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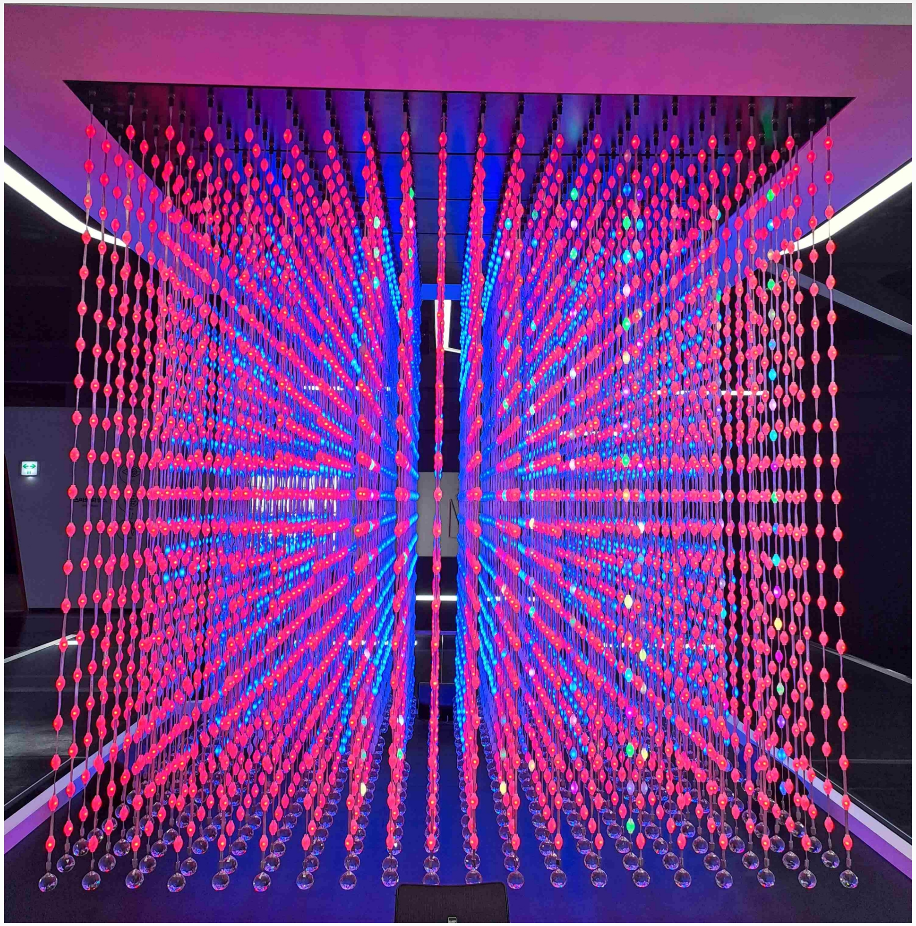
Trillion

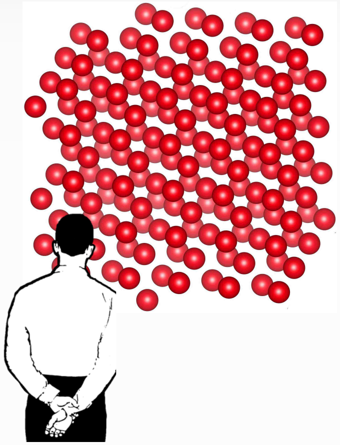
Applications of steering and radiation effects in oriented crystals and their implementation into Geant4

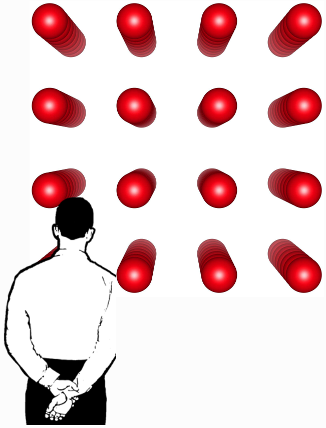
Dr. Alexei Sytov, Dr. Laura Bandiera, Prof. Kihyeon Cho

2023 KPS Spring Meeting
Daejeon, April 19, 2023

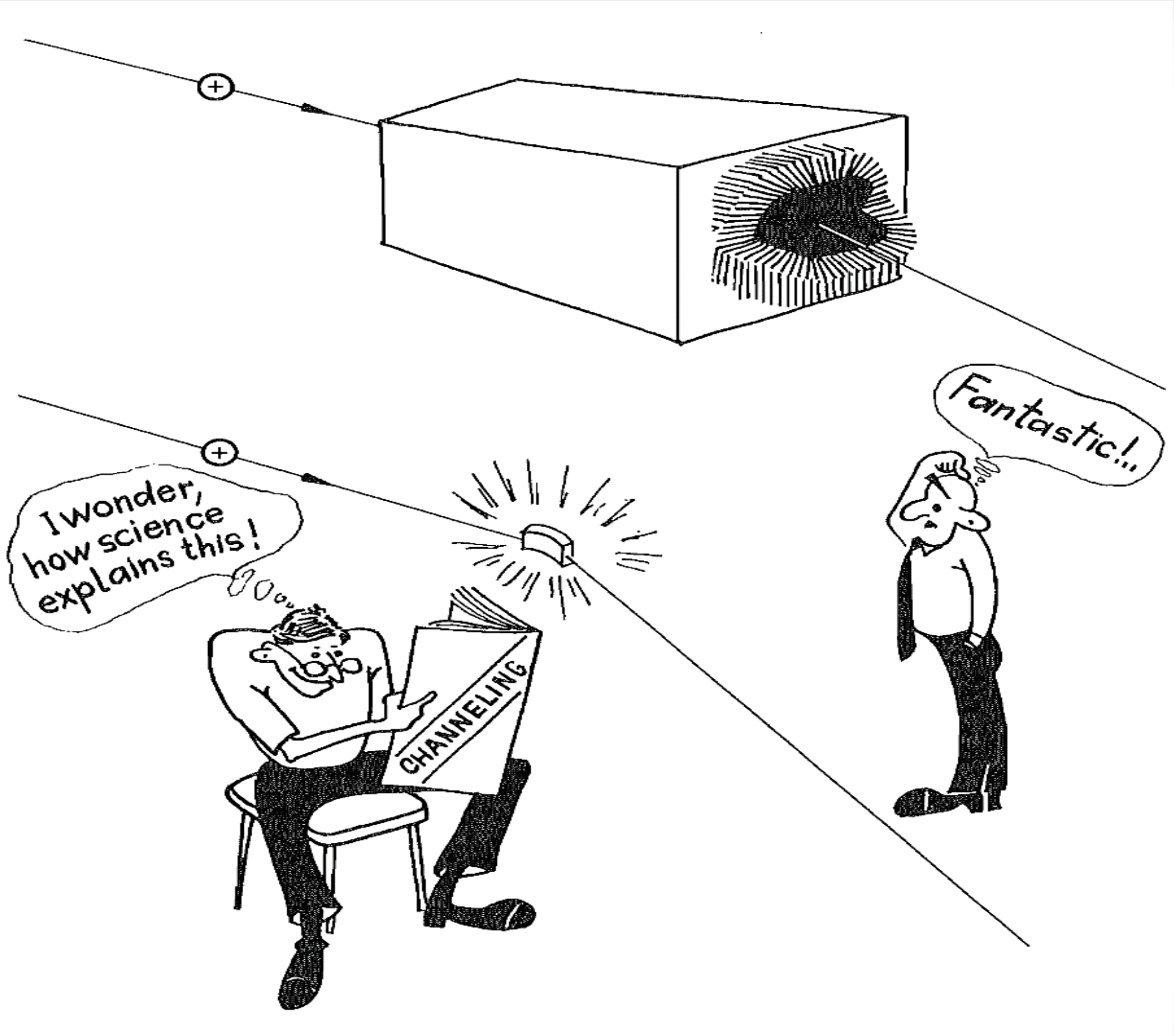
How a crystal lattice looks like
(from National Science Museum, Daejeon, Korea)





