INFN
Istituto Nazionale di Fisica Nucleare

European Commission

Trillion

GA 101032975

(is finished)

GEANT4
A SIMULATION TOOLKIT

Simulations with Geant4 G4ChannelingFastSimModel and BDSim

Dr. Alexei Sytov

On behalf of INFN Ferrara group

Relativistic Electron Beam Dynamics in Crystals and Related Electrodynamic Processes

DESY 09/12/2025

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.

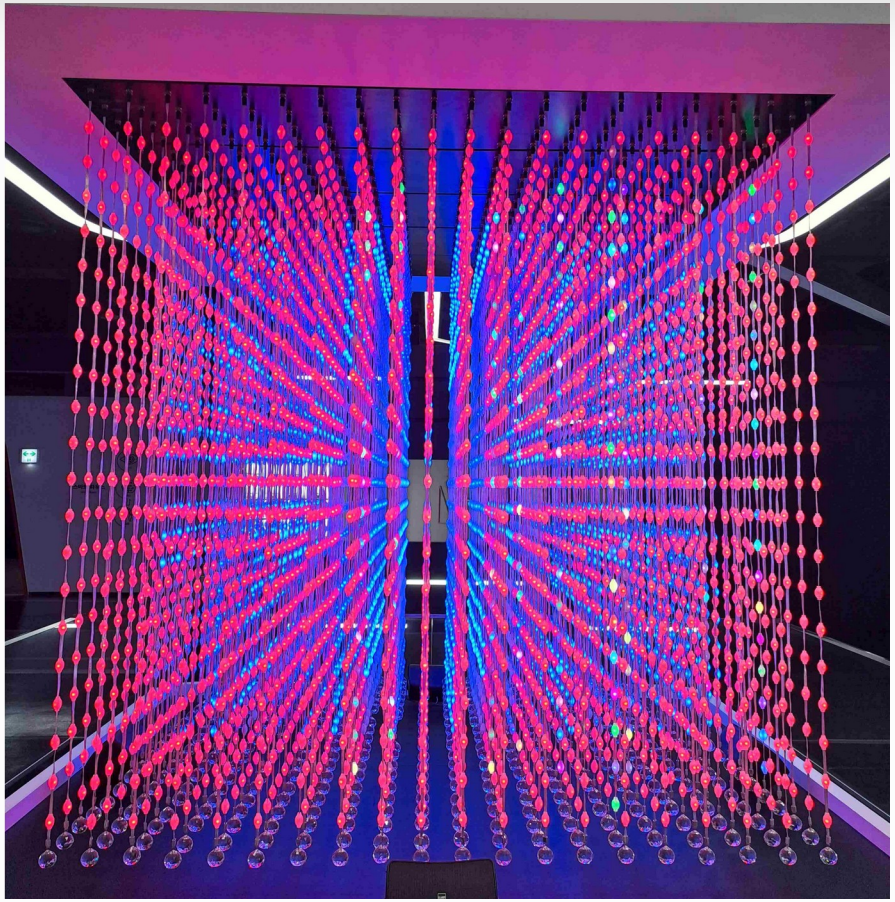
Group:

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

Location:

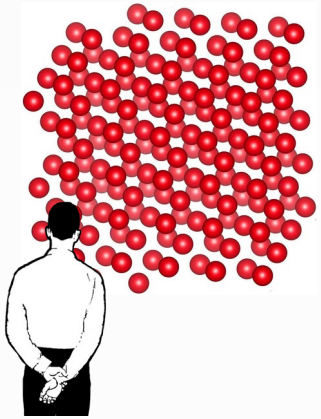
- 2 years at **KISTI** (partner organization)
- 1 year at **INFN Section of Ferrara** (host organization)
- 1 month of secondment at **DESY** (partner organization)
- 1 month of secondment at **IJCLab Orsay** (partner organization)

How an oriented crystal looks like

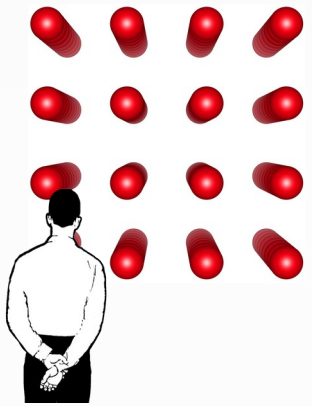


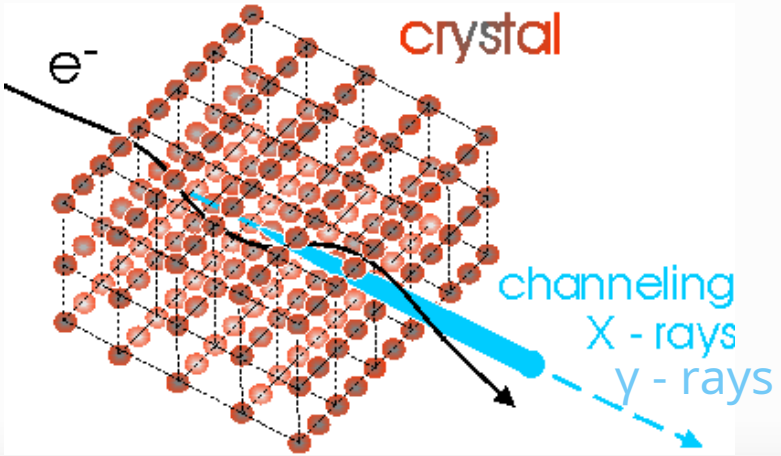
from National Science Museum, Daejeon, Korea

Non-oriented crystal

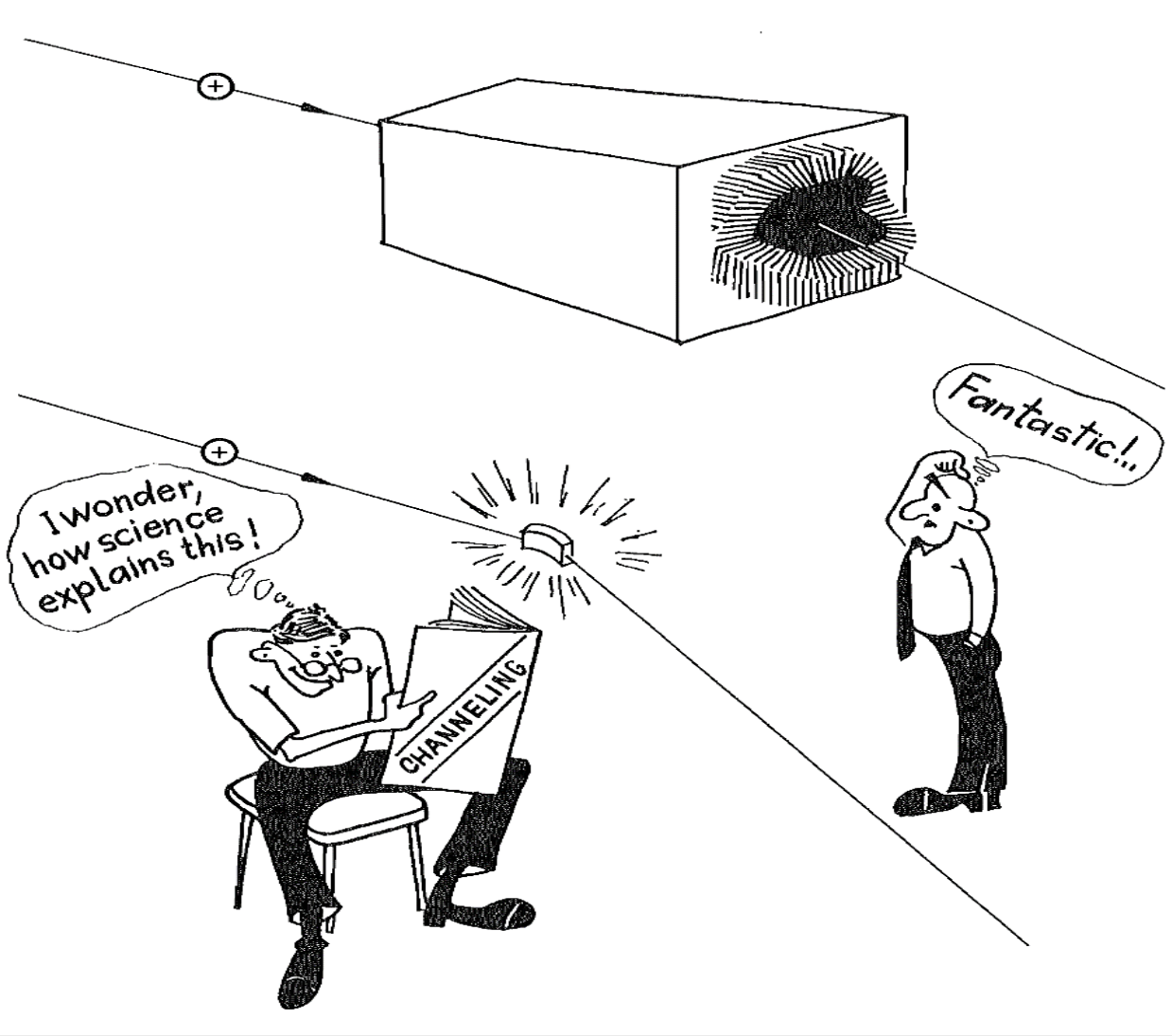


Oriented crystal



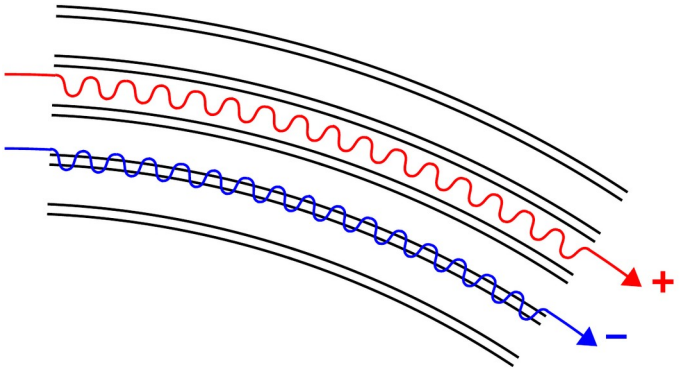


The world of the channeling effect



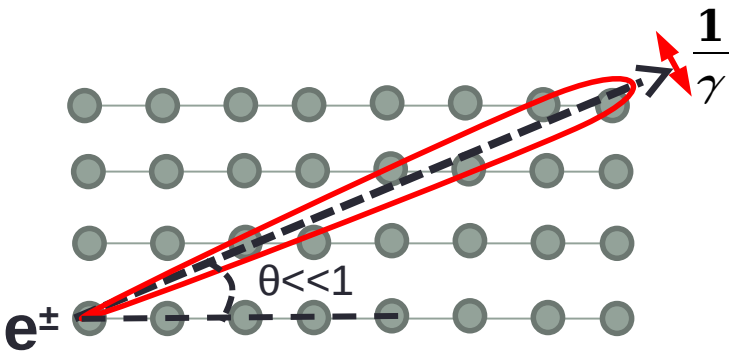
The idea: MC simulations of coherent effects in a crystal

