Crystals as innovative components of particle accelerators: applications and future perspectives

Andrea Mazzolari (INFN-Ferrara, Italy)

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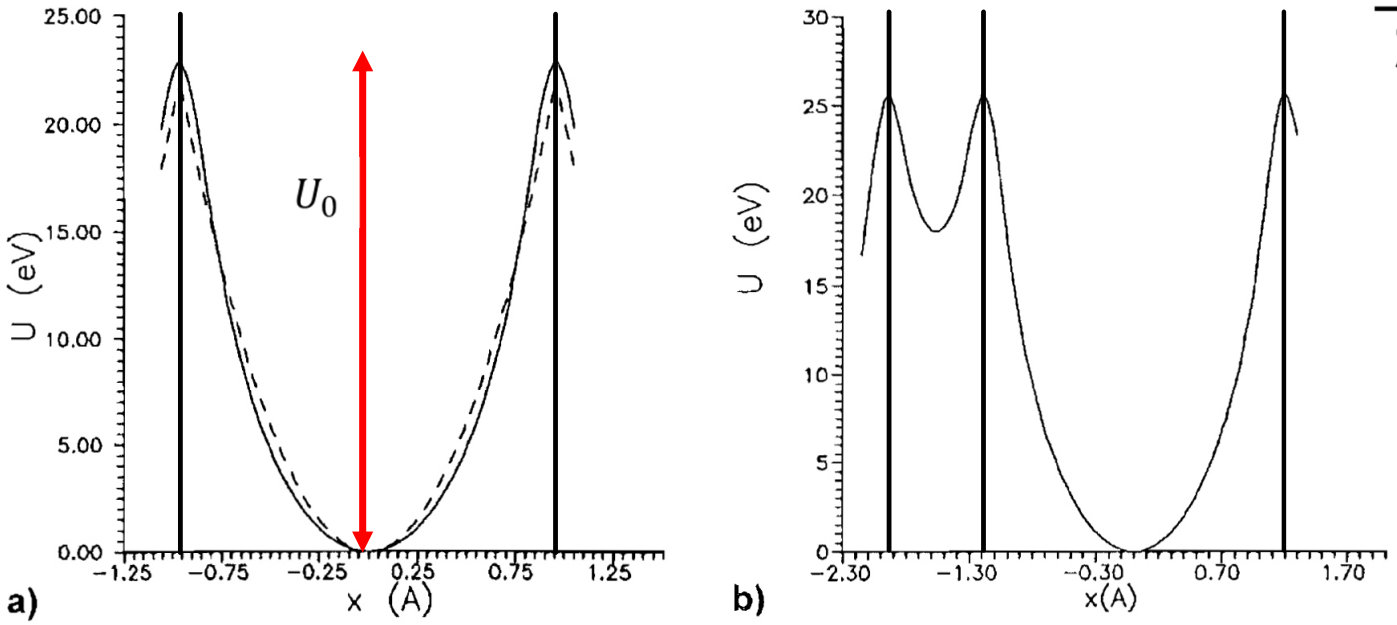
OUTLINE

- A brief introduction
- Coherent interactions between charged particle beams and crystal
- Particle beam steering
- Innovative sources of radiation
- Future developments
- Conclusions

INTRODUCTION TO CHANNELING



$$\frac{pv}{2}\vartheta^2 + U(x) < U_0$$

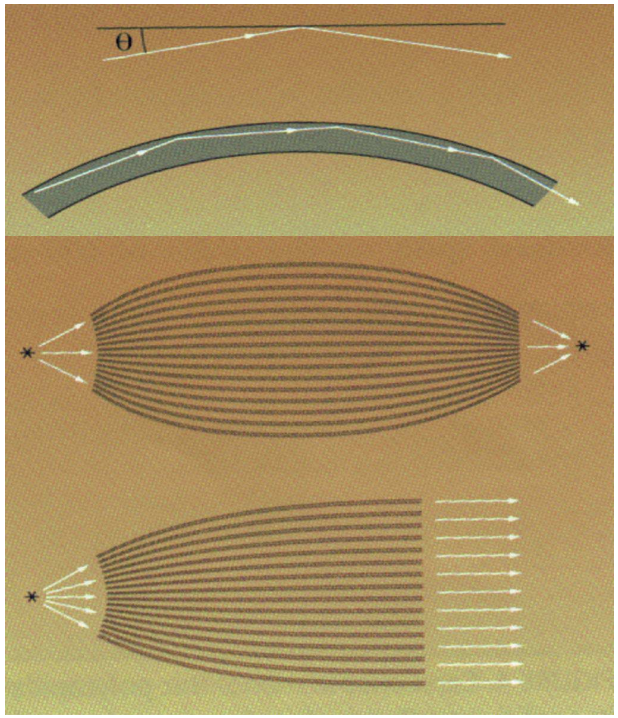
$$\vartheta < \sqrt{\frac{2U_0}{pv}}$$

Motion of a particle in a potential well + multiple coulomb scattering

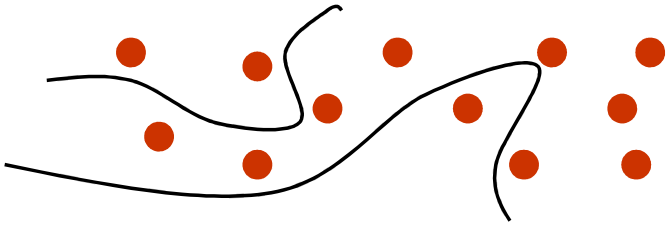
Fig. 1.7. The interplanar Moliére potential for (a) the Si channels (110) and (b) the Si channels (111). The dashed line is the harmonic approximation.

X-Ray AND NEUTRON POLYCAPILLARY OPTICS

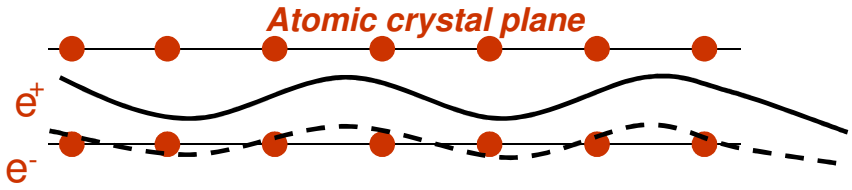
Basic idea of **polycapillary optics** is very close to the phenomenon of charged **particle "channeling"**.



@ Amorphous:

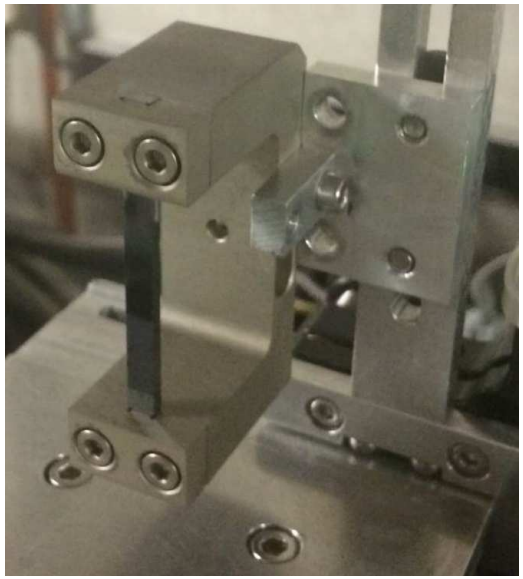


@ Planar channeling



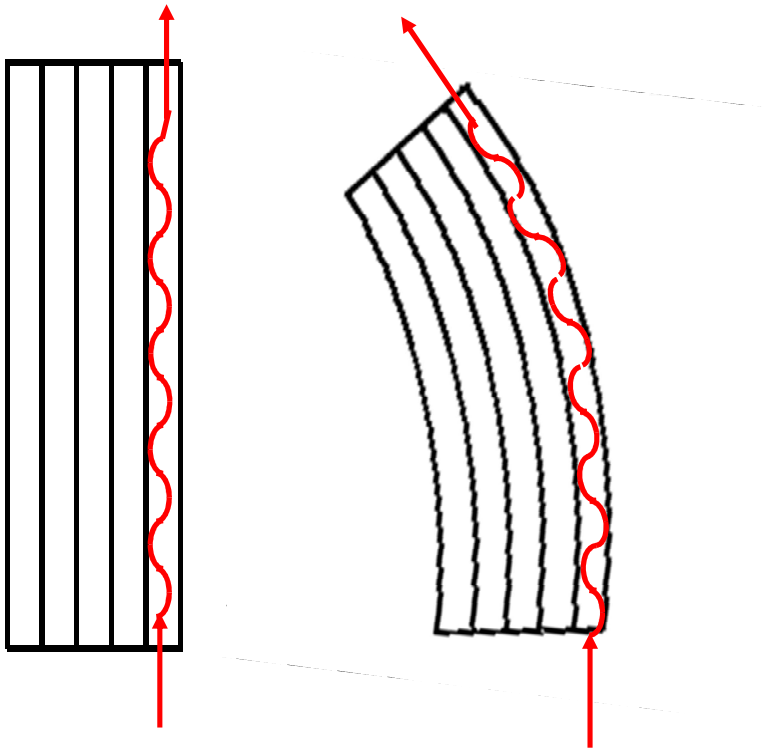
COHERENT INTERACTIONS BETWEEN CHARGERD PARTICLE BEAMS AND CRYSTALS

- UA9, AXIAL, CRYSBEAM, SELDOM @ CERN
- Innovative high-brillance X-Ray sources @ DESY, MAMI, SLAC
- Future developments



COHERENT INTERACTIONS AND STEERING OF CHARGED PARTICLE BEAMS

CHANNELING IN A BENT CRYSTAL



E. Tsyganov, 1976

Channeling of a charged particle beam in a bent crystal results in steering of its trajectory

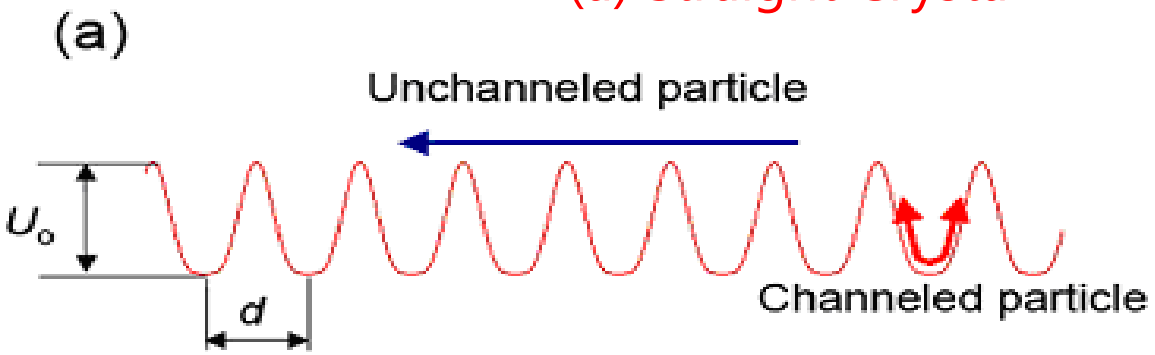
Bent crystals can be used in particle accelerators as collimating or extraction element

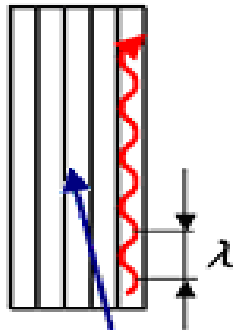
CHANNELING IN CIRCULAR ACCELERATORS– ONLY MILESTONES –

Year	Where	Accelerator	Beam	Energy	Efficiency
1984	Dubna (Russia)	JINR	Protons	8.4 GeV	~10^{-4}
1991	Moscow (Russia)	U70	Protons	70 GeV	~10^{-3}
1993	Geneva (Switzerland)	SPS	Protons	270 GeV	~10%
1996	Chicaco,	Tevatron	Protons	980 GeV	~25%
1998	New York	RHIC	Au ions/Protons	Au@100 GeV/u Protons @ 250 GeV	~23%
1997-today	Geneva (Switzerland)	SPS Extracted lines	Protons	400 GeV	>98%
2016-today	Geneva (Switzerland)	LHC	Protons, ions	7 TeV	…see later…