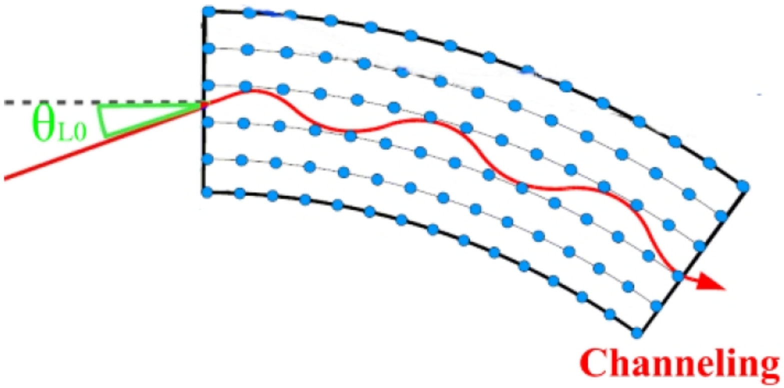


The world of the channeling effect



Coherent effects in a crystal

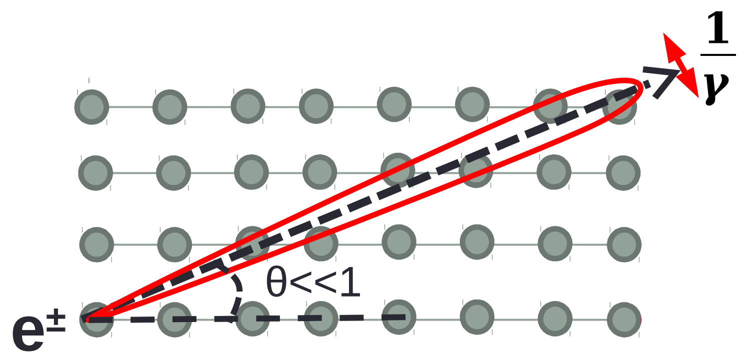
Channeling*



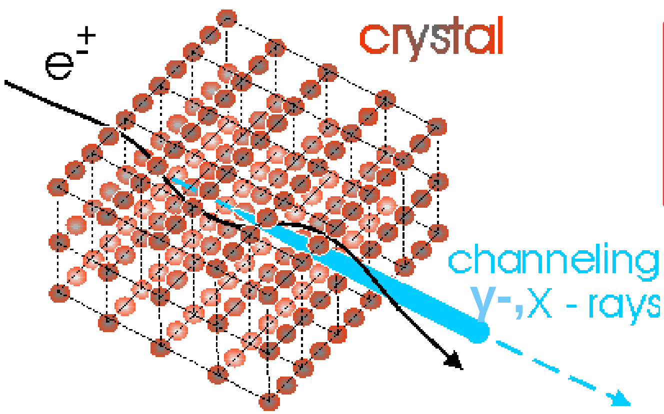
Enegies:
MeV - TeV

Equivalent magnetic field: more than 100 T

Coherent bremsstrahlung***

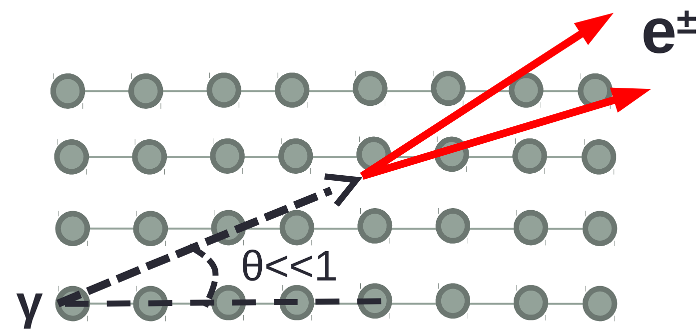


Channeling radiation**



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

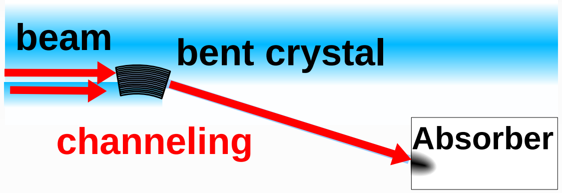
Coherent pair production****



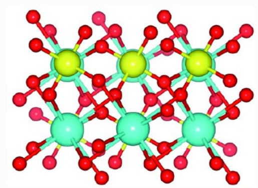
*J. Stark, Zs. Phys. 13, 973–977 (1912); J. A. Davies, J. Friesen, J. D. McIntyre, Can J. Chem. 38, 1526–1534 (1960)
**M.A. Kumakhov, Phys. Lett. A 57(1), 17–18 (1976)
***B. Ferretti, Nuovo Cimento 7, 118 (1950); M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).
**** H. Überall, Phys. Rev. 103, 1055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

Applications*

Crystal-based collimation or beam extraction from an accelerator

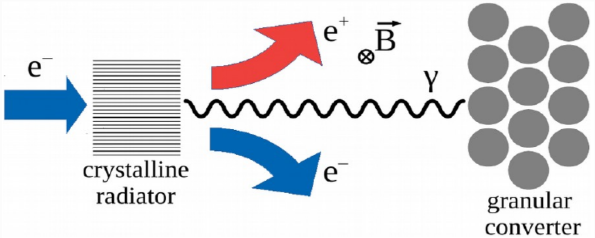


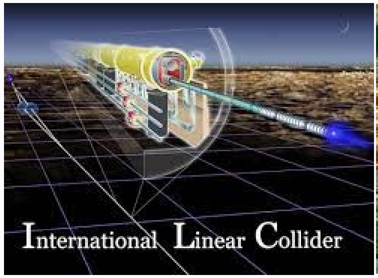
Ultrashort crystalline calorimeter

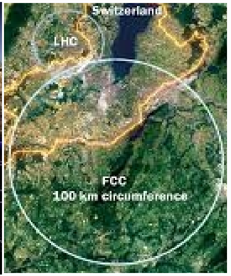


Gamma-ray Space Telescope

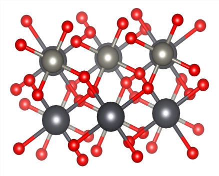
Positron source for future e+/e- and muon colliders