Channeling*

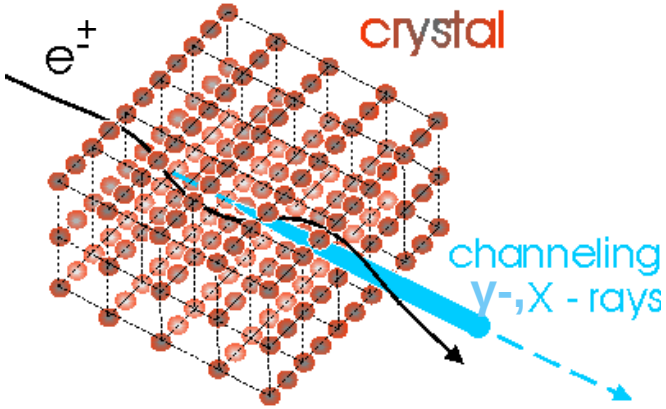


Channeling

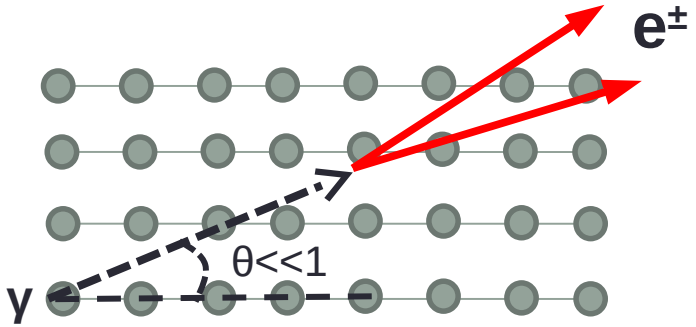
Coherent bremsstrahlung***



Channeling radiation**



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)

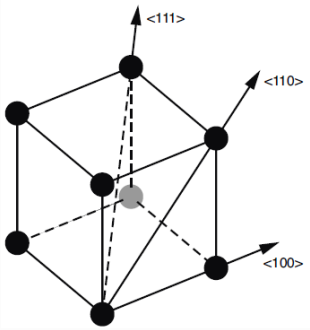
***B. Ferretti, Nuovo Cimento 7, 118 (1950); M. Ter-Mikaelian, Sov. Phys. JETP 25, 296 (1953).

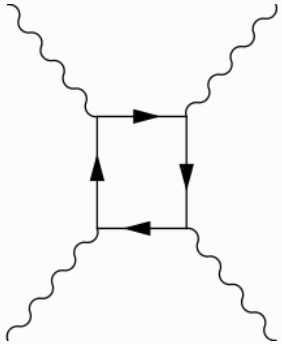
**** H. Überall, Phys. Rev. 103, 1055 (1956).

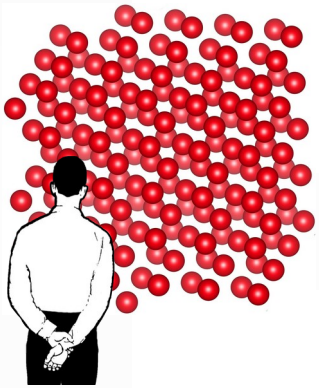
Electromagnetic shower acceleration

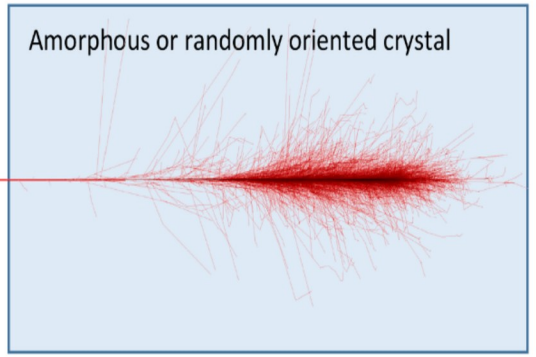
Axial field
10^{11} V/cm

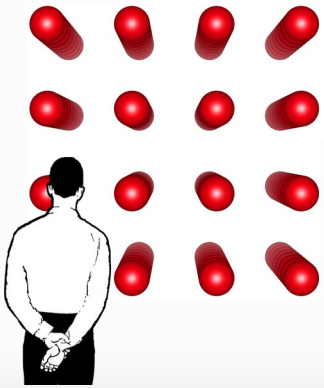
Approaching the **Schwinger limit** starting from few **GeV** for **e+/e-**

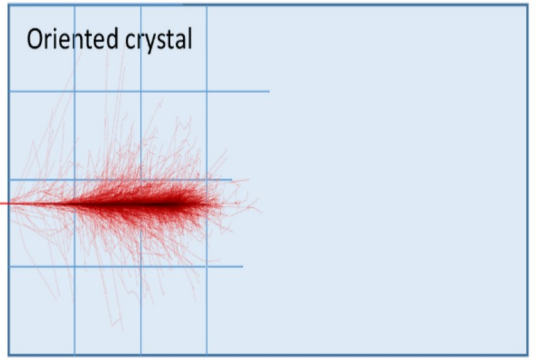










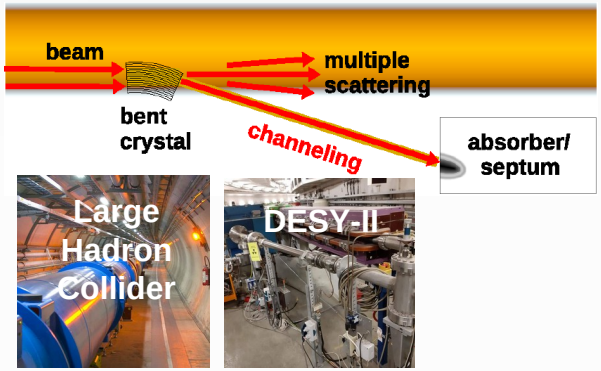


The **radiation** intensity and the **pair production** cross-section **drastically increase** in **oriented crystals!**

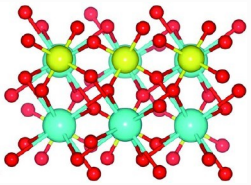
Shower development in the field of axes is **accelerated**. The radiation length is considerably reduced.

Applications*

Crystal-based collimation or beam extraction from an accelerator

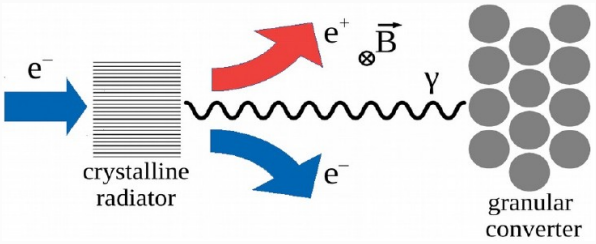


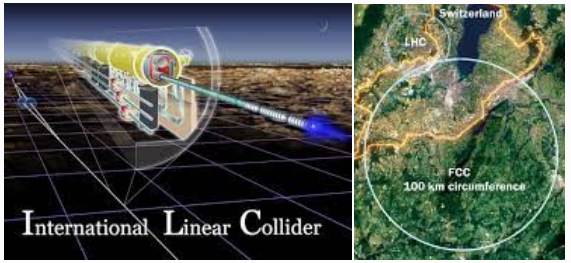
Ultrashort crystalline calorimeter



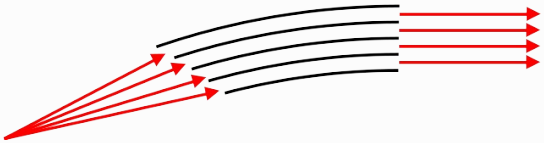
Gamma-ray Space Telescope

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

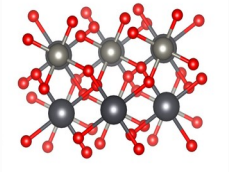




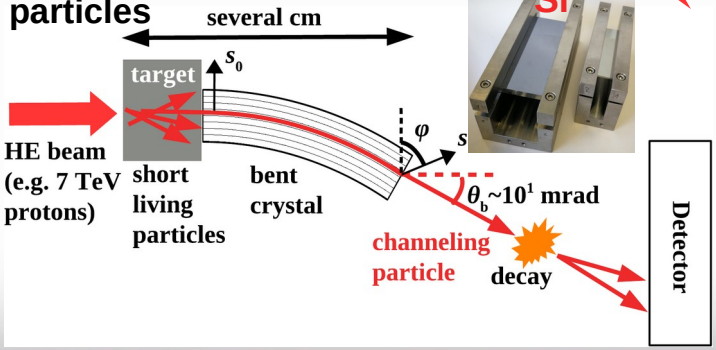
Beam focusing



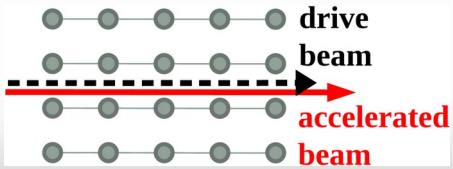
Oriented crystals



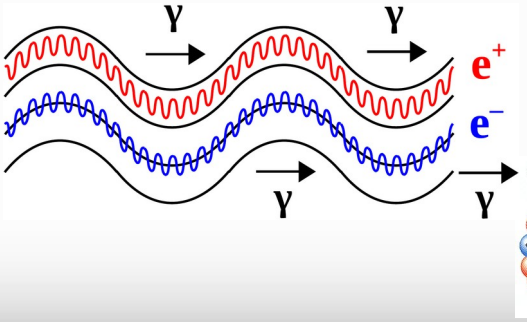
Measurement of dipole magnetic and electric moments of exotic particles



Plasma acceleration



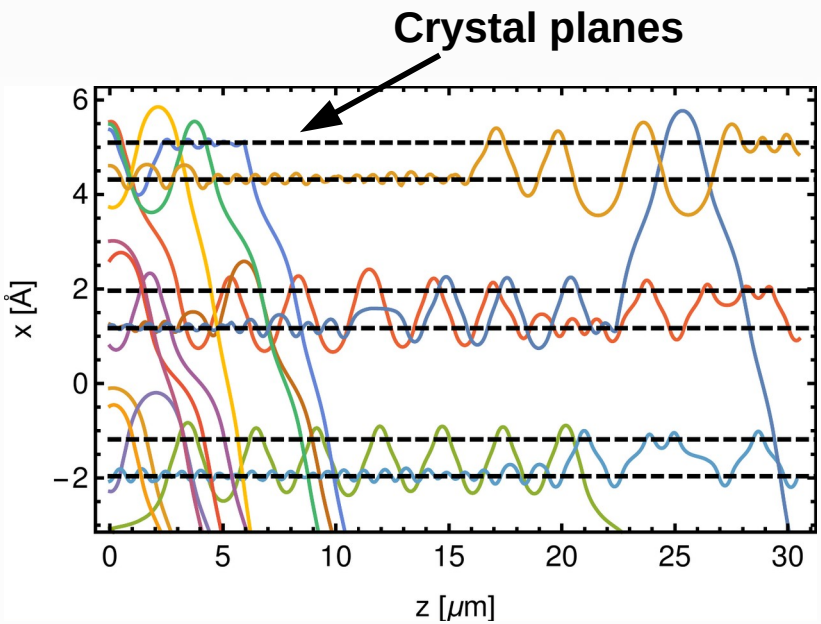
X and y-ray source for nuclear and medical physics



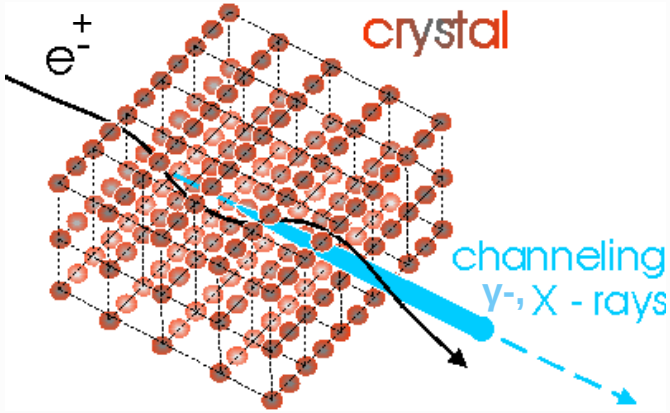
*A. Sytov et al. Journal of the Korean Physical Society 83, 132-139, (2023)