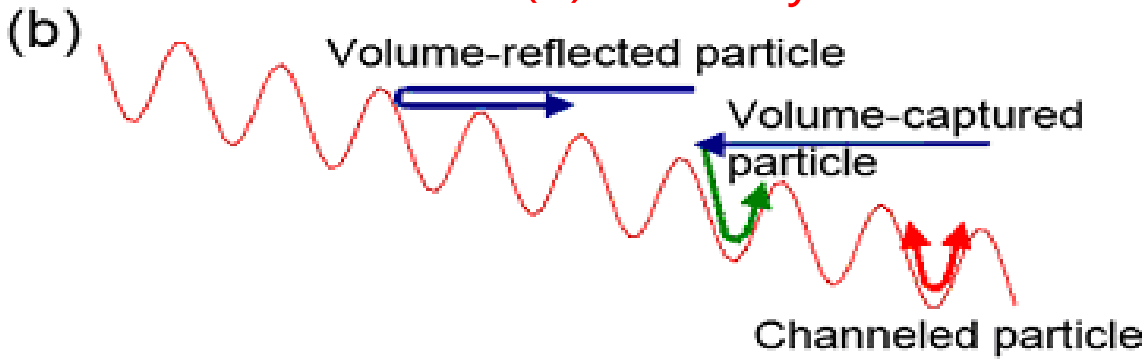
CHANNELING AND VOLUME REFLECTION

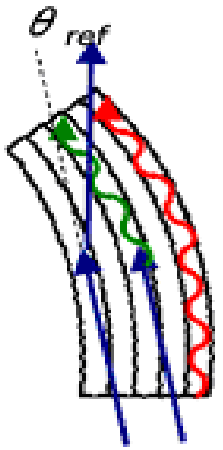
(a) Straight Crystal





(b) Bent Crystal





Volume reflection was predicted by Taratin and Vorobiov in 1988

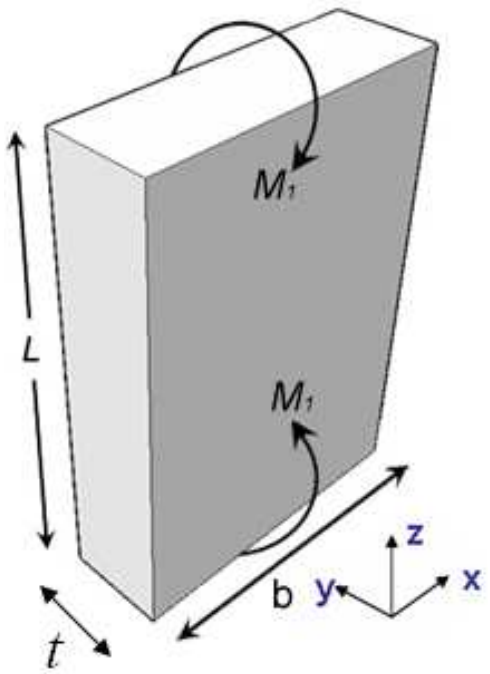
CRYSTAL BENDING

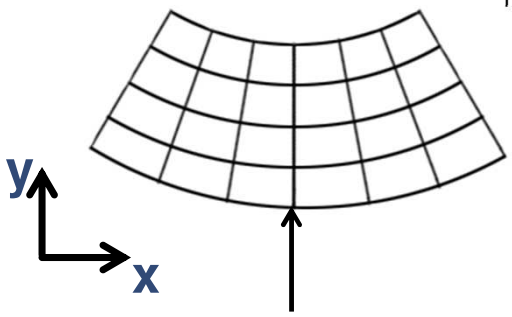
Silicon plate under bending

$$u = \frac{M_1}{2I_1}\left(2a_{13}xy + a_{36}y^2 + a_{35}yz\right)$$

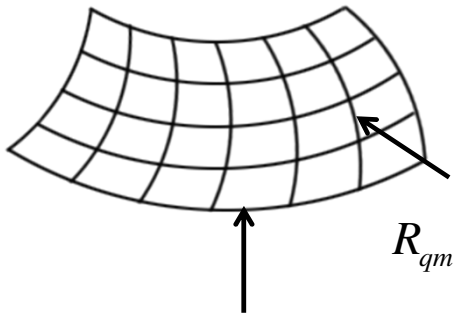
$$v = \frac{M_1}{2I_1}\left(-a_{13}x^2 + a_{23}y^2 + a_{33}(Lz - z^2) - a_{35}yz\right)$$

$$w = \frac{M_1}{2I_1}\left(a_{35}xy + a_{34}y^2 + a_{33}y(2z - L)\right)$$





$$R_a = \frac{a_{13}}{a_{33}}R_p$$



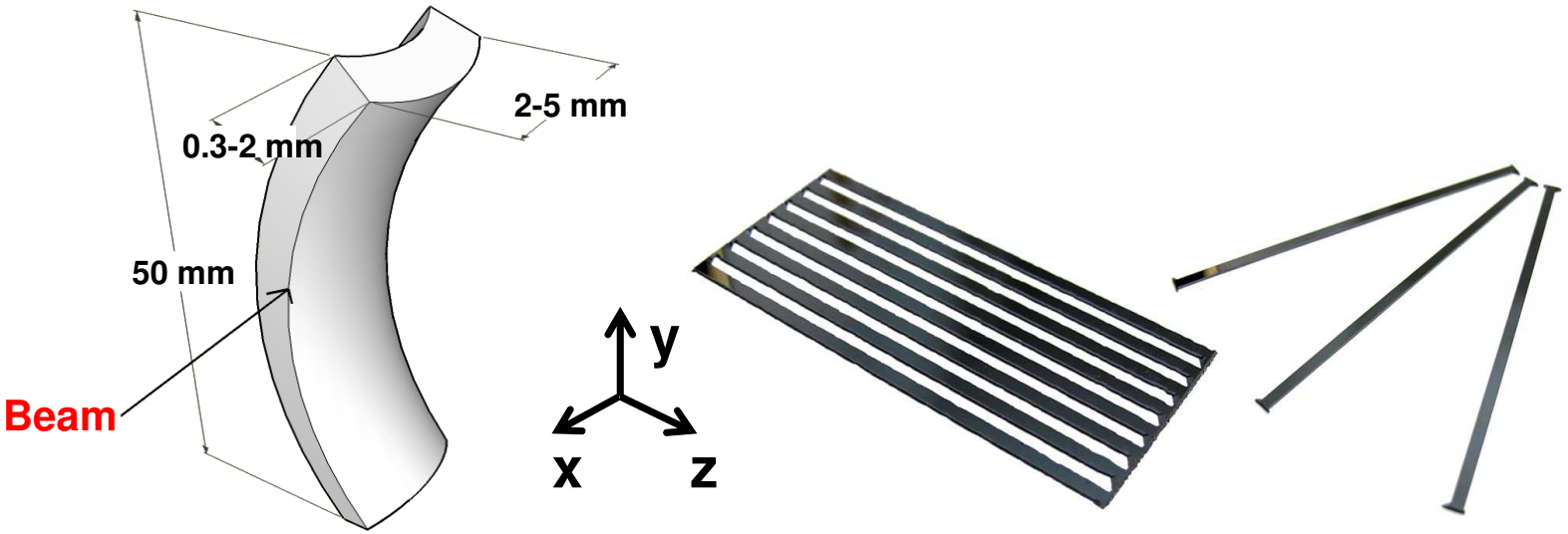
$$R_{qm} = \frac{a_{36}}{a_{33}}R_p$$

$$R_a = \frac{a_{13}}{a_{33}}R_p$$

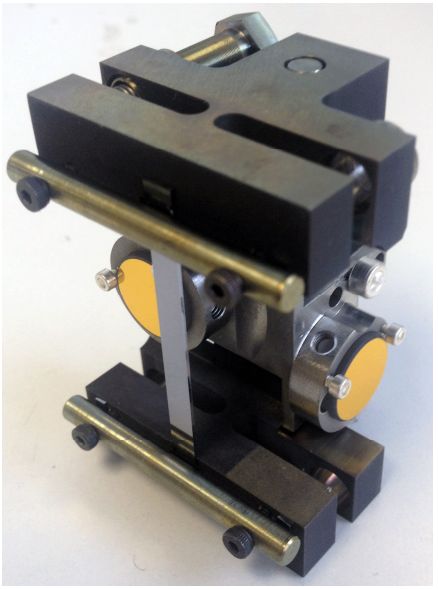
R. Camattari et al., J. Appl. Cryst., (2015) 48, 943
R. Camattari et al., J. Appl. Cryst., (2015) 48, 977

