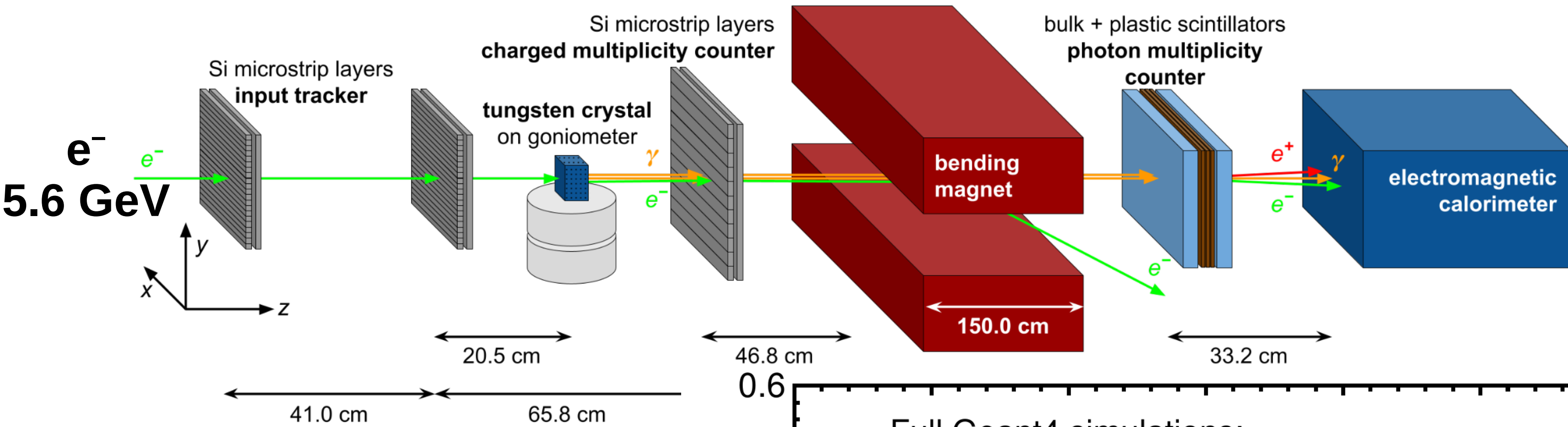
Potential challenges:
Target overheating/melting

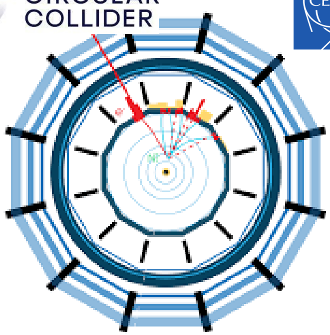
Peak Energy Deposition Density (**PEDD**) limit: **35 J/g** for **W***

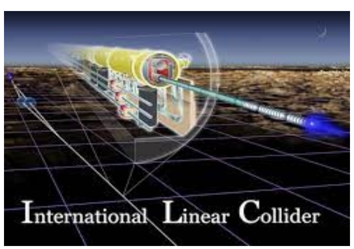
The main **challenge**:
to **increase positron yield** and to **decrease PEDD**

