A. Sytov[1,2], **L. Bandiera**[1], **K. Cho**[2], **G. A. P. Cirrone**[3], **H. Ehrlichmann**[4], **V. Guidi**[1,5], **V. Haurylavets, G. Kube**[4], **A. Mazzolari**[1], **M. Romagnoni**[1], **M. Soldani**[1,3], **M. Stanitzki**[4], **M. Tamisari**[5], **G. V. Tikhomirov, K. Wittenburg**[4]

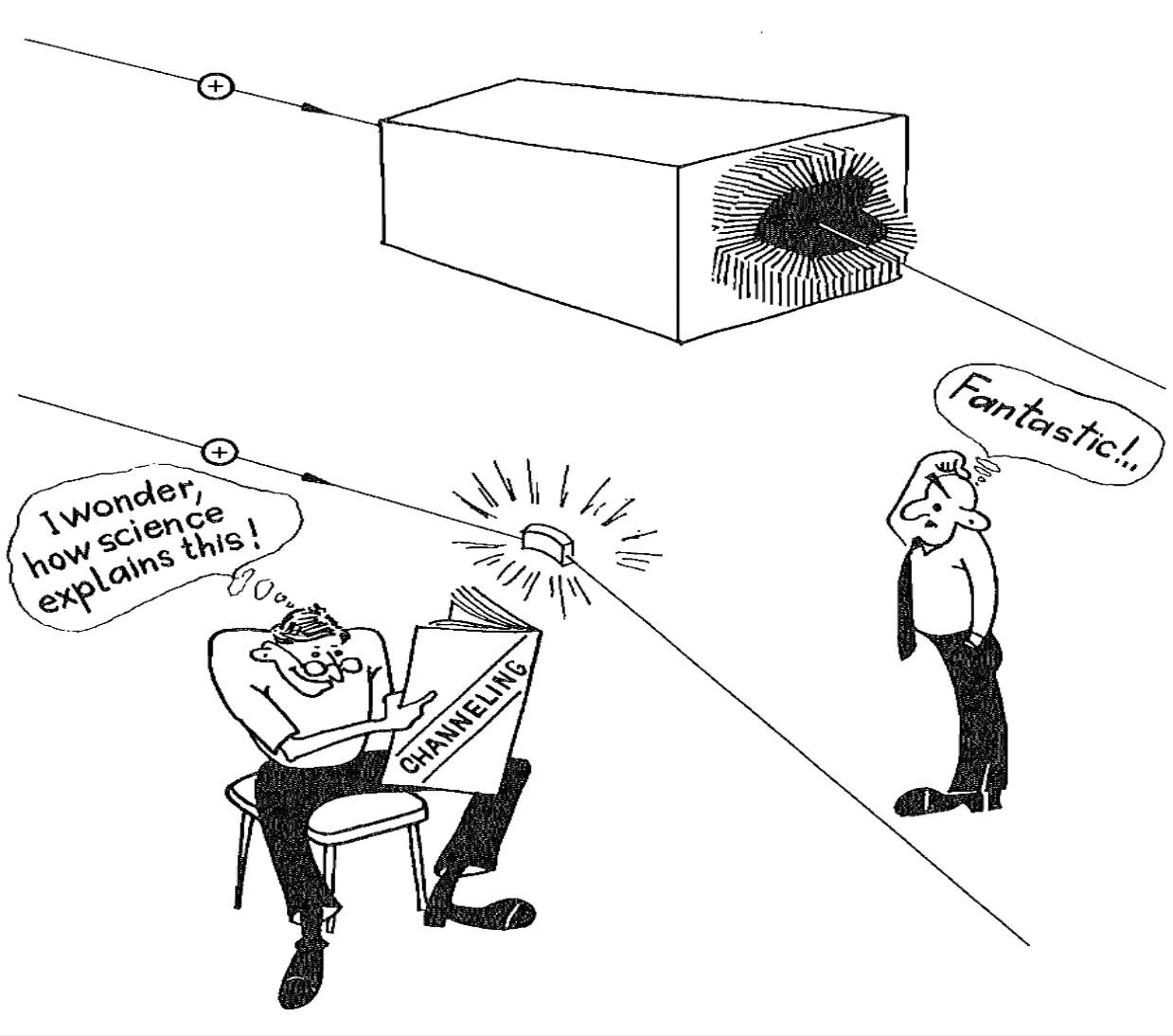
[1]Istituto Nazionale di Fisica Nucleare Sezione di Ferrara, Ferrara. Italy
[2]Korea Institute of Science and Technology Information (KISTI), Daejeon, Korea
[3]Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud, Catania, Italy
[4]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[5]Università degli Studi di Ferrara, Ferrara, Italy

FUTURE DESY II BOOSTER SYNCHROTRON PROOF-OF-PRINCIPLE EXPERIMENT FOR A CRYSTAL-BASED EXTRACTION OF ELECTRONS

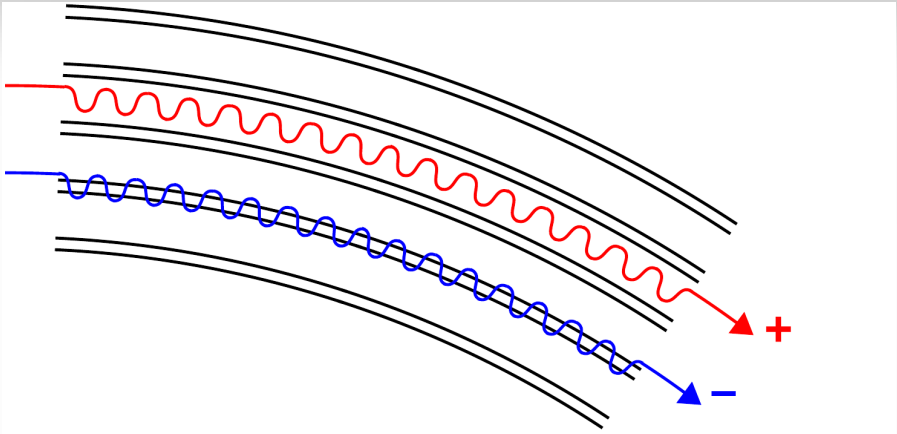
The 24th International Conference on Accelerators and Beam Utilizations ICABU2022

Gyeongju, 2022/11/10

The world of the channeling effect



Crystal-based extraction: the idea

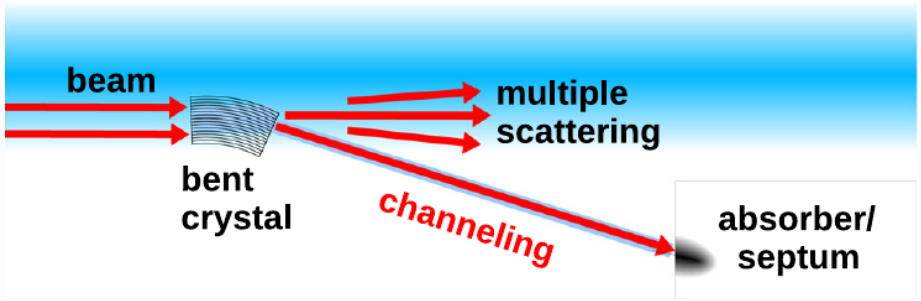


Channeling

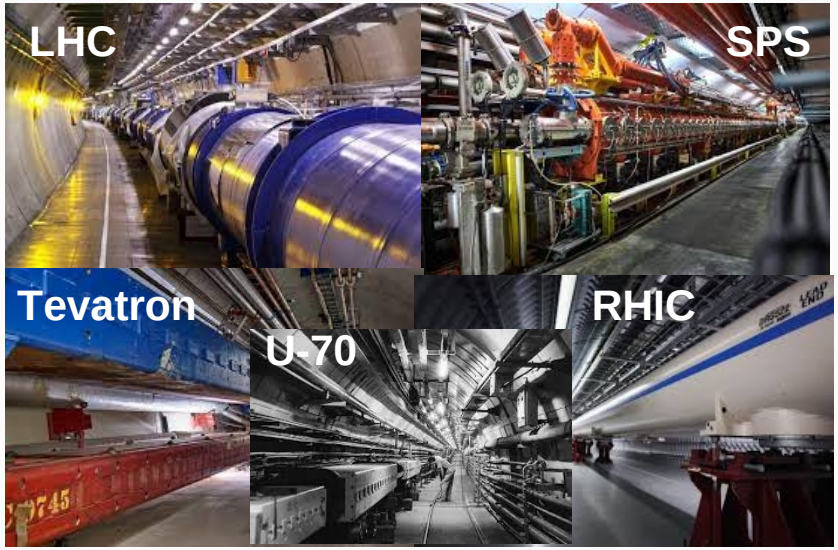
Planar channeling*:

- 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**

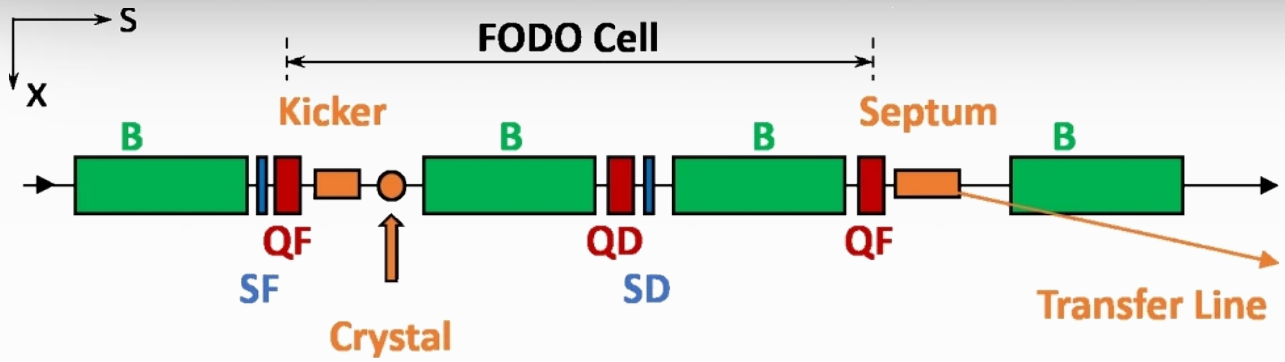


Crystal-based extraction/collimation: applied only for hadrons, not yet for e-

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 extraction: possible setup at DESY-II



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

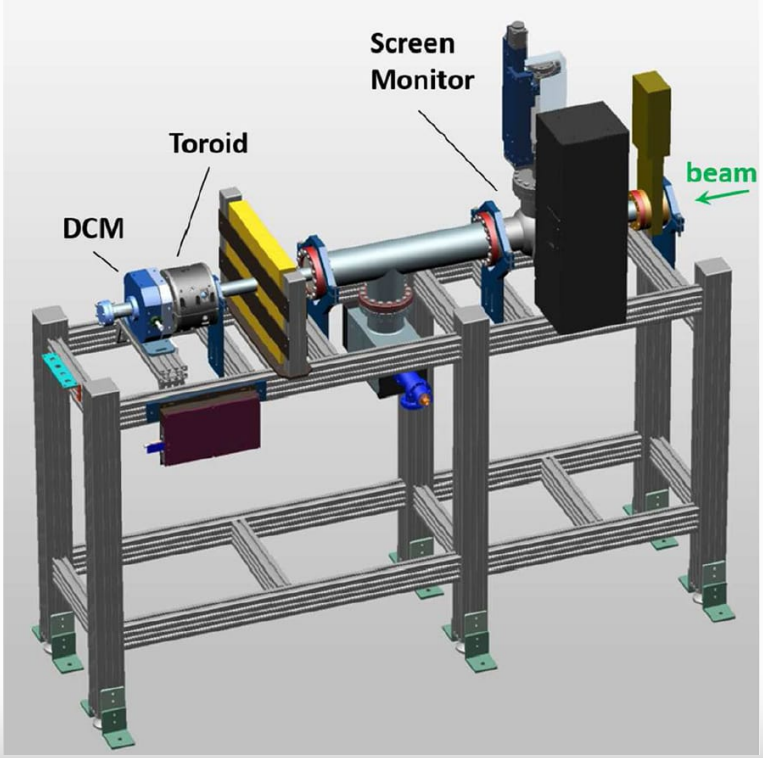
6 GeV electrons

Advantages:

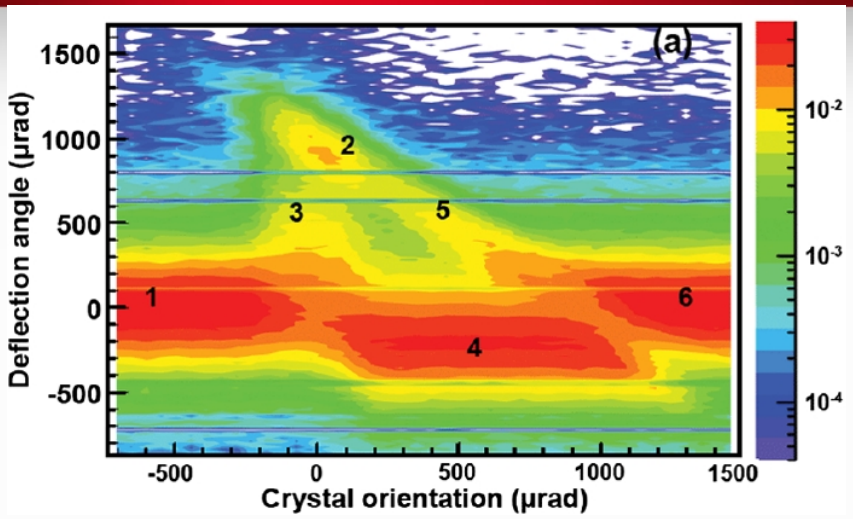
- Extraction of **primary** low-emittance and very **intense electron beam** in a **parasitic mode**.
- The **extraction line** including septum magnets already **exists => ideal for prove-of-principle**
- **Few GeV** electron beam, **typical for synchrotron light sources** existing in the world.

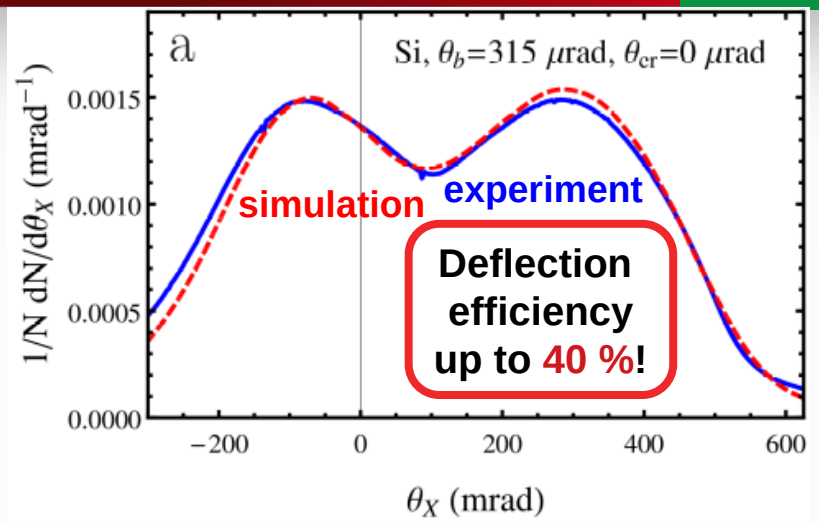
Applications:

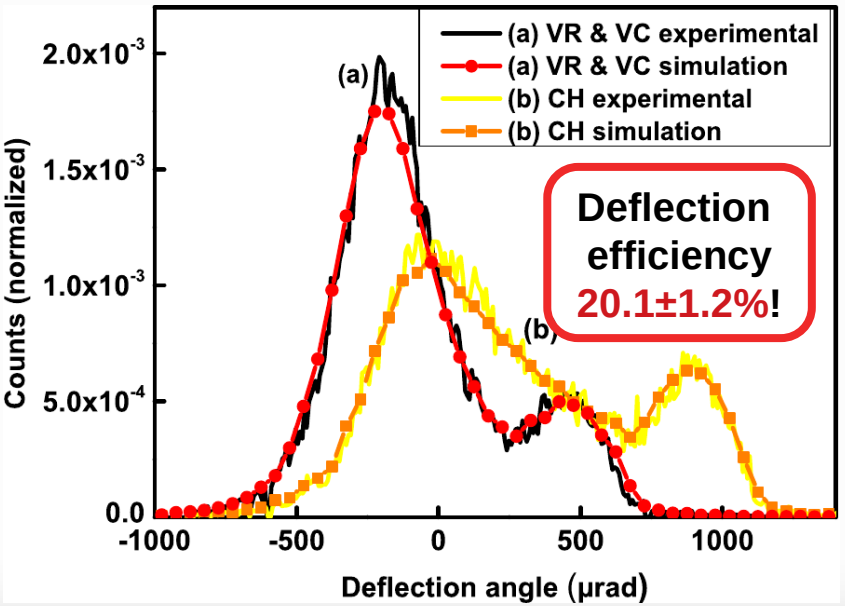
- Nuclear and particle physics detectors and generic **detector R&D**
- Fixed-target experiments in **high-energy physics** including future **lepton colliders**
- Also: **crystal-based collimation** (**synchrotron light sources**, **colliders**)