Geant4 G4ChannelingFastSimModel

Main conception – simulation of classical trajectories of charged particles in a crystal in averaged atomic potential of planes or axes. Multiple and single **scattering simulation** at every step



channeling*



Baier-Katkov formula:

integration is made over the classical trajectory

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

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. Journal of the Korean Physical Society 83, 132–139 (2023)

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

Channeling, radiation and coherent pair production models (2022-2024)

Home > Geant4 > geant4-v11.3.0 > source > parameterisations > channeling > **src**


G4BaierKatkov.cc

Radiation spectrum, generation of secondary photons (Baier-Katkov method)


G4ChannelingFastSimCrystalData.cc

Crystal structure input&crystal geometry


G4ChannelingFastSimInterpolation.cc

Interpolation of **G4CHANNELINGDATA**


G4ChannelingFastSimModel.cc

Channeling model


G4CoherentPairProduction.cc

NEW: Coherent pair production model


G4VChannelingFastSimCrystalData.cc

Coulomb scattering and ionization losses models in a crystal

Home > Geant4 > geant4-v11.3.0 > source > physics_lists > constructors > gamma_lepto_nuclear > **src**


G4CoherentPairProductionPhysics.cc

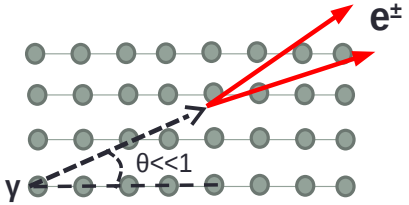
NEW: Coherent pair production physics

Channeling, radiation and coherent pair production models: future plans

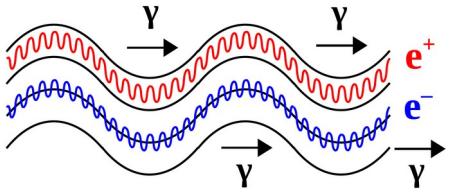
Home > Geant4 > geant4-v11.3.0 > source > parameterisations > channeling > **src**

- G4BaierKatkov.cc
- G4ChannelingFastSimCrystalData.cc
- G4ChannelingFastSimInterpolation.cc
- G4ChannelingFastSimModel.cc
- G4CoherentPairProduction.cc
- G4VChannelingFastSimCrystalData.cc

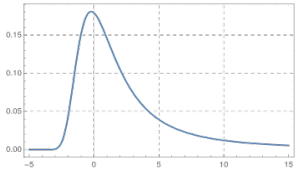
Further **experimental validation**



Updates in **geometry** (complex internal geometry from input file)

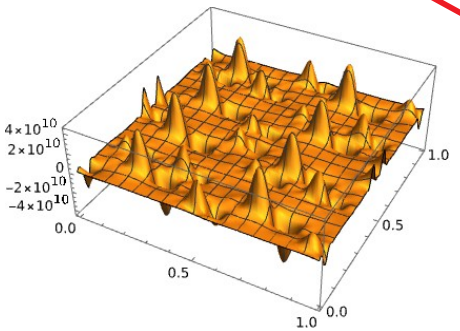


Updates in **ionization losses** model

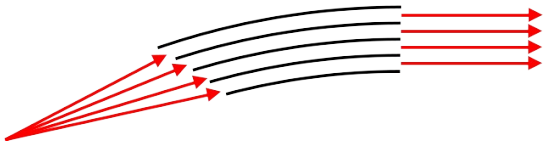


Implementation of **hadronic physics** into channeling model

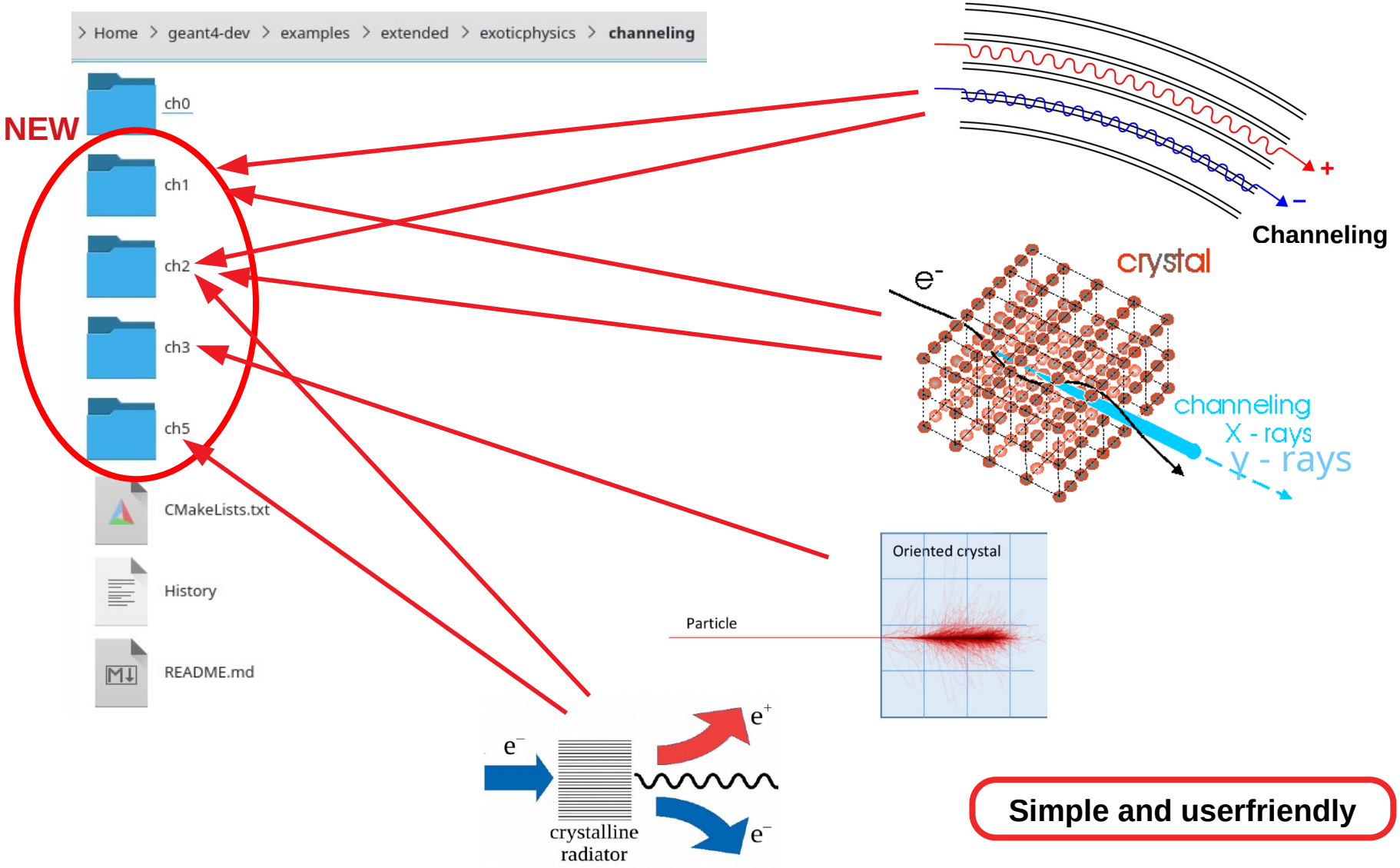
NEW crystal materials and crystallographic directions into **G4CHANNELINGDATA**



Surface geometry developments: lateral surface for **crystal-based extraction/ collimation**; **crystal for focusing**

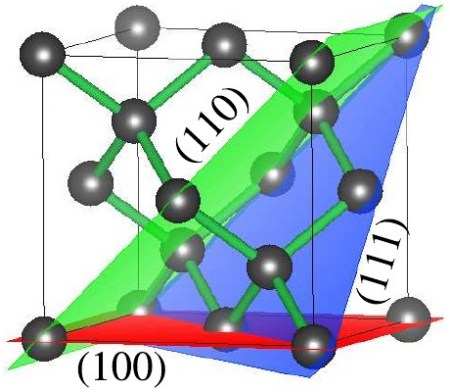


List of channeling Geant4 examples successfully implemented in 2024-2025



G4CHANNELINGDATA 2.0

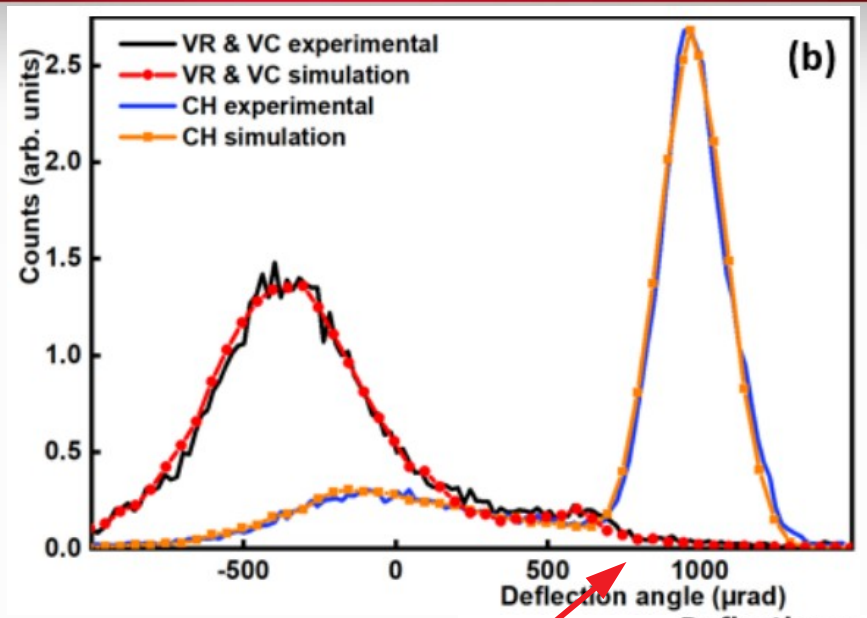
Diamond_axes_100.dat
Diamond_axes_110.dat
Diamond_axes_111.dat
Diamond_planes_100.dat
Diamond_planes_110.dat
Diamond_planes_111.dat
Ge_axes_100.dat
Ge_axes_110.dat
Ge_axes_111.dat
Ge_planes_100.dat
Ge_planes_110.dat
Ge_planes_111.dat
History
README
Si_axes_100.dat
Si_axes_110.dat
Si_axes_111.dat
Si_planes_100.dat
Si_planes_110.dat
Si_planes_111.dat
W_axes_111.dat