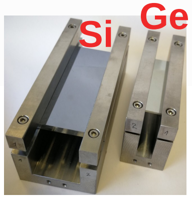


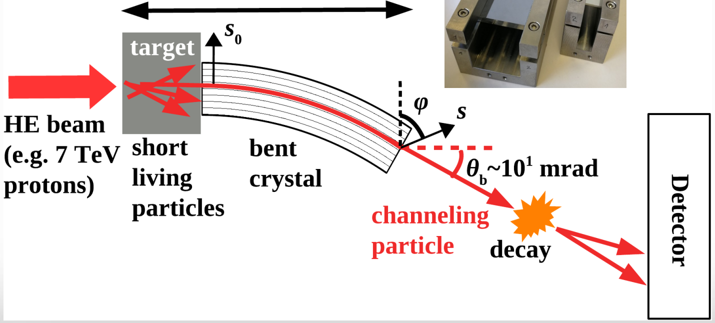


Oriented crystals

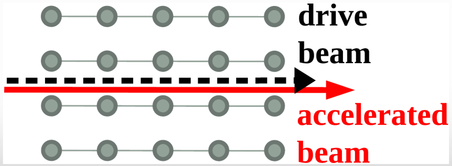


Measurement of dipole magnetic and electric moments of exotic particles

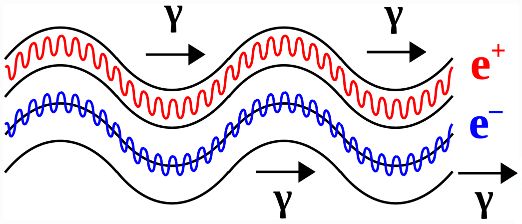


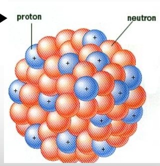


Plasma acceleration

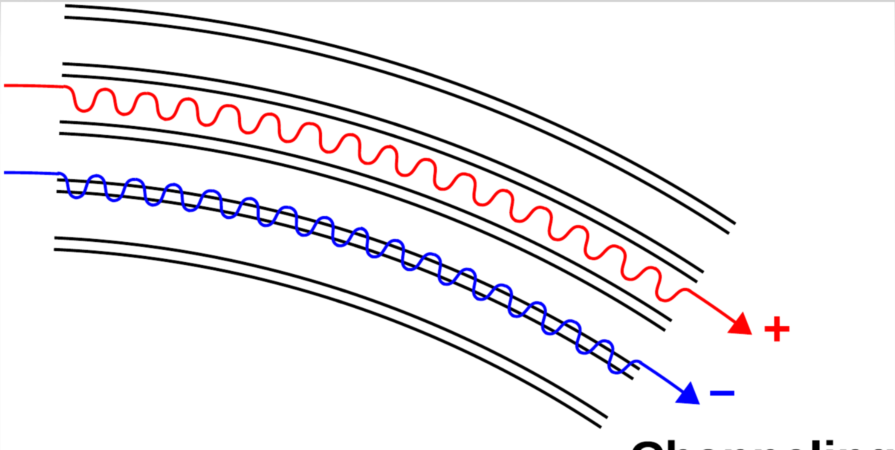


X and γ-ray source for nuclear and medical physics



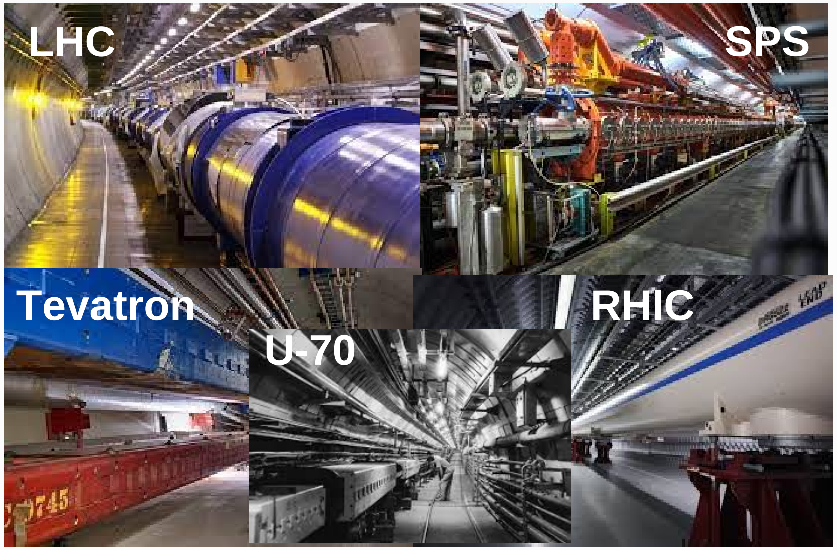


Crystal-based extraction

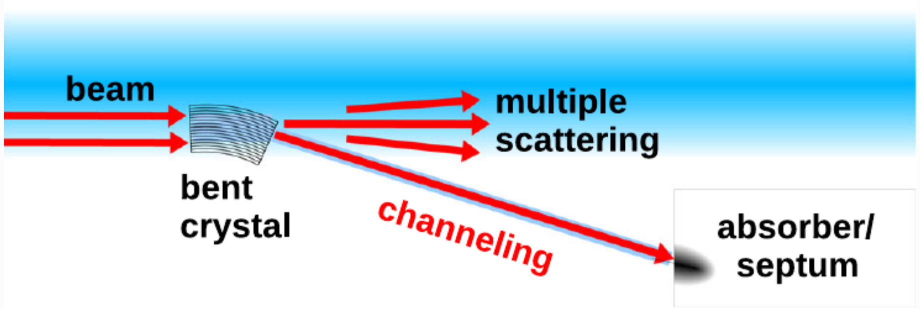


Planar channeling*:
Charge particle penetration through a monocrystal along its atomic planes

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

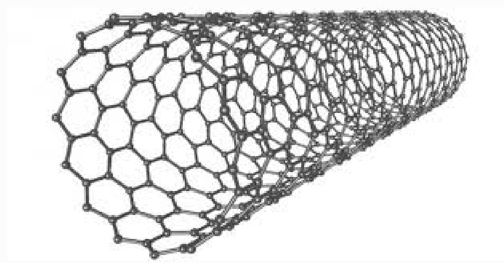
Plasma wake-field acceleration in oriented crystals/carbon nanotubes*

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

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

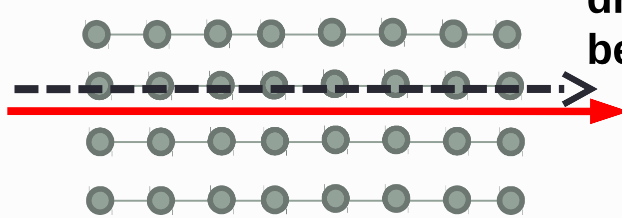
Considerably **higher electron density** in a **solid state** than in a gaseous plasma

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



Possible drive beam:

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

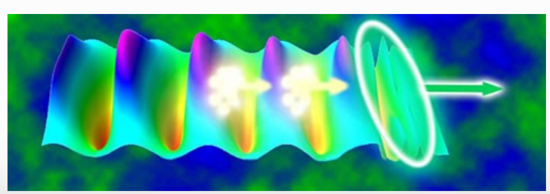


drive beam

accelerated beam

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).

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

GEANT4
A SIMULATION TOOLKIT

Location:

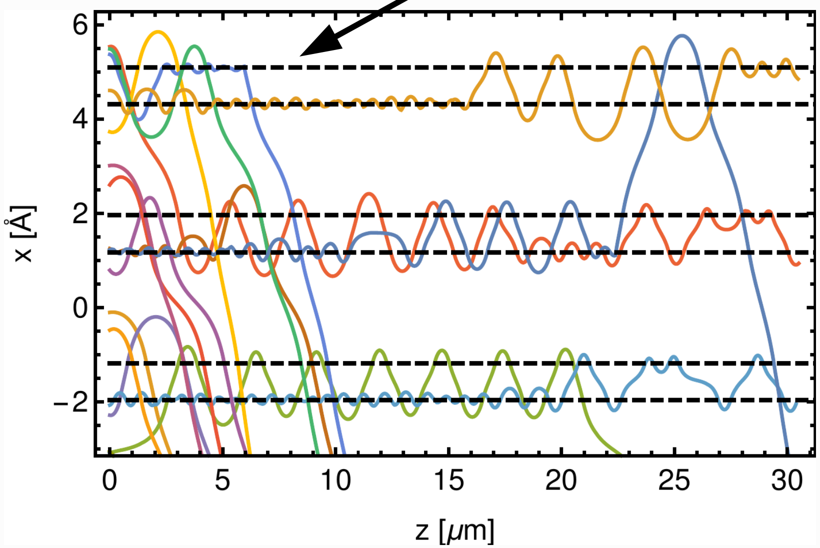
- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