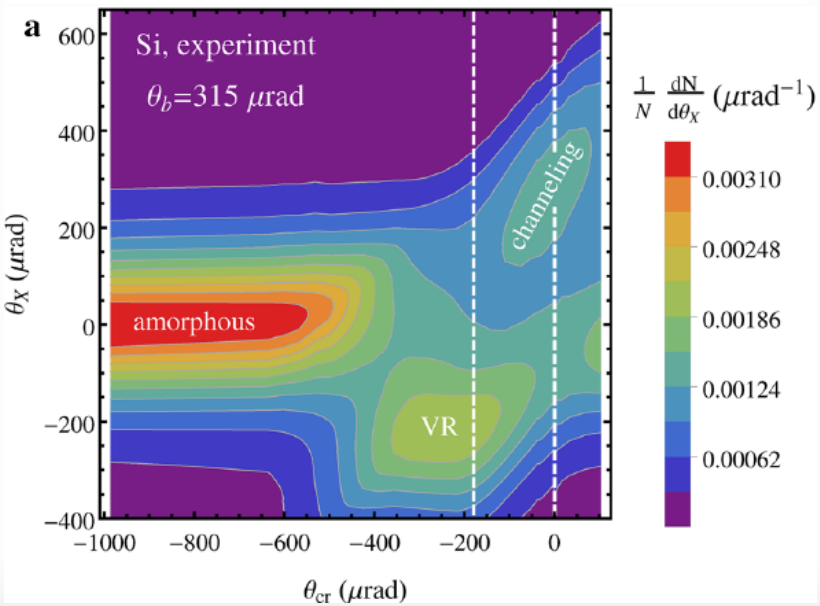


Steering of a Sub-GeV electron beam using new generation of crystals @INFN Ferrara





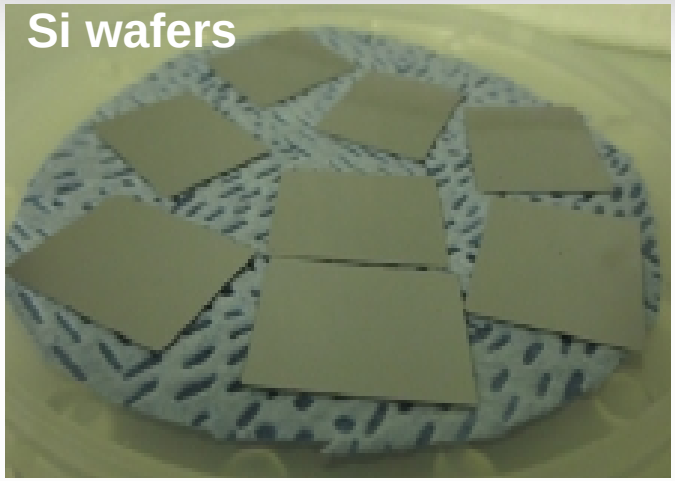


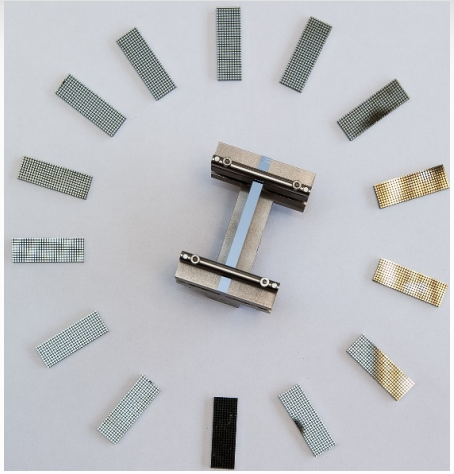


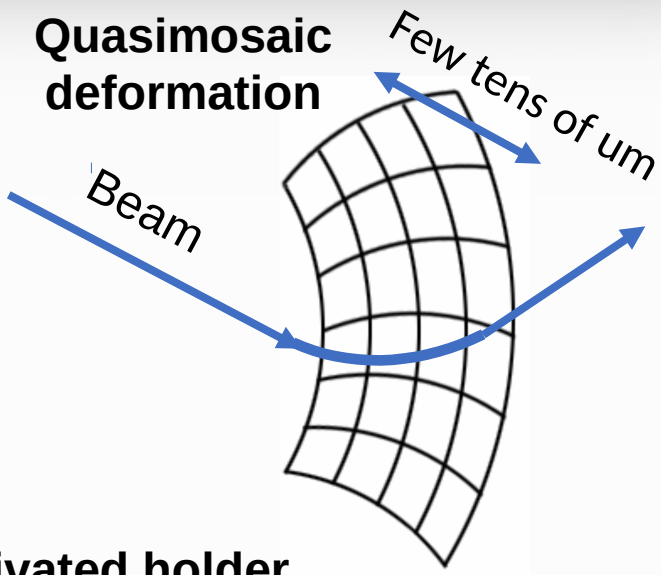
A.I. Sytov, L. Bandiera et al. Eur. Phys. J. C 77, 901 (2017)

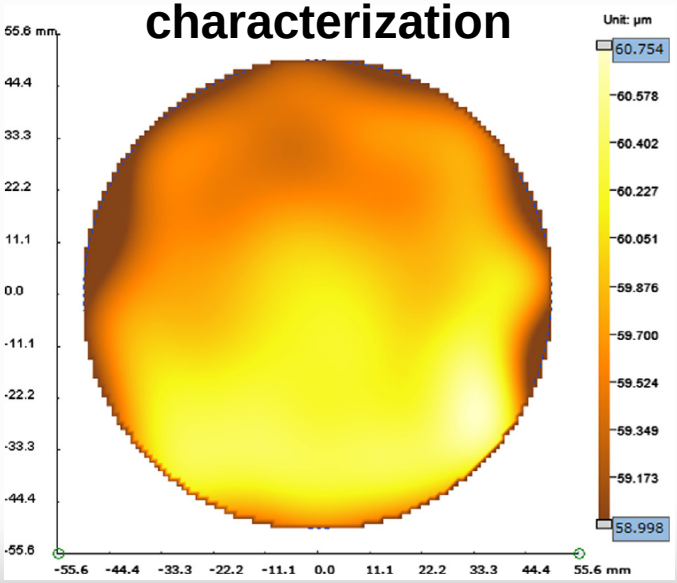
A. Mazzolari et al. PRL 112, 135503 (2014)

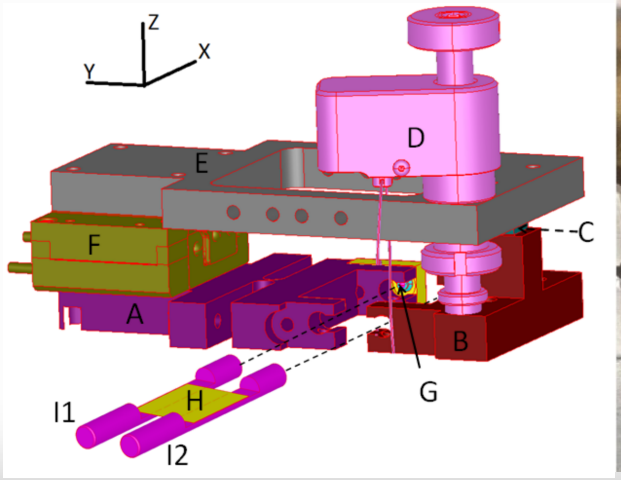
Manufacturing and characterization of bent silicon crystals @INFN Ferrara