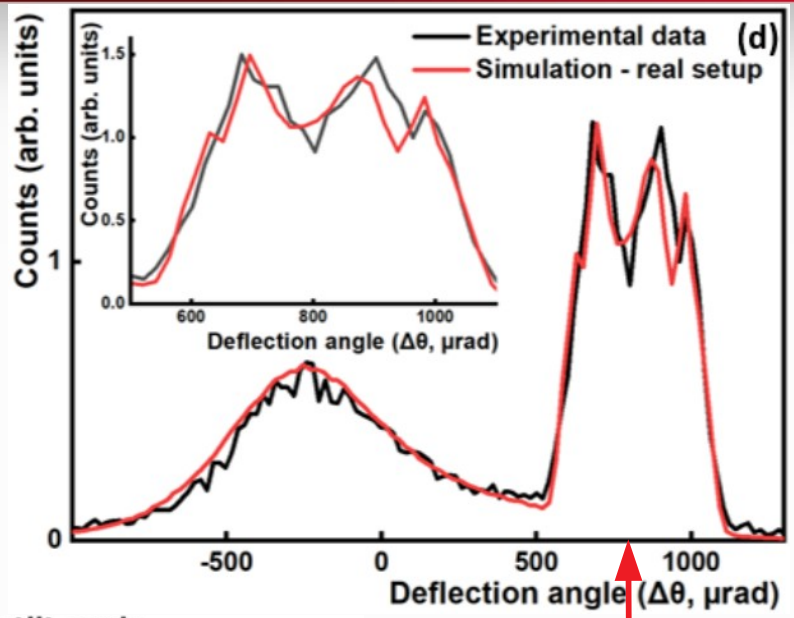


Diamond, Si and Ge: (100), (110), (111), <100>, <110>, <111>
W: <111>

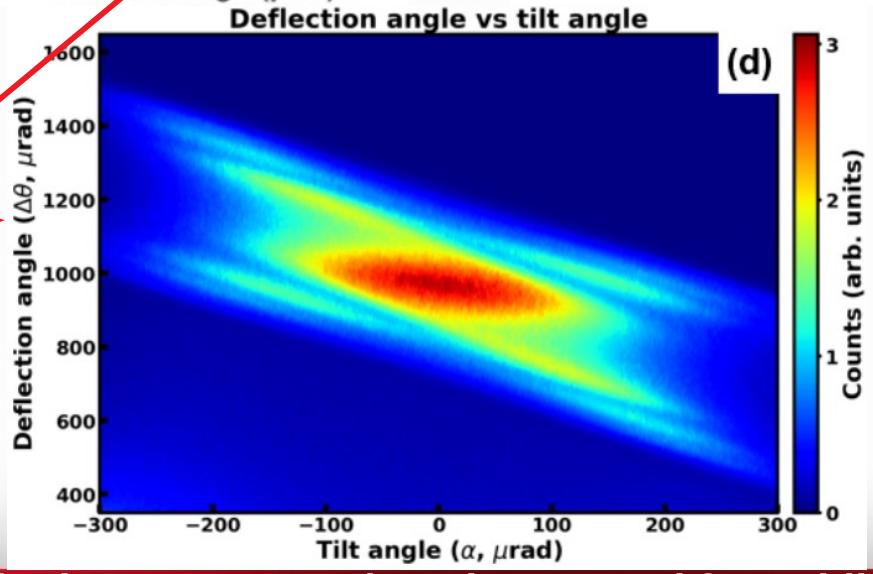
To be extended the next year!

Superfresh experimental validation – channeling of positrons at Mainz Mikrotron MAMI. PRL accepted*

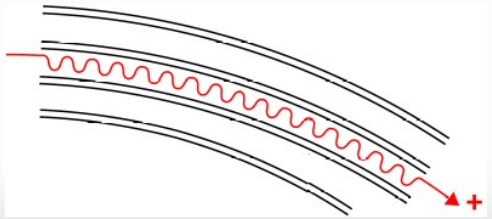




Channeling e+



Channeling e+

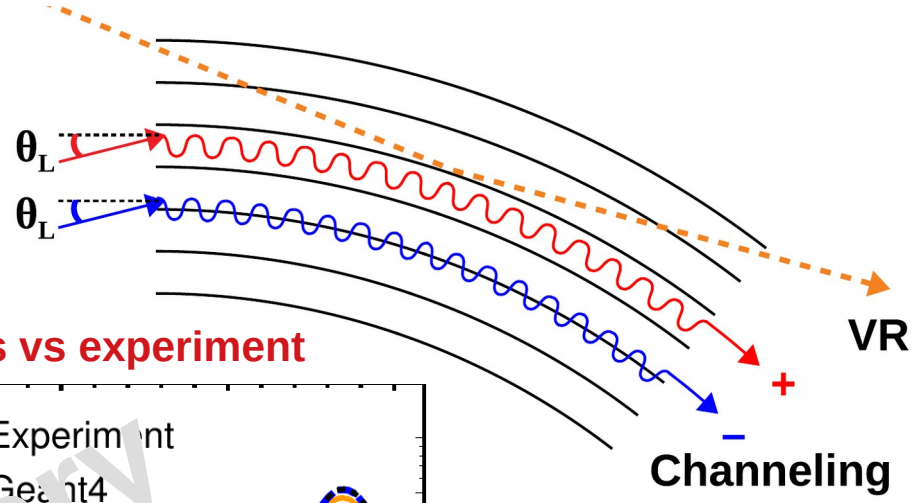


*A. Mazzolari et al. Phys. Rev. Lett. (2025) Accepted for publication 15/10/2025

More Geant4 channeling model validation: quasichanneling oscillations* at SLAC FACET Facility

20.35 GeV positrons

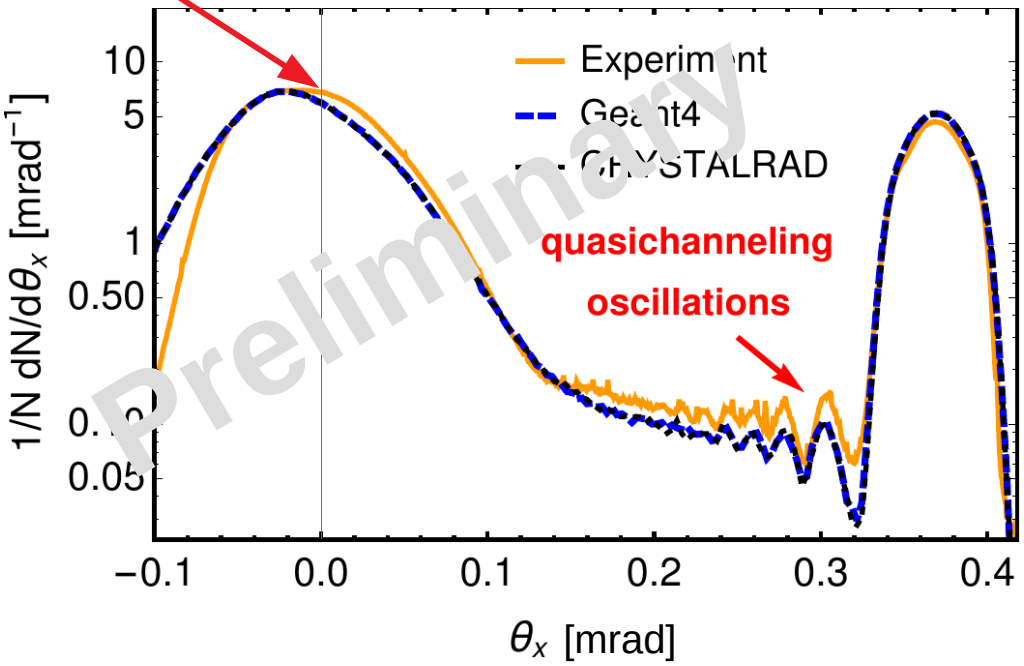
60 µm thick bent crystal



volume reflection (VR)

channeling

Geant simulations vs experiment



To be submitted for publication soon

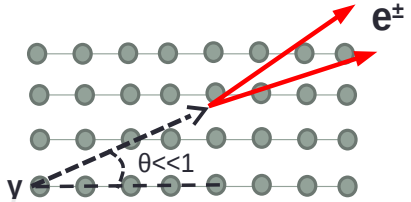
*T. N. Wistisen, …, and A. Sytov, Phys. Rev. Lett. 119, 024801 (2017)

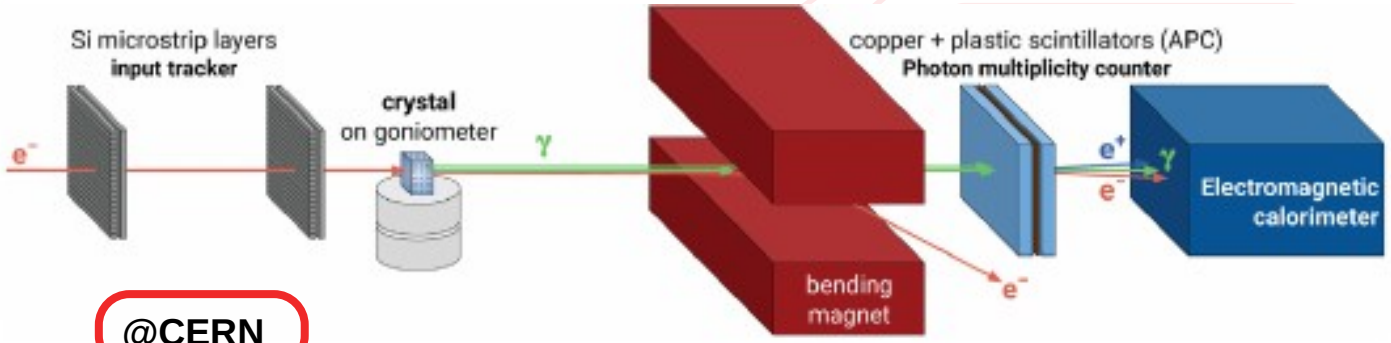
Fresh experimental validation of the radiation model*

Home > Geant4 > geant4-v11.3.0 > source > parameterisations > channeling > **src**

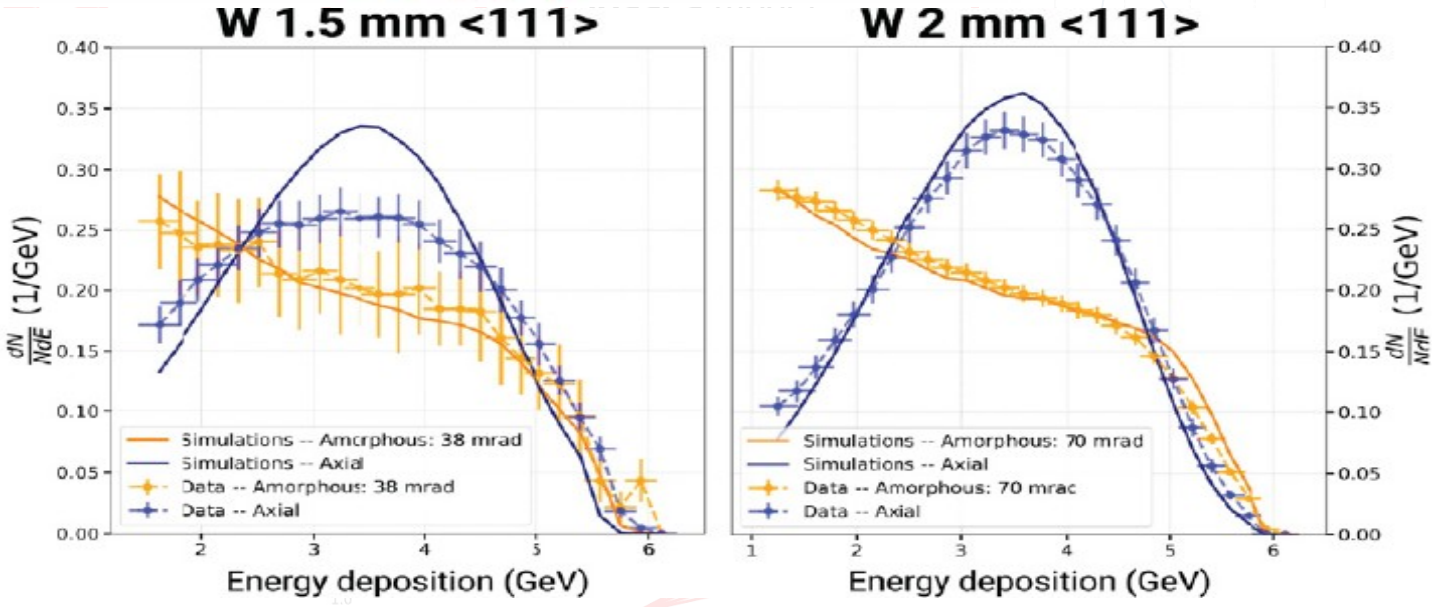
G4BaierKatkov.cc

Further **experimental validation**





@CERN



NEW crystal materials and crystallographic directions into **G4CHANNELINGDATA**

*N. Canale et al. NIM A, 1075, 170342 (2025)