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

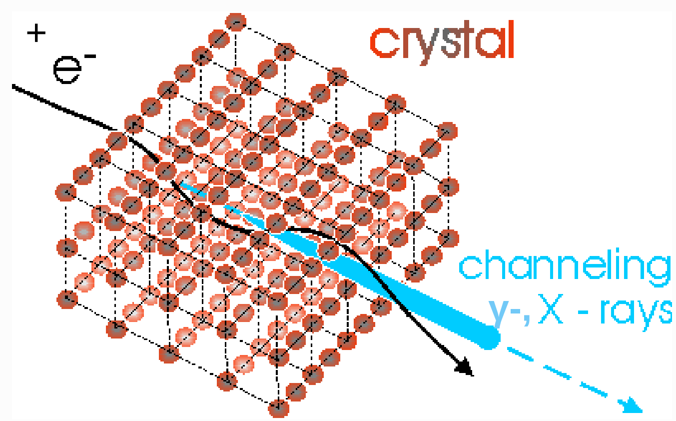
Crystal planes



channeling*

Advantages:

- High calculation speed
- **MPI** parallelization for high performance computing



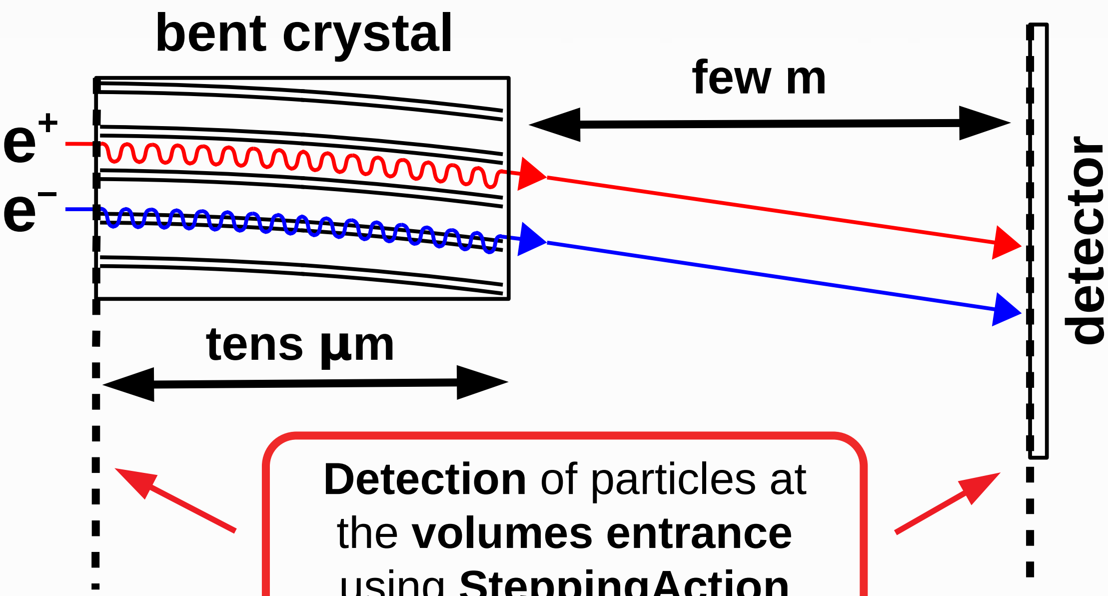
Baier-Katkov formula:
integration is made over the classical trajectory

$$\frac{dE}{d^3k}=\omega\frac{dN}{d^3k}\ \frac{\alpha}{4\pi^2}\iint dt_1 dt_2\ \frac{\left[(E^2+E'^2)(v_1v_2-1)+\omega^2/\gamma^2\right]}{2E'^2}e^{-ik'(x_1-x_2)}$$

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. arXiv: 2303.04385, Accepted for publication in JKPS**
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)

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

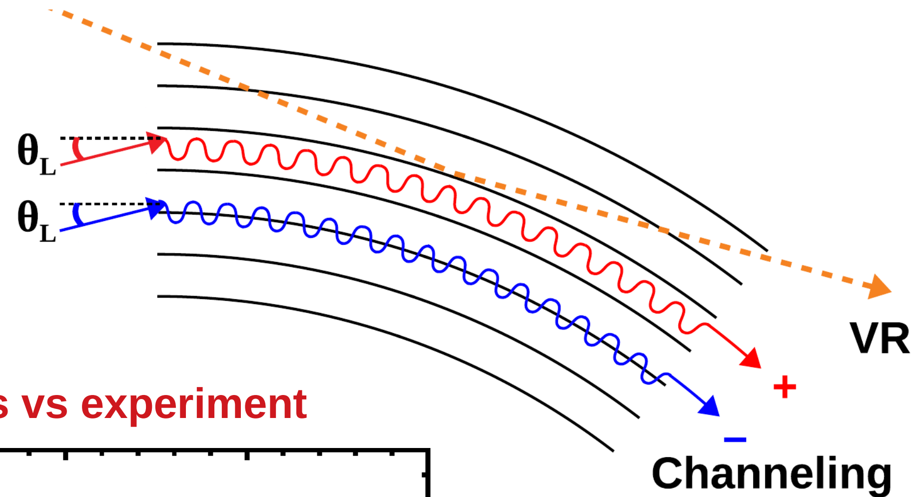
***A. Mazzolari et al. Phys. Rev. Lett. 112, 135503 (2014)**

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

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

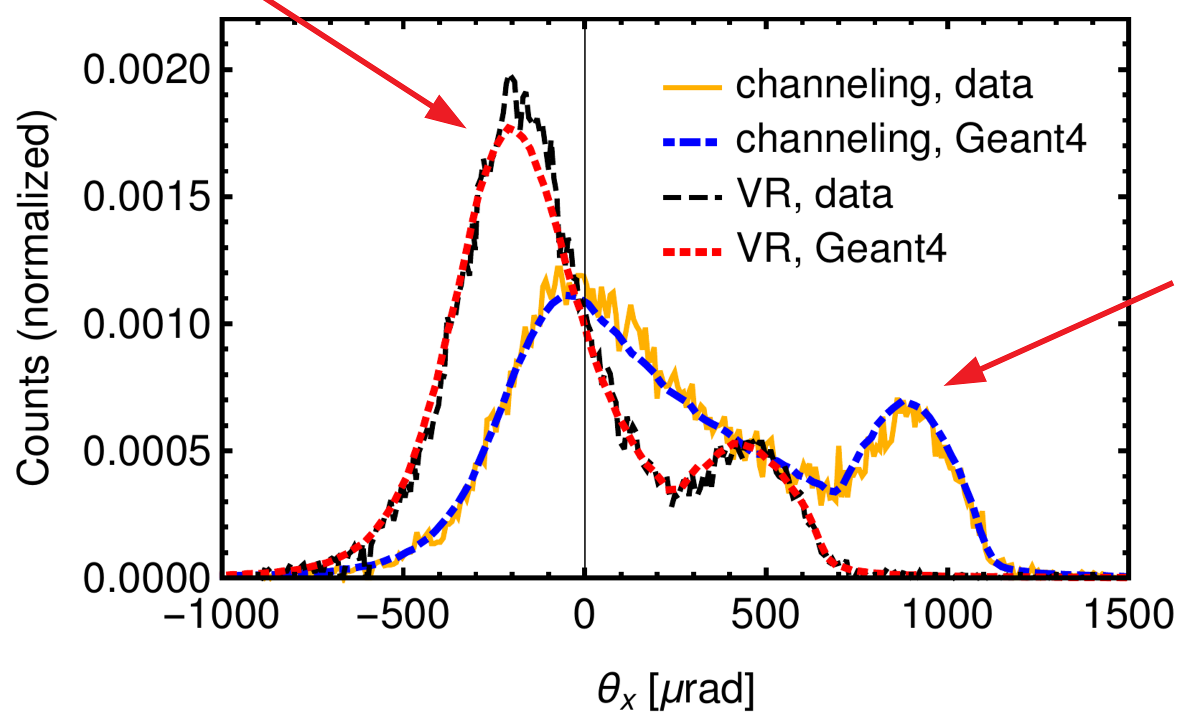
855 MeV electrons

15 µm thick bent crystal



volume reflection (VR)