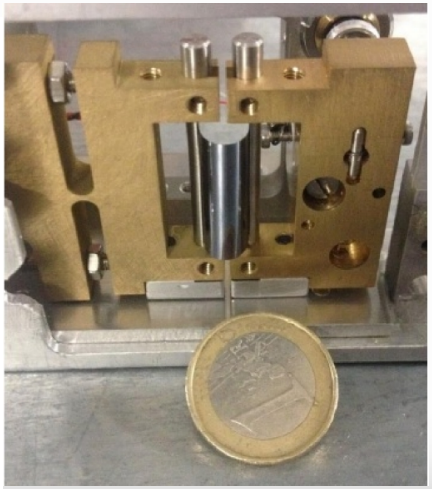




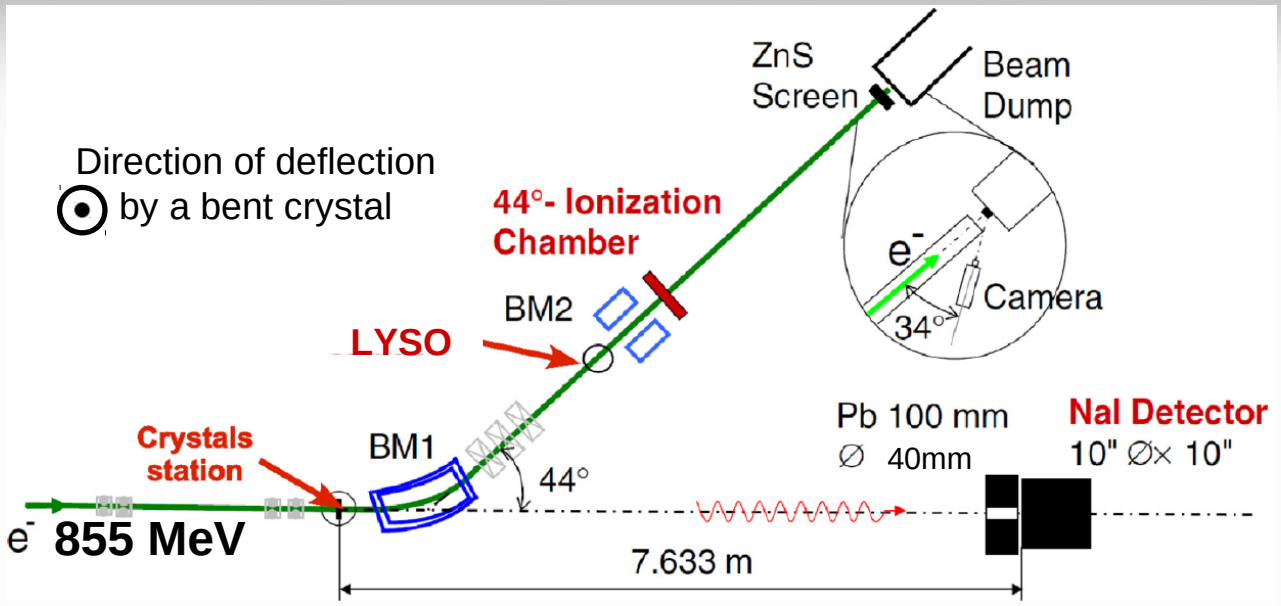




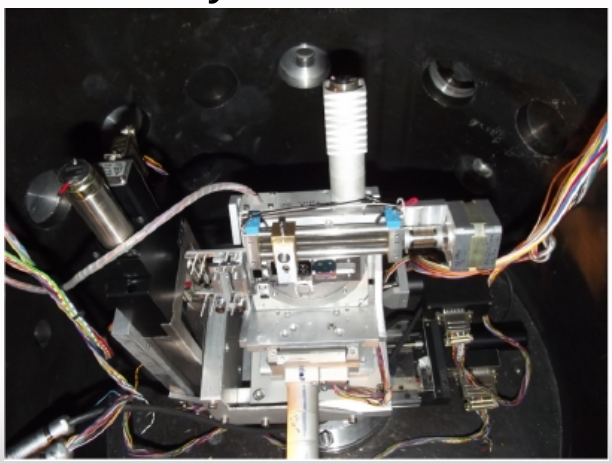




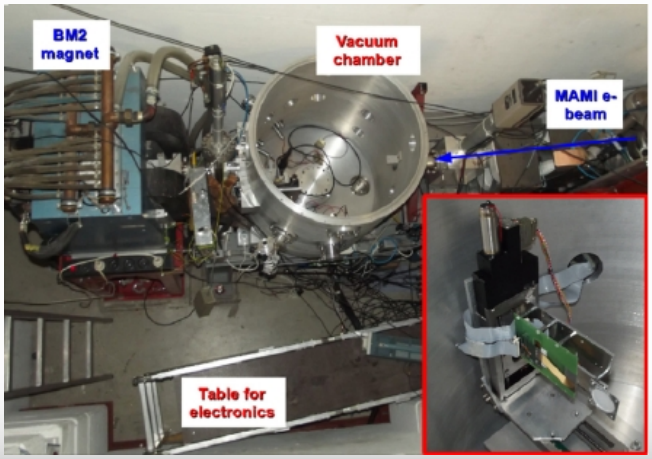
Experimental setup at Mikrotron MAMI



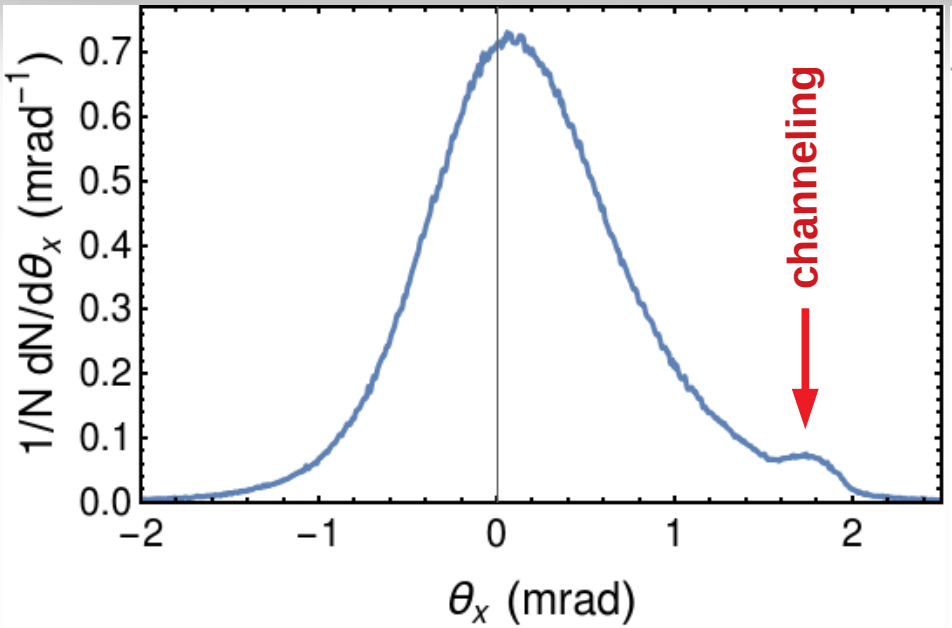
Crystal station

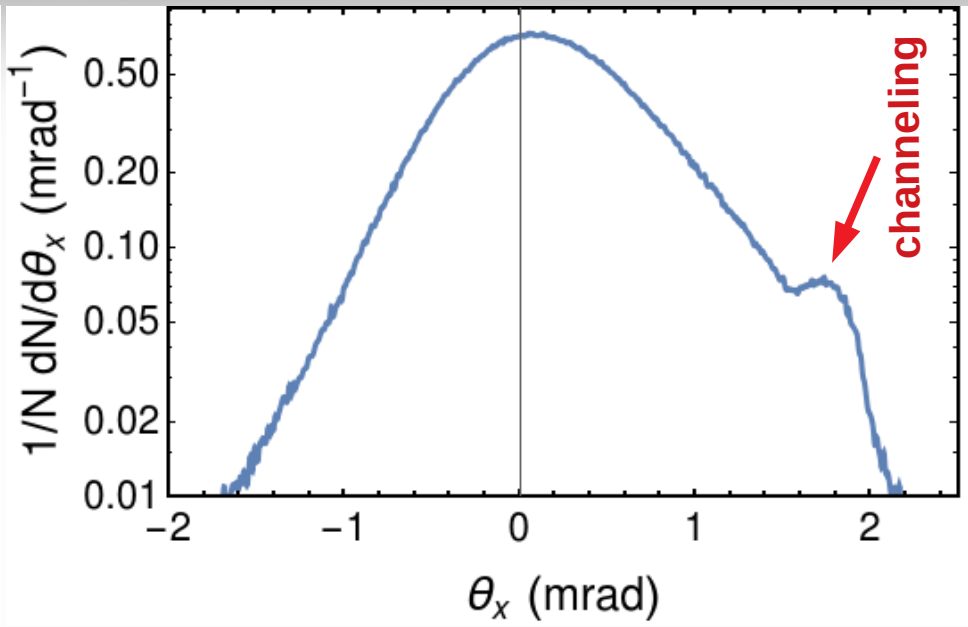


Detector station



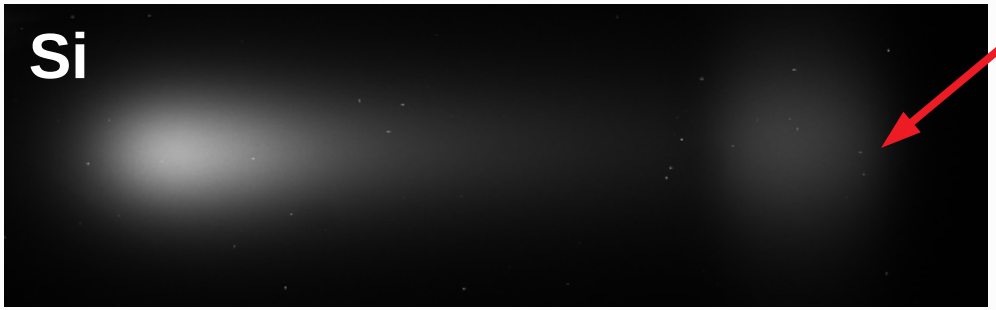
Crystal characterization: simulations of the deflection of 855 MeV electrons at Mainz Mikrotron MAMI





LYSO screen photo example

channeling



Simulation parameters:

- **855 MeV electrons**
- **Si (111)**
- bending angle **1.75 mrad**
- Crystal length **0.175 mm**

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

D. De Salvador et al. JINST 13, C04006 (2018)

A. Mazzolari, A.I. Sytov, et al. Eur. Phys. J. C 80, 63 (2020)

CRYSTALRAD simulation code*

Main conception – tracking of charged particles in a crystal in averaged atomic potential

Program modes:

- **1D** model – particle motion in an interplanar potential
- **2D** model – particle motion in an interaxial potential

Simulation of the different physical processes:

- Multiple and single **Coulomb scattering** on nuclei and electrons.
- **Nuclear scattering**
- **Ionization energy losses**
- **Crystal geometry**

Multiturn simulations** taking into account both **betatron** and **synchrotron oscillations** with **radiation losses** in a **crystal**

Simulation of **radiation losses** by Baier-Katkov formula

Advantages:

- High calculation speed (up to **10^3 particles/s/core**)
- **MPI** parallelization for high performance computing

