A. Sytov[1,2], **L. Bandiera**[1], **G. Kube**[2], **A. Mazzolari**[1], **G. Paternò**[1], **S. Strokov**[2], **K. Wittenburg**[2]

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[2]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

FULL SIMULATIONS OF BEAM DYNAMICS OF CRYSTAL-BASED EXTRACTION FROM THE DESY II BOOSTER SYNCHROTRON USING BDSIM SIMULATION CODE BOOSTED WITH G4CHANNELINGFASTSIMMODEL

Channeling 2024

Riccione, 10/09/24

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:

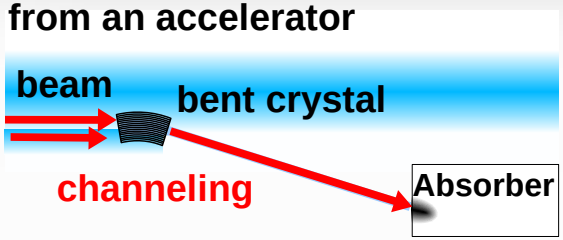
- **A. Sytov** – project coordinator
- **L. Bandiera** – INFN supervisor
- **K. Cho** – KISTI supervisor
- **G. Kube** – DESY supervisor
- **I. Chaikovska** – IJCLab Orsay supervisor

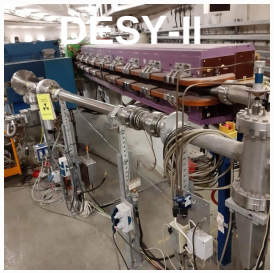
Location:

- 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)

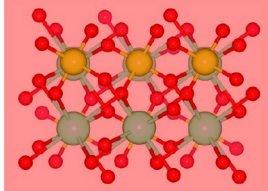
Applications*

Crystal-based beam extraction from an accelerator



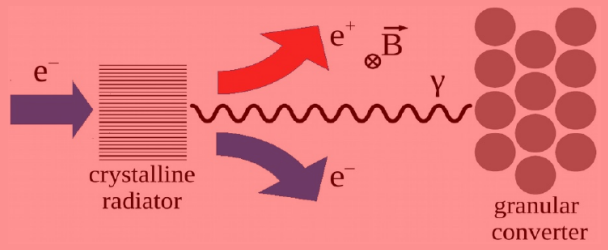


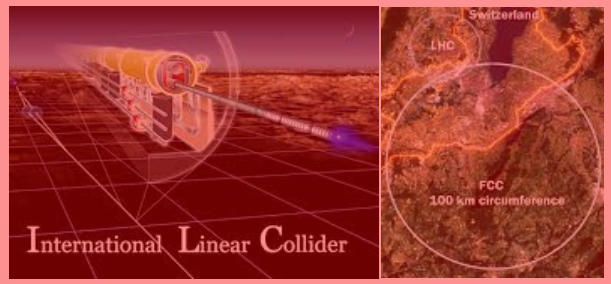
Ultrashort crystalline calorimeter



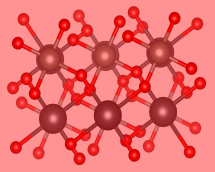
Gamma-ray Space Telescope

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



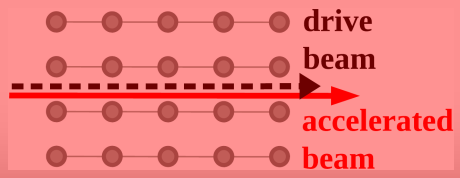


Oriented crystals

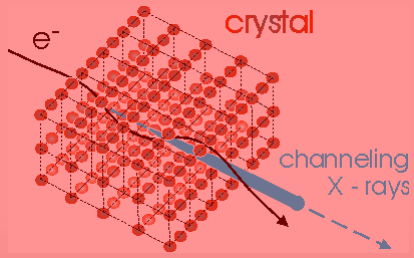


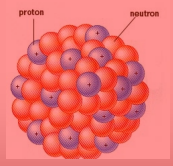
Measurement of dipole magnetic and electric moments of exotic particles

Plasma acceleration



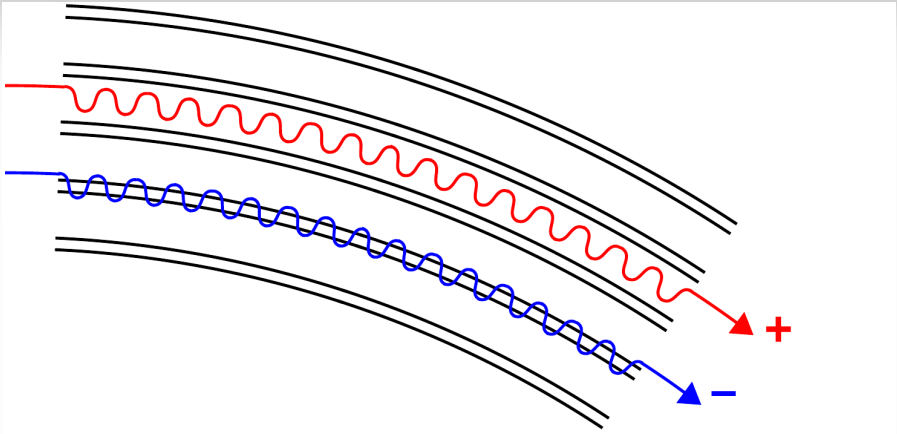
X and γ-ray source for nuclear and medical physics





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

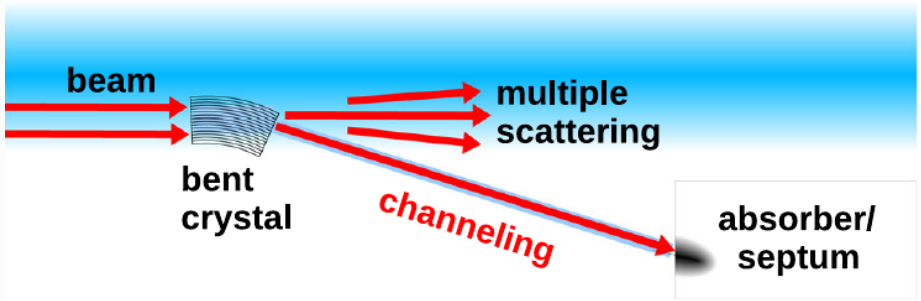
Crystal-based extraction: the idea



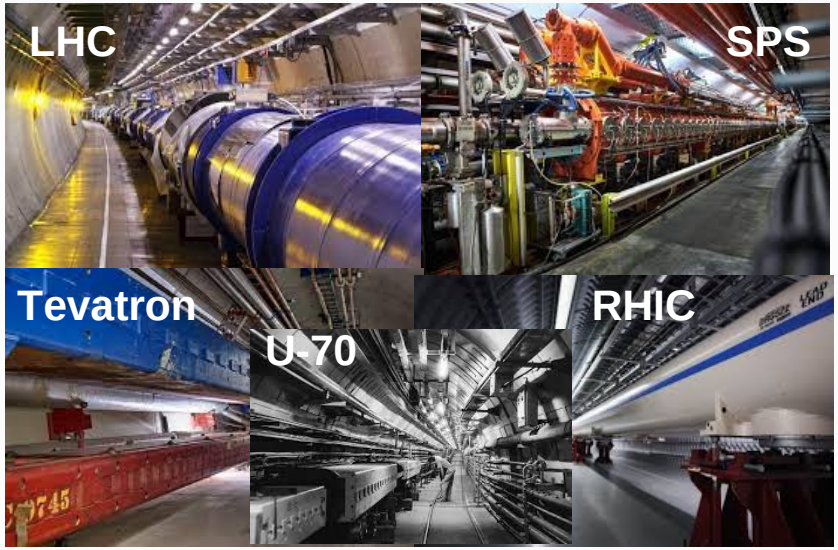
Planar channeling*:

- 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**

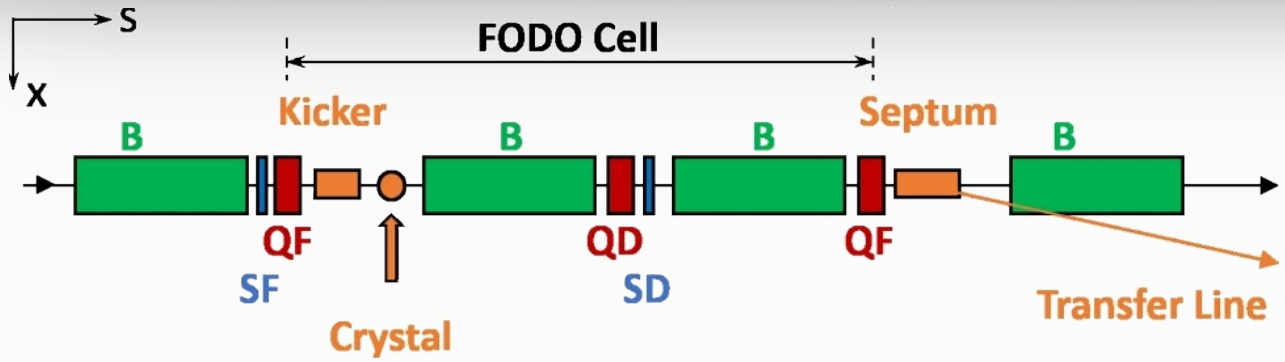


Crystal-based extraction/collimation: applied only for hadrons, not yet for e-

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

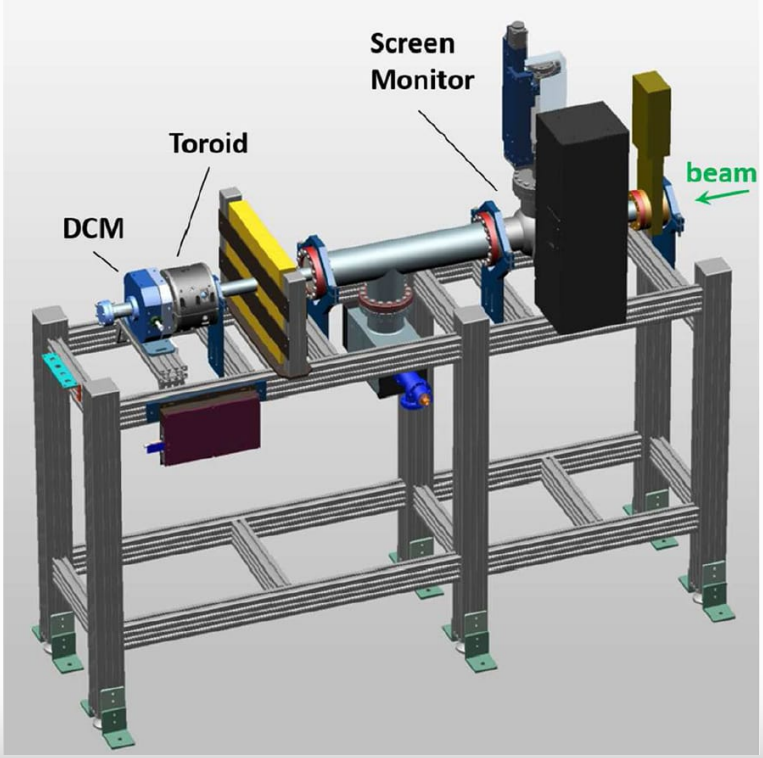
6 GeV electrons

Advantages:

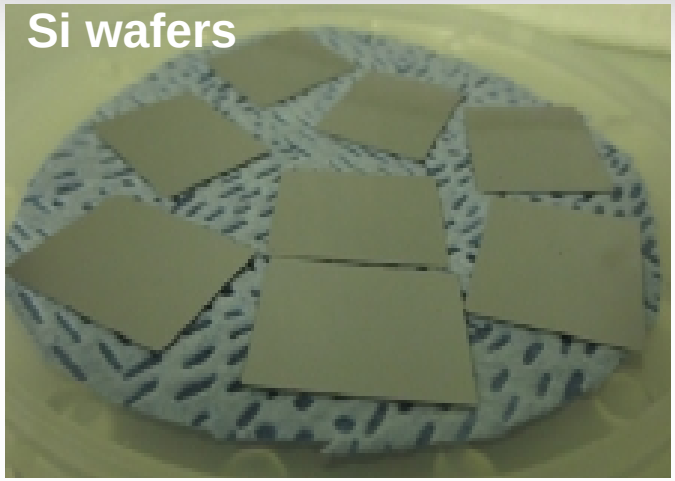
- Extraction of **primary** low-emittance and very **intense electron beam** in a **parasitic mode**.
- The **extraction line** including septum magnets already **exists => ideal for prove-of-principle**
- **Few GeV** electron beam, **typical for synchrotron light sources** existing in the world.

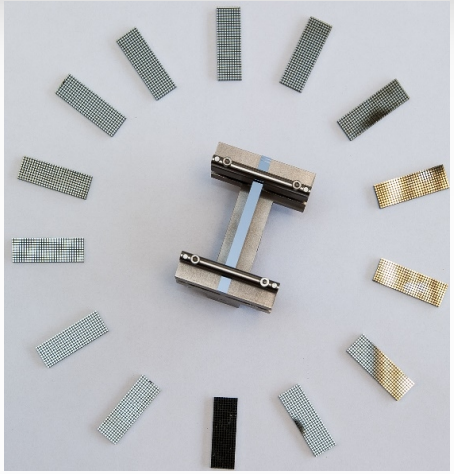
Applications:

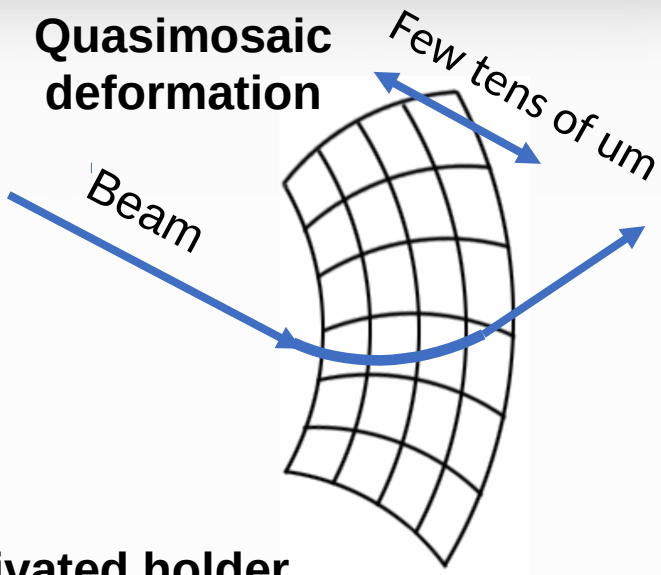
- Nuclear and particle physics detectors and generic **detector R&D**
- Fixed-target experiments in **high-energy physics** including future **lepton colliders**
- Also: **crystal-based collimation** (**synchrotron light sources**, **colliders**)

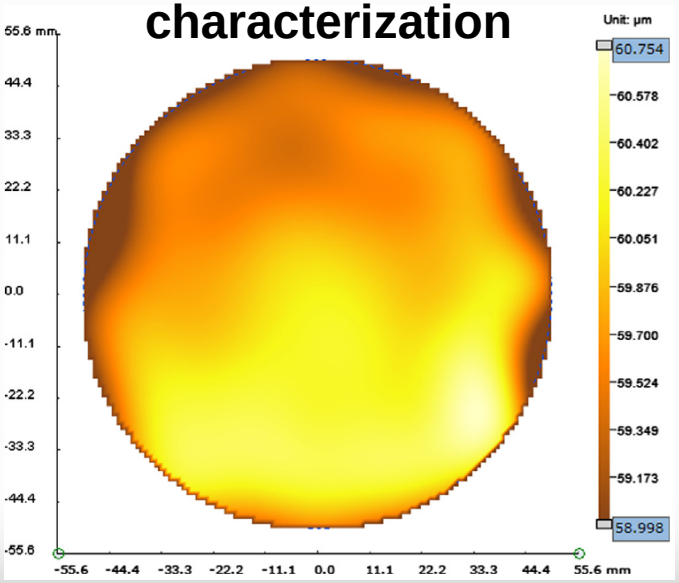


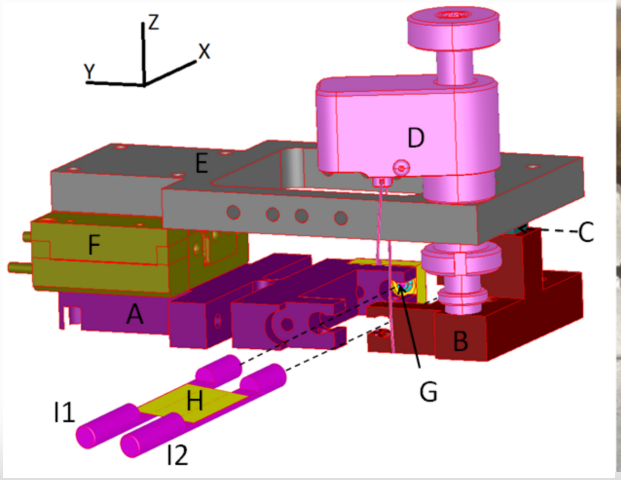
Manufacturing and characterization of bent silicon crystals @INFN Ferrara