Geant simulations vs experiment



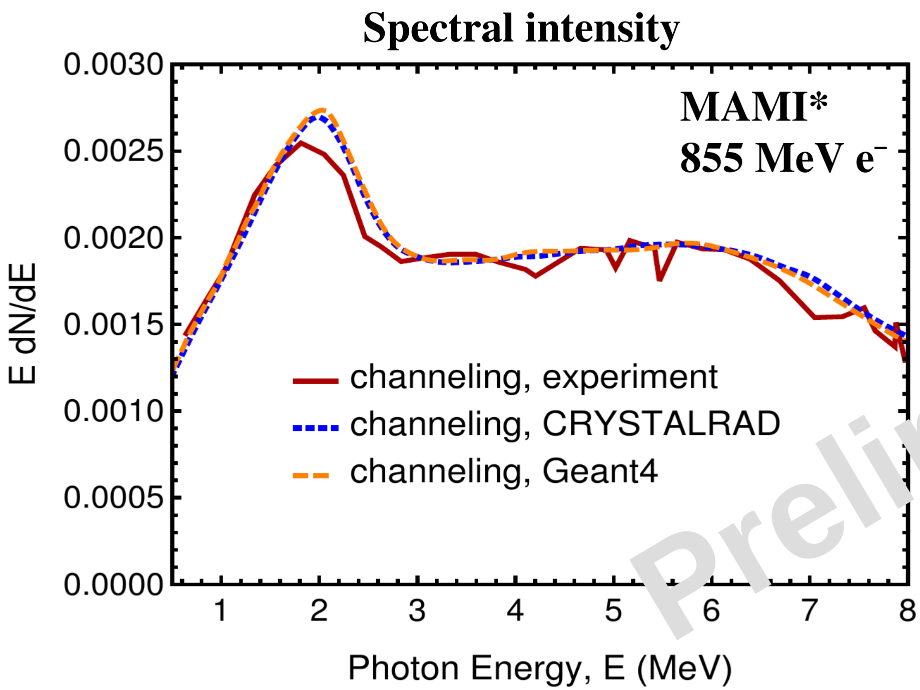
channeling

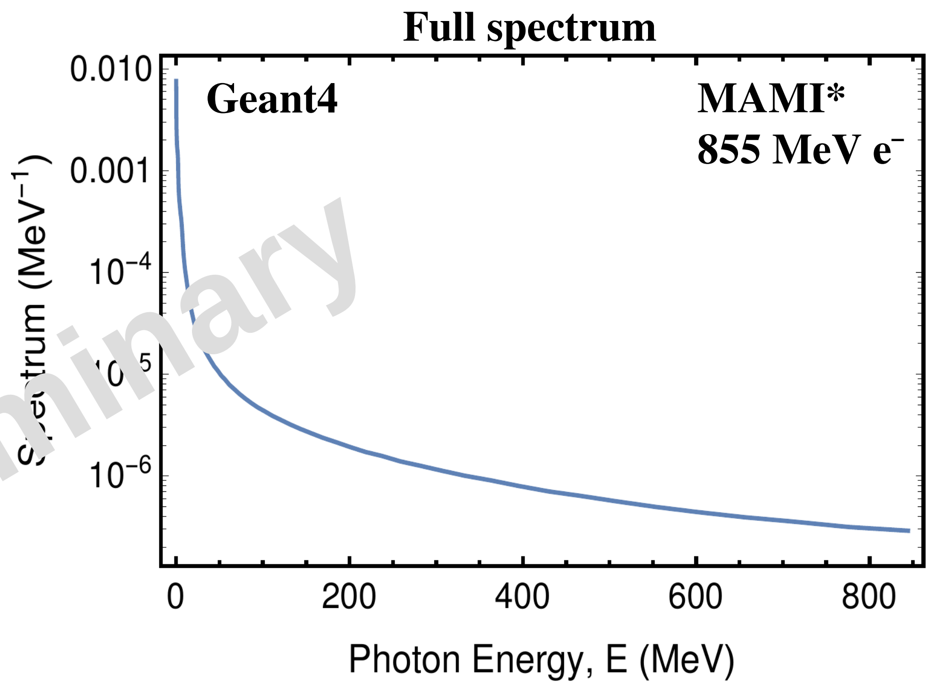
First Geant4 Baier-Katkov radiation model: radiation by 855 MeV electrons at Mainz Mikrotron MAMI*

G4BaierKatkov:

- **Physics list independent**
- Activated in the **DetectorConstruction** and used in **ChannelingFastSimModel**
- Can be used **outside channeling model** (e.g. in **SteppingAction**)
- Provides **radiation spectrum** for single-photon radiation mode
- Provides generation of **secondary photons**