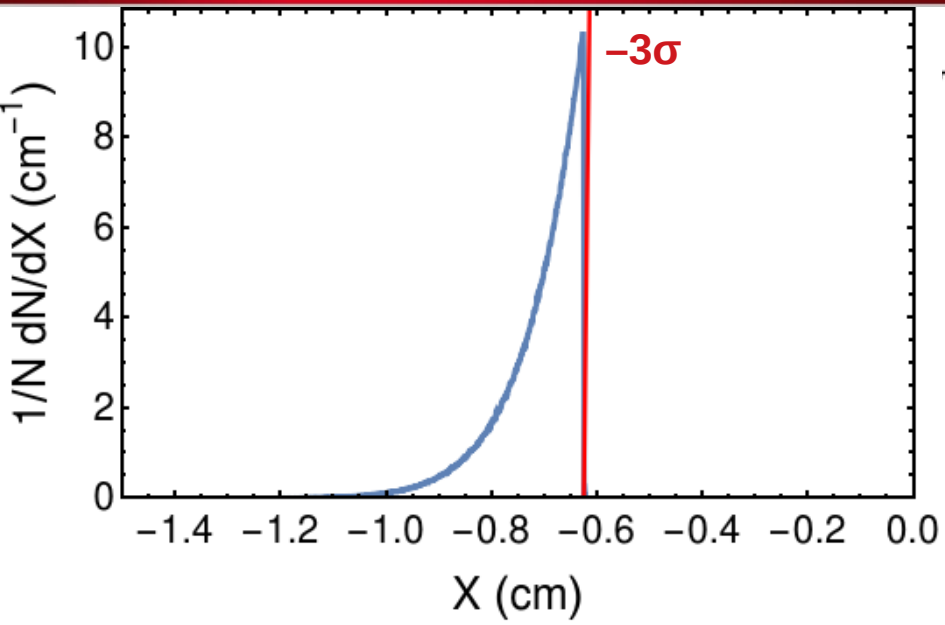
Marie Curie Marie Sklodowska-Curie Action Global Fellowships by A. Sytov in 2021-2024, Project TRILLION

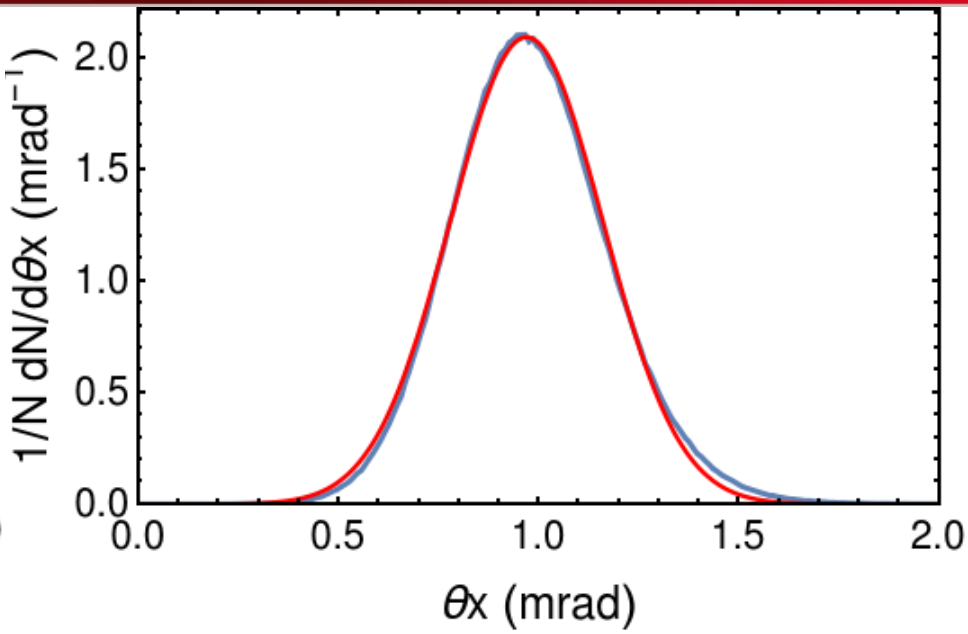
Dedicated supercomputer time at CINECA: project LEADER and MIRACLE Cineca ISCRA Class B

***A.I. Sytov, V.V. Tikhomirov and L. Bandiera Phys. Rev. Acc. and Beams 22, 064601 (2019)**

****A. I. Sytov, V. V. Tikhomirov, and A. S. Lobko. Phys. Rev. Acc. and Beams 20, 071001 (2017)**

Setup for simulations and beam at the crystal entrance





Beam Parameters:

- ϵ_x=339 nm, ϵ_y=35 nm, σe/E=0.977e-3, E=6 GeV
- **σ**=√βϵ_x (betatron sigma)
- xcrystal= –3σ, xseptum=4σ

Cuts for the extracted beam:

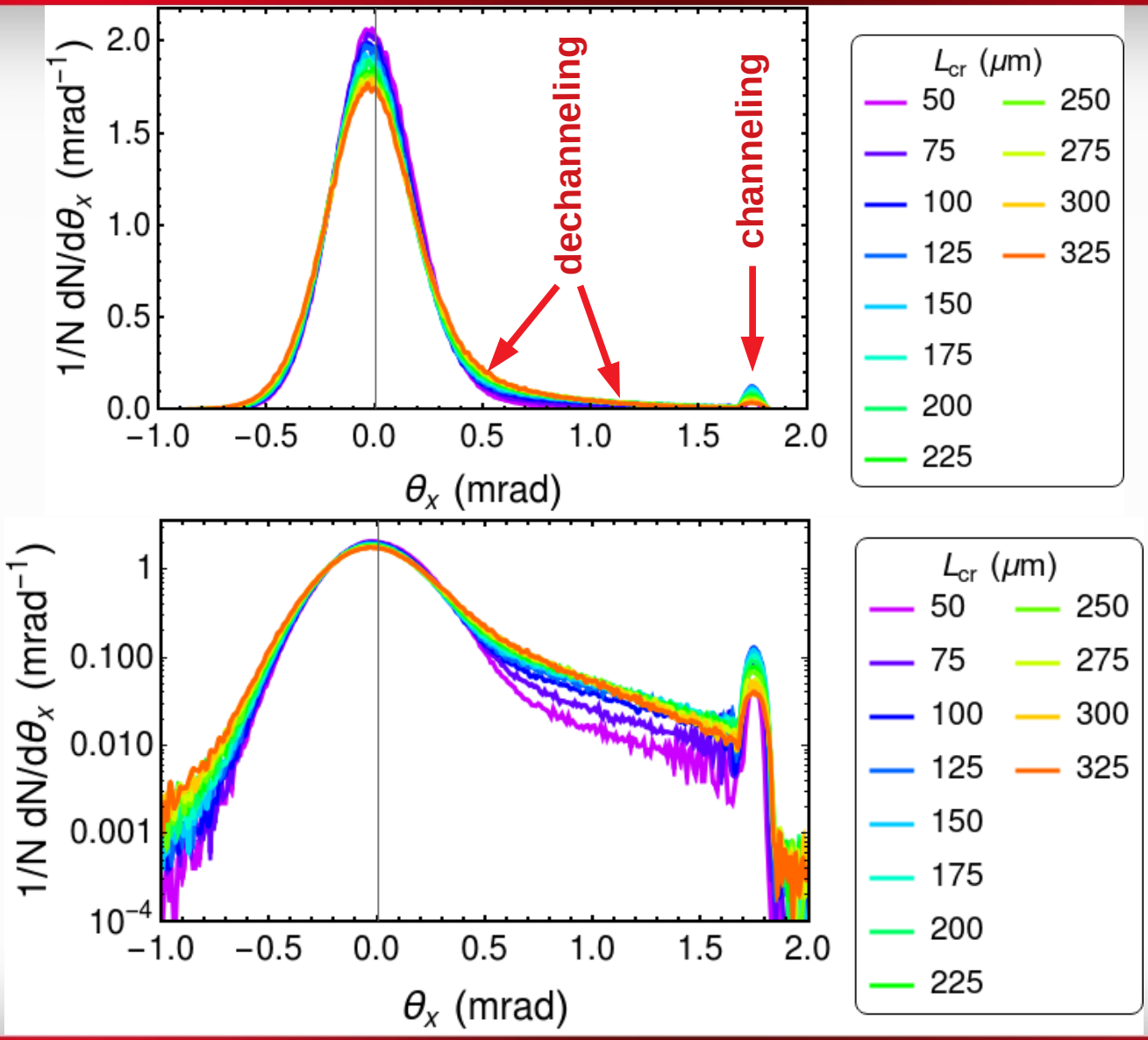
- **x** > 4 σ = 0.98 cm
- -4 mrad < $\boldsymbol{\theta}_x$ < 0 mrad
- **E** = **6.0±0.1 GeV**
- **Nturns** = 100

Beam **angular divergence** at the crystal entrance: **0.18 mrad**

Critical channeling angle: **0.07 mrad** (Si, (111))