CRYSTALS BENDING

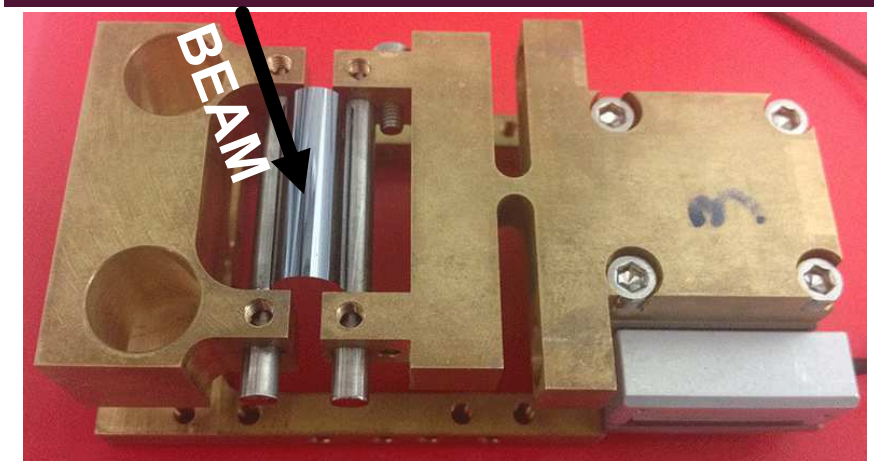
Anticlastic deformation

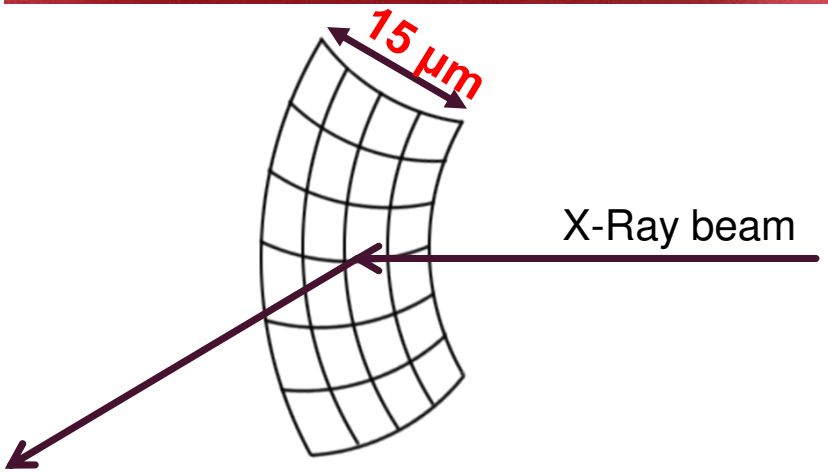


Crystal installed and tested in the LHC

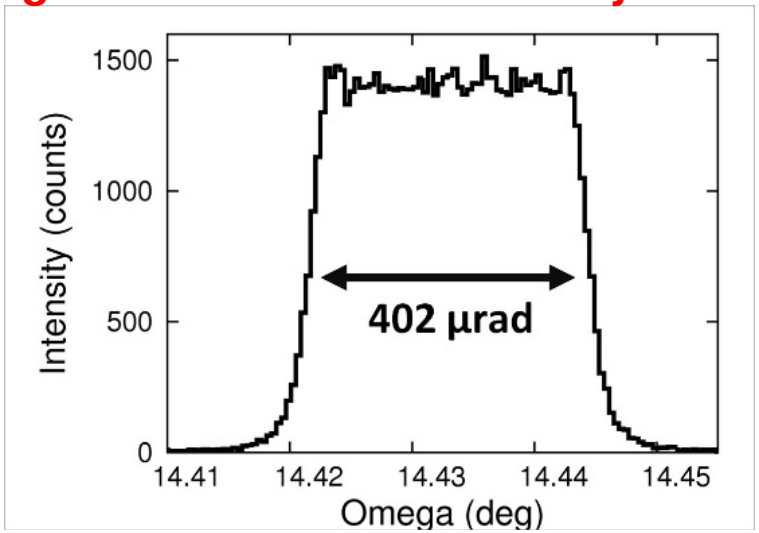


QUASI-MOSAIC DEFORMATION





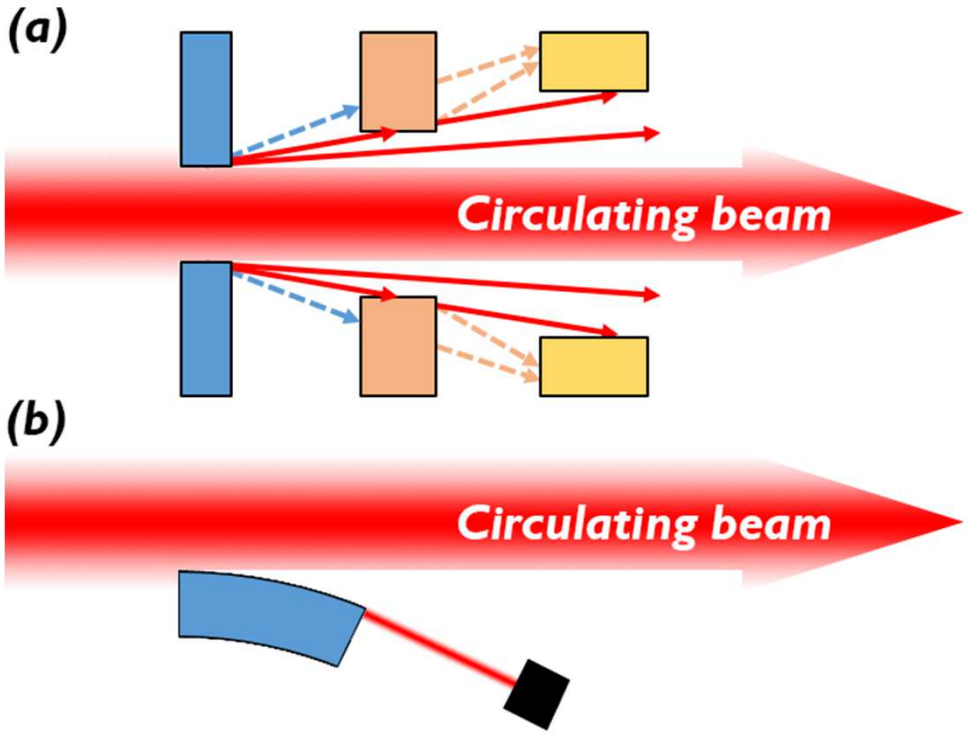
- Rocking curve profile
- 60 µm thick crystal bent at 3 cm radius
- (111) Diffracting planes
- Quasi mosaic deformation exploited
- Crystal mounted on a piezo attuated holder to adjust bending and remove torsion
- **Rocking curve recorded on Panalytical XRD**



COLLIMATION OF HI-ENERGY AND HIGH-INTENSITY CIRCULATING PARTICLE BEAMS

BEAM COLLIMATION IN PARTICLE ACCELERATORS

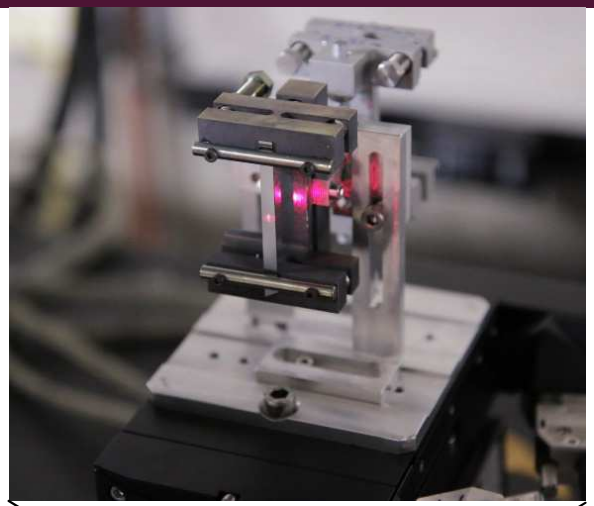
Particle beam collimation: classic vs innvoative approach

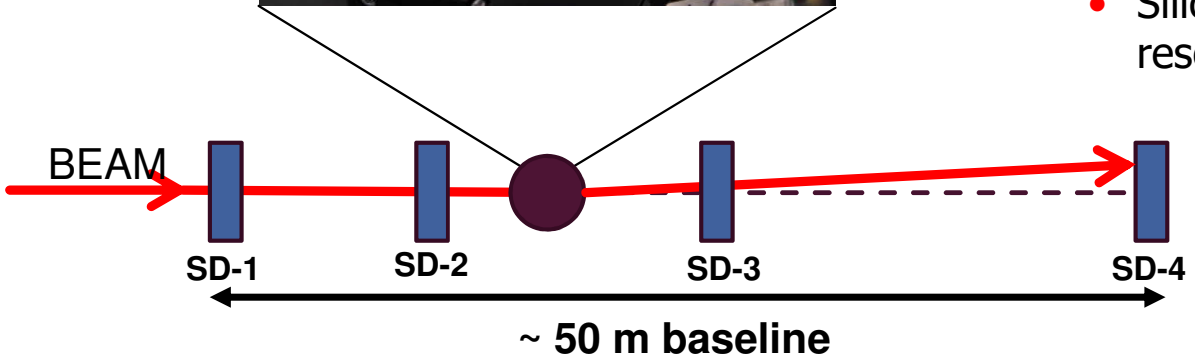


- Collimation is needed to prevent supermagnets quenching
- Primary collimator (bulky «absorber»)
- Spray of secondary **unwanted** particles
- Secondary collimator
- Tertiary collimator...

- Bent crystal act as a primary collimator
- Avoided **spray** of secondary particles
- **Secondary, tertiary... colimators no more needed**

EXPERIMENTAL SETUP





H8 and H4 external beam lines at CERN SPS

- 400 GeV/c protons
- 120 GeV/c e+/e-
- Pb or Ar ions
- Divergence < 10 μrad

- **High resolution goniometer**

- Silicon micro-strip detectors (10/30 μm spatial resolution) allows particle tracking.

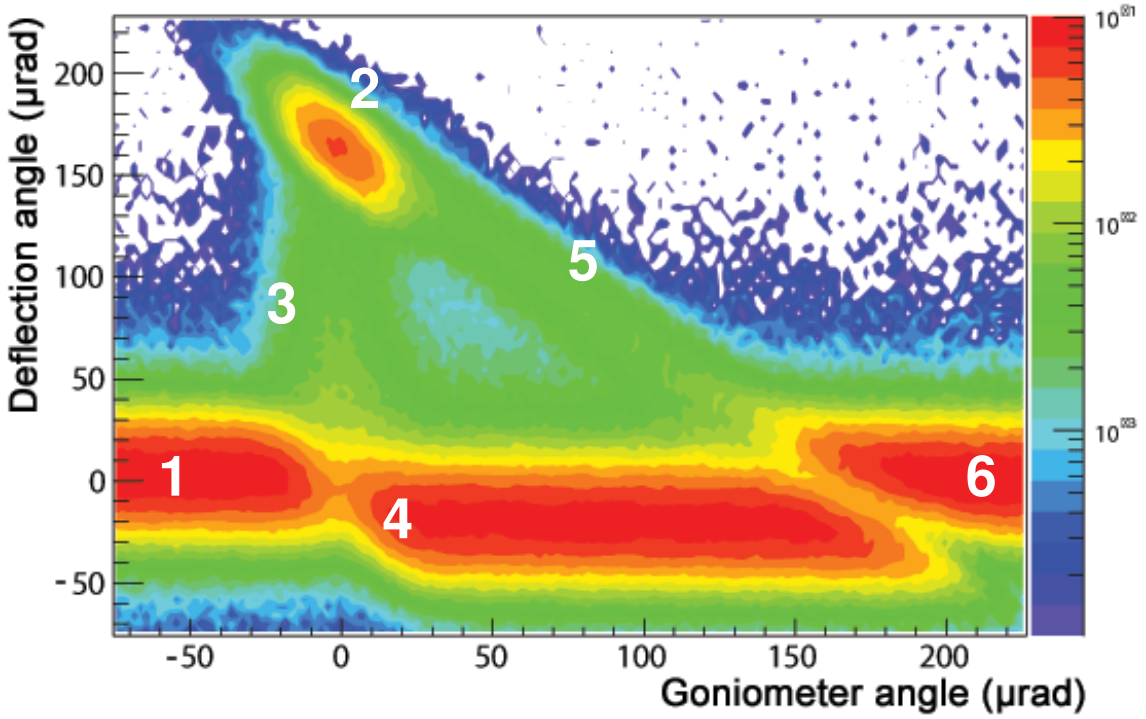
CHANNELING AND VOLUME REFLECTION

•400 GeV proton beam

•Deflection at channeling ~ 160 µrad
•Channeling efficiency ~ 60%

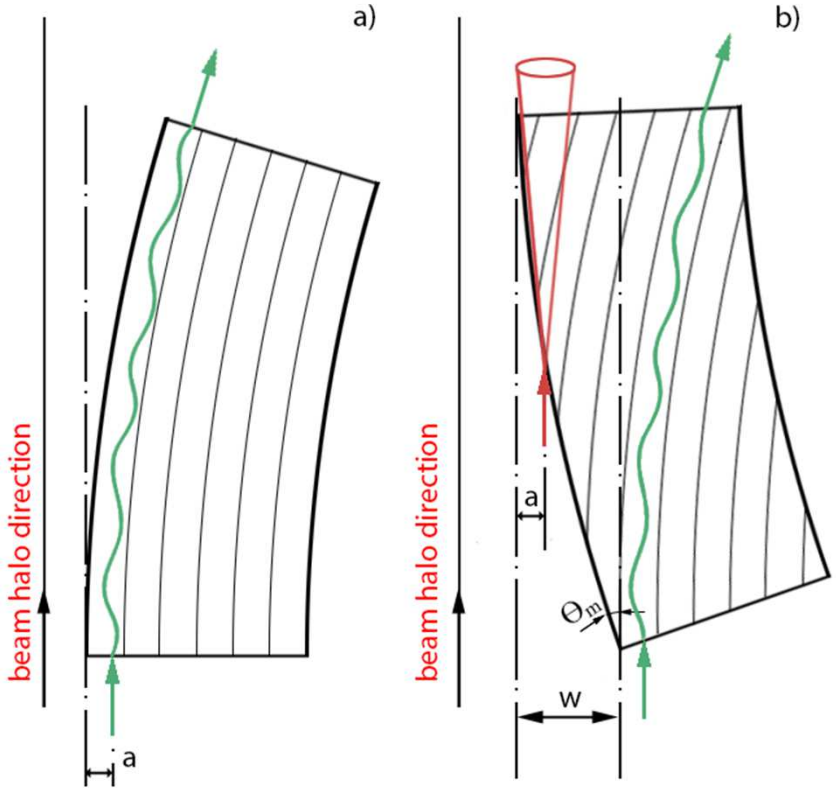
•Volume reflection deflection at about 13.5 µrad
•Fraction of diverted particles larger that 97%
•Large acceptance