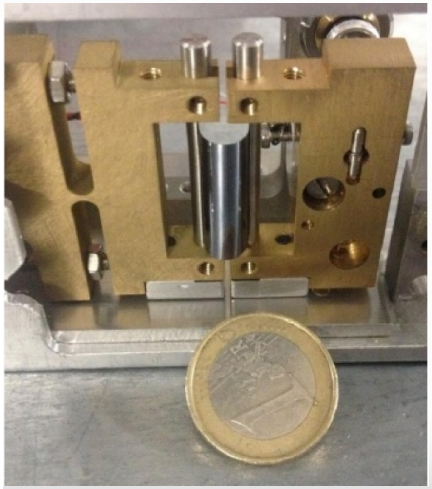




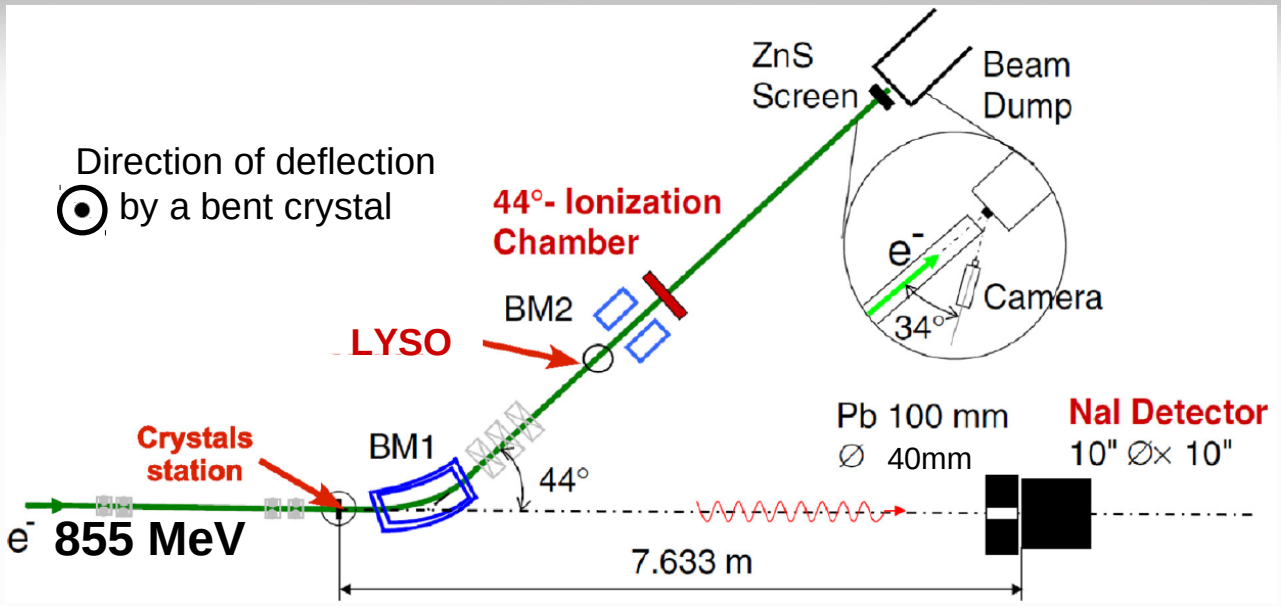




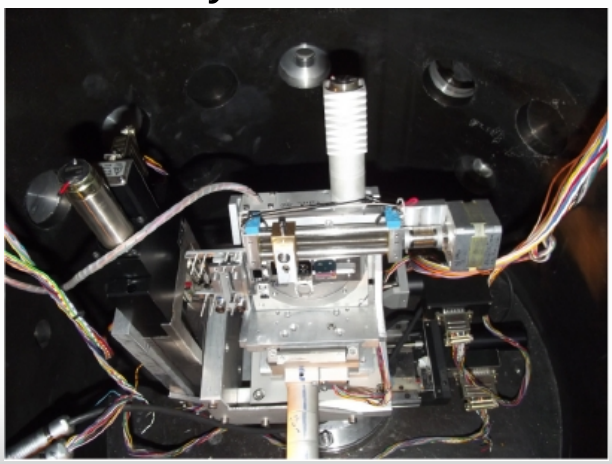




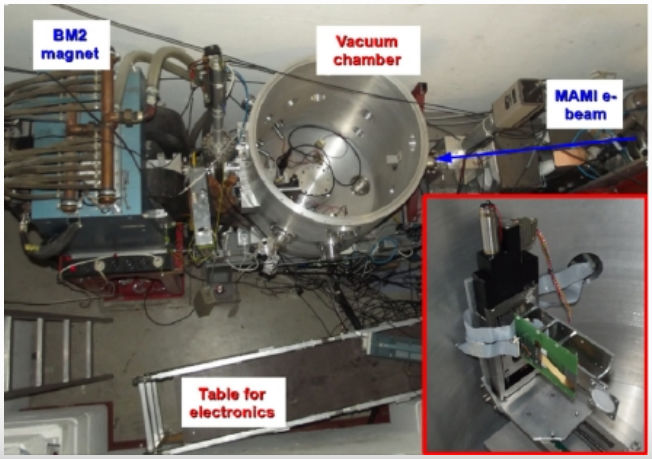
Experimental setup at Mikrotron MAMI



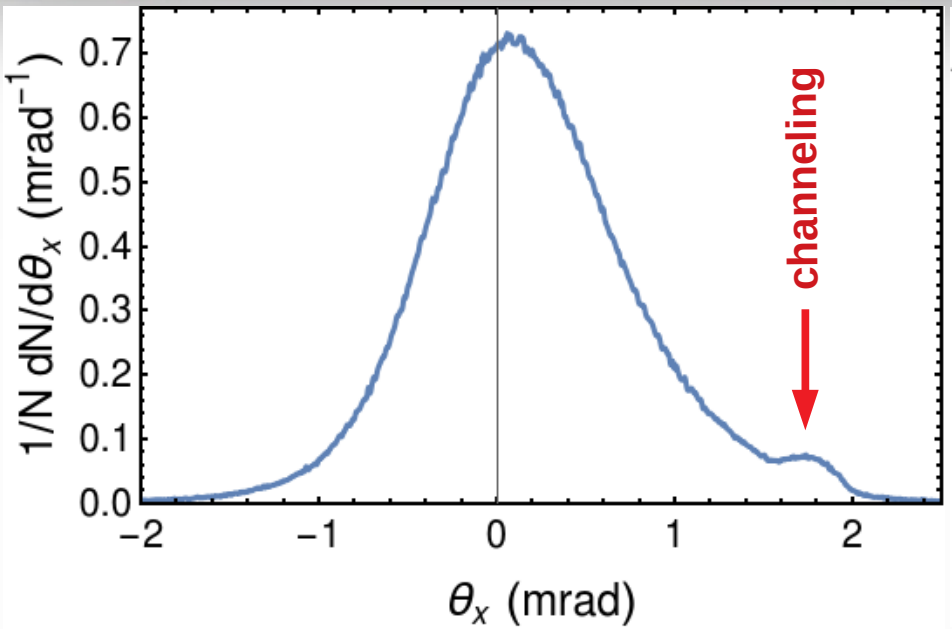
Crystal station

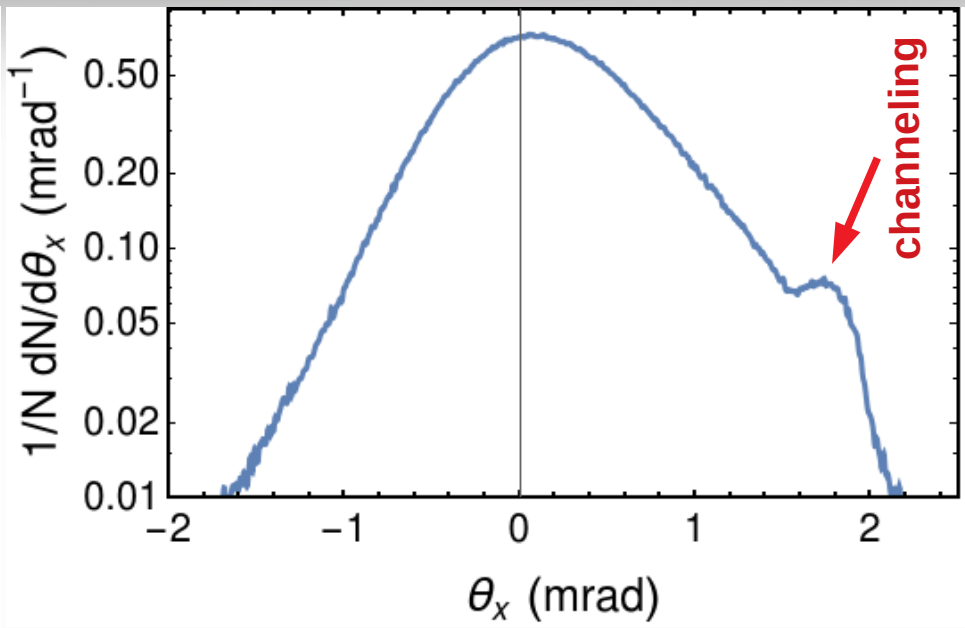


Detector station

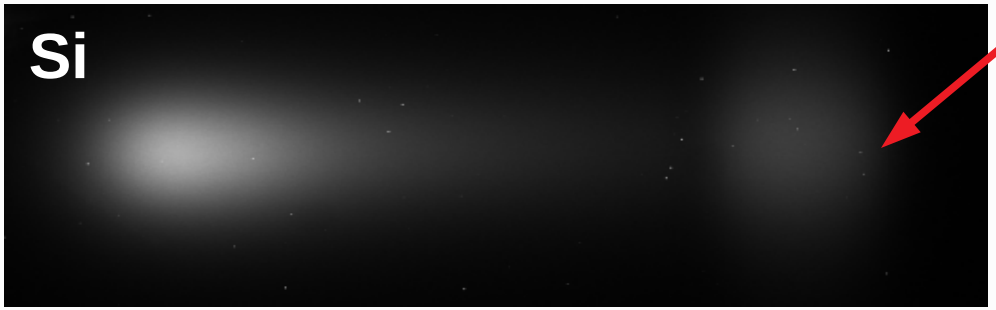


Crystal characterization: simulations of the deflection of 855 MeV electrons at Mainz Mikrotron MAMI





LYSO screen photo example



Simulation parameters:

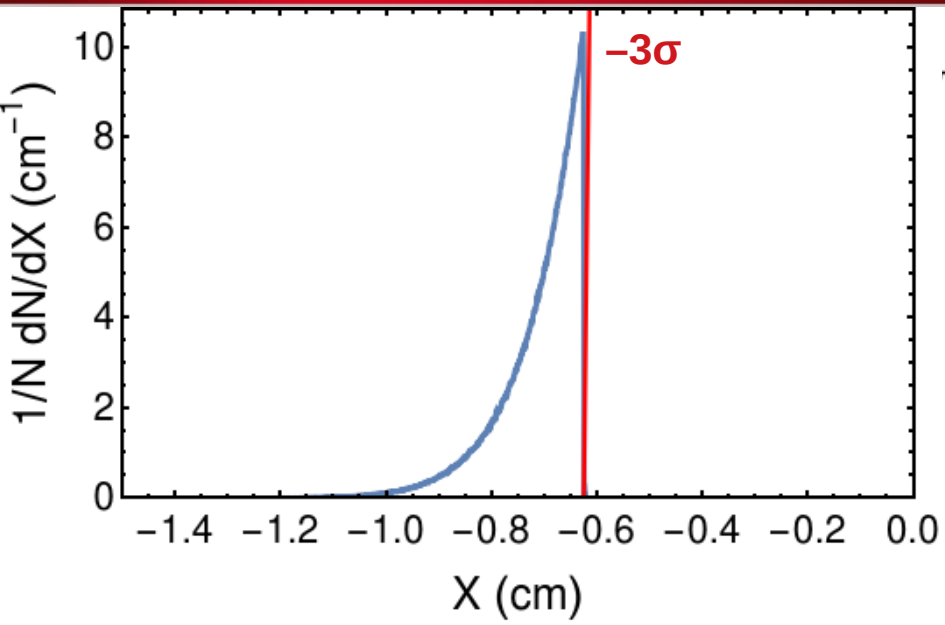
- **855 MeV electrons**
- **Si (111)**
- bending angle **1.75 mrad**
- Crystal length **0.175 mm**

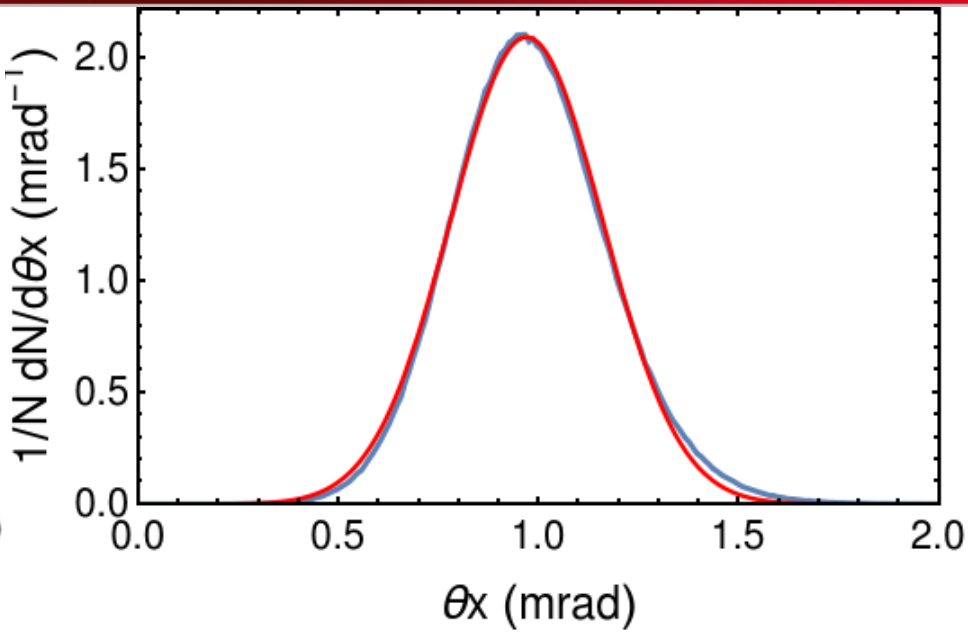
A.I. Sytov, L. Bandiera et al. Eur. Phys. J. C 77, 901 (2017)

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

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

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

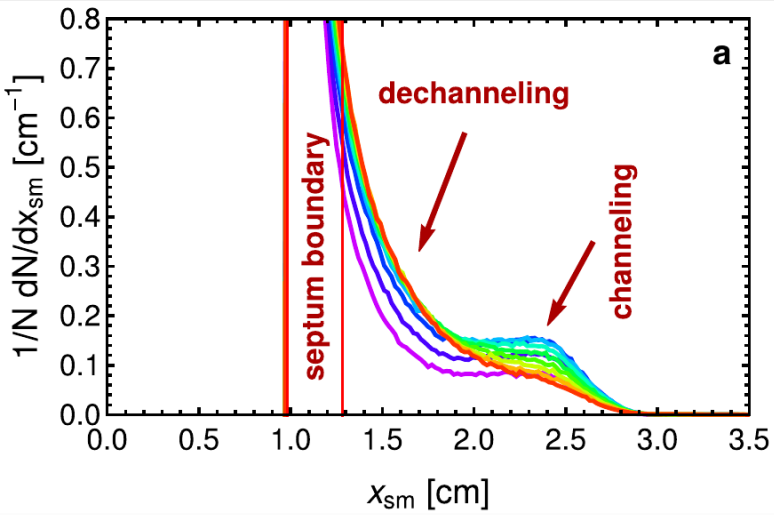
Beam **angular divergence** at the crystal entrance: **0.18 mrad**

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

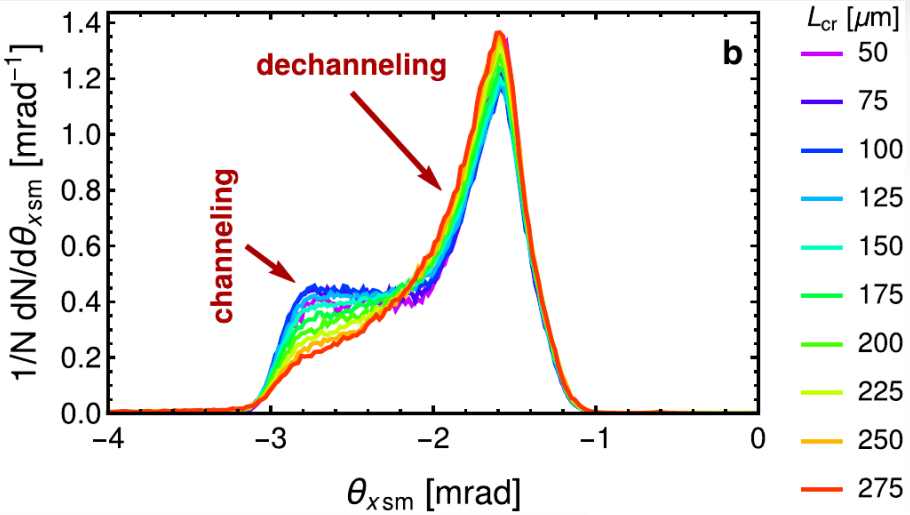
Optimal alignment at –3σ: **0.97 mrad**

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

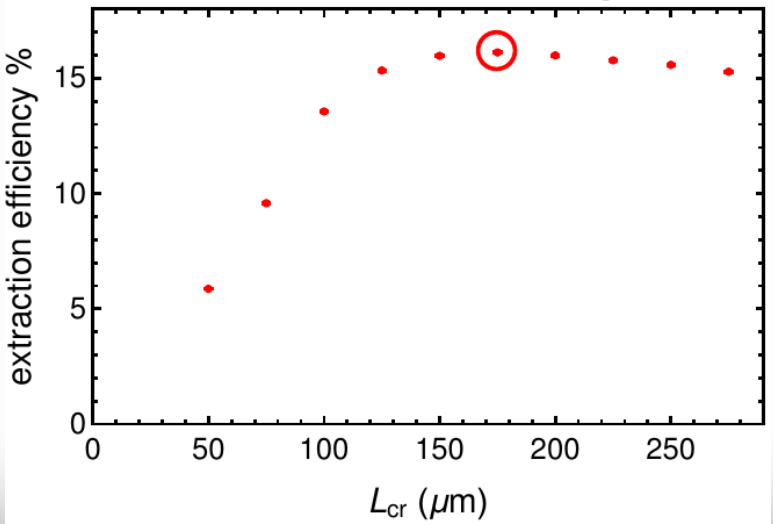
Coordinate distribution of extracted beam

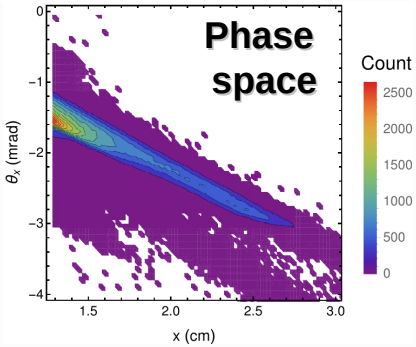


Angular divergence of extracted beam



Extraction efficiency





Crystal parameters:

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

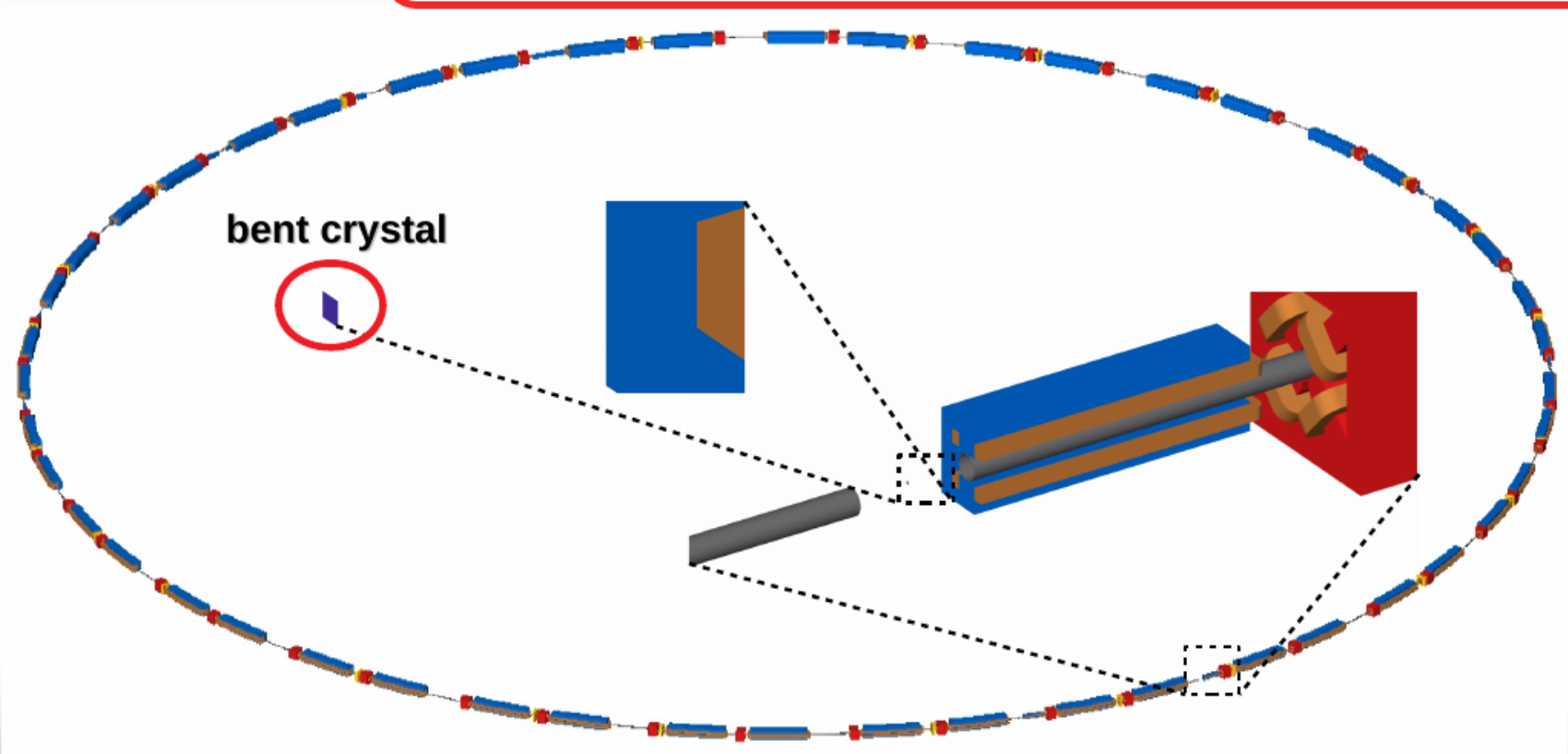
Maximal extraction efficiency:
16.1 %

*A. Sytov 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);
```

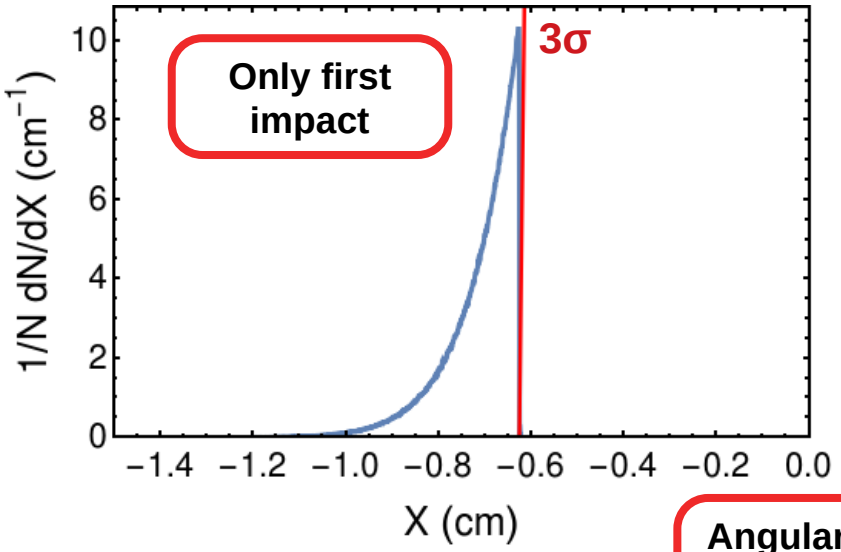
```
D12H: drift, l=0.4125;
CR1: usercomponent, userTypeName="crystaldeflector",
l=0.4125, xsize=1*cm, ysize=1*cm,
materialThickness=0.175*mm, offsetX=-1.126046*cm,
offsetY=0*mm, axisX=0.000, axisY = -0.00097, axisZ = 0.,
horizontalWidth=1*m,  material="G4_Si",
vacuumMaterial="vacuum",
userParameters="crystalRegion:crystal1
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;
```

CrystalDeflector.cc

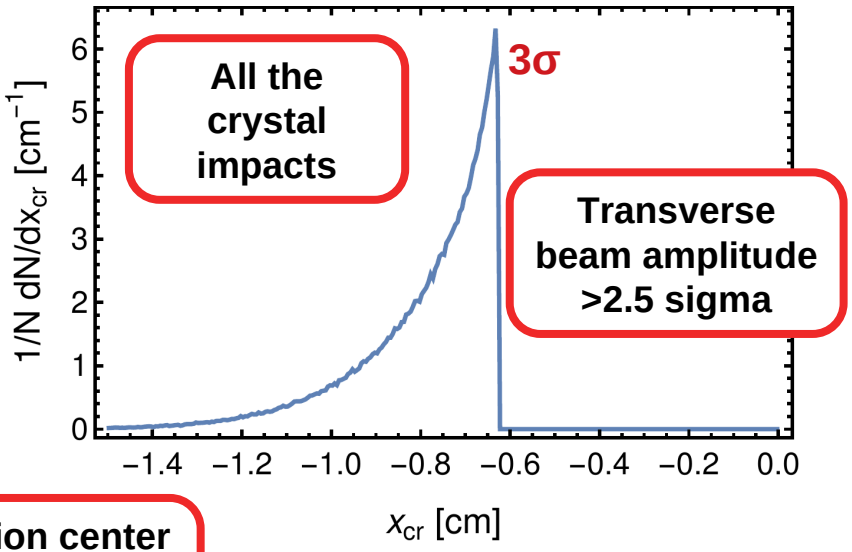
```
void CrystalDeflector::BuildCrystal()
{
    //build crystal solid
    G4Box* crystalSolid = new G4Box(name + "_crystal_solid",
                                    crystalXSize * 0.5,
                                    crystalYSize * 0.5,
                                    crystalMaterialThickness * 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 impact
(both transverse and energy spread is taken into account)