Current status

In Geant4 since geant4-11.2.0 !

geant4-v11.3.2/source/parameterisations/channeling/

Please use it!

https://geant4.web.cern.ch/download

Don't hesitate to contact me in the case of any problems/issues/suggestions

sytov@fe.infn.it

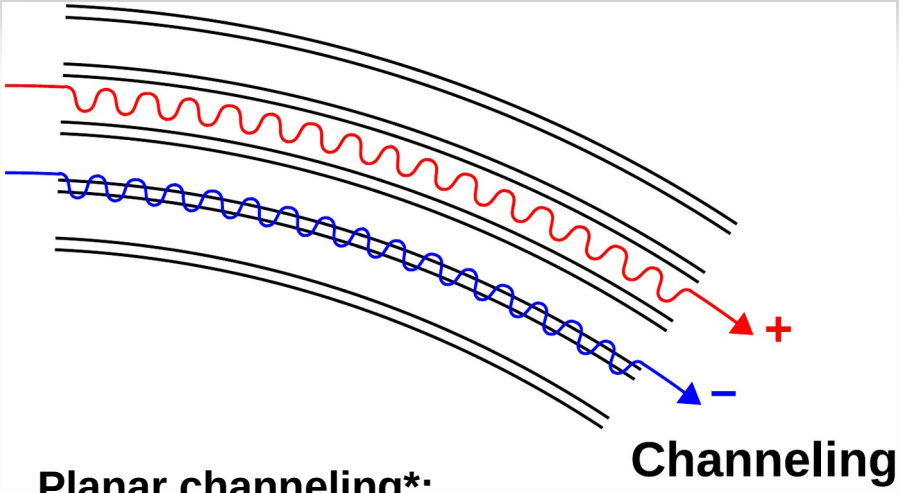
Geant4 Physics Reference Manual:

https://geant4-userdoc.web.cern.ch/UsersGuides/PhysicsReferenceManual/html/solidstate/channeling/channeling_fastsim.html

Please cite our papers if you use our model:

1. **A. Sytov et al. Journal of the Korean Physical Society 83, 132–139 (2023)**
2. **A. I. Sytov, V. V. Tikhomirov, and L. Bandiera. PRAB 22, 064601 (2019)**

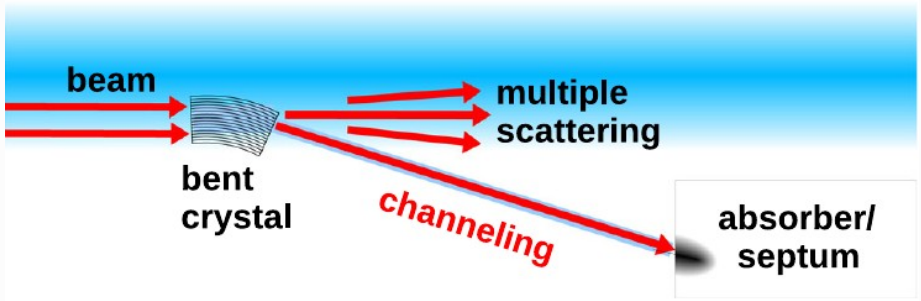
Crystal-based extraction



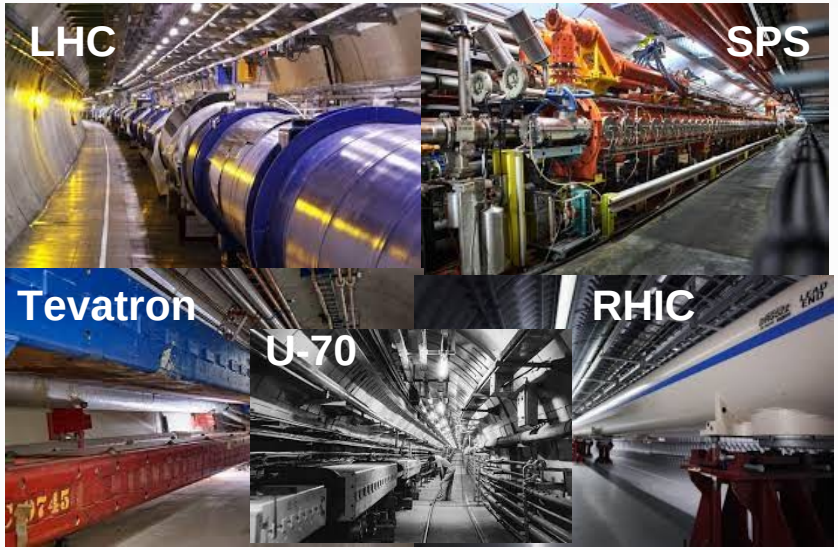
Planar channeling*:

- 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**

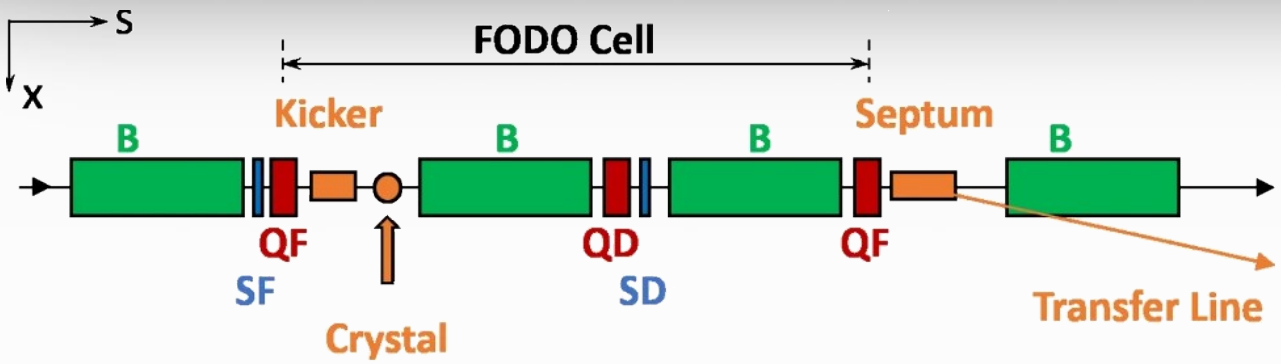


Crystal-based extraction/collimation: applied only for hadrons, not yet for e-

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

Crystal-based extraction: possible setup at DESY-II



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

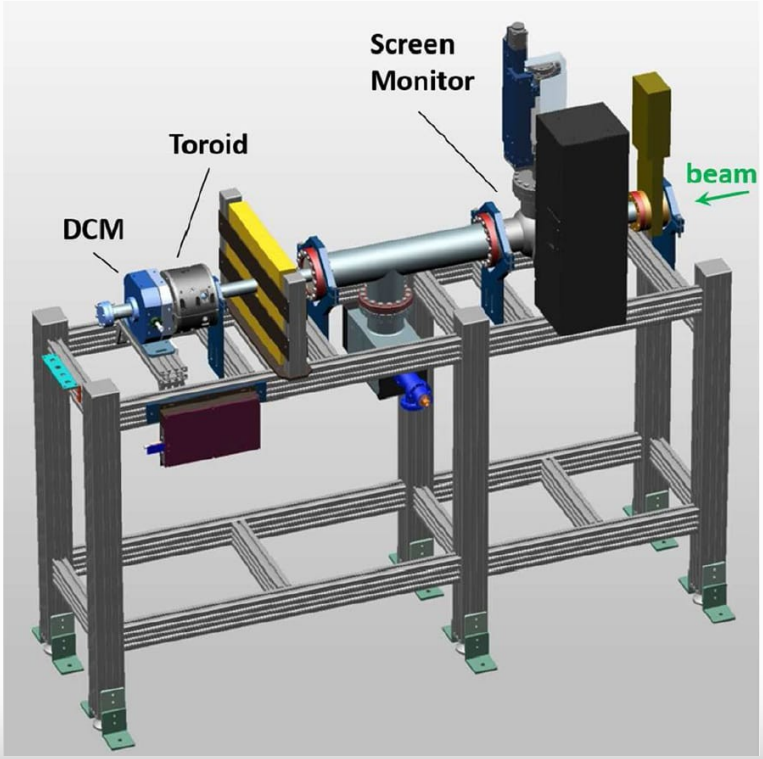
6 GeV electrons

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.

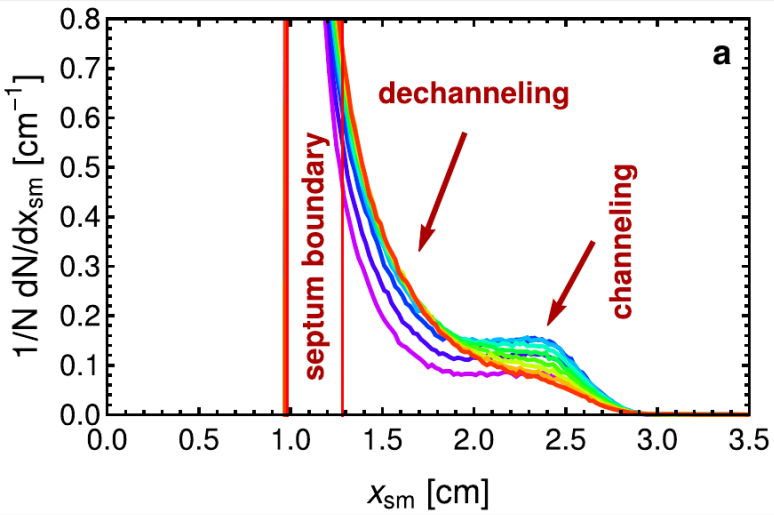
Applications:

- 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**)

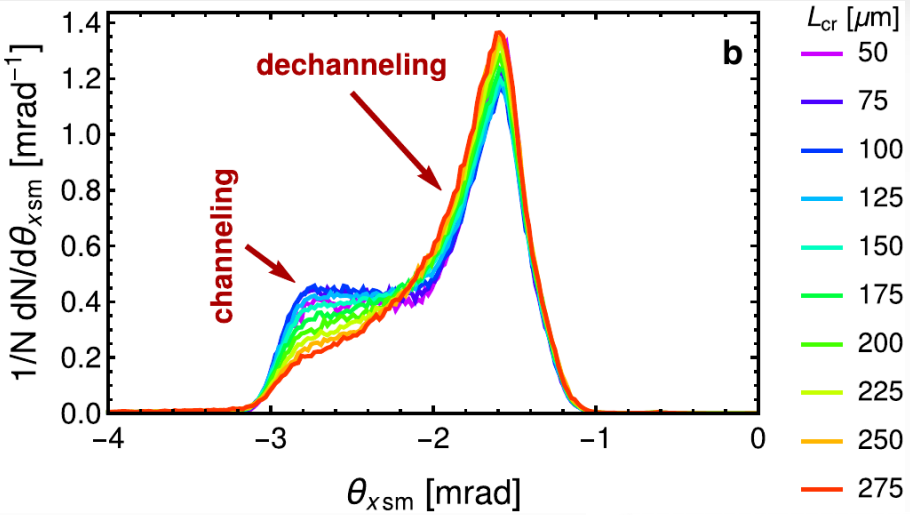


Crystal-based extraction: old simulation results* with CRYSTALRAD simulation code