1. Primary beam
2. Channeling
3. Dechanneling
4. Volume reflection
5. Volume capture
6. Primary beam



W. Scandale et al., Phys. Rev. Letters 97 (2006) 144801
W. Scandale et al., Phys. Rev. Letters 97 98 (2007) 154801

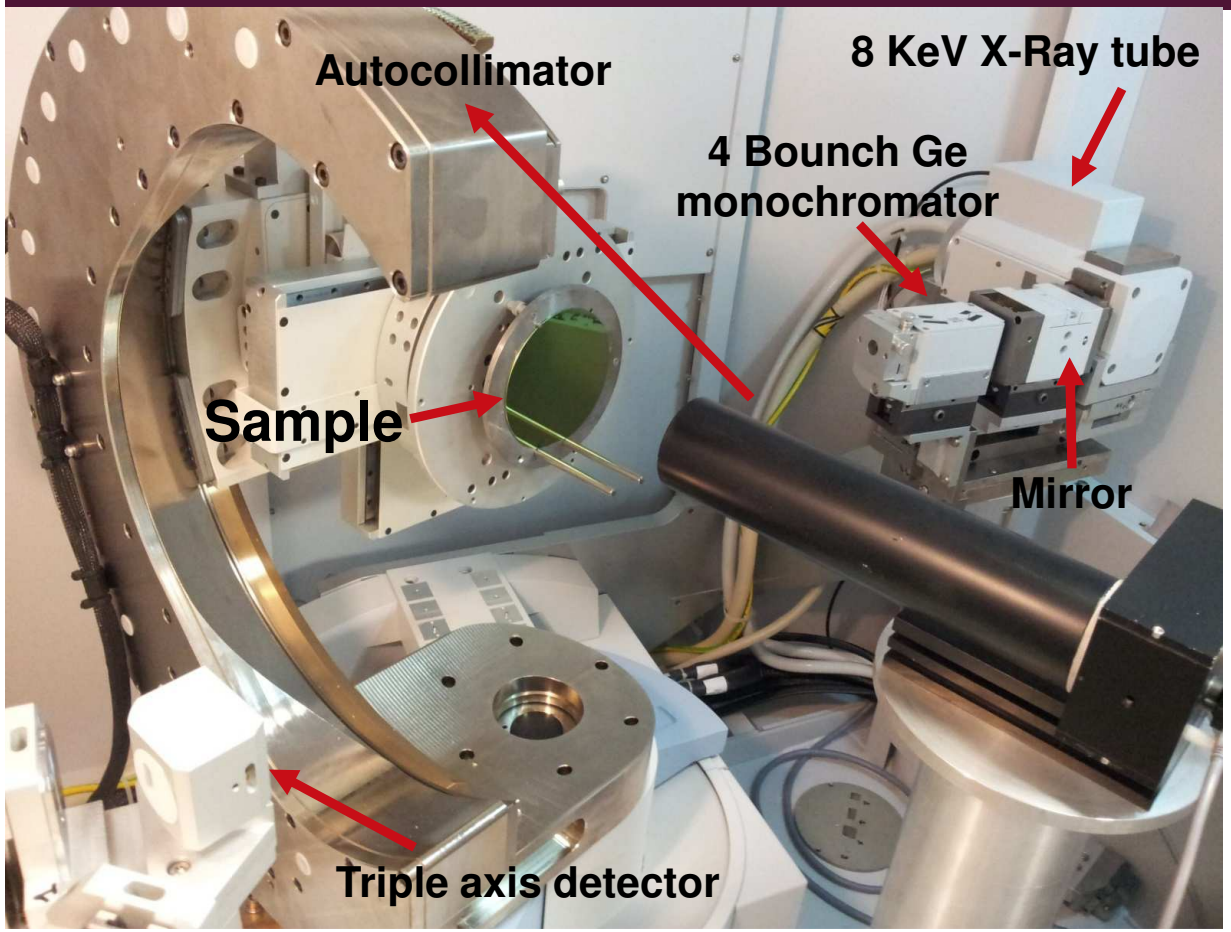
THE ROLE OF «MISCUT» FOR PARTICLE BEAM COLLIMATION



- «miscut» angle is defined as the angle between the optical surface of the crystal and its atomic planes
- Miscut angle of silicon crystals is tipically larger than 0.5 deg

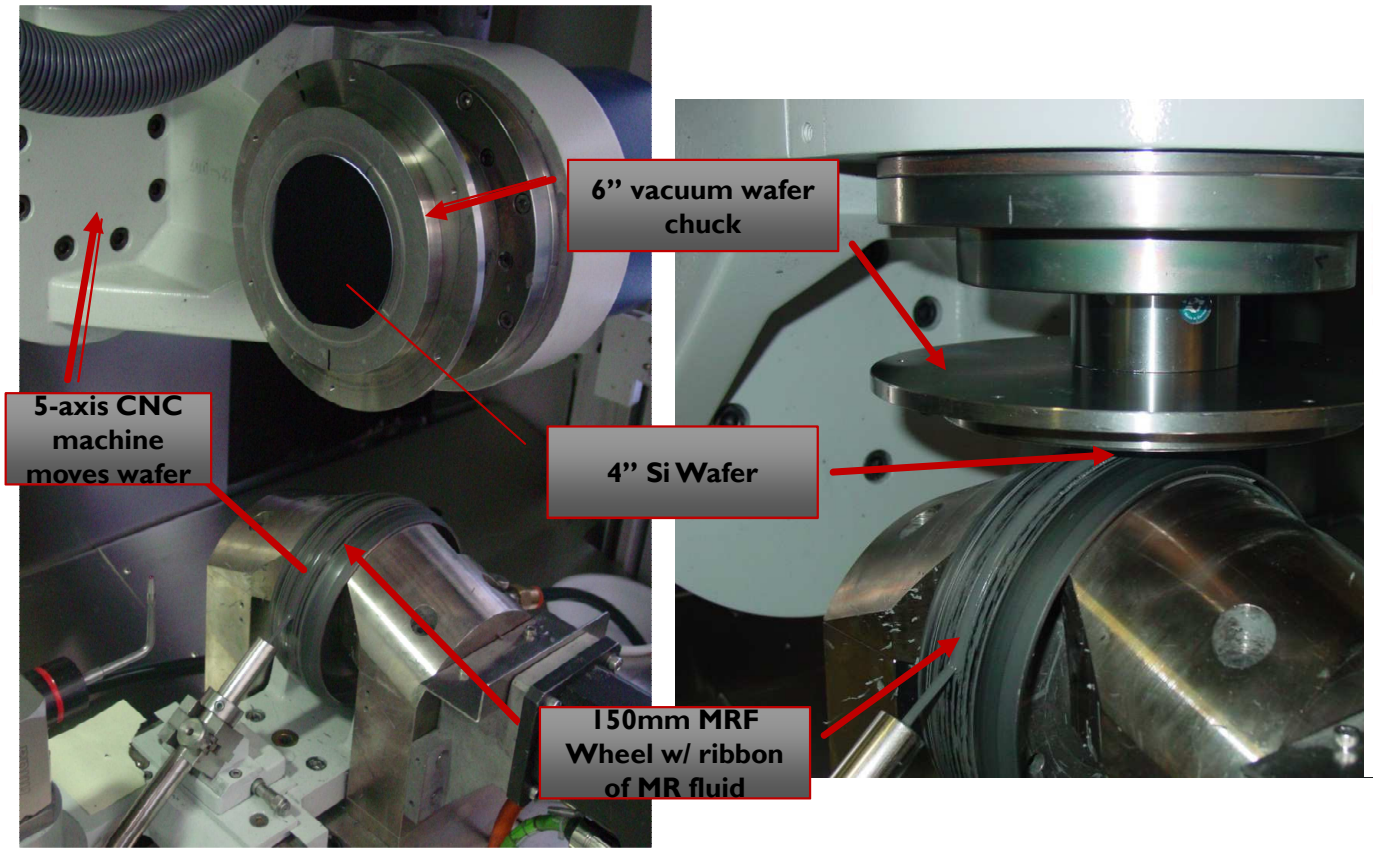
For LHC→required < 10 μrad! Extremely challenging to measure and to adjust !!

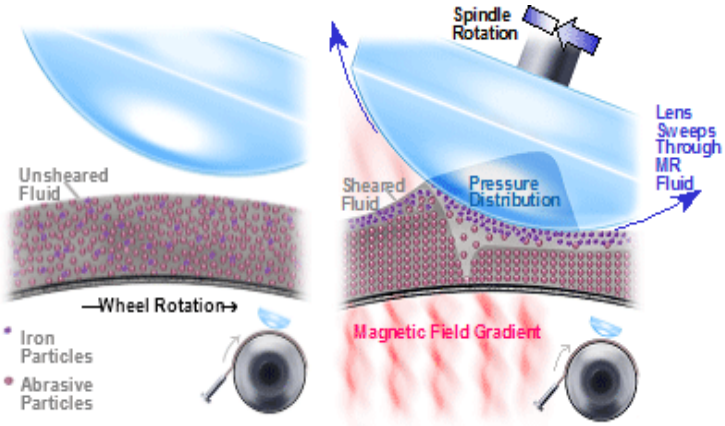
CRYSTALS MANUFACTURING – OFF AXIS MEASUREMENT



- **Off-axis: angle between atomic planes and optical surface.**
- **Required off-axis<0.0006° (very tricky to measure with standard methods).**
- **High resolution X-Ray diffractometer equipped with a custom-made autocollimator.**

CRYSTALS MANUFACTURING – MRF POLISHING –

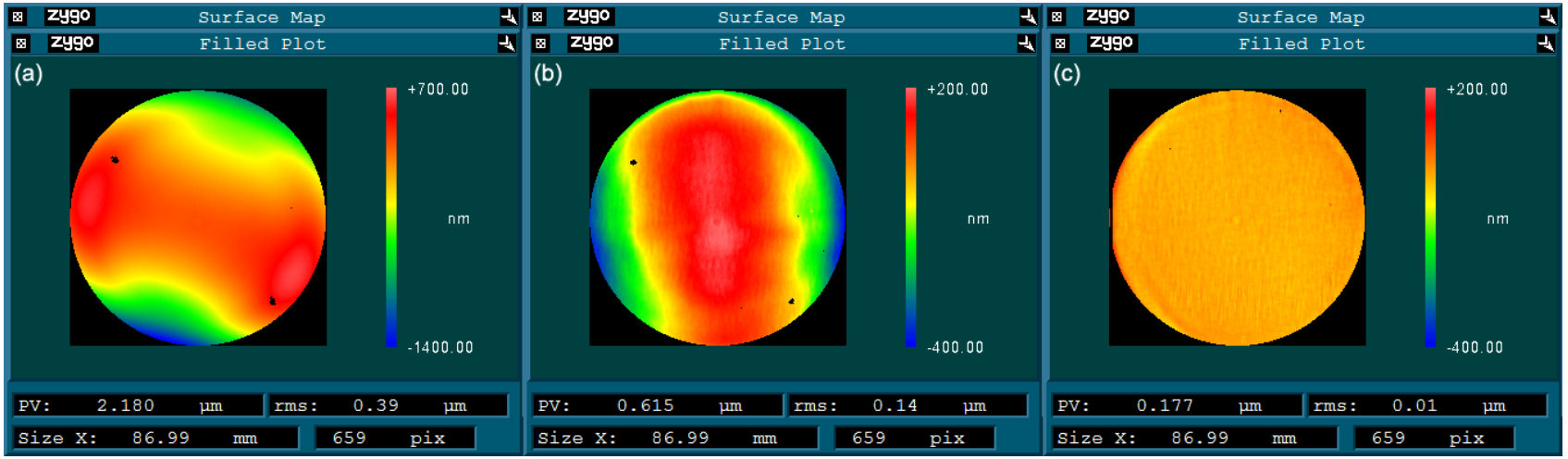




MRF technique developed as a tool to deliver high precision optics (also for x-ray mirrors in commerical XRD...)