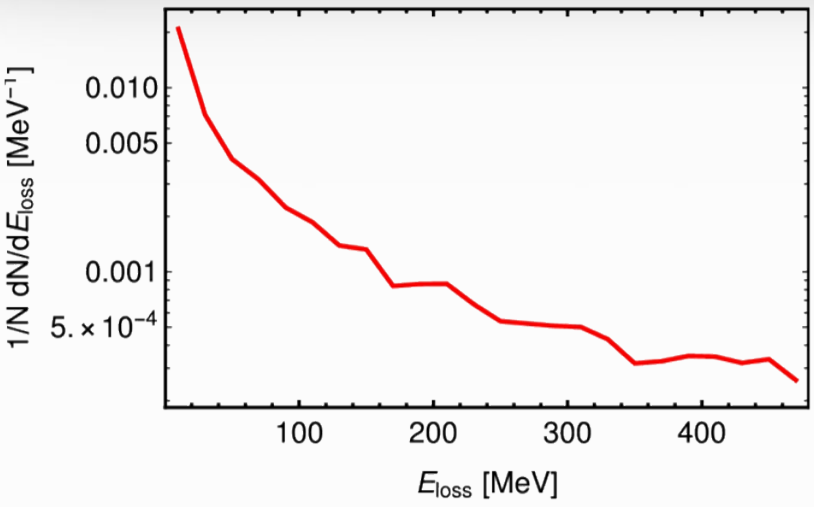
Optimal alignment at –3σ: **0.97 mrad**

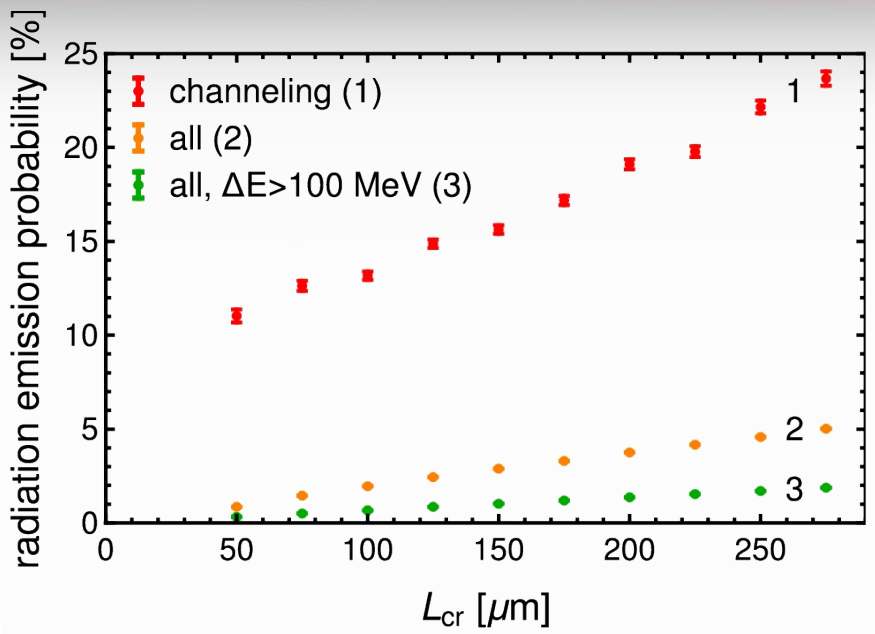
Simulated angular distributions of deflected beam



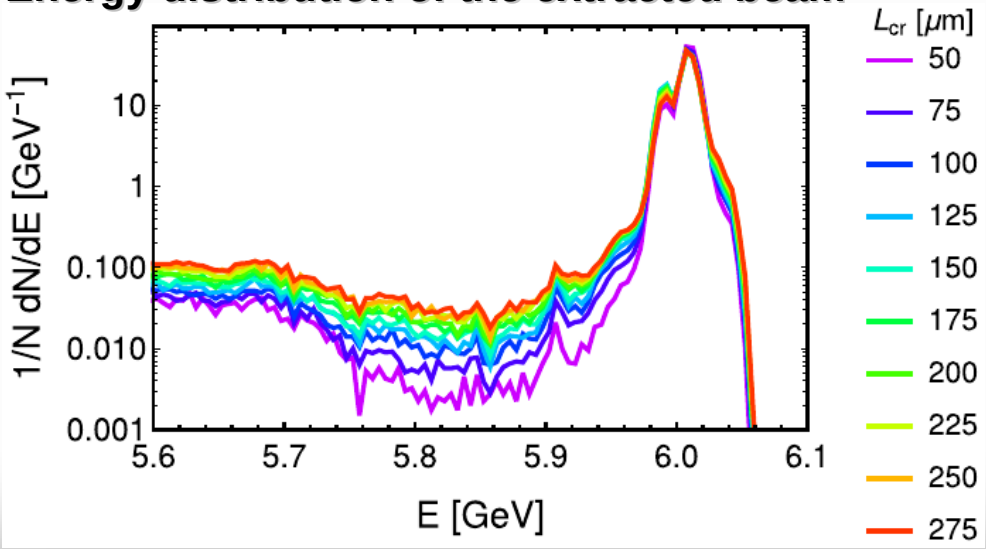
Crystal-based extraction simulations: energy losses

Radiation spectrum





Energy distribution of the extracted beam

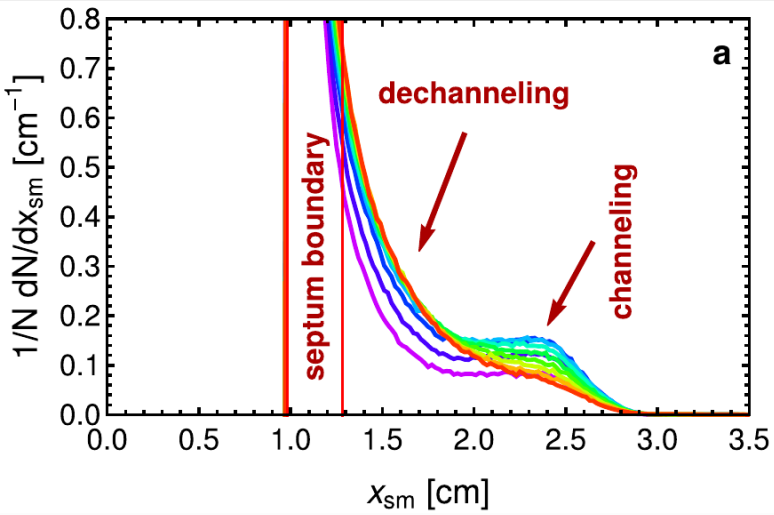


Radiation emission probability as function of the crystal thickness for (**red**) channeled particles, for (**yellow**) all particles and for (**green**) particles with radiation energy losses exceeding 100 MeV.

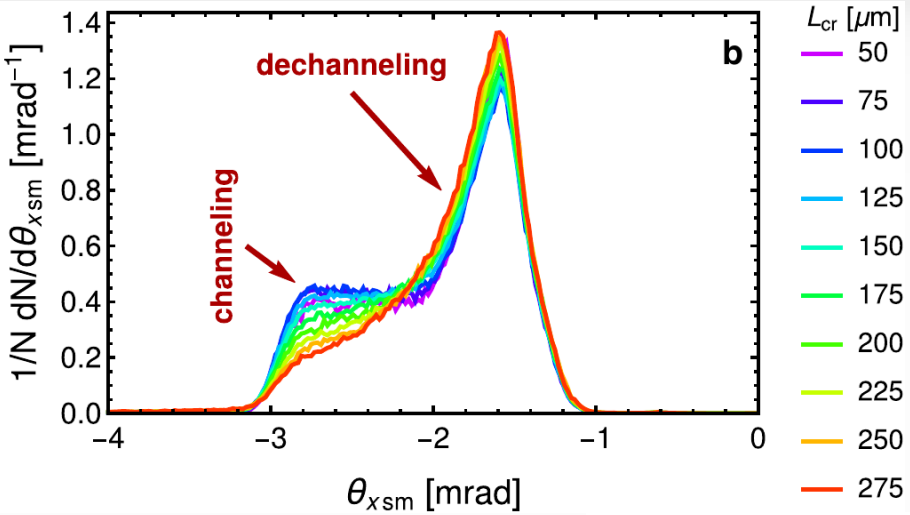
Energy remains within **RF bucket**

Crystal-based extraction: simulation results

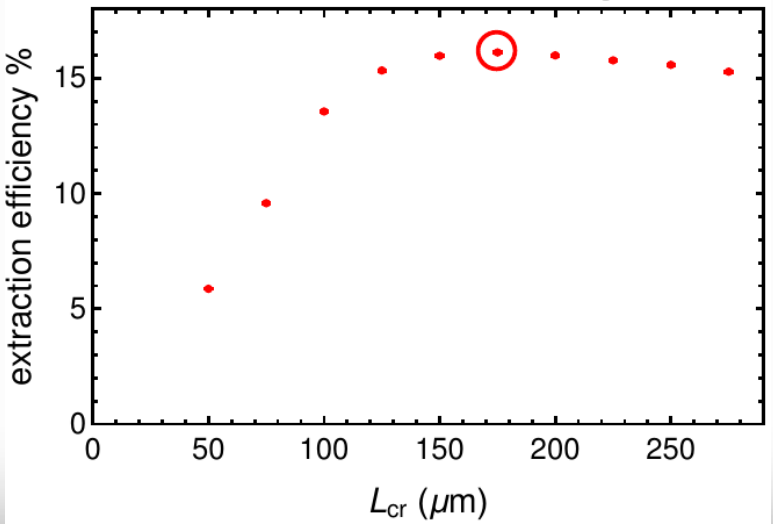
Coordinate distribution of extracted beam