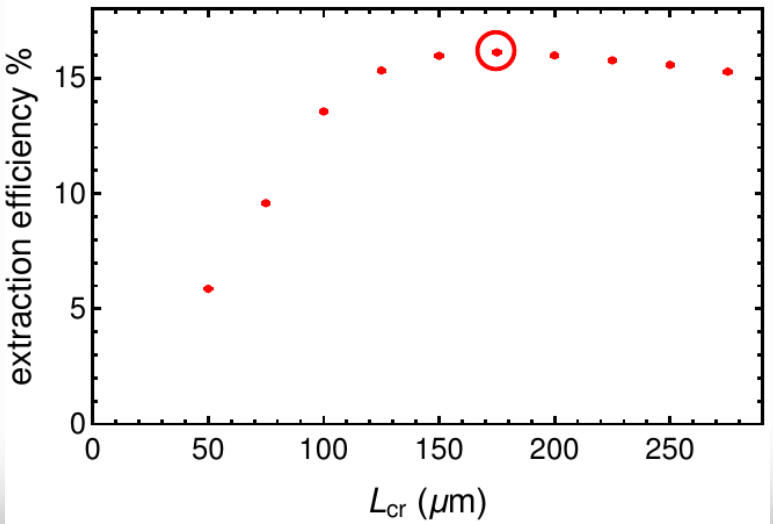
Coordinate distribution of extracted beam

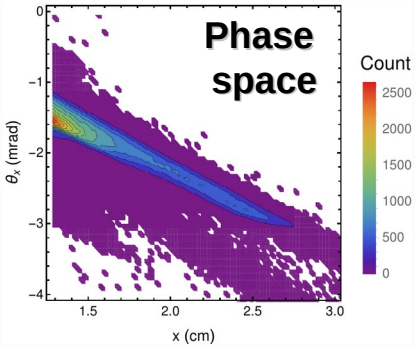


Angular divergence of extracted beam



Extraction efficiency





Crystal parameters:

- **Si (111)**
- bending angle **1.75 mrad**
- Crystal length **0.175 mm**
- Crystal transverse thickness **1 cm**

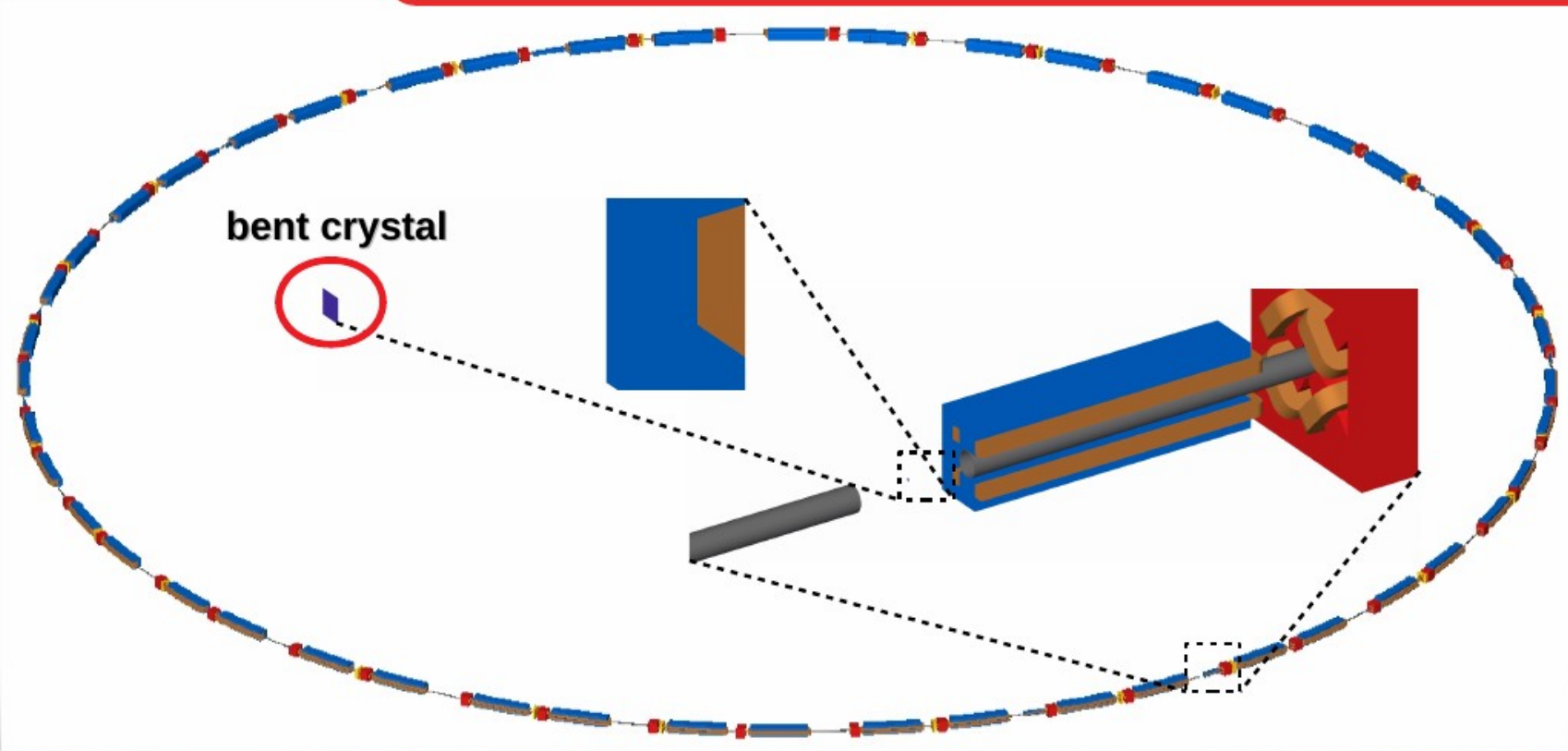
Maximal extraction efficiency:
16.1 %

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

My mission to DESY: full simulations with the BDSim simulation code

BDSIM
Beam Delivery Simulation

Purpose of BDSIM:
Beam Delivery Simulation (BDSIM) is a C++ program that utilises the **Geant4 toolkit** to simulate both the **transport of particles in an accelerator** and their **interaction with the accelerator material**. BDSIM is capable of **simulating a wide variety of accelerator components and magnets** with Geant4 geometry dynamically built based on a text input file. **Thick lens accelerator** tracking routines are provided for fast accurate tracking in a vacuum.



Implementation of a new component and a new physics list

```cpp
#include "BDSIMClass.hh" // bdsim interface

#include "CrystalDeflector.hh"
#include "CrystalDeflectorConstructor.hh"

#include "FTFP_BERT.hh"
#include "G4FastSimulationPhysics.hh"
#include "G4StepLimiterPhysics.hh"
#include <iostream>

int main(int argc, char** argv)
{
  // construct an instance of bdsim
  BDSIM* bds = new BDSIM();

  // Physics list
  G4VModularPhysicsList* physicsList = new FTFP_BERT;
  // -- Create helper tool, used to activate the fast simulation:
  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 );
  physicsList->RegisterPhysics(new G4StepLimiterPhysics());
  bds->RegisterUserPhysicsList(physicsList);

  // register a custom component by name udipole with a user-provided constructor
  // BDSIM will delete the constructor at the end.
  bds->RegisterUserComponent("crystaldeflector", new CrystalDeflectorConstructor());

  // construct geometry and physics
  bds->Initialise(argc, argv);
  if (!bds->Initialised()) // check if there was a problem.
    {std::cout << "Intialisation failed" << std::endl; return 1;}

  bds->BeamOn(); // run the simulation
  delete bds;    // clean up
  return 0;      // exit nicely
}
```

CrystalDeflectorConstructor.cc

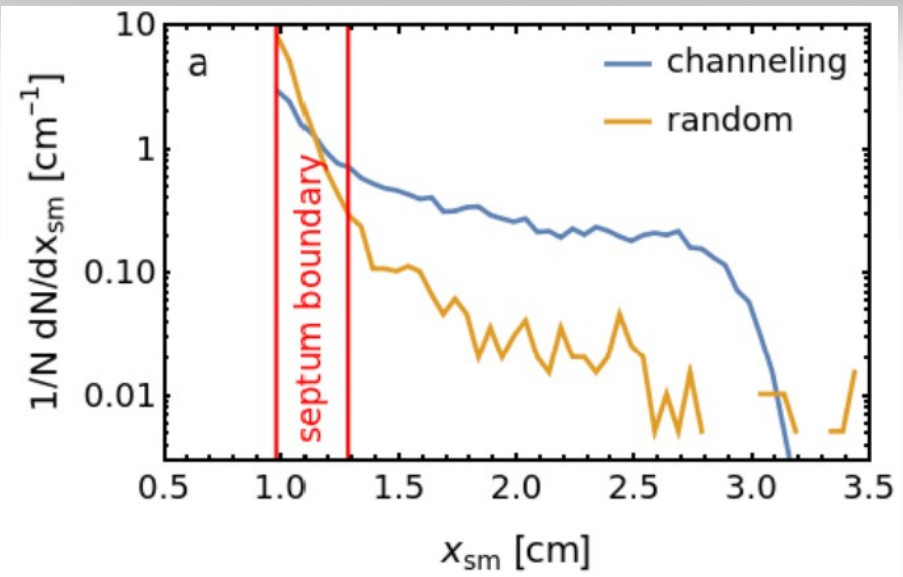
```cpp
BDSAcceleratorComponent* crystal = new CrystalDeflector(element->name,
                                                        element->l*CLHEP::m,
                                                        element->xsize*CLHEP::m,
                                                        element->ysize*CLHEP::m,
                                                        element->materialThickness*CLHEP::m,
                                                        element->axisX,
                                                        element->axisY,
                                                        element->axisZ,
                                                        horizontalWidth*CLHEP::m,
                                                        bendingAngle,
                                                        material,
                                                        vacuumMaterial,
                                                        crystalLattice,
                                                        region,
                                                        colour,
                                                        radiationModel);
```

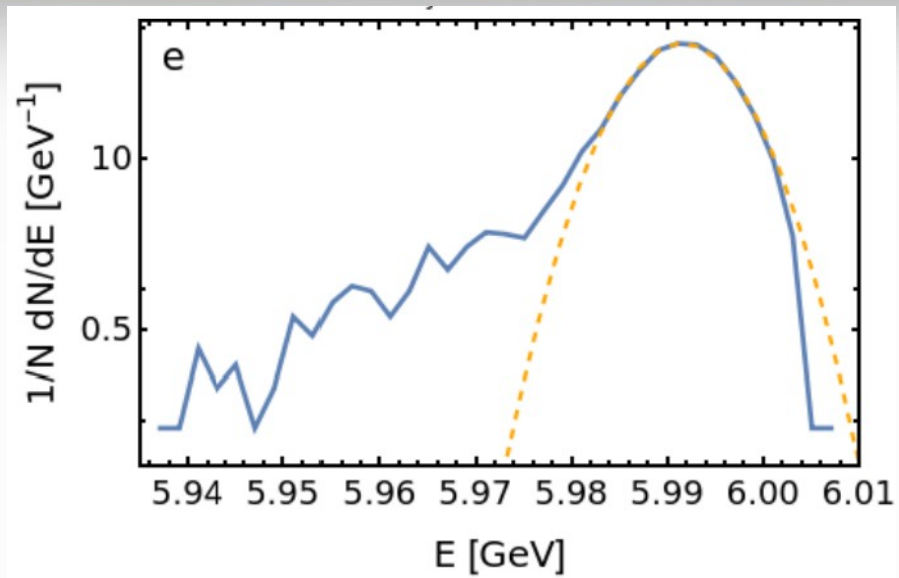
```
D12H: drift, l=0.4125;
CR1: usercomponent, userTypeName="crystaldeflector",
l=0.4125, xsize=1*cm, ysize=1*cm,
materialThickness=0.175*mm, offsetX=-1.126046*cm,
offsetY=0*mm, axisX=0.000, axisY = -0.00097, axisZ = 0.,
horizontalWidth=1*m,  material="G4_Si",
vacuumMaterial="vacuum",
userParameters="crystalRegion:crystal1
crystalBendingAngle:0.00175 crystalLattice:(111)
colour:decapole radiationModel:false"; dump1: dump,
l=1*mm, horizontalWidth=4*cm,
apertureType="rectangular",offsetX=2.98*cm;
D18: drift, l=0.495;
```