Scientific partnership with company QED-MRF (USA)

CRYSTALS MANUFACTURING – MRF POLISHING



Starting wafer surface
PV 2.18 um
RMS 0.39 um

Surface after a first MRF iteration
PV 0.615 um
RMS 0.14 um

Final wafer surface
PV 0.177 um
RMS 0.01 um

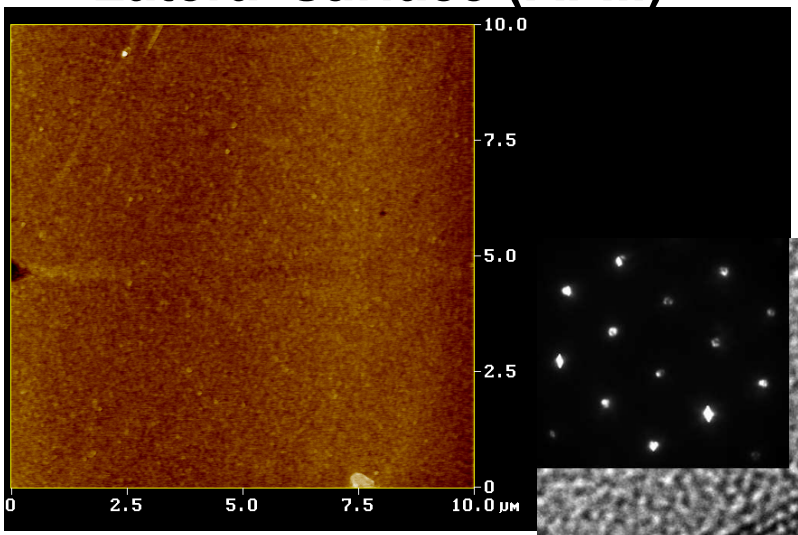
- **Magneto Reological Finishing (MRF) has the capabilities to remove material with nm accuracy from selected areas.**

- **MRF polishing is a powerful tool to reduce crystals off-axis**

CRYSTAL MANUFACTURING – AFM AND HRTEM –

High-quality surfaces achieved via anisotropic chemical etching

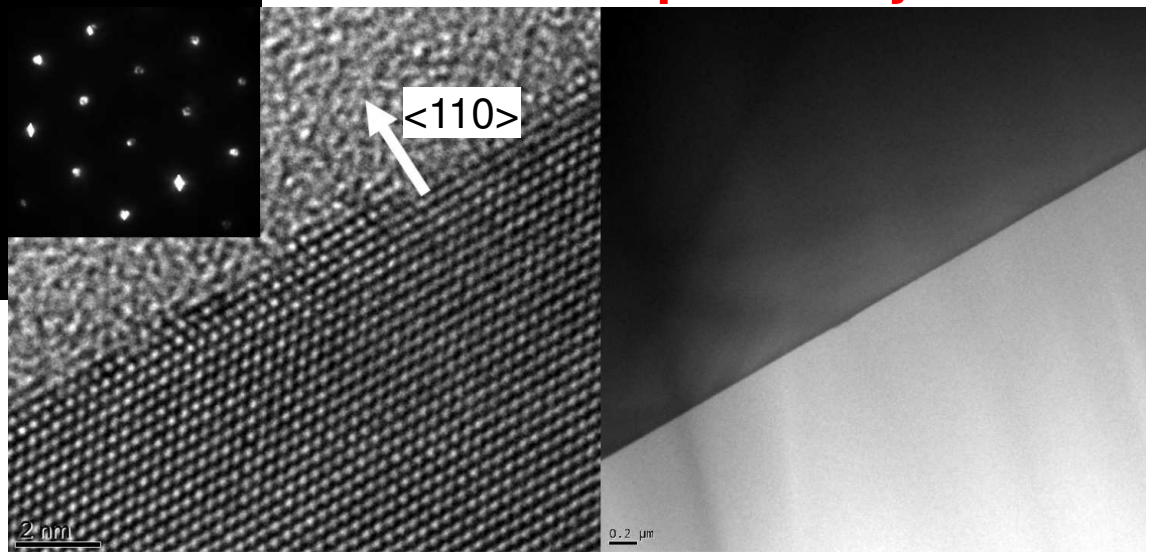
Lateral surface (AFM)



Sub-nm roughness achieved (0.2 nm)

Entry surface (High Resolution transmission electron microscopy).

Zero nm amorphous layer



CRYSTALS FOR THE LHC

Thickness along the beam: 4.0±0.1 mm
Height < 55 mm.
Weight < 150 g
Channeling plane: (110)
Channeling axis: <111> or <110>
Miscut for axial channeling: 0±18 mrad
Miscut for planar channeling: < 10 µrad.
Torsion: < 1 µrad/mm
Bending angle: 47.5-52.5 µrad
Dislocation density < 1 cm^2

Bake out

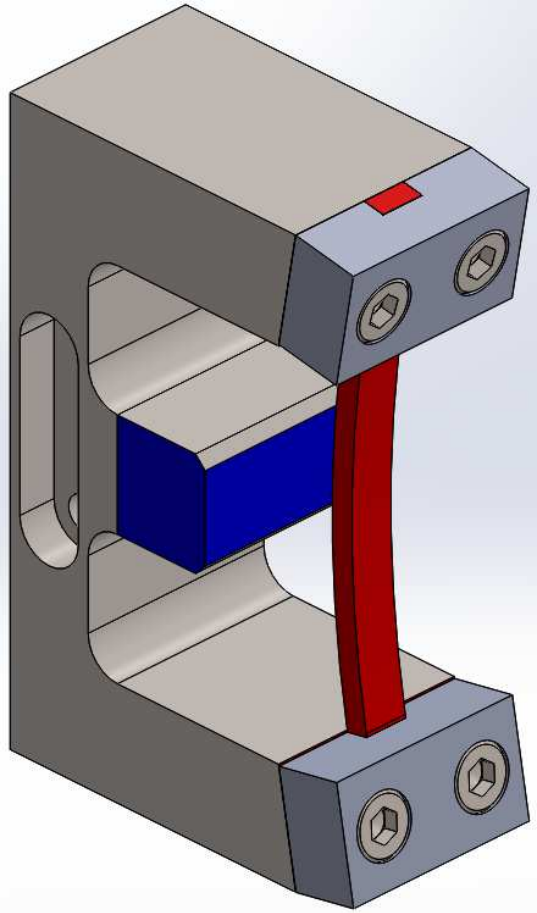
- Bake out temperature= 250°C
- heating ramp= 50°C/h
  - Bake out time =48h00
  - Number of thermal cycles: 3 at least
- Maximum allowed total outgassing after each bake out: $1*10^{-7}$ mbar·l·s^{-1}

The compliance of the mechanical properties of the crystal assemblies to the specifications of Table 1, in particular the bending angle, must be assessed after at least 3 thermal cycles.

CHALLENGING ASPECTS

- ✓ Planar miscut: < 10 µrad→ MRF finishing
- ✓ Torsion: < 1 µrad/mm → ultra precise machining and assembly.
- ✓ Bending angle: 47.5-52.5 µrad → ultra precise machining and assembly.
- ✓ Dislocation density < 1 cm^2 → standard for microelectronics is 1 order of magnitude higher→ purchase of large quantity of silicon wafers and selection of the best ones.

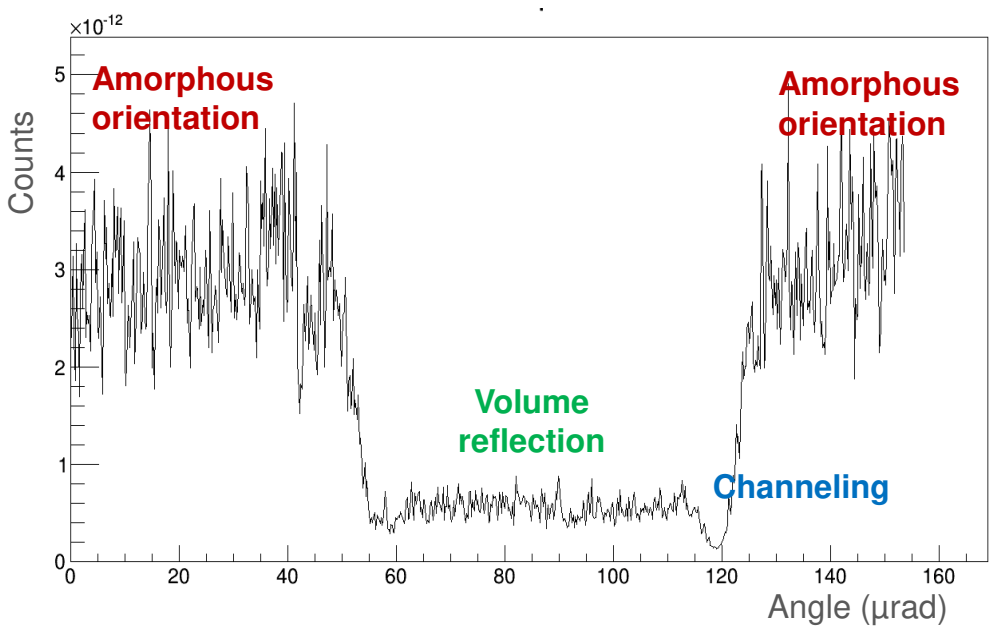
HIGH-ACCURACY MECHANICAL MACHINING



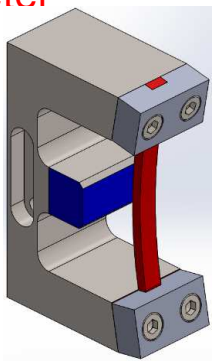
Surfaces in contact with the crystal→ slope 0.0471°+/-0.0022°

- High precision mechanical machining
- Control of crystal deformational state in terms of twist and bending

CHANELLING AT LHC ENERGIES

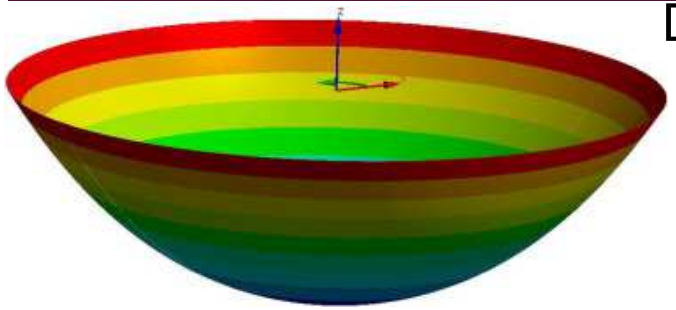


- Proton beam @ 6.5 TeV (**LHC**)
- Worldwide energy record
- Observation of a strong reduction in nuclear interactions
- Crystals based LHC beam collimation looks feasible
- Ultra high accuracy piezo-driven goniometer



EXTRACTION OF HI-ENERGY AND HIGH-INTENSITY CIRCULATING PARTICLE BEAMS

SELF STANDING CRYSTALS

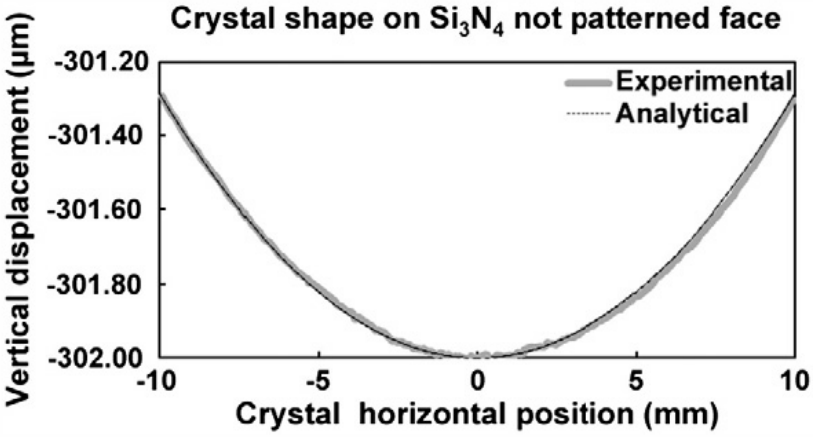


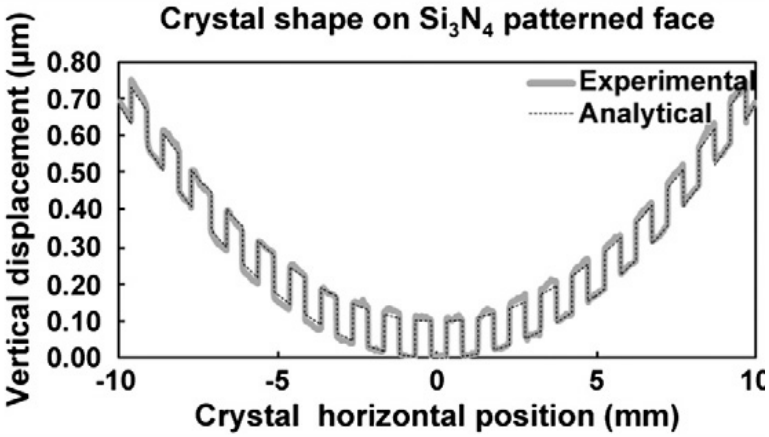
Deposition of a few hundred nm of silicon nitride on silicon

Temperature: 900 °C

Stress and deformation as conseguence of mismatch between thermal expansion coefficients

- Light and compact crystals
- FEM assisted design.