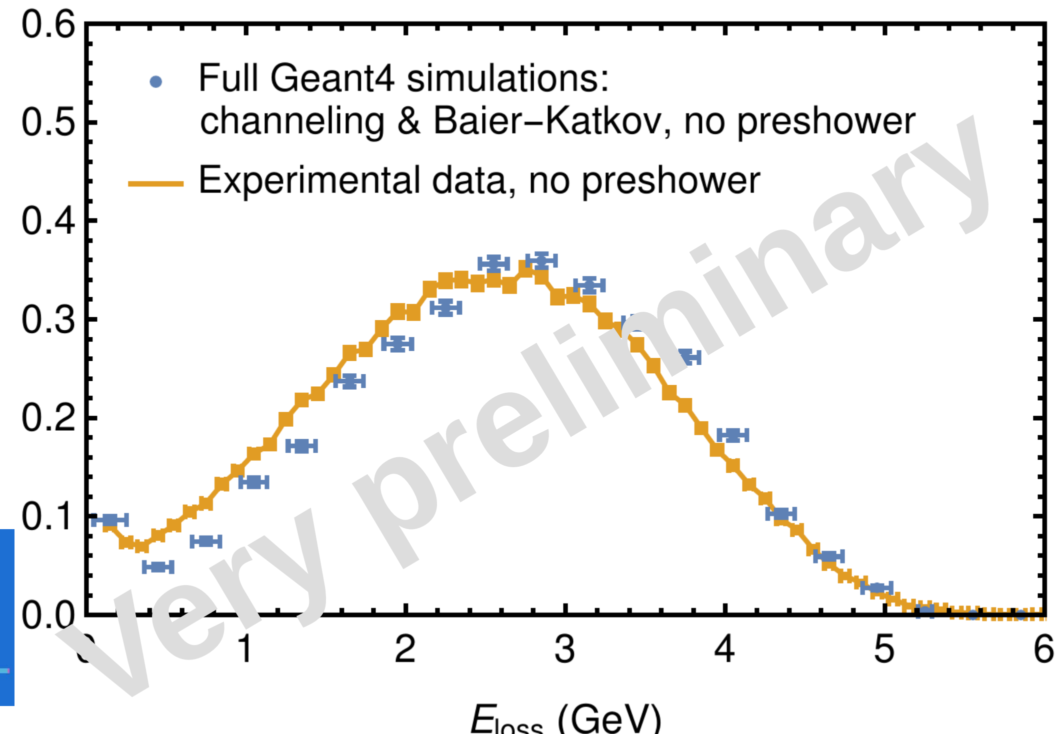
*S. Maloy et al., Slc target analysis. LANL LA UR-01-1913 72 (2001)

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









***Intense positron source Based On Oriented crySTals - e+BOOST* (PI L. Bandiera)**
PRIN2022-2022Y87K7X
Financed by Italian Ministry of University and Research - PRIN project

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)

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**.