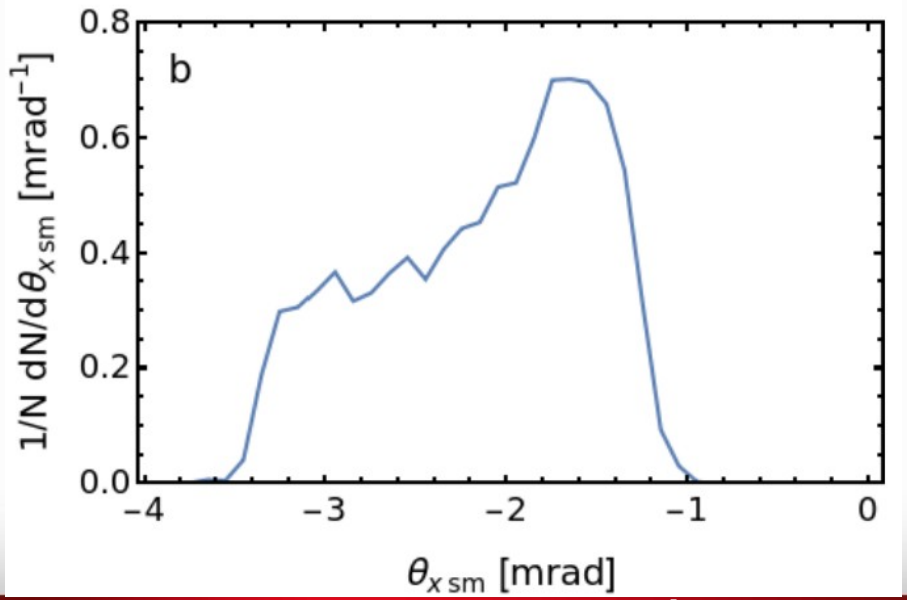
CrystalDeflectorConstructor.cc

```
void CrystalDeflector::BuildCrystal()
{
    //build crystal solid
    G4Box* crystalSolid = new G4Box(name + "_crystal_solid",
                                    crystalXSize * 0.5,
                                    crystalYSize * 0.5,
                                    crystalMaterialThickness * 0.5);
    RegisterSolid(crystalSolid); // for deletion by bdsim

    // make a logical volume for the crystal
    G4LogicalVolume* crystalLV = new G4LogicalVolume(crystalSolid,
                                                     crystalMaterial,
                                                     name + "_crystal_lv");

    // visualisation attributes - make it nicely visible
    G4VisAttributes* crystalVis = new G4VisAttributes(*BDSColours::Instance()->GetColour(crystalcolour));
    crystalVis->SetVisibility(true);
    crystalLV->SetVisAttributes(crystalVis);
    RegisterVisAttributes(crystalVis);// for deletion by bdsim
    RegisterLogicalVolume(crystalLV); // for deletion by bdsim

    G4RotationMatrix* crystalRM = new G4RotationMatrix();
    crystalRM->rotateX(crystalAxisX);
    crystalRM->rotateY(crystalAxisY);
    crystalRM->rotateZ(crystalAxisZ);
    RegisterRotationMatrix(crystalRM); // for deletion by bdsim
    G4double crystalZPos = 0*CLHEP::cm;
    G4ThreeVector crystalPos = G4ThreeVector(0,0, crystalZPos);

    //physical volume
    auto crystalPV = new G4PVPlacement(crystalRM,
                                       crystalPos,
                                       crystalLV,
                                       name + "_crystal",
                                       containerLogicalVolume,
                                       false,
                                       0,
                                       checkOverlaps);
    RegisterPhysicalVolume(crystalPV); // for deletion by bdsim

    G4Region* crystalRegion = new G4Region(crystalRegionName);
    crystalRegion->AddRootLogicalVolume(crystalLV);

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

    if(crystalRadiationModel){ChannelingModel->RadiationModelActivate();}
```

Crystal-based extraction: simulation results distributions at the septum magnet entrance