Geant simulations vs experiment and CRYSTALRAD simulations



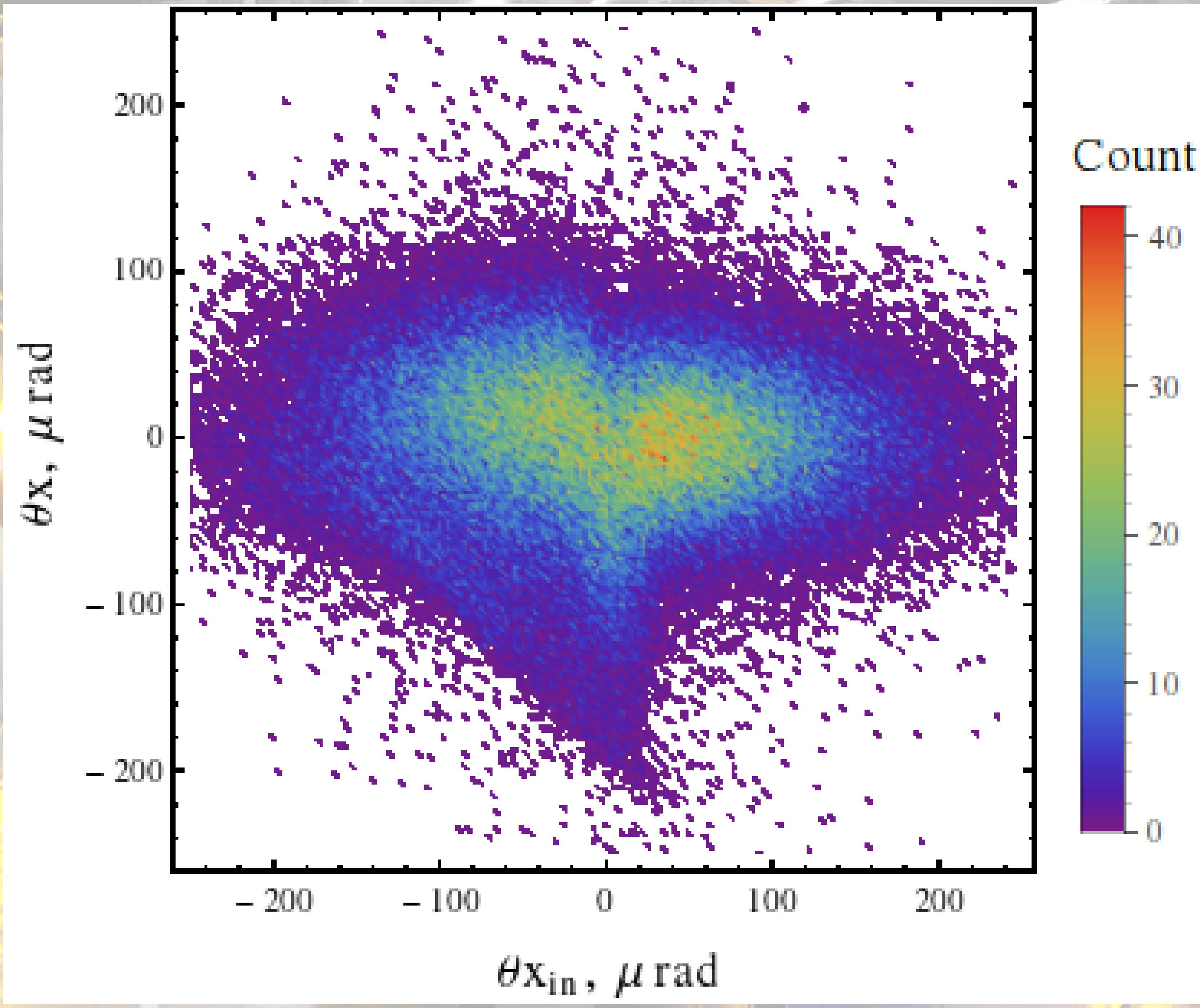


*L. Bandiera et al. Phys. Rev. Lett. 115, 025504 (2015)

Conclusions

- **Oriented crystals** can be **applied**:
- at **e-/e+/hadron synchrotrons** (crystal-based beam extraction/ collimation)
- in **nuclear** and **medical physics** (radiation source)
- at e-/e+ colliders – **ILC**, **FCC-ee** and **muon collider** (positron source)
- as **ultrashort electromagnetic calorimeters**
- for **MDM** and **EDM** measurement
- ultrahigh gradient (more than 1 **TeV/m**) **plasma wakefield acceleration**

- 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.



Thank you for attention!

Geant4 FastSim interface

A. Sytov thanks **Prof. Vladimir Ivanchenko** (**CERN**) for this solution, **Prof. Pablo Cirrone** and **Dr. Luciano Pandola** (**INFN LNS**), **Dr. Gianfranco Paternò** and **Dr. Laura Bandiera** (**INFN Ferrara**), **Prof. Kihyeon Cho** and **Dr. Kyungho Kim** (**KISTI**), **Prof. Susanna Guatelli** and **Prof. Anatoly Rosenfeld** (**University of Wollongong**), **Marc Verderi** (**IN2P3/LLR**) for help and fruitful discussions!

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.);
G4LogicalVolume* crystalLogic = new G4LogicalVolume(crystalSolid,Silicon,"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
   ChannelingFastSimModel* ChannelingModel = new ChannelingFastSimModel("ChannelingModel",RegionCh);
   //set the type of crystal planes
   G4String lattice = "(111)";
   //activate the channeling model
   ChannelingModel->Input(crystalLogic,lattice);
   //setting bending angle of the crystal planes (default is 0)
   BendingAngle = 0.905*mrad;
   ChannelingModel->GetCrystalData()->SetBendingAngle(BendingAngle);