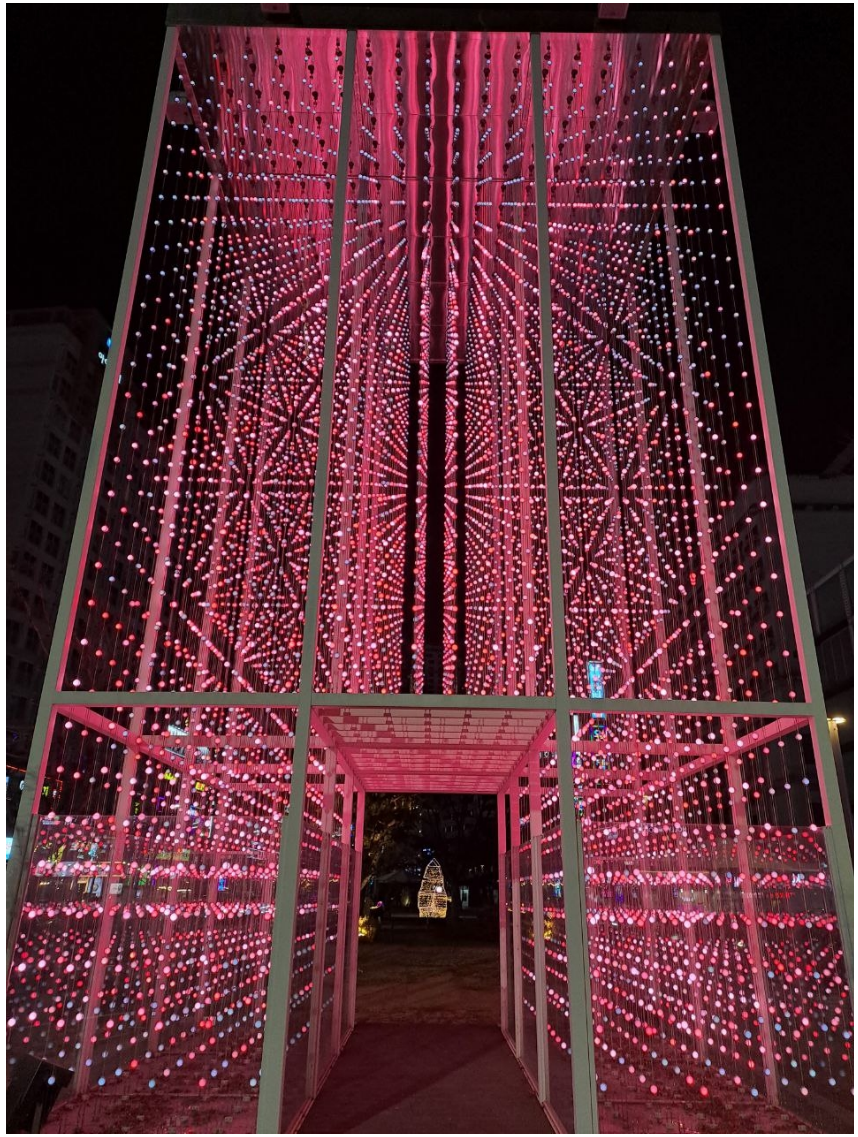
Acknowledgments

Marie Sklodowska-Curie Action Global Individual Fellowships TRILLION (G.A. 101032975) is in synergy with the following projects I would like to acknowledge:

- **MC-INFN** project (INFN Geant4 group);
- **INFN OREO** project; **INFN GALORE** project;
- **e+BOOST**, PRIN2022-2022Y87K7X (Italian Ministry of University and Research)
- **H2020-MSCA-RISE N-LIGHT** (G.A. 872196) and **EIC-PATHFINDER-OPEN TECHNO-CLS** (G.A. 101046458) projects.
- 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 Korean National Supercomputing Center with supercomputing resources including technical support (**KSC-2022-CHA-0003**).

I also thank the **Geant4 collaboration** members, in particular:

Prof. Vladimir Ivanchenko (**CERN**), **Prof. Pablo Cirrone and Dr. Luciano Pandola** (**INFN LNS**), **Prof. Kihyeon Cho, Prof. Soonwook Hwang** and **Dr. Kyungho Kim** (**KISTI**), **Prof. Susanna Guatelli** and **Prof. Anatoly Rosenfeld** (**University of Wollongong**), **Dr. Gianfranco Padernò (INFN Ferrara) as well as Prof. Makoto Asai (Jlab) and Prof. Marc Verderi (IN2P3/LLR)** for fruitful collaboration and discussions!



Thank you for attention!

How to implement an external code into Geant4?
Geant4 FastSim interface, a solution of most of challenges

FastSim model:

- **Physics list independent**
- Declared in the **DetectorConstruction** (just **few lines of code**)
- Is activated **only** in a **certain G4Region** at a **certain condition** and only for **certain particles**
- **Stops Geant processes** at the step of FastSim model and then resumes them

```
G4bool TestModel::IsApplicable(const G4ParticleDefinition& particleType)
{
  return
    &particleType == G4Proton::ProtonDefinition()||
    &particleType == G4AntiProton::AntiProtonDefinition()||
    &particleType == G4Electron::ElectronDefinition() ||
    &particleType == G4Positron::PositronDefinition();// ||
    //&particleType == G4Gamma::GammaDefinition();
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo......

G4bool TestModel::ModelTrigger(const G4FastTrack& fastTrack)
{
}

//....oooOO0OOooo........oooOO0OOooo........oooOO0OOooo........oooOO0OOooo......

void TestModel::DoIt(const G4FastTrack& fastTrack,
                     G4FastStep& fastStep)
{
```