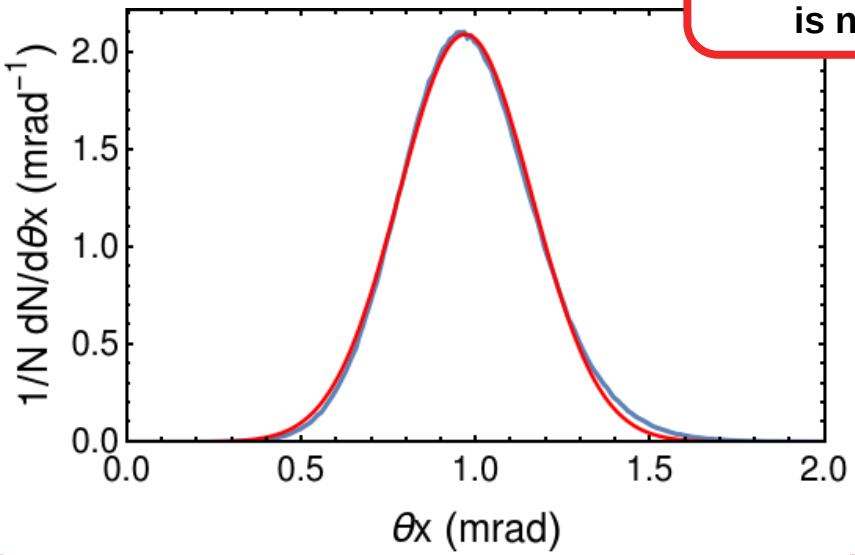
Old paper*

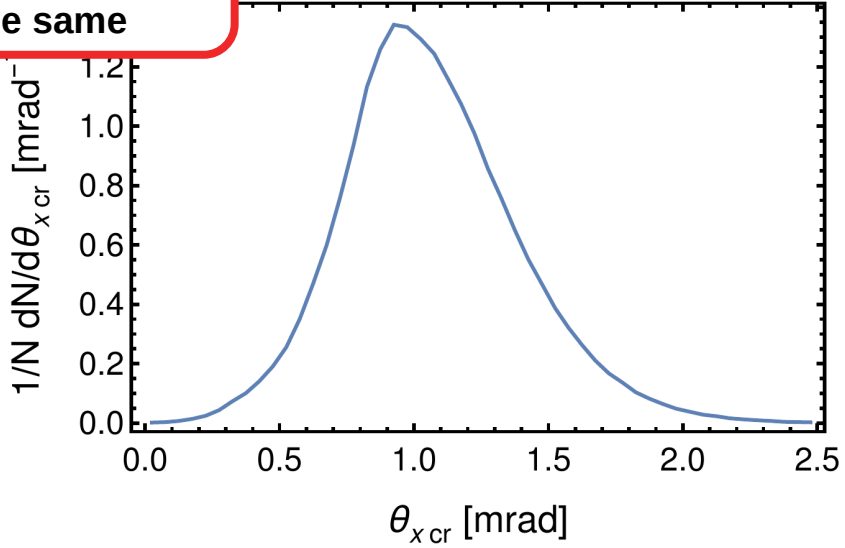


BDSim



Angular distribution center is nearly the same

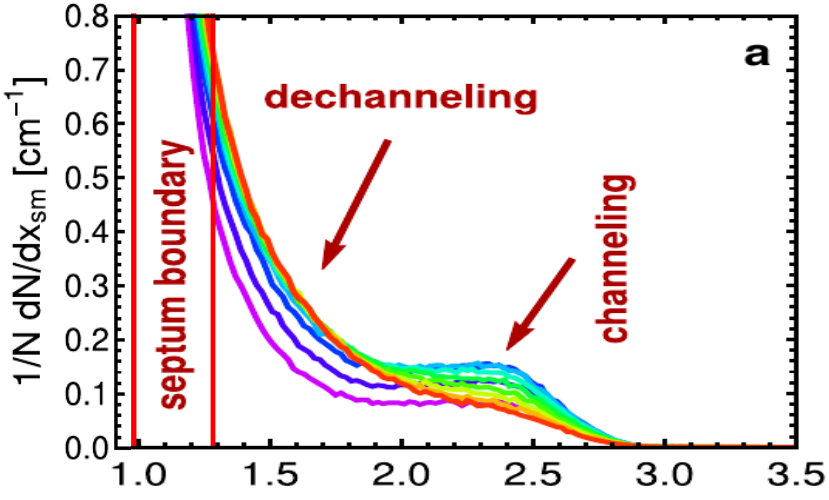




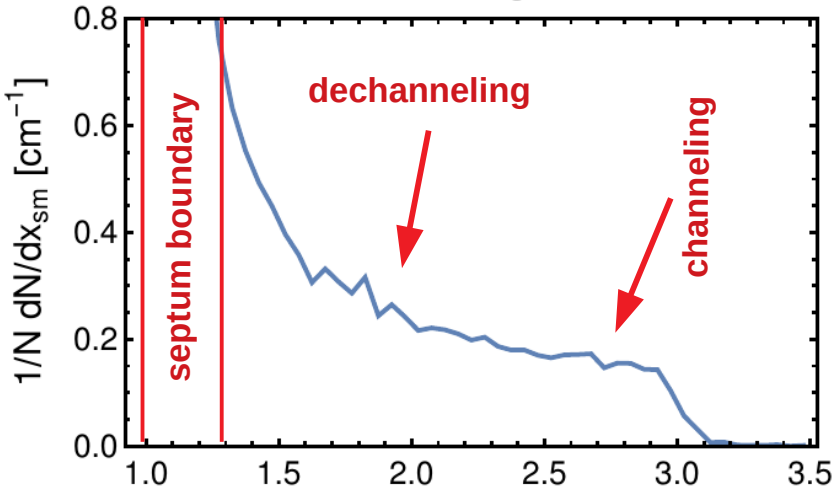
A. Sytov, G. Kube et al. Eur. Phys. J. C 82, 197 (2022)

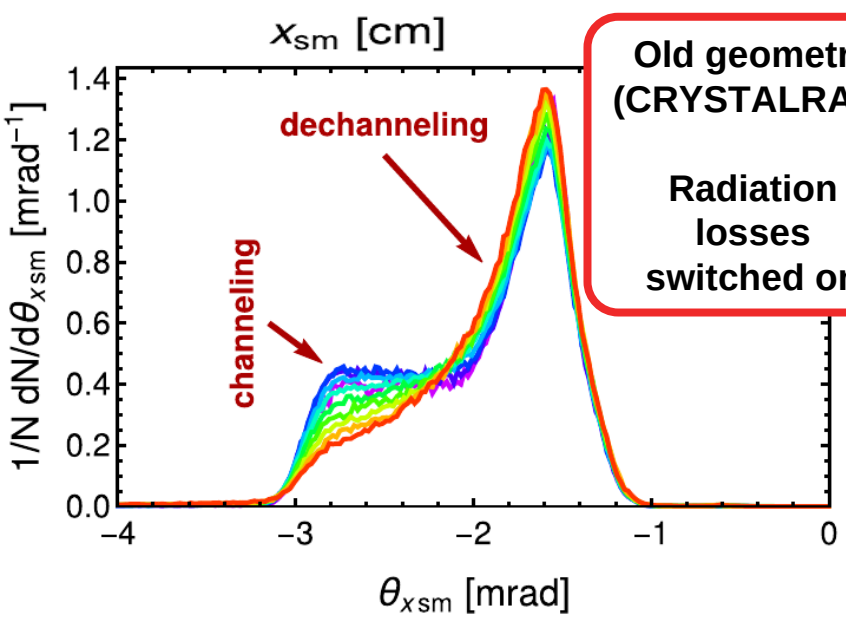
Crystal-based extraction: simulation results distributions at the septum magnet entrance

Old paper*



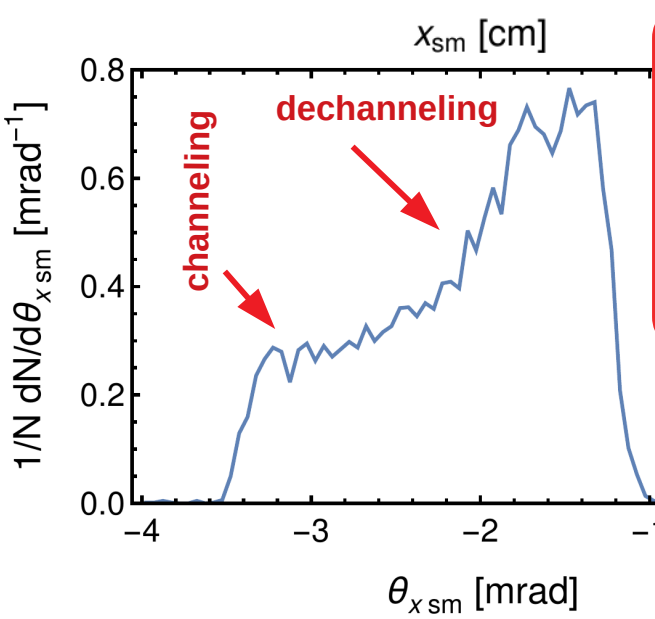
BDSim & ChannelingFastSimModel





Old geometry (CRYSTALRAD)

Radiation losses switched on



Updated crystal geometry

Radiation losses switched off

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

Summary and Future plans 2024

parameters* (still valid)

Bent crystal thickness	175 μm
Bent crystal bending angle	1.75 mrad
Bent crystal transverse position	−0.63 cm
Bent crystal angular alignment	0.97 mrad
Septum magnet transverse position	0.98 cm

Main part of the **beam** will **not touch** the **crystal**

5% of the **beam will enter** into the **septum magnet**

~50 pC can be extracted

Future plans

- **Turn on cavities** and **radiation losses** in the **crystal**
- **Track** the particles also in the **extraction line**
- Calculate the **beam emittance** and **beam charge** at the extraction line exit
- Simulation of **ionization losses** in the crystal to estimate the radiation damage if any
- Further **optimization** of the crystal geometry and location
- Consider **other crystal materials/crystalline effects**