   //activate radiation model (do it only when you want to take into account
   //radiation production in an oriented crystal; it takes a lot of computational power)
   ChannelingModel->RadiationModelActivate();
}
```

Get crystal region

Channeling FastSim model declaration

Logical volume

Model activation

Additional options

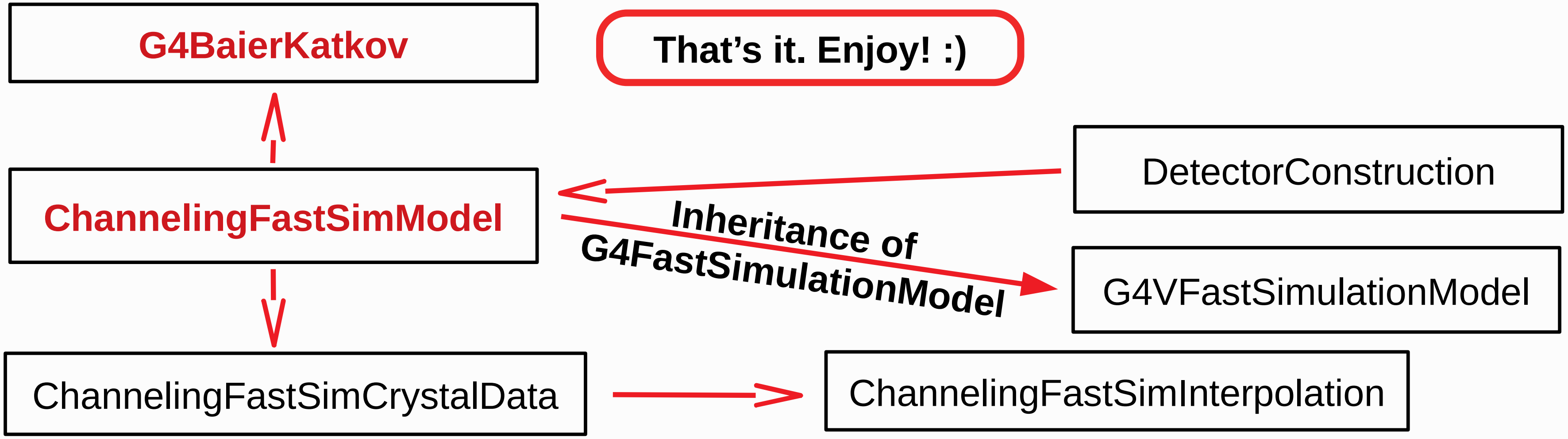
Radiation model activation

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

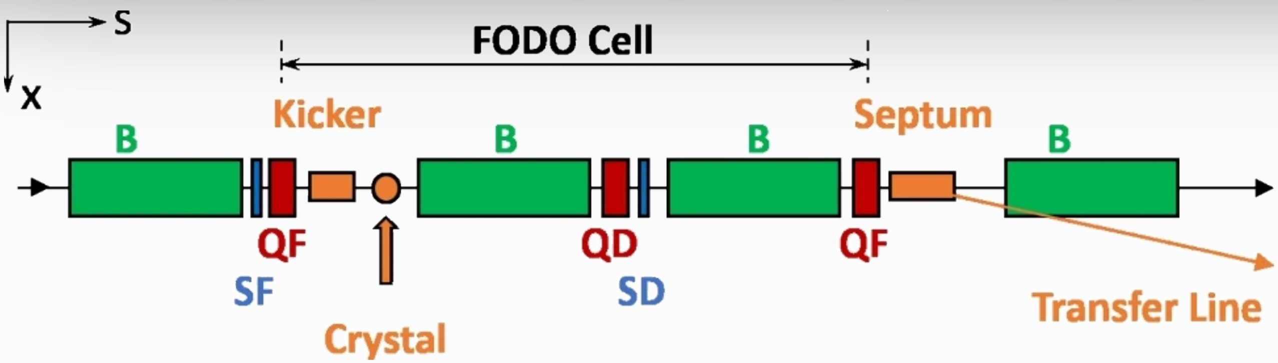
New channeling model implementation into Geant4

The channeling model is ready to be inserted into the next Geant4 release

To implement:

- **Channeling** model using FastSim interface: **READY** (only trajectories)
- **Radiation** model (Baier-Katkov method) **TESTING NOW**
- **Pair production** model **COMING SOON**
- **Radiation** and **positron source examples** **END OF THE YEAR**
- **Beam extraction example** **2024**

Crystal-based extraction: possible setup at DESY-II



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

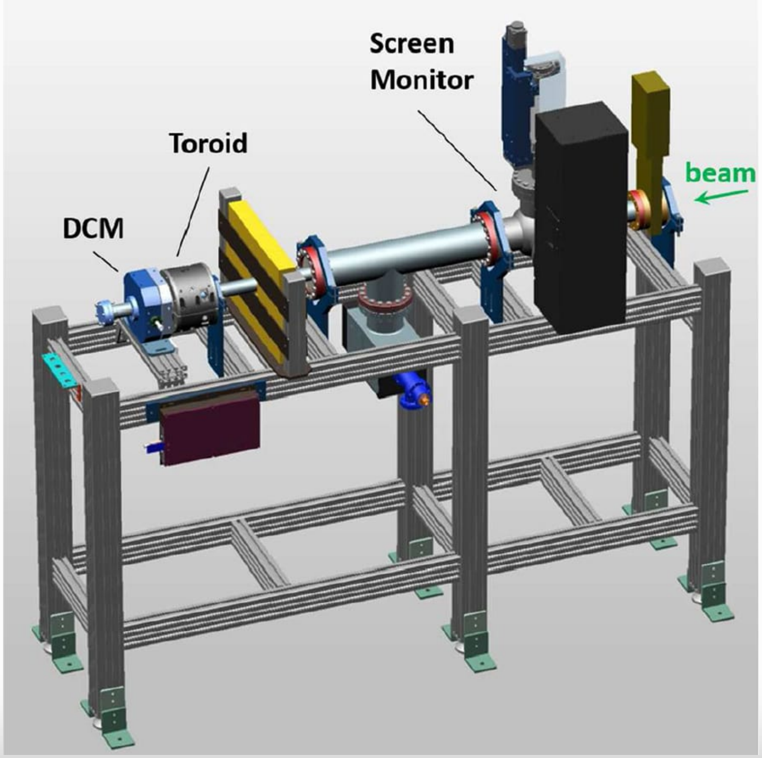
6 GeV electrons

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:

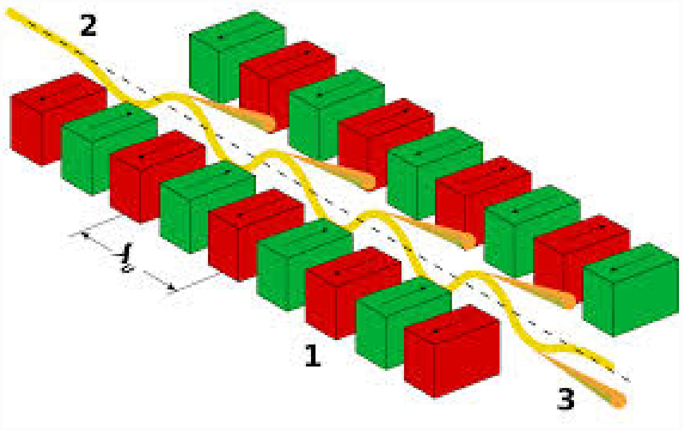
- Nuclear and particle physics detectors and generic **detector R&D**
- Fixed-target experiments in **high-energy physics** including future **lepton colliders**
- Also: **crystal-based collimation** (**synchrotron light sources**, **colliders**)



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

Channeling radiation in a bent crystal: Crystalline undulator

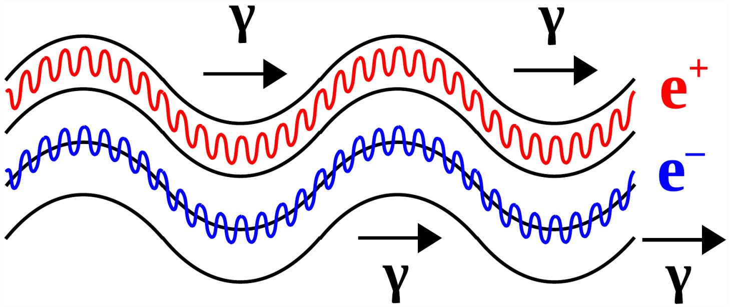
Classical scheme: magnetic undulator in a free electron laser soft X-rays $\lambda_u \sim$ cm