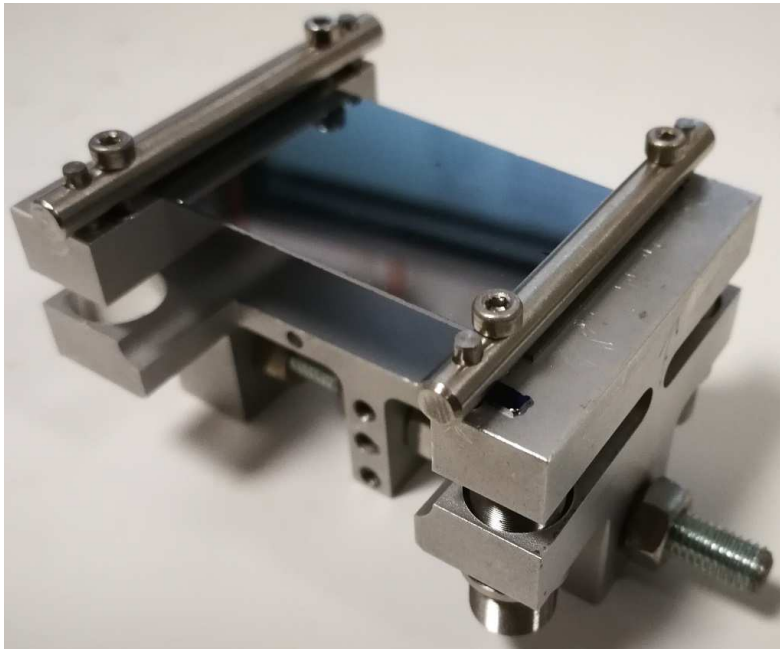


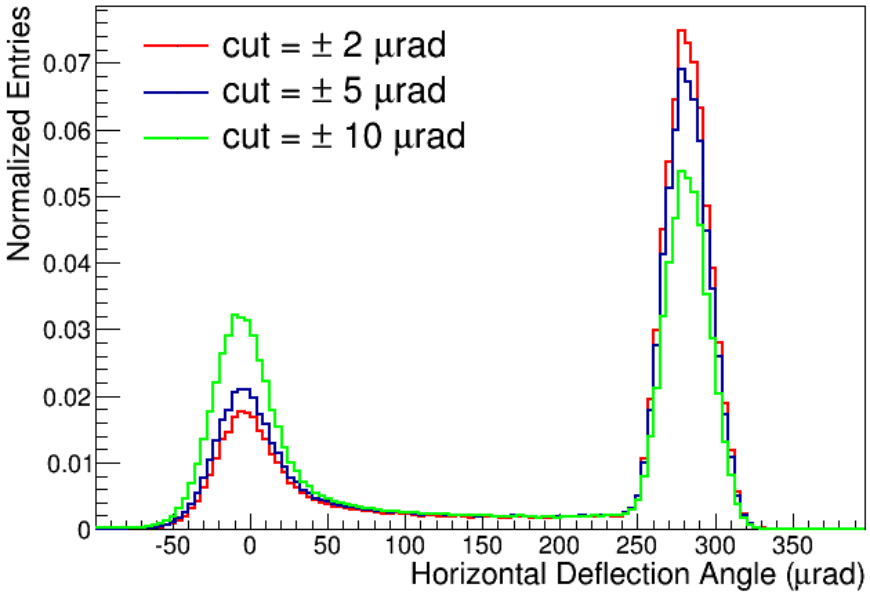


CRYSBEAM EU PROJECT

European Research Council
Established by the European Commission

Motivation: extraction of the LHC circulating beam, delivering extracted particle beams to users



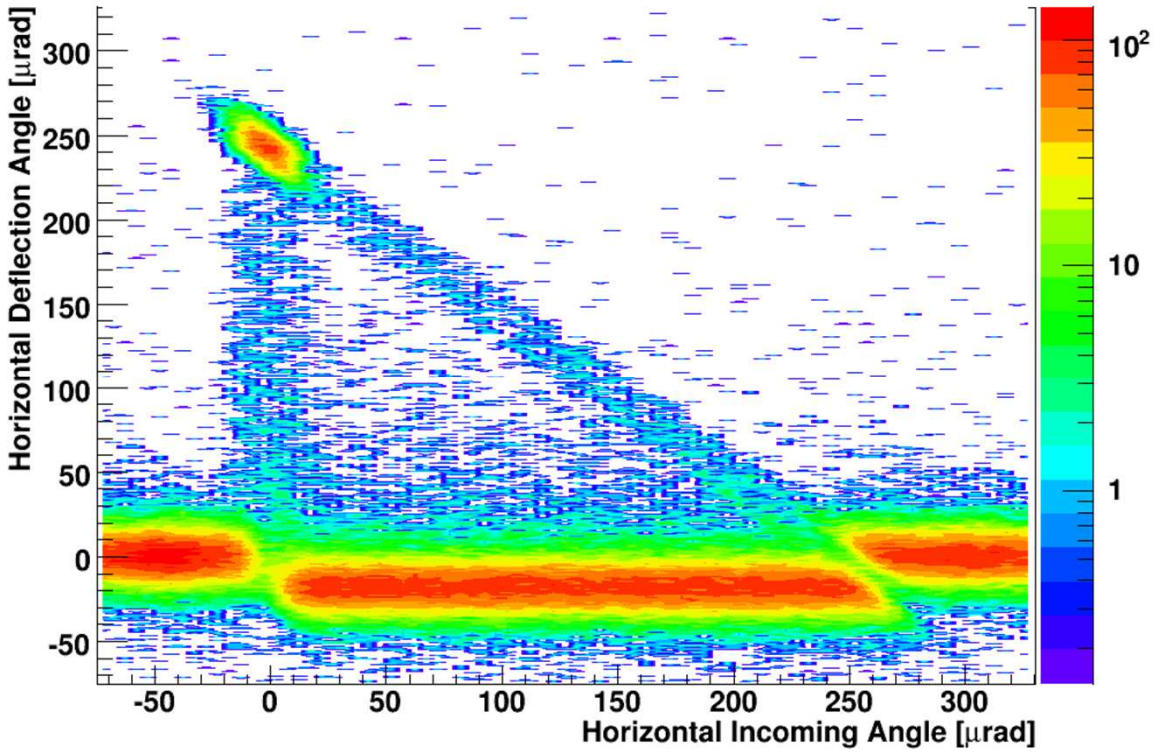


Deflection ~280 µrad

Crystal bent at a few hundred µrad, very uniform bending radius over tens of cm length. Radius>80 m

GERMANIUM CRYSTALS

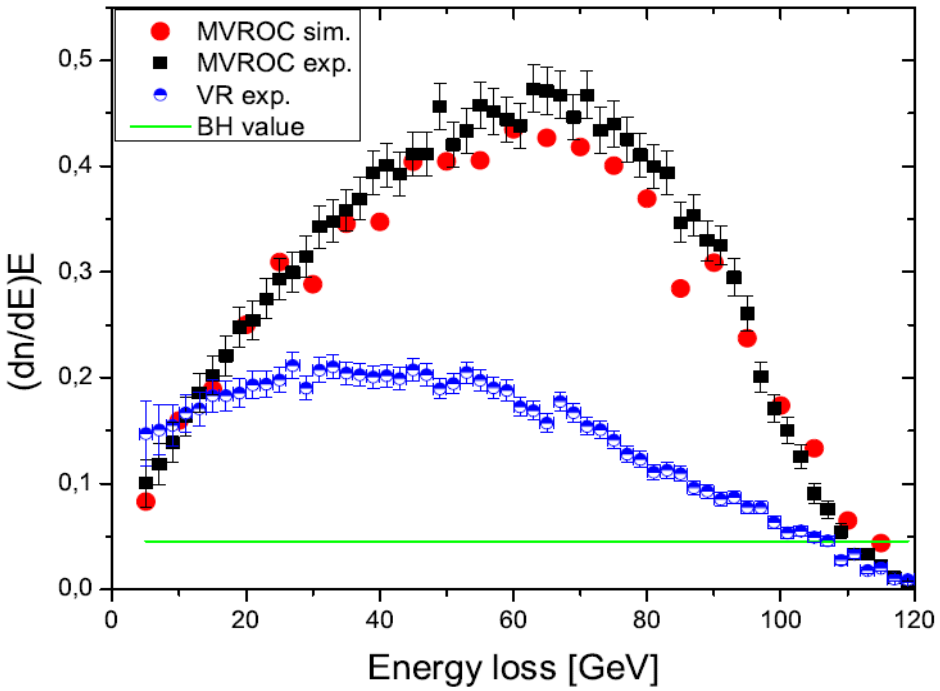
- We own the know-how and equipment to machine also germanium crystals
- Mechanical machining without inducing any lattice damage.



INNOVATIVE SOURCES OF E.M. RADIATION

E.M. RADIATION (QUASI-AXIAL ALIGMENT)

120 GeV/c e^- under MVROC

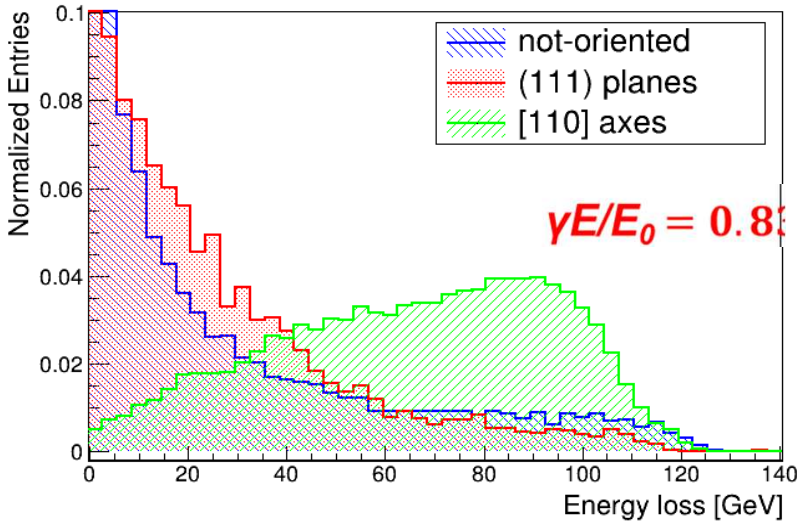


Collimation of e^+e^- collider

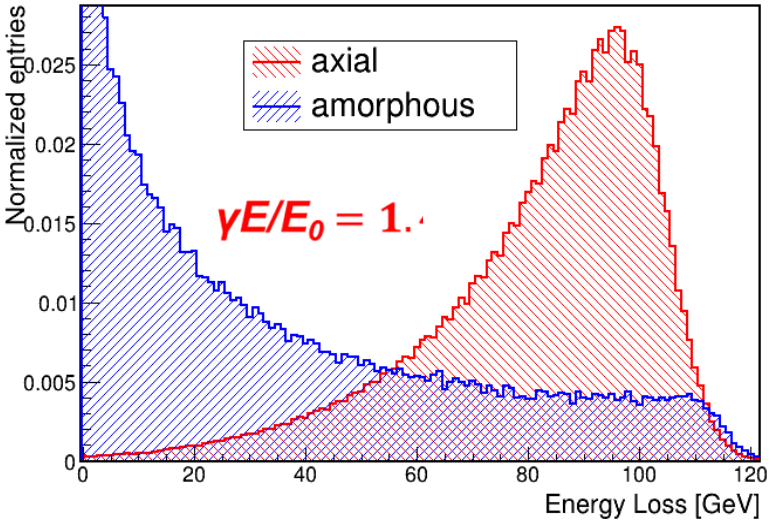
The combination of deflecting power and intense radiation generation can be exploited for a new scheme of beam collimation in future electron-positron colliders, such as ILC or FCC.