Insert particles for which the model is applicable

Insert the condition to enter the model

Insert what the model does

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

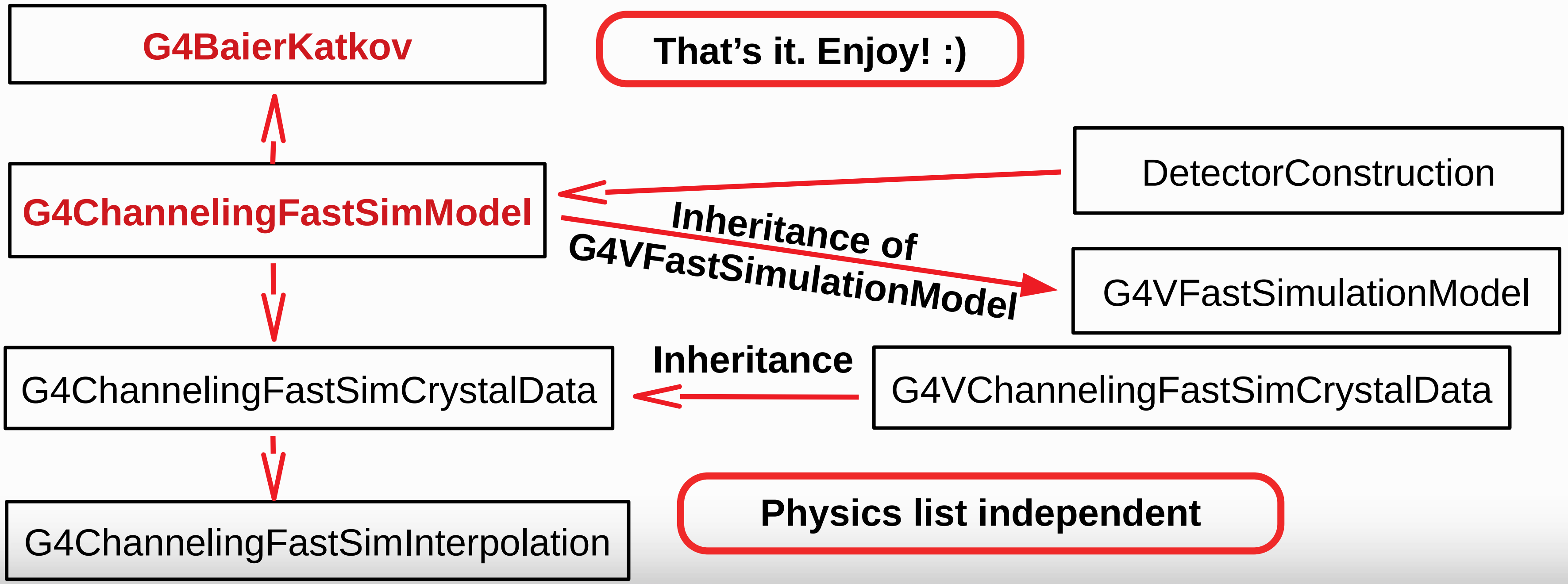
Optional

Radiation model activation

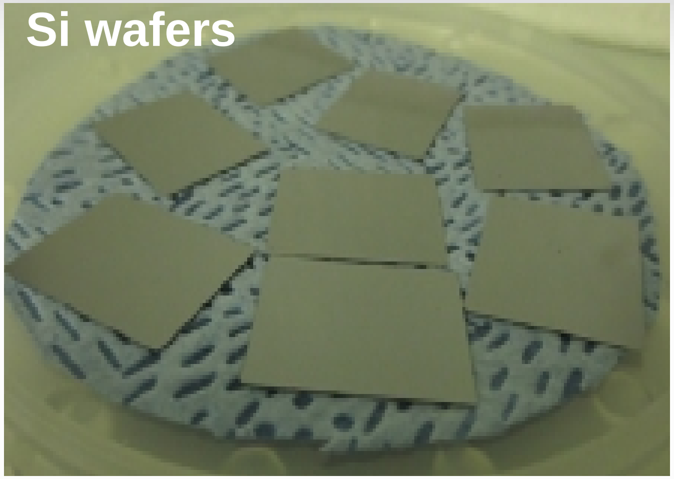
How to use the Geant4 channeling model in your example?

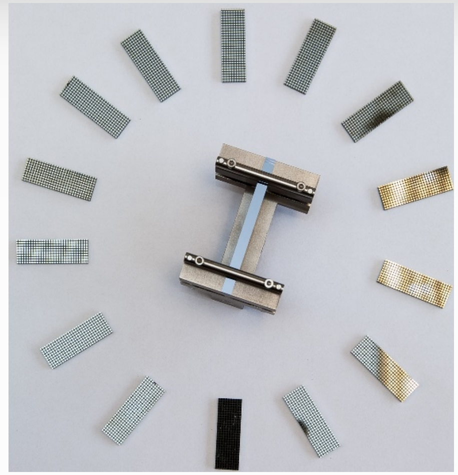
- **Add to main:** **Register FastSimulationPhysics**

```
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 );
```