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

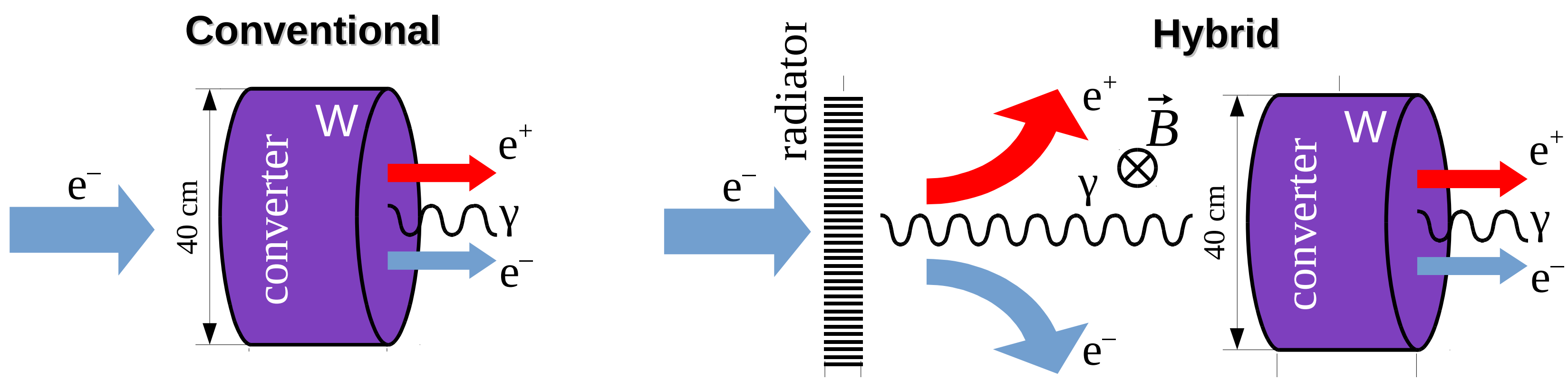


Crystalline X and gamma-ray source **can be applied** in:

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

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

Crystal-based hybrid positron source*



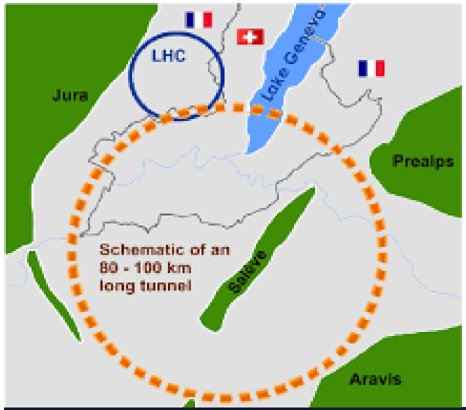
Coherent effects in a crystal **accelerate electromagnetic shower** development

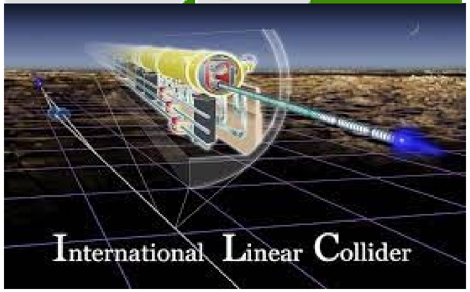
Advantages of the hybrid positron source:

- **Higher** positron yield
- Considerably lower peak deposited energy inside the target => **higher beam intensities**, **longer target lifetime**

Hybrid positron source can be applied at:

- **FCC-ee**
- **ILC**
- **Muon collider**



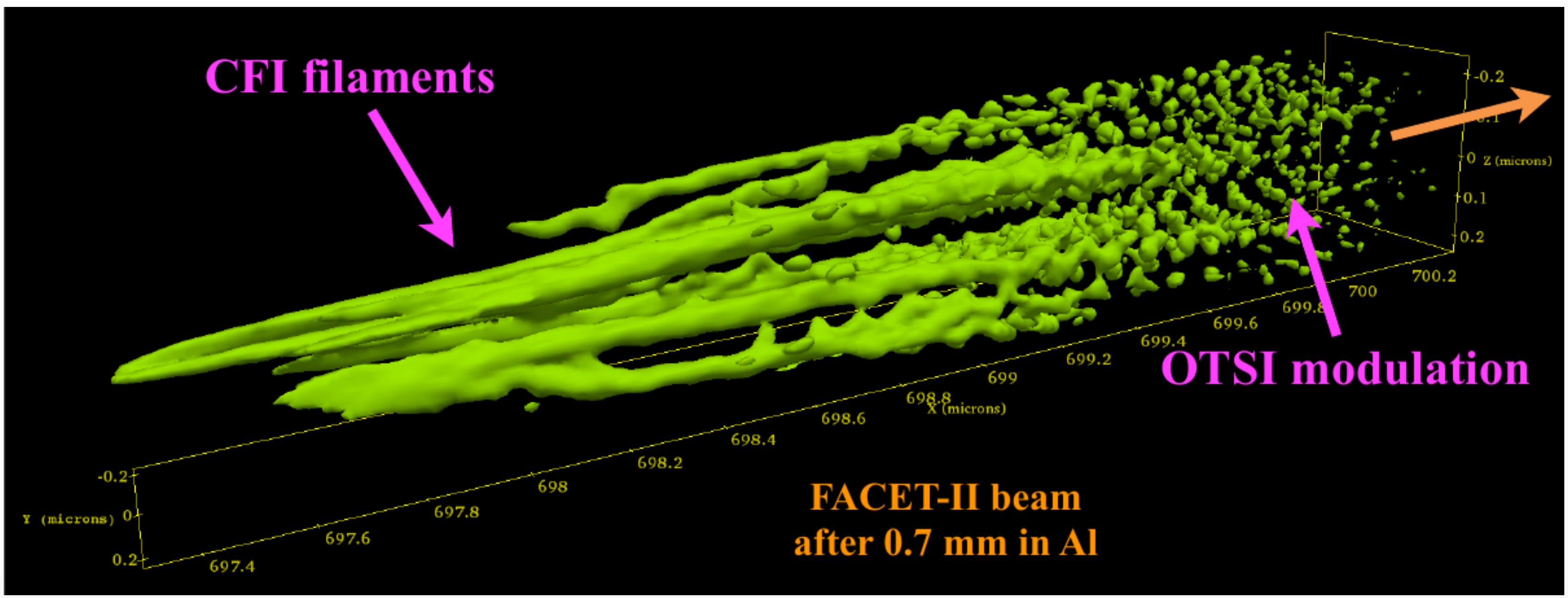


Simulation model can be also applied for **ultrashort crystalline calorimeter**

E336 collaboration
future experiment at SLAC FACET-II

Channeling Acceleration in Crystals and Nanostructures and Studies of Solid Plasmas: New Opportunities

Robert Ariniello[1], Sebastien Corde[2], Xavier Davoine[3], Henrik Ekerfelt[4], Frederico Fiuza[4], Max Gilljohann[2], Laurent Gremillet[3], Yuliia Mankovska[2], Henryk Piekarz[5], Pablo San Miguel Claveria[2], Vladimir Shiltsev[5], Peter Taborek[6], and Toshiki Tajima[6]

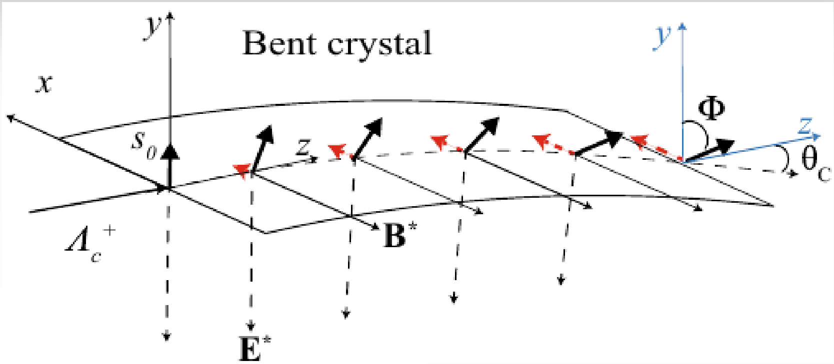


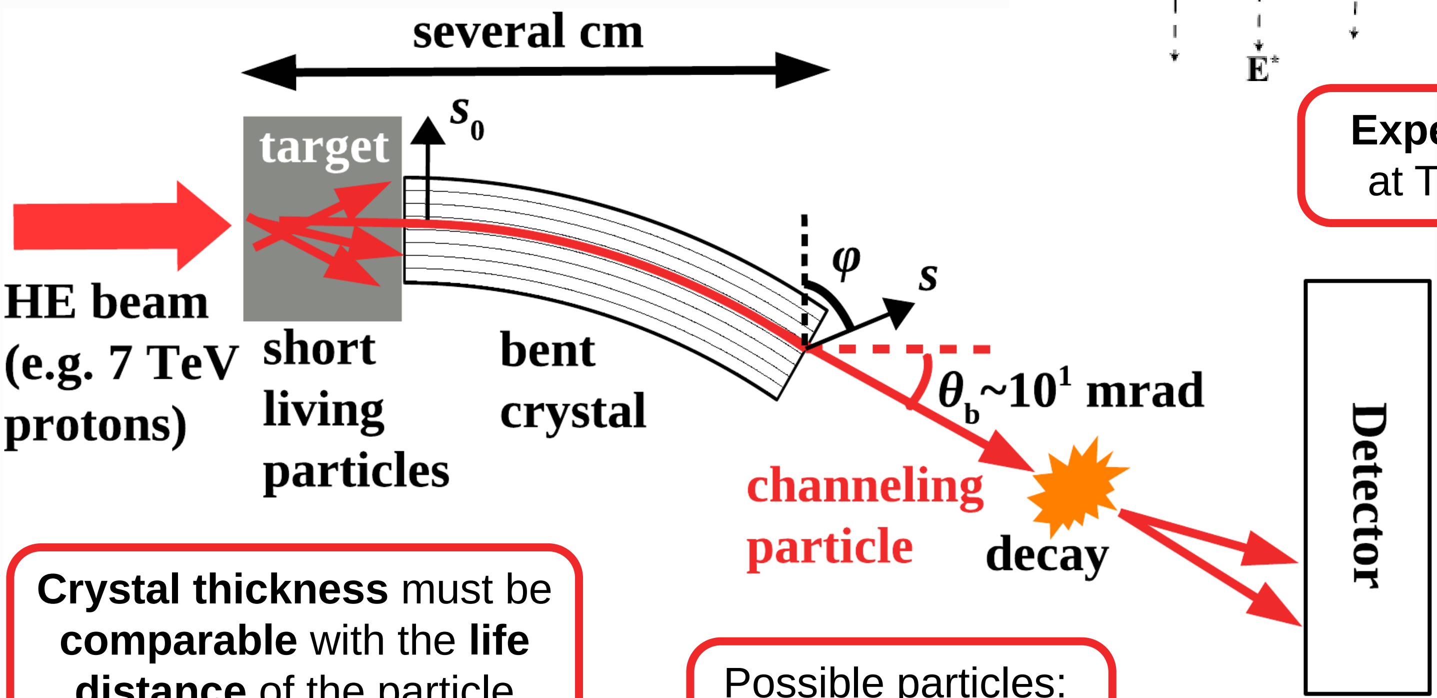
* R. Ariniello, …, and T. Tajima, Snowmass'2021 AF6: Advanced Acceleration Concepts, arXiv: 2203.07459
T.Tajima, M.Cavenago, Crystal X-ray accelerator, Phys. Rev. Lett., 59(13), 1440 (1987).

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^+**

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)