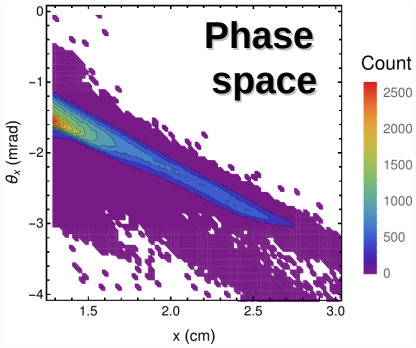


Angular divergence of extracted beam



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 %

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

In the future:
Crystal-based extraction from the DESY II synchrotron as a **Geant4 example**

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)

More details in my poster PU-9

Conclusions

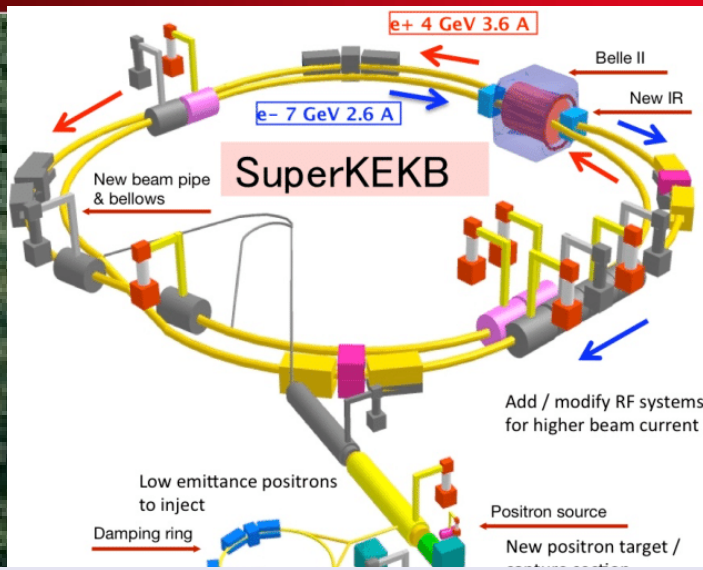
- The **first proof-of-principle experiment** on electron crystal-based extraction by using planar channeling in a bent crystal has been proposed for the **DESY II Booster Synchrotron**.
- The **extraction** line already **exists**, only a bent crystal should be installed.
- Simulations of the DESY crystal-based extraction show that the multiturn extraction efficiency may reach **16 %**.
- Crystal thickness was optimized to be **0.175 mm** for the deflection angle **1.75 mrad**.

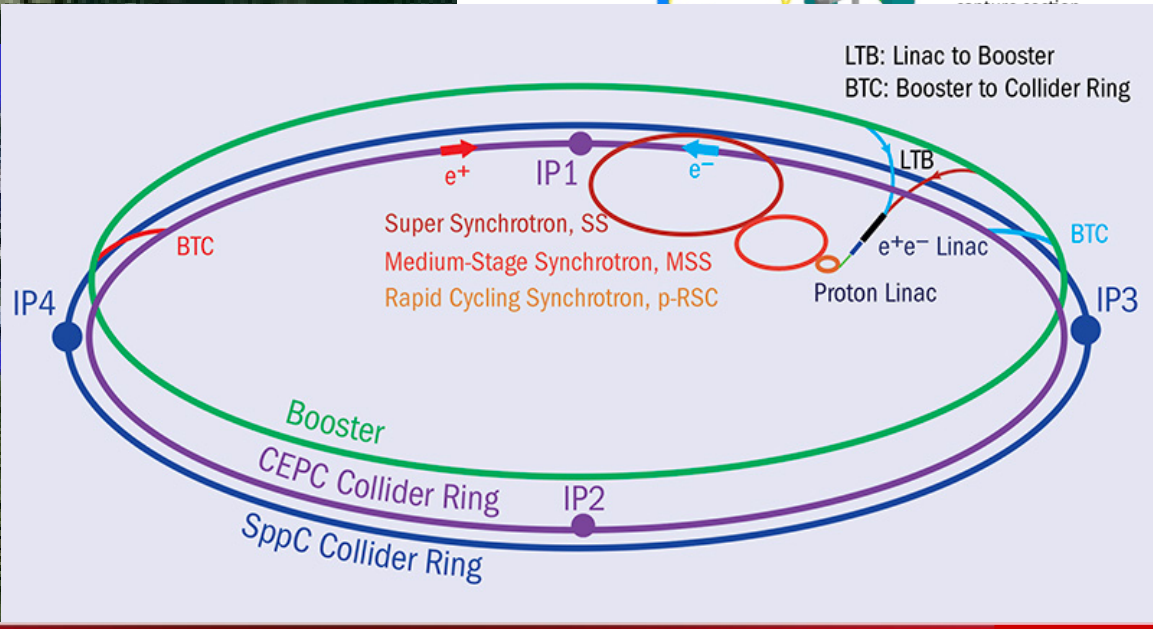
Applications:

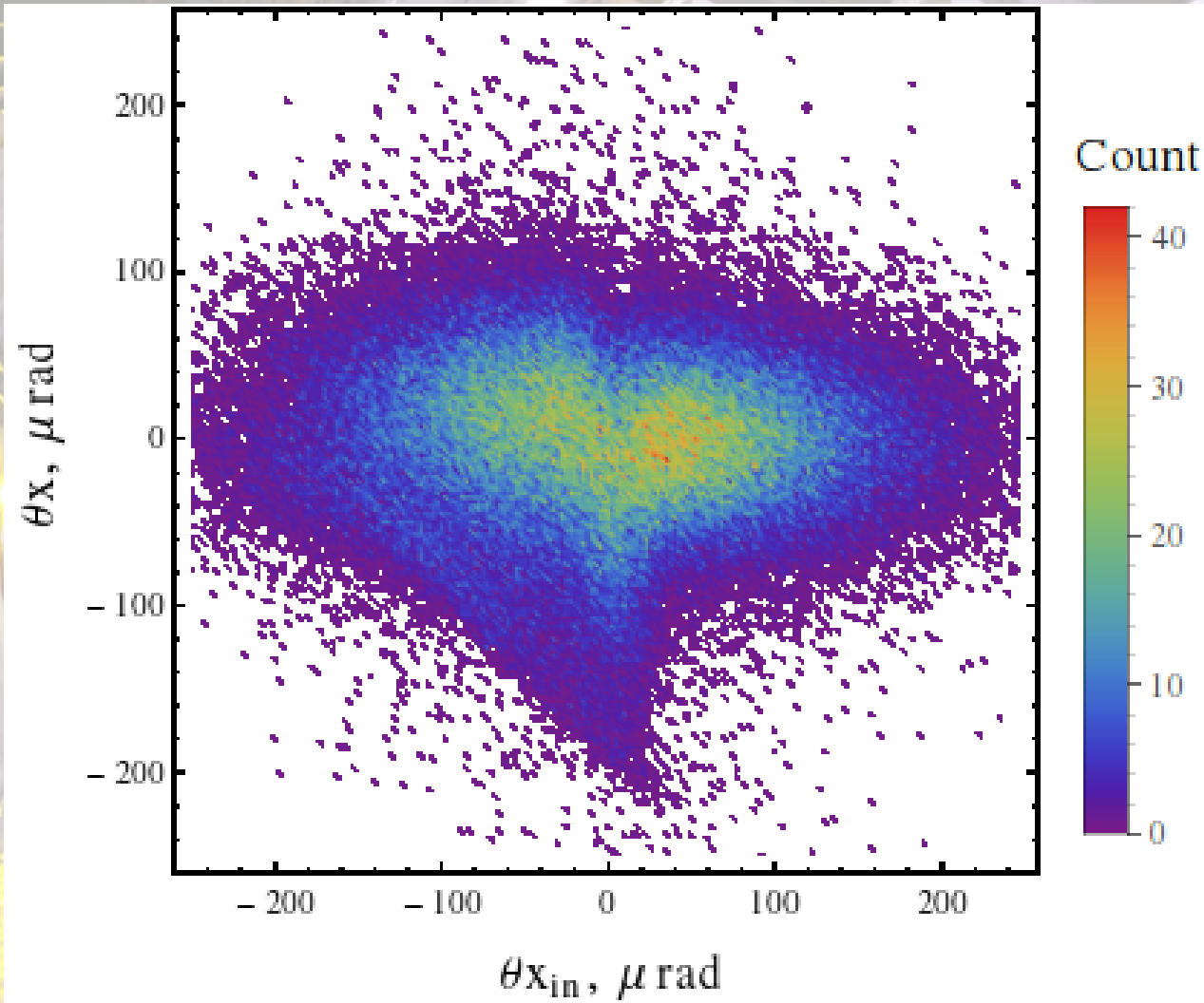
- Nuclear and particle physics detectors and generic **detector R&D**
- **Fixed-target experiments** in **high-energy physics** including future **lepton colliders**
- Also: **crystal-based collimation** (**synchrotron light sources**, **colliders**)

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

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



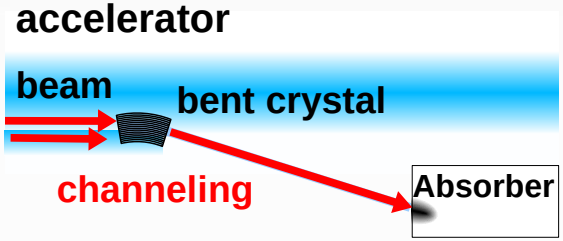


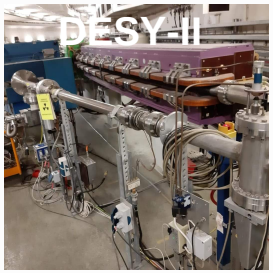


Thank you for attention!