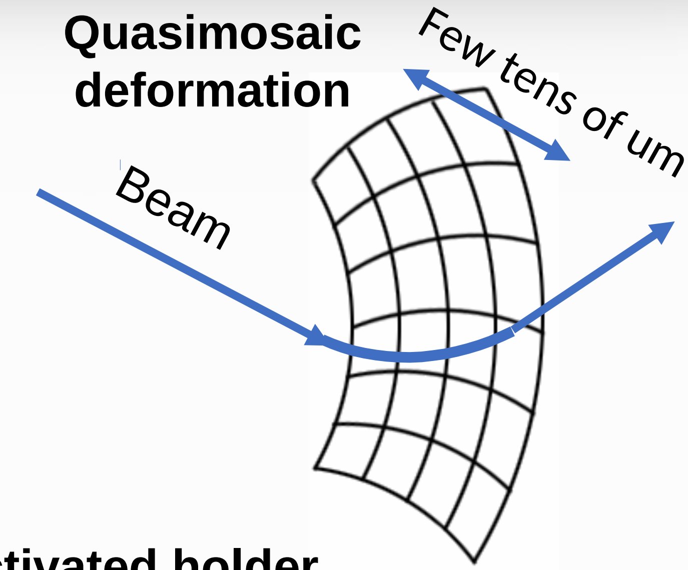


Manufacturing and characterization of bent silicon crystals @INFN Ferrara

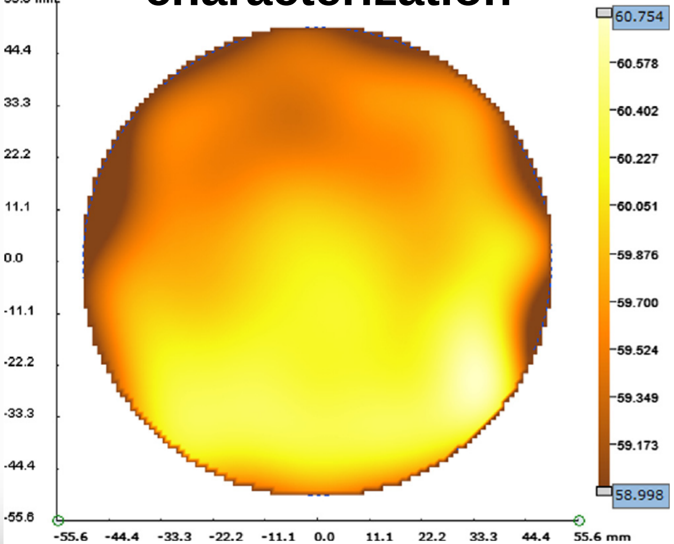




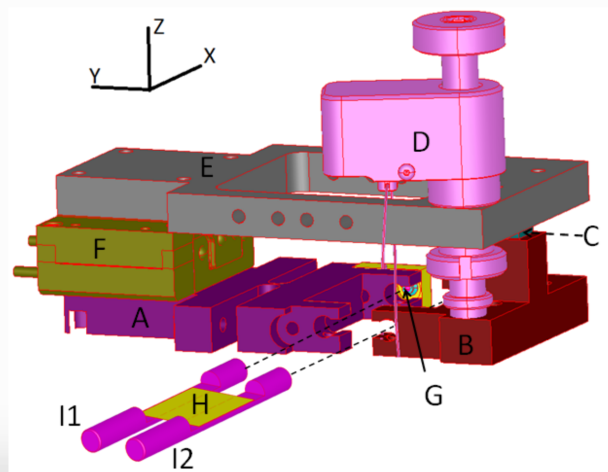
Quasimosaic deformation

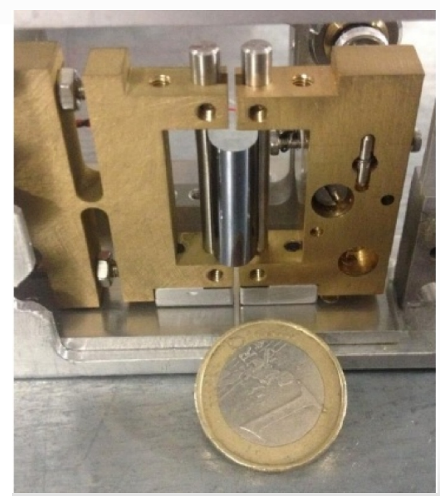


characterization



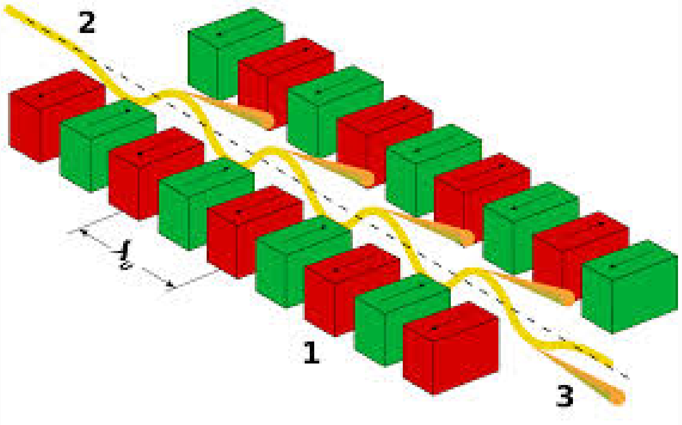
Piezo-activated holder



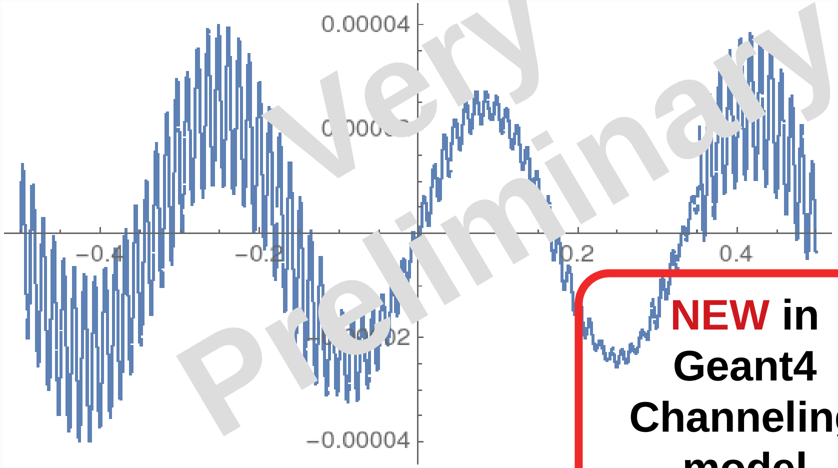


Channeling radiation in a bent crystal: Crystalline undulator

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



NEW in Geant4 Channeling model

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**

H2020-MSCA-RISE N-LIGHT (G.A. 872196) and
EIC-PATHFINDER-OPEN TECHNO-CLS (G.A. 101046458)