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

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

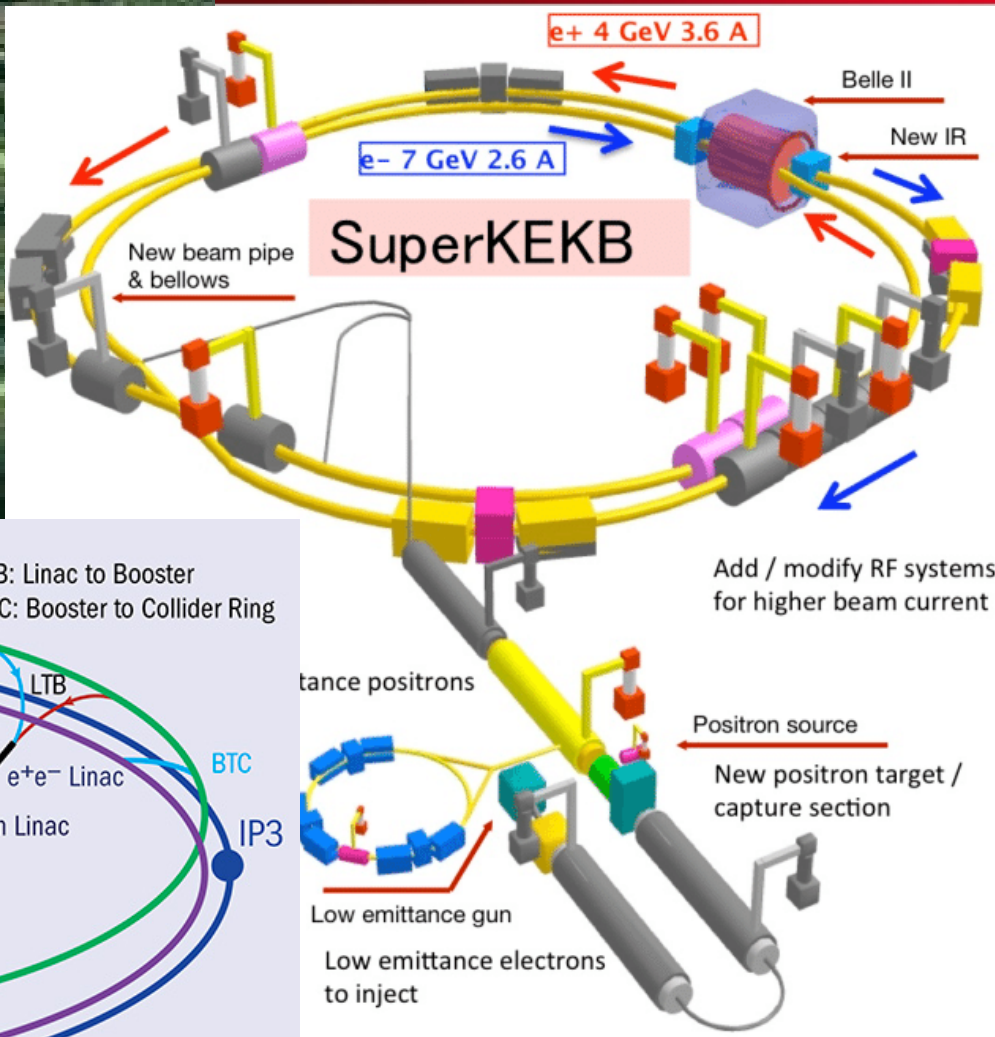


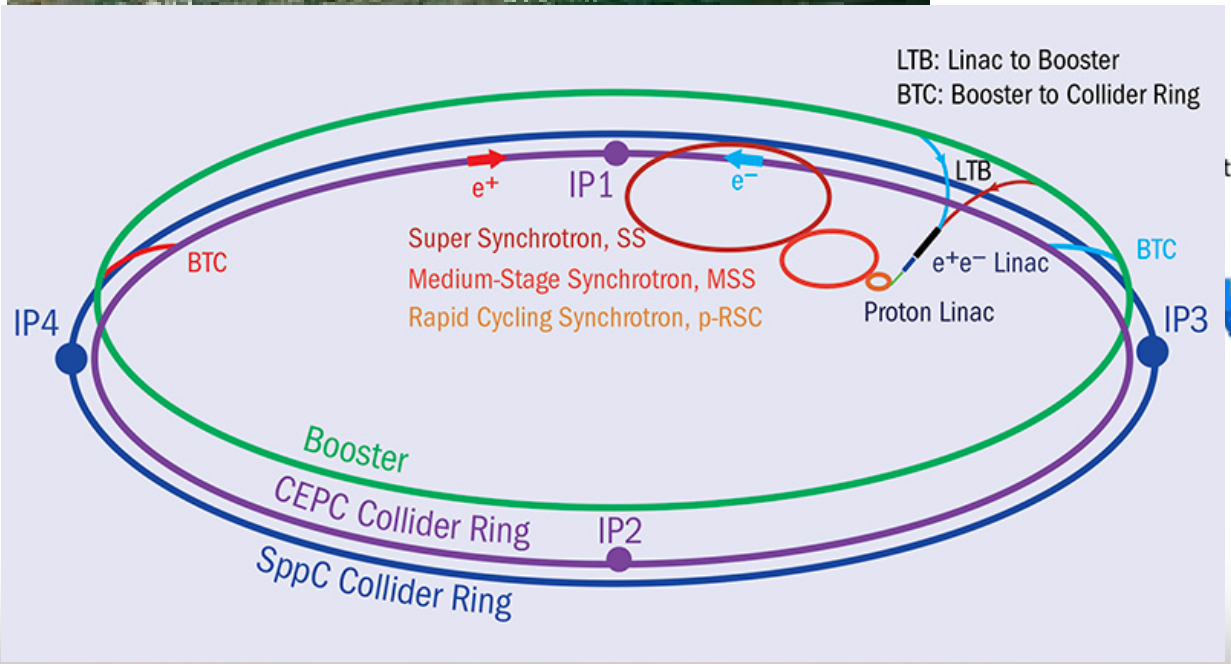






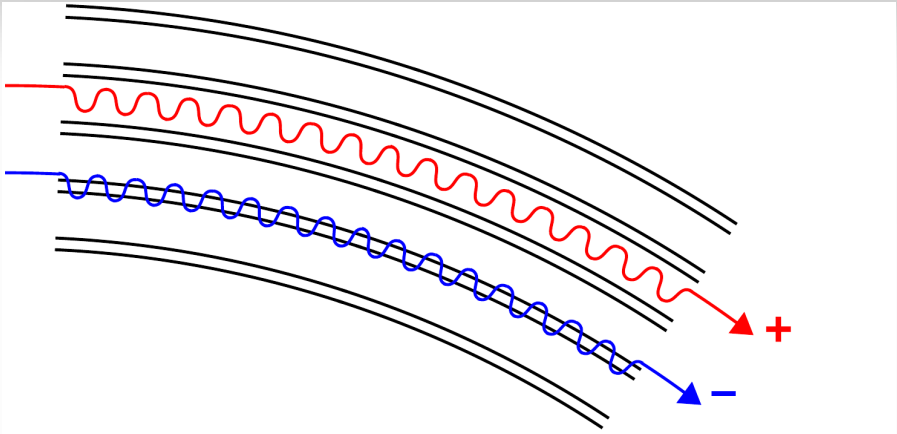
Where the crystal-based extraction of electrons can be applied?






Thank you for attention!

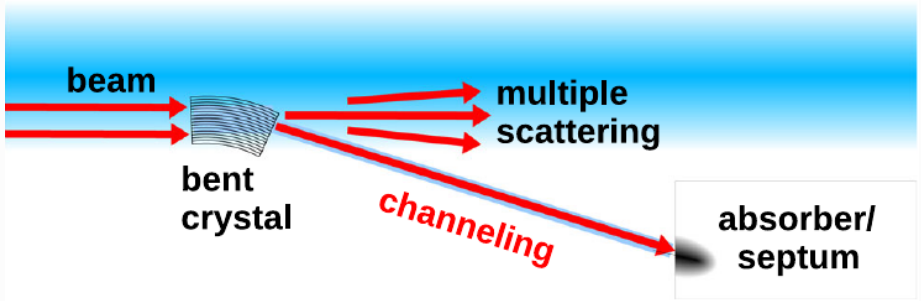
Crystal-based extraction: the idea



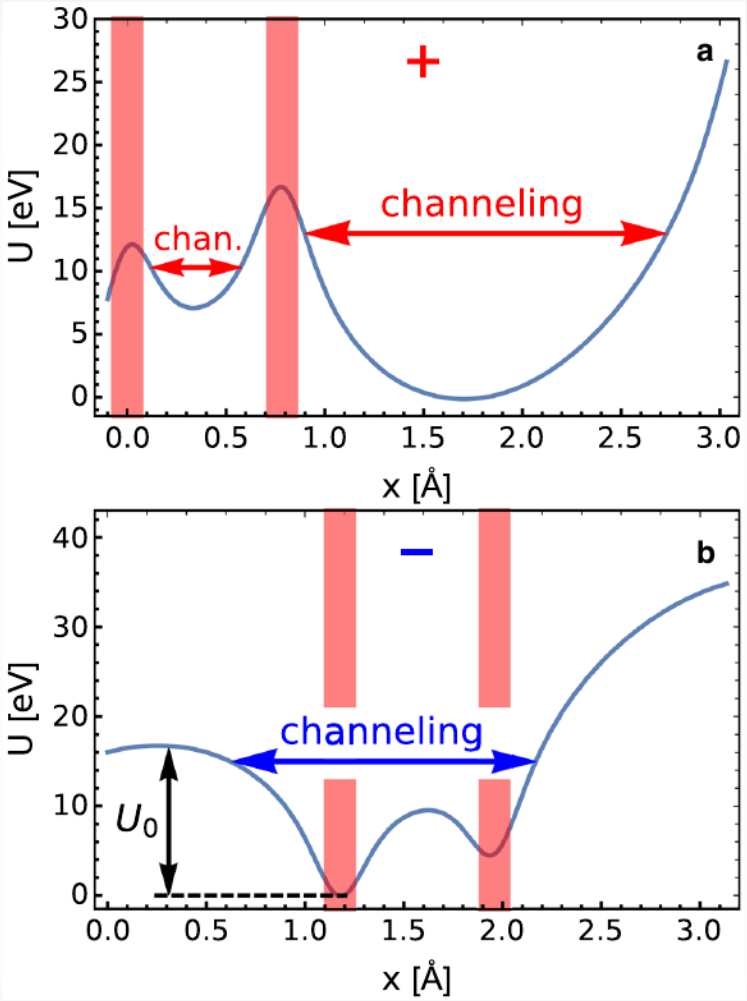
Planar channeling*:

- Charge particle penetration through a monocrystal along its atomic planes

Crystal-based extraction**



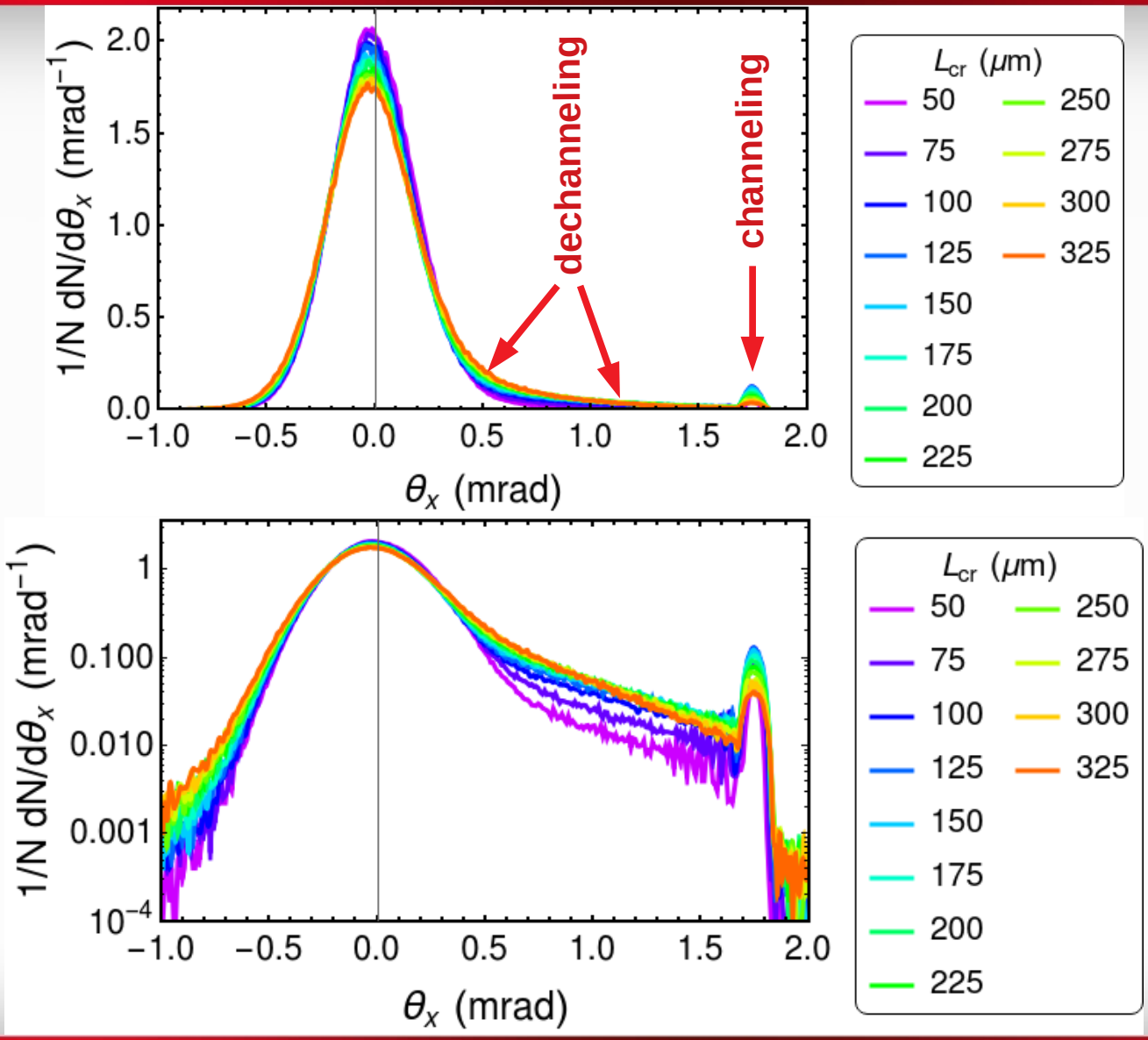
Interplanar potential



*J. Lindhard, Kgl. Dan. Vid. Selsk. Mat.-Fys. Medd. 34 No 4, 2821–2836 (1965)
E.N. Tsyganov, Fermilab TM-682 (1976)

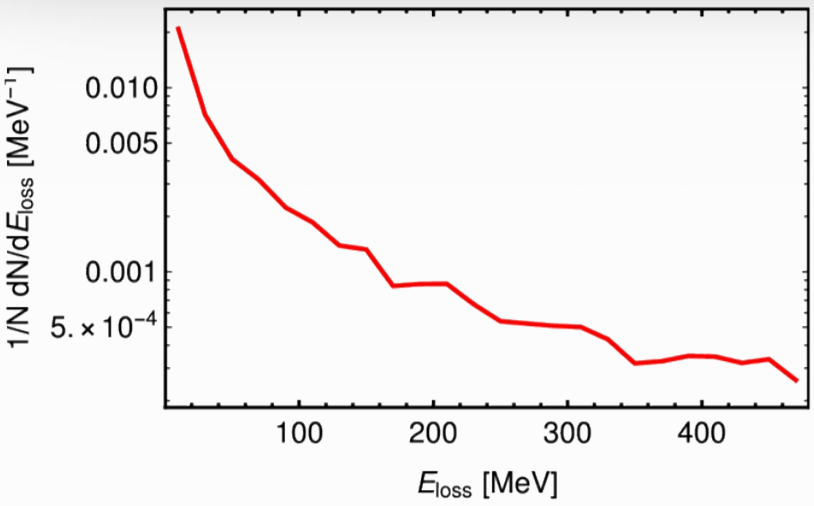
**A. Sytov et al., Eur. Phys. J. C (2022) 82:197

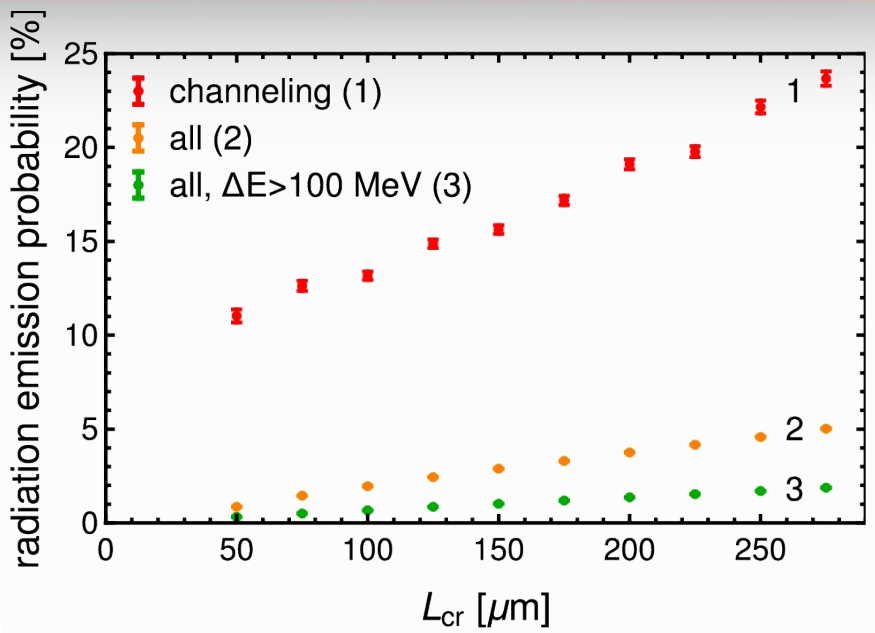
Simulated angular distributions of deflected beam



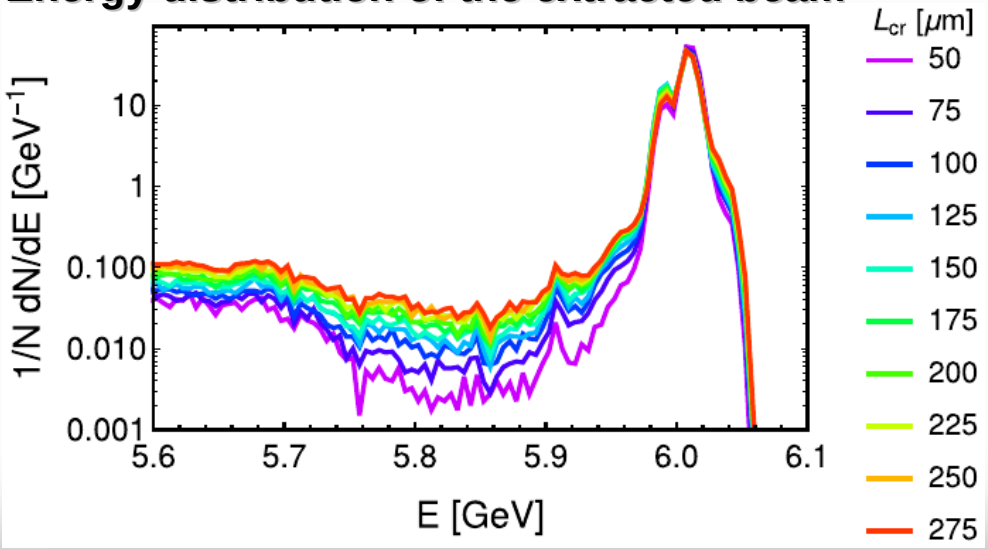
Crystal-based extraction simulations: energy losses

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**