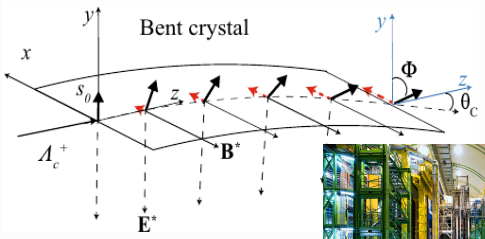
Applications*

Crystal-based collimation or beam extraction from an accelerator

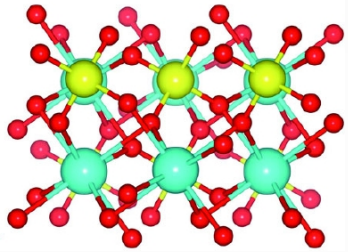




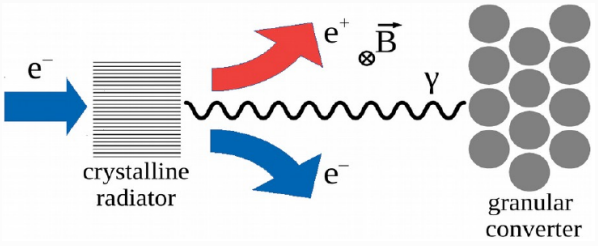
Measurement of dipole magnetic and electric moments of exotic particles

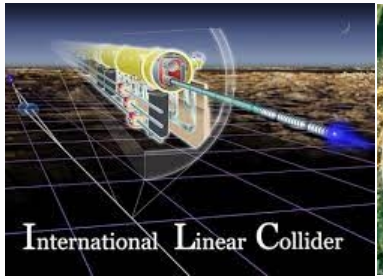


Ultrashort crystalline calorimeter

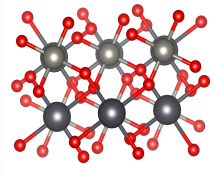


Positron source for future e+/e- and muon colliders

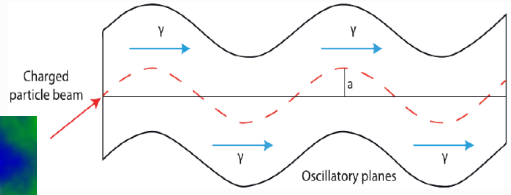


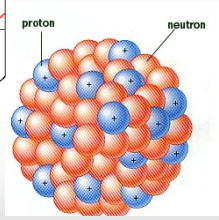


Oriented crystals

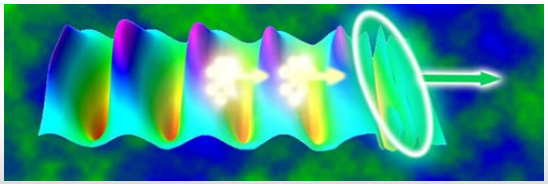


X and γ-ray source for nuclear and medical physics



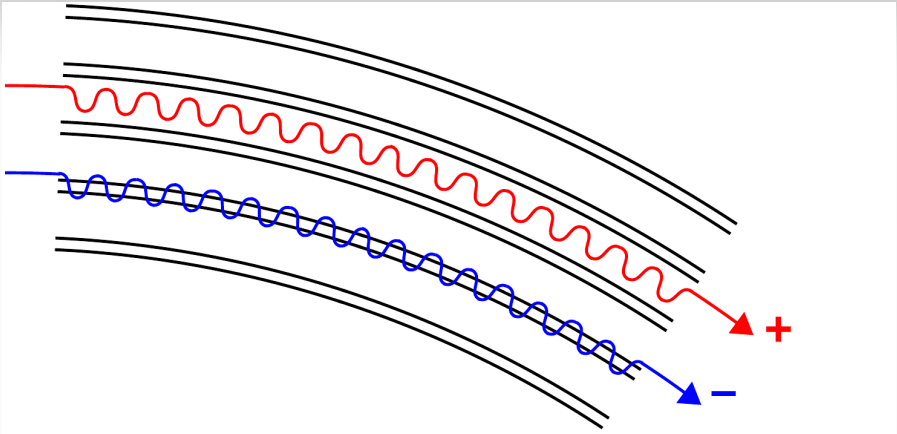


Plasma acceleration



*From A. Sytov presentation at the European Researchers' Night 2021

Crystal-based extraction: the idea

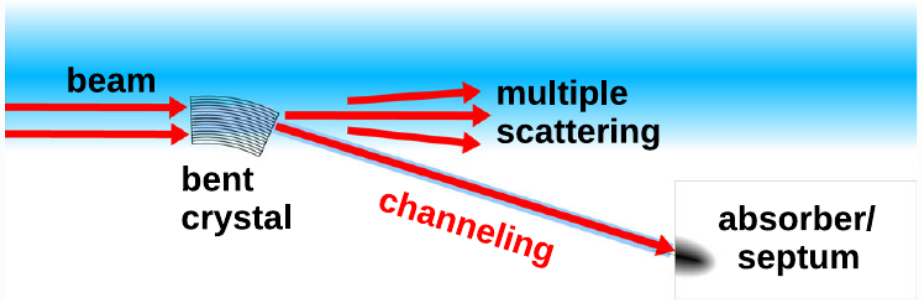


Channeling

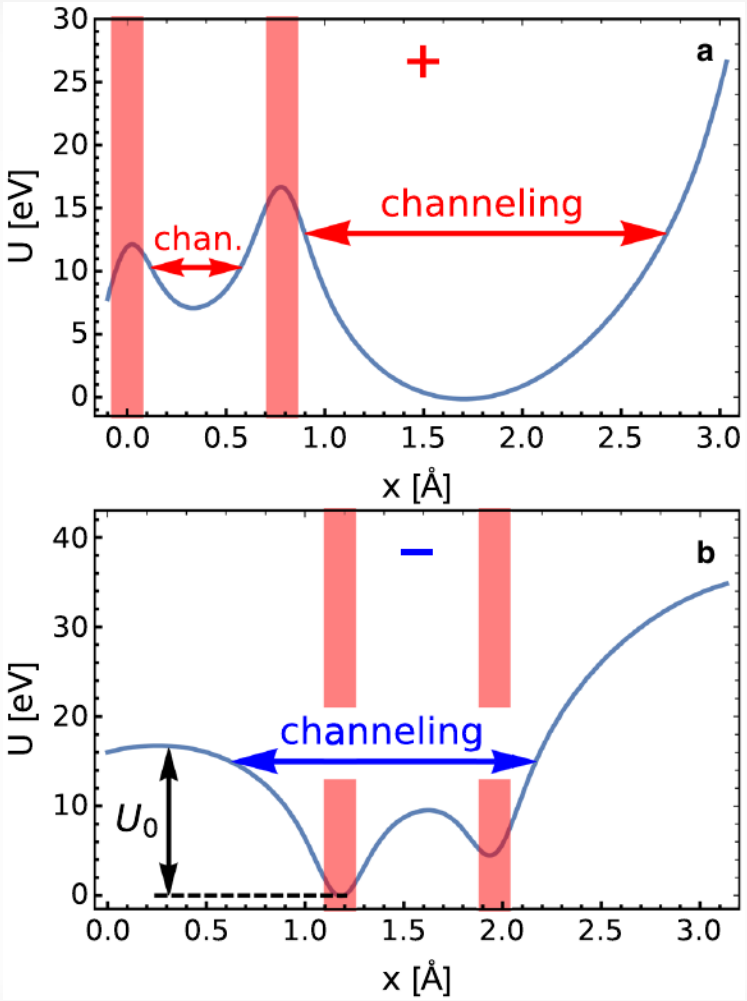
Planar channeling*:

- Charge particle penetration through a monocrystal along its atomic planes

Crystal-based extraction**



Interplanar potential



*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