Coordinator MBN RESEARCH CENTER (Germany)

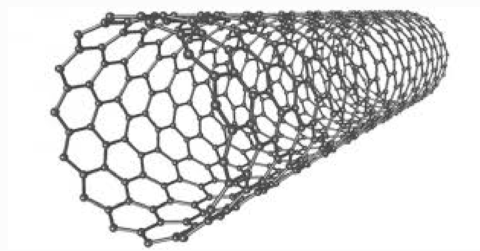
Plasma wake-field acceleration in nanostructures

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

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

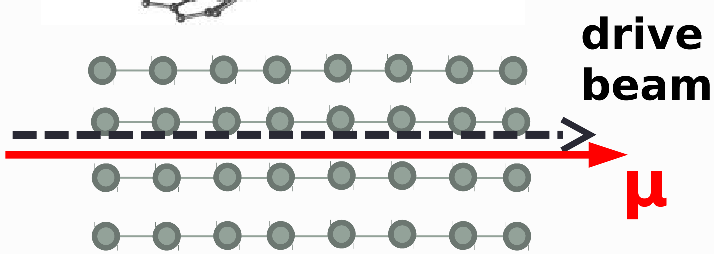
Considerably **higher electron density** in a **solid state** than in a gaseous plasma

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



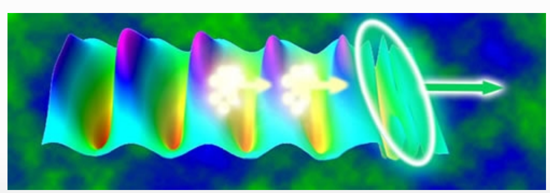
Possible drive beam:

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



Possible accelerated beam:

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



Compact muon collider?