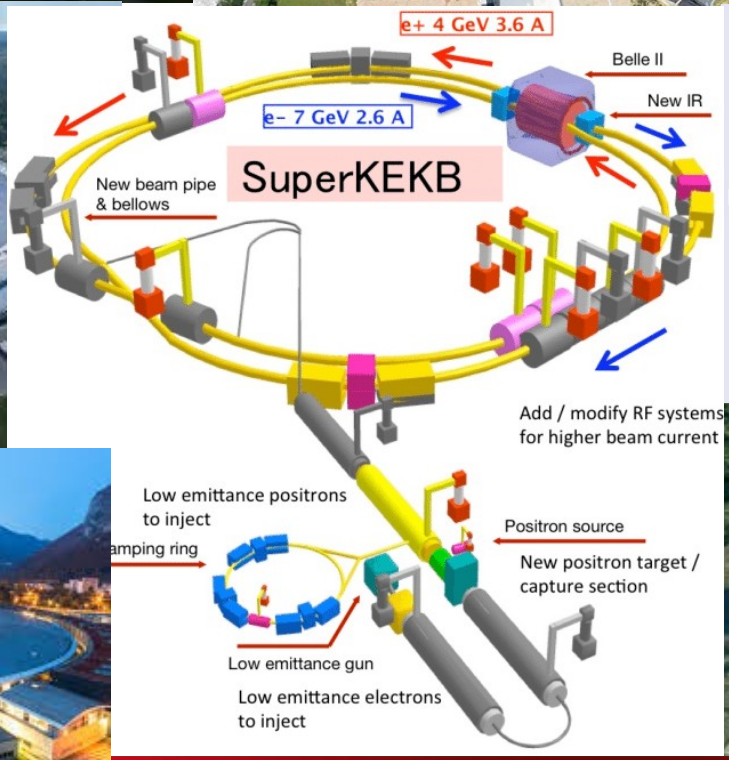


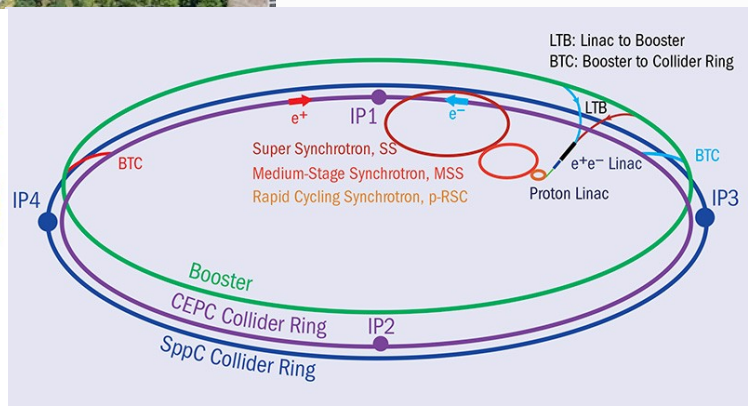


~23 pC can be extracted

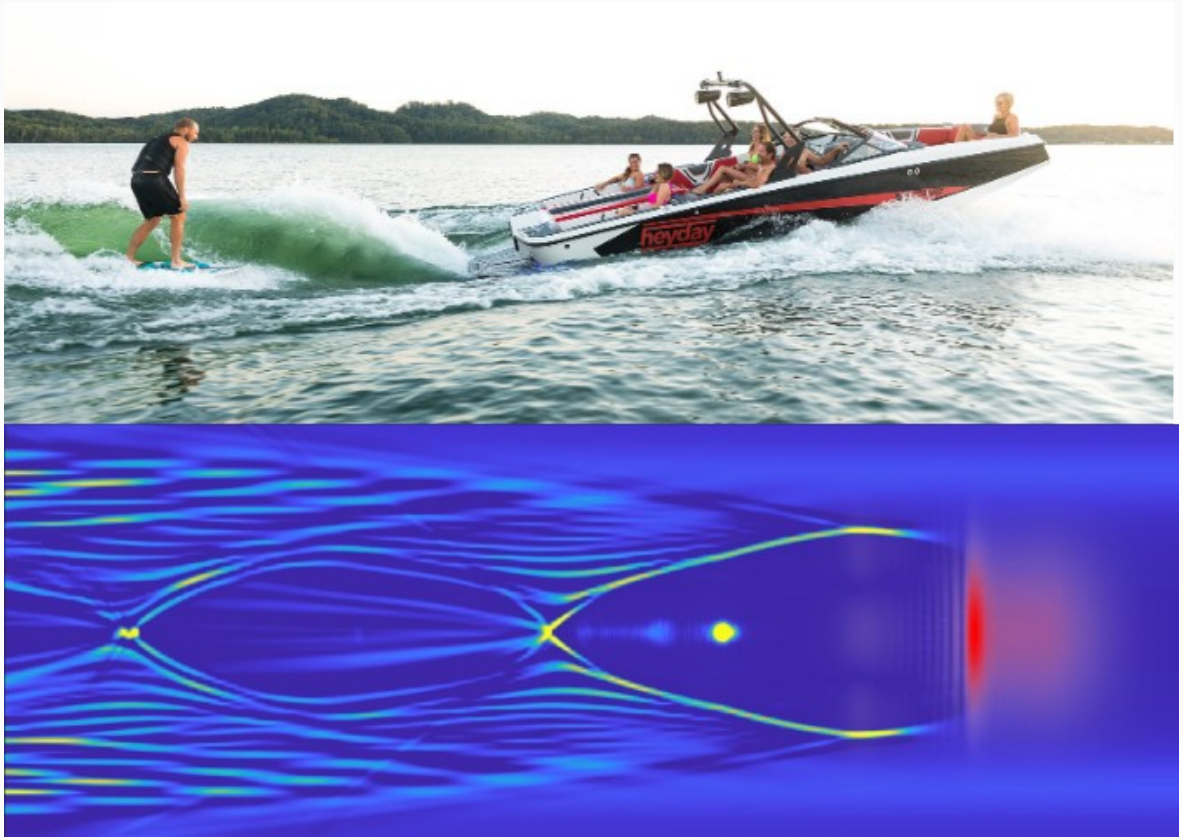
~0.008 energy spread

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



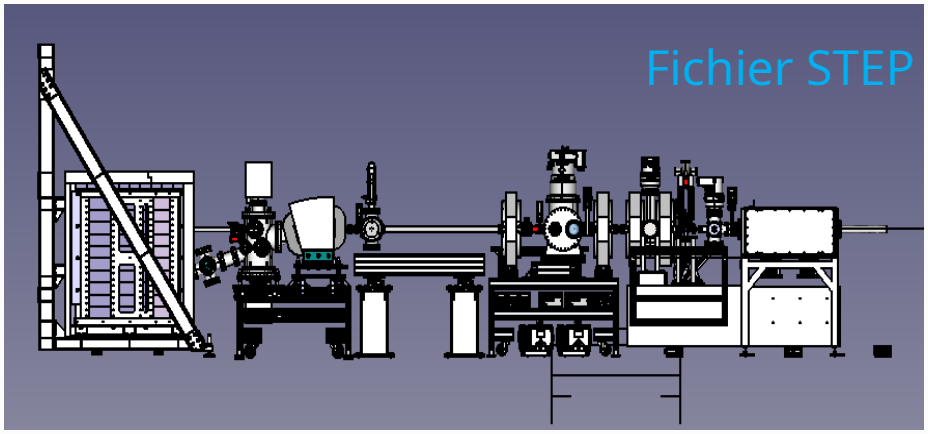


Channeling& Geant4 for plasma wakefield acceleration



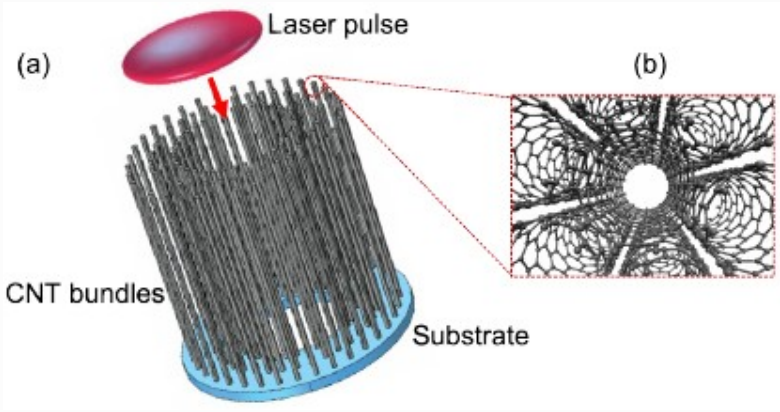
Recently started activities in plasma acceleration

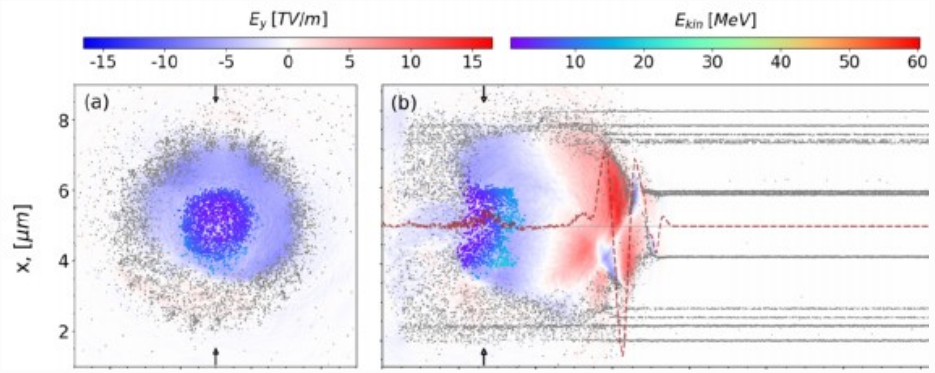
PALLAS Project: Test facility for laser-plasma injector. Partner of EuPRAXIA



Courtesy of Arnaud Huber

Laser plasma wakefield acceleration in nanostructures: NanoAc Collaboration





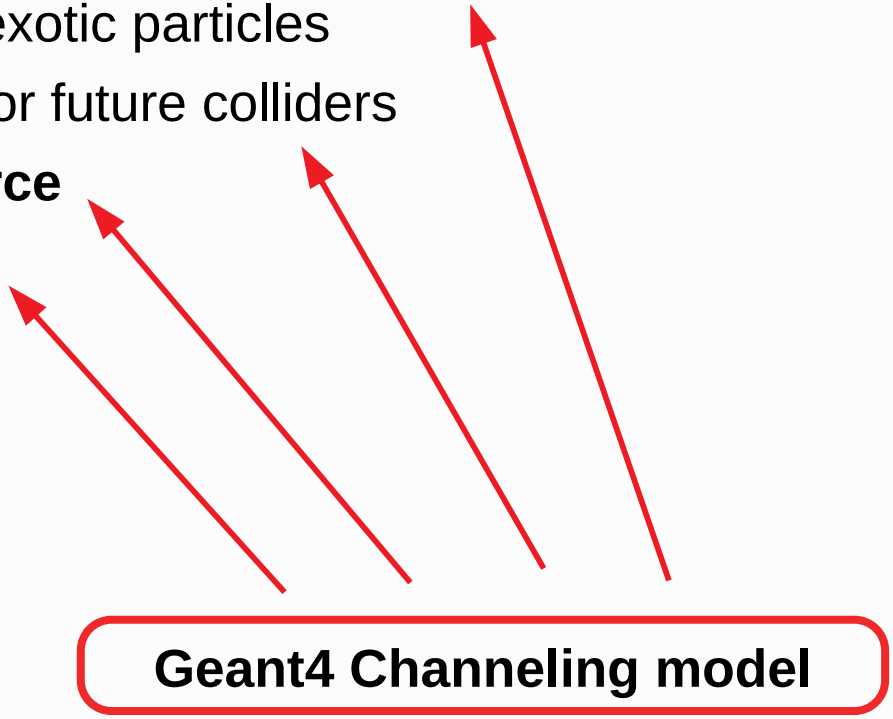
Acceleration gradient > TeV/m!

A. Sytov et al. arXiv:2503.12154 (2025)

C. Bonţoiu et al. Sci. Rep. (2025) in press

Summary of applications

- **Beam manipulation**: crystal-based extraction/collimation, beam focusing; measurement of MDM and EDM of exotic particles
- **Crystal-based positron source** for future colliders
- **X-ray and gamma radiation source**
- Ultrashort **crystalline calorimeter**
- **Plasma wakefield accelerarion**



Geant4INFN/MC-INFN & TRILLION publications

2022-2024

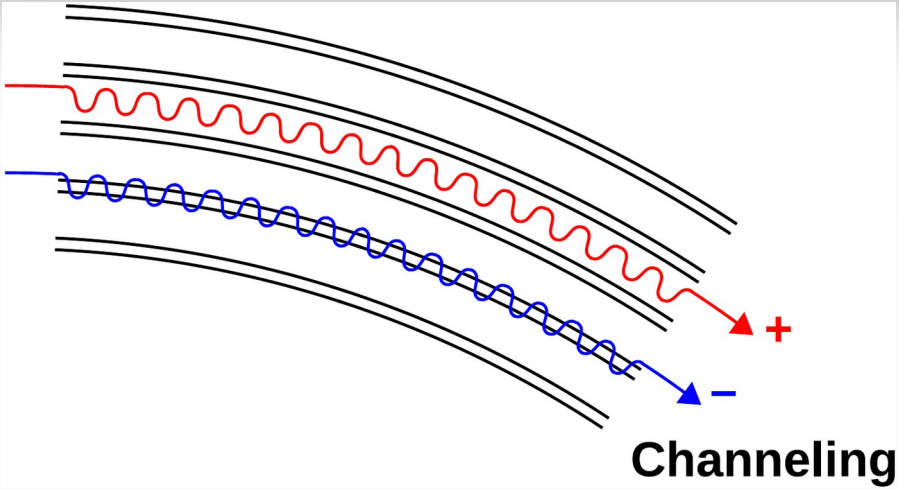
- A. Sytov et al. Journal of the Korean Physical Society 83, 132-139, (2023). ← **The model**
- L. Bandiera, ..., A. Sytov, et al. Eur. Phys. J. C 82, 699 (2022). ← **Positron source**
- A. Sytov et al. Eur. Phys. J. C 82, 197 (2022). ← **Crystal-based extraction @DESY**
- M. Soldani, …, A. Sytov et al. Eur. Phys. J. C 83, 101 (2023). ← **Calorimeter**
- L. Bandiera, …, A. Sytov et al. Frontiers in Physics 11 Pages: 1254020 (1-11) (2023).
- L. Bandiera, …, A. Sytov et al. NIM A 1060, 169022 (2024). ← **Radiation**
- A. Mazzolari ,…, A. Sytov et al. Phys. Rev. Lett. 135, 205002 (2025). ← **Beam steering**

RECENT – LAST YEAR

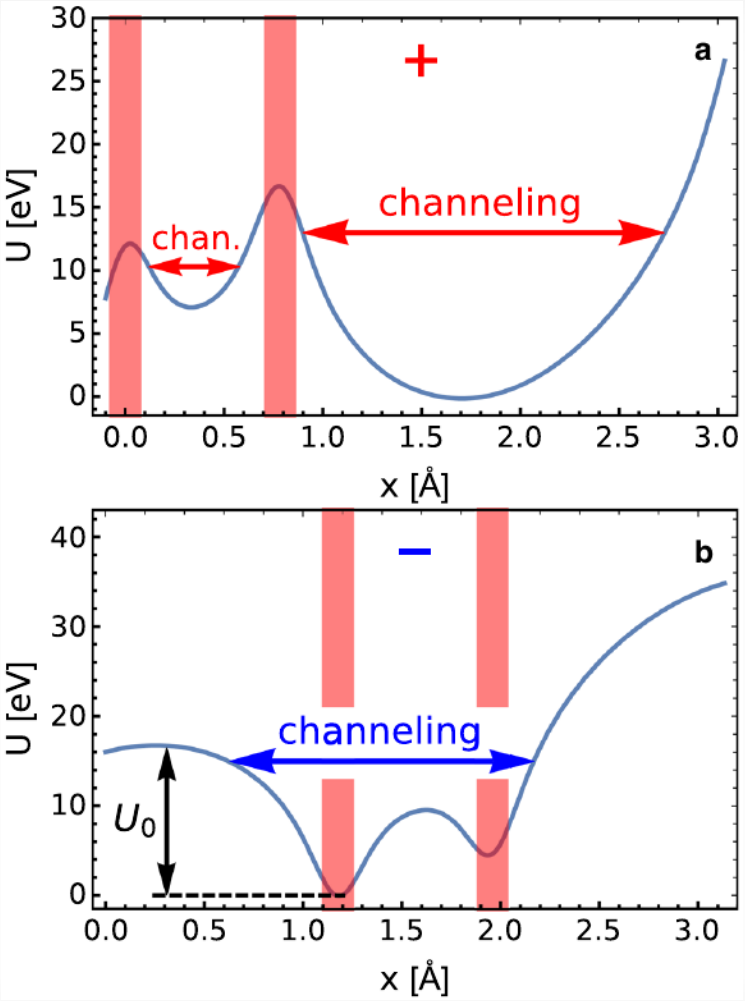
- P. Monti-Guarnieri, …, A. Sytov et al. JINST 19, P10014 (2024) ← **Calorimeter**
- R. Negrello, …, A. Sytov. NIM A 1074, 170277 (2025) ← **Radiation**
- N. Canale, …, A. Sytov et al. NIM A, 1075, 170342 (2025) ← **Radiation**
- F. Alharthi, …, A. Sytov et al. NIM A, 1075, 170412 (2025) ← **Positron source**
- A. Sytov et al. arXiv2412.10715v2 (2024) ← **Crystal-based extraction&BDSim @DESY**
- A. Sytov et al. arXiv2503.12154 (2025) ← **ML for plasma acceleration**

Thank you for attention!

Channeling



Interplanar potential



Channeling*:

Charge particle penetration through a monocrystal along its atomic planes/axes

trajectory equation:

$$\frac{d^2x}{dz^2} + \frac{U'_{pl\ x}}{pv} + \frac{1}{R} = 0$$

***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 (2022) 82:197**