L. Bandiera et al., Phys. Rev. Lett. 111 (2013)255502

Si & Ge crystals
Radiation generation under axial alignment 120 GeV/c e-



Silicon crystal (2 mm long)
<110> axis



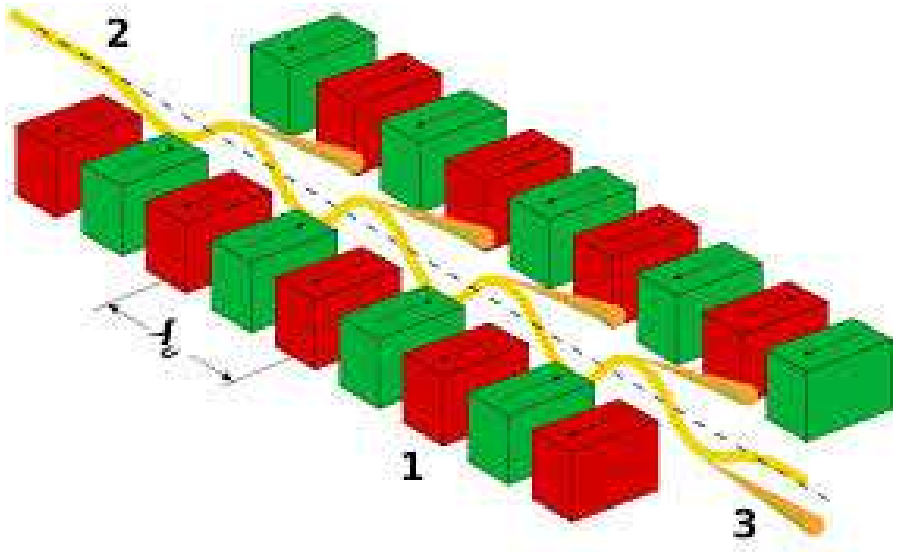
Germanium crystal (2.8 mm long)
<110> axis

Energy loss spectrum

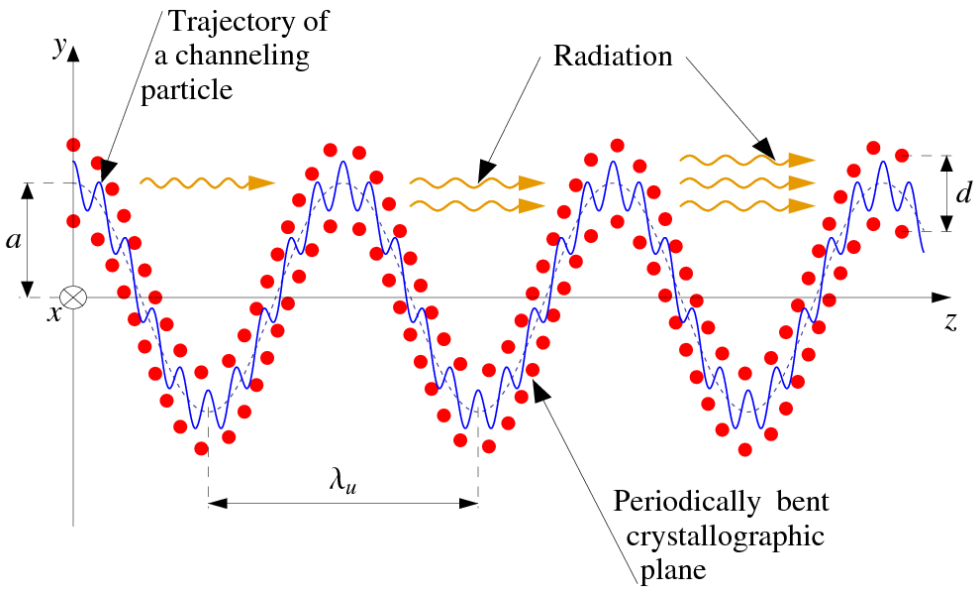
Stronger Energy loss for Ge is mainly due to its higher Z and larger X parameter

INNOVATIVE HIGH-BRILLIANCE X-RAY SOURCES

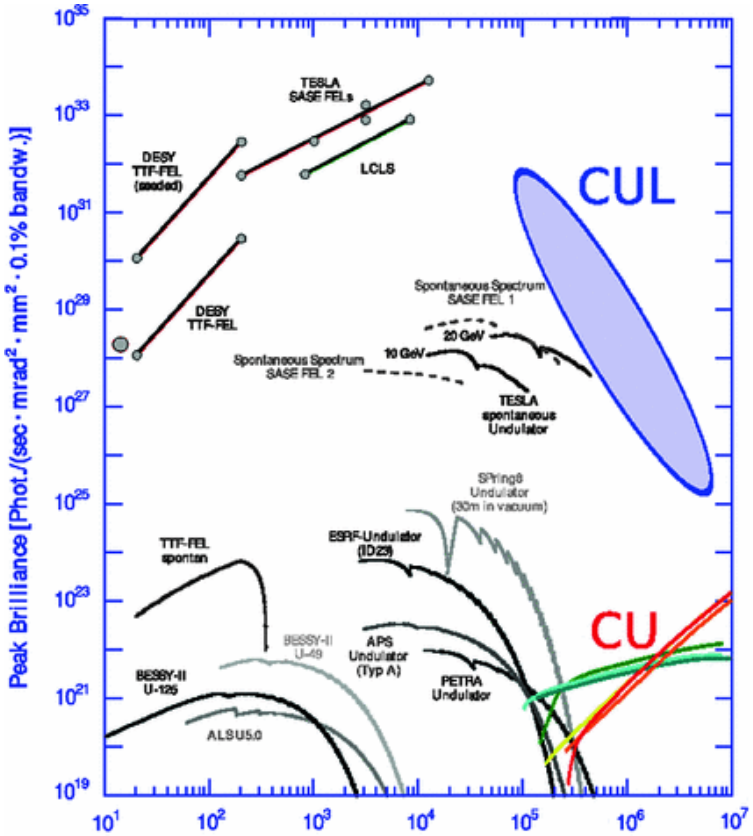
A classical scheme: FEL

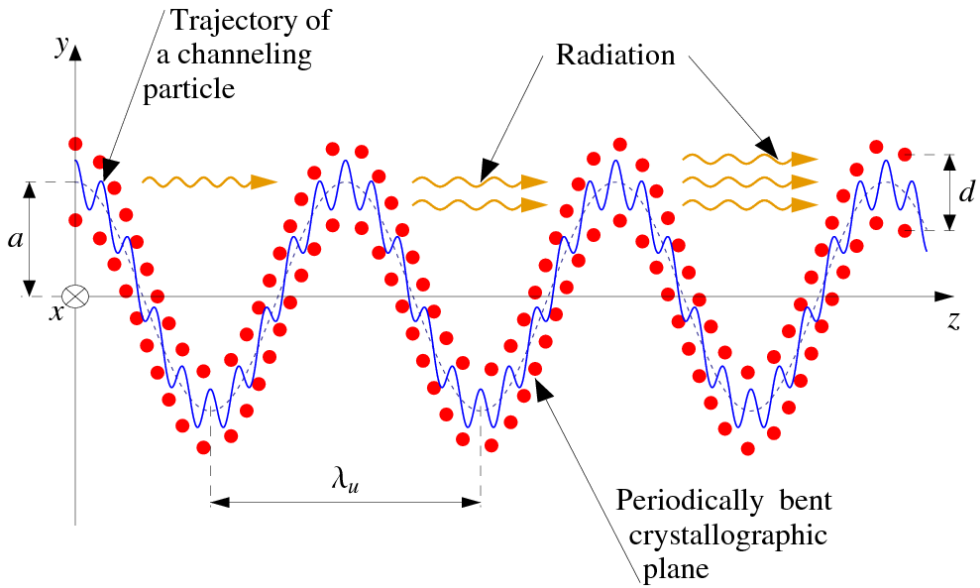


Innovation: crystalline undulator

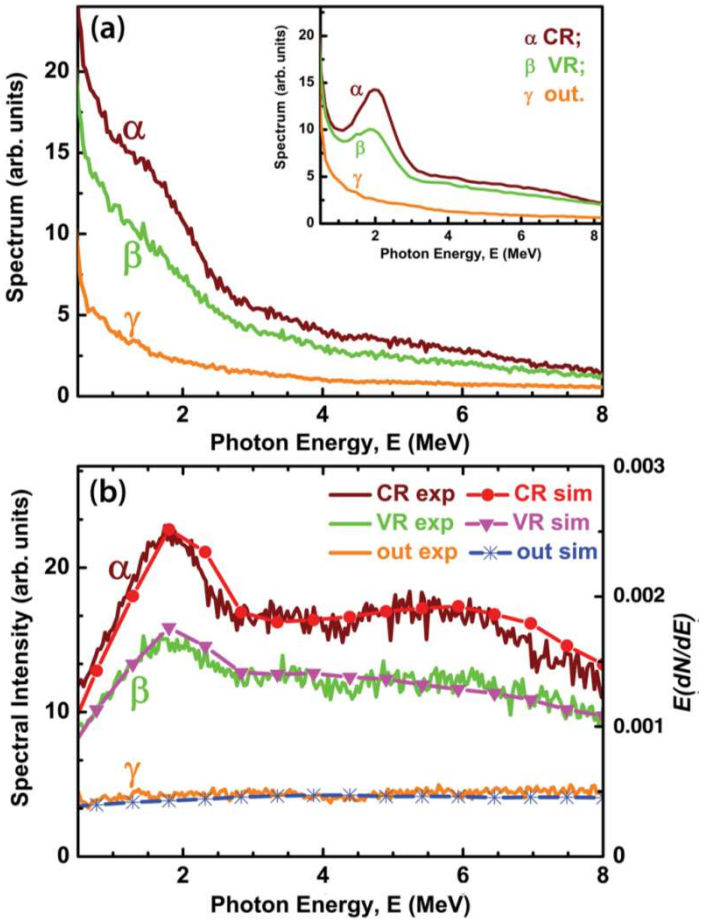


INNOVATIVE HIGH-BRILLIANCE X-RAY SOURCES





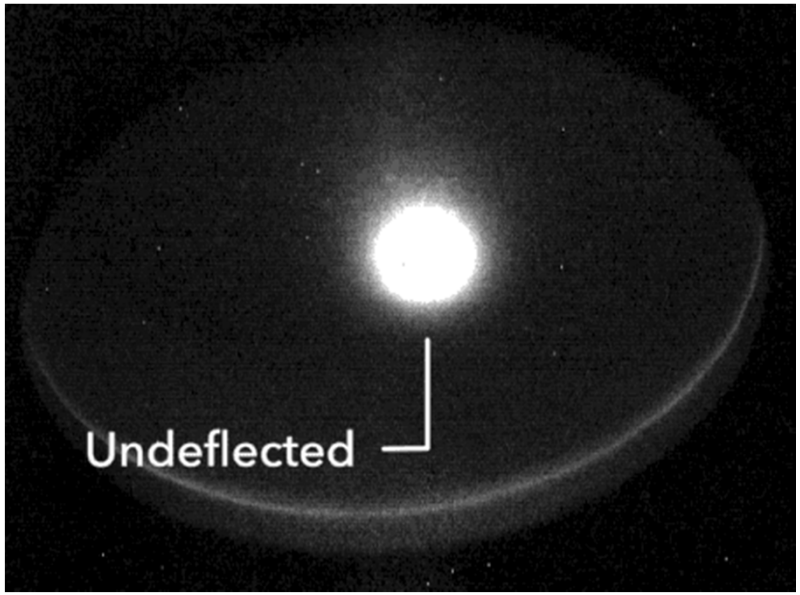
INNOVATIVE HIGH-BRILLIANCE X-RAY SOURCES



- Experiments at MAMI (Mainz) mictrotron
- Channeling peak at $E_\gamma \sim 1.8$ MeV for 855 MeV electrons in (111) Si bent planes
- A C++ routine, named RADCHARM++ [1], for radiation calculation based on the Direct Integration of Baier-Katkov quasi-classical formula (DIBK) method has been implemented in the DYNECHARM++ code [2], which numerically solves the equation of motion.

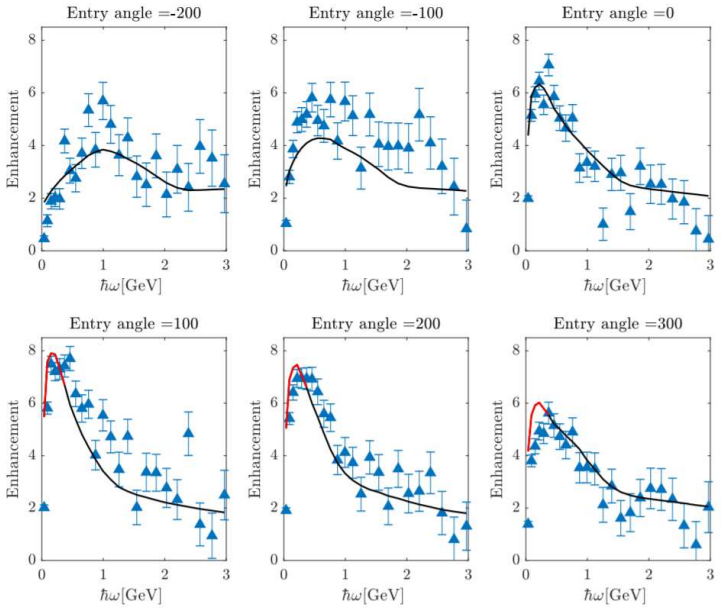
L. Bandiera et al., Phys. Rev. Lett. 115, (2015) 025504
E. Bagli, V. Guidi, Nucl. Inst. Meth. in Phys. Res. B 309, 124 (2013)

INNOVATIVE HIGH-BRILLIANCE X-RAY SOURCES



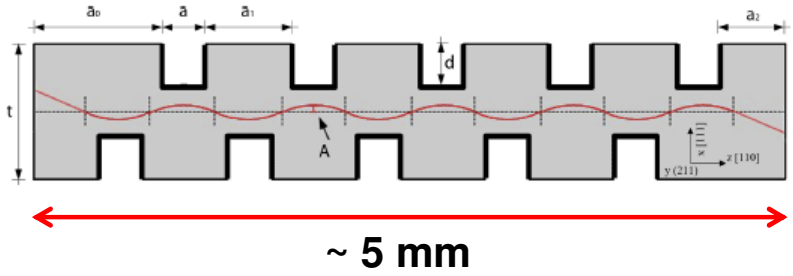
First Demonstrated Deflection @ 4.2 GeV

Investigated steering of multi GeV electron and positron beams



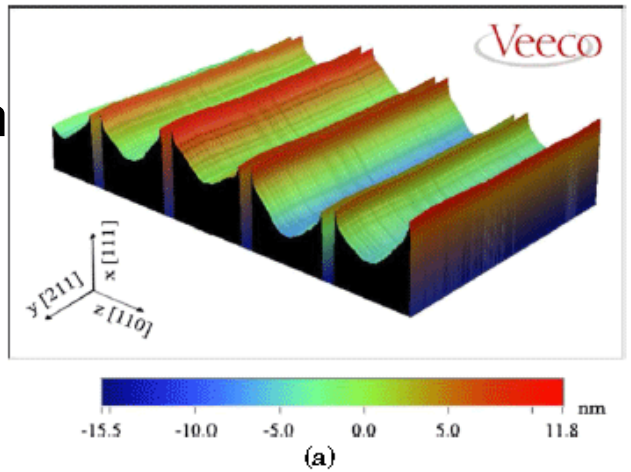
CRYSTALLINE UNDULATOR – MANUFACTURING AND CHARACTERIZATIONS –

Crystalline undulator manufactured grooving a silicon substrate by means of a high precision dicing machine.

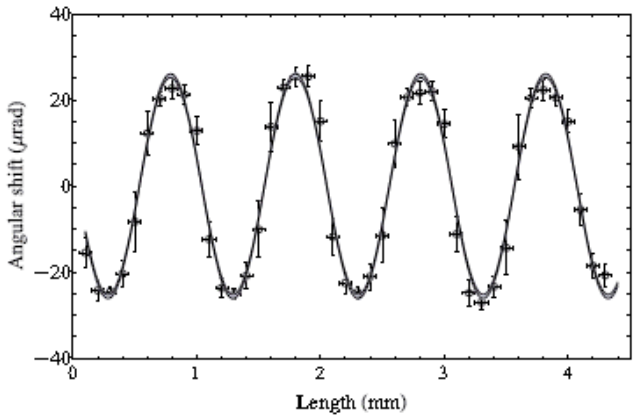


A periodical deformation is Imparted to the crystal

Interferometric characterization (Veeco)



Characterization @ ESRF (BM-05)

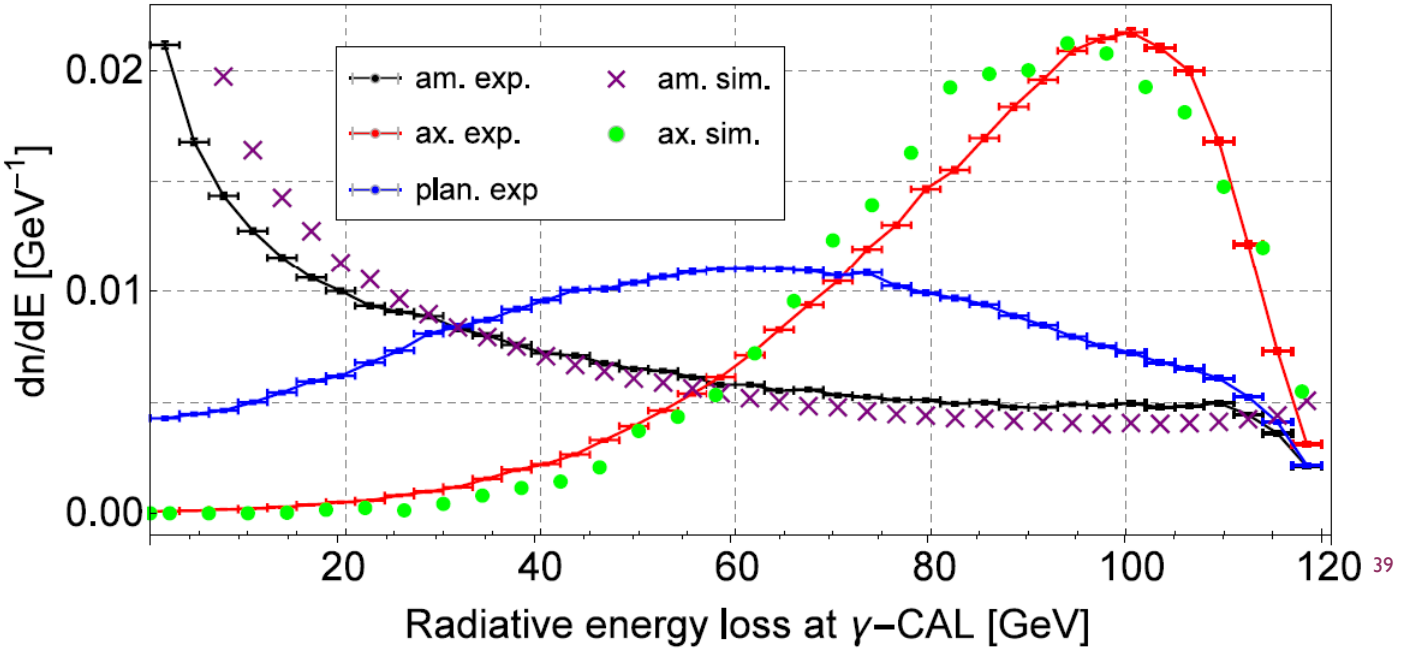


FUTURE DEVELOPMENTS («NEW PHYSICS»)

$PBWO_4$ AXIAL RADIATION FROM 120 GEV/C ELECTRONS

- The crystal once aligned absorbed particle energy as much as a material with fivefold reduced radiation length (no material exists with radiation length so small)
- More energetic beam would further increase the reduction of radiation length

Fivefold reduced radiation length



BREMSSTRHALUNG AND PAIR PRODUCTION IN SCINTILLATING CRYSTALS

- High-Z crystals (PWO, CsI, etc…) are used in electromagnetic calorimeters in high energy physics and astrophyics

- Coherent interactions in a crystals might lead to an increase of the generated e.m. radiaction and of pair production, with applications in high-energy phyiscs and astrophysics.

- First evidence recorded at CERN in the interaction of 120 GeV electron beam with a PWO crystal aligned to the beam long its <100> axis.

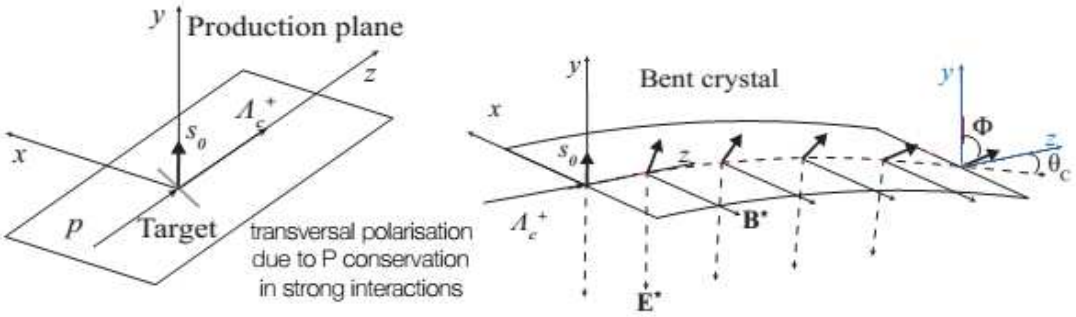
COLLIMATION OF HI-ENERGY AND HIGH-INTENSITY CIRCULATING PARTICLE BEAMS

BENT CRYSTALS FOR EDM AND MDM STUDIES

European Research Council
Established by the European Commission

Search for Λ_c^+, Ξ_c^+ baryon EDM at LHCb

- Fixed-target experiment for charm MDM measurement proposed in L. Burmistrov et al., CERN-SPSC-2016-030
- EDM can be searched for using identical experimental setup



- Experimental setup: fixed-target+bent crystal in LHC beam pipe. Impinging protons extracted from LHC beam halo using bent crystals ≈100 m upstream of the target
- Feasibility proved by UA9 experiment

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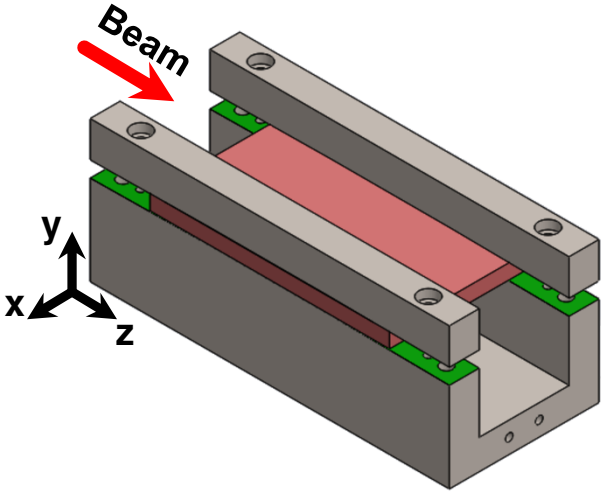
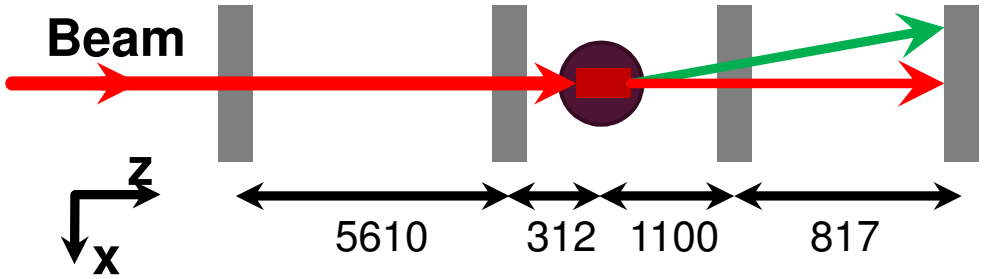