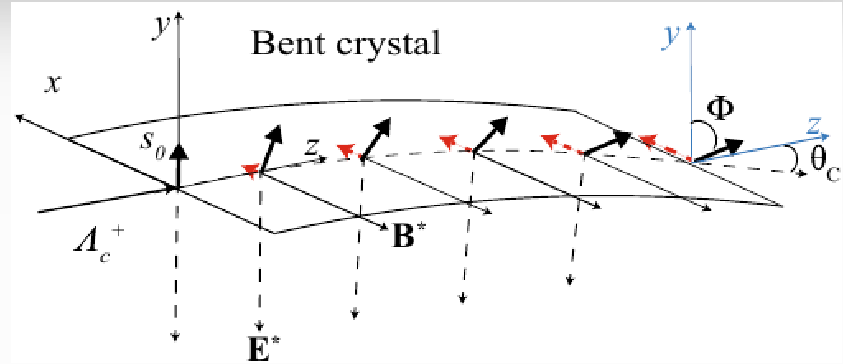
* R. Ariniello, …, and T. Tajima, Snowmass'2021 AF6: Advanced Acceleration Concepts, arXiv: 2203.07459

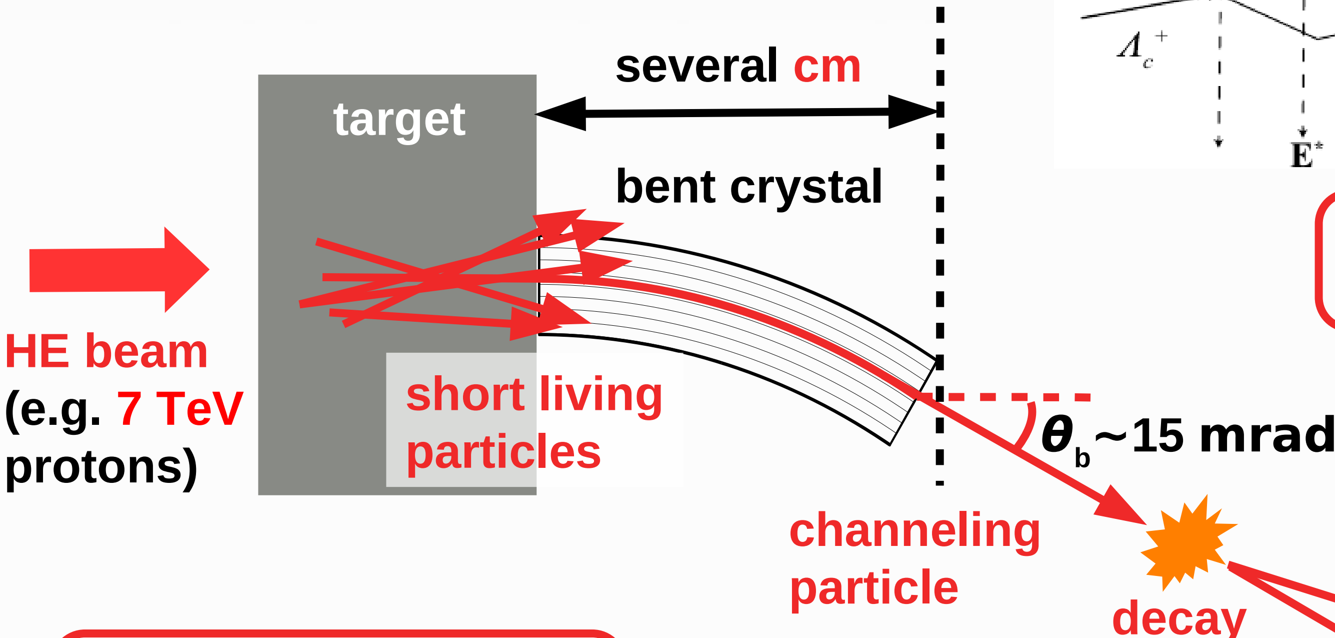
T.Tajima, M.Cavenago, Crystal X-ray accelerator, Phys. Rev. Lett., 59(13), 1440 (1987).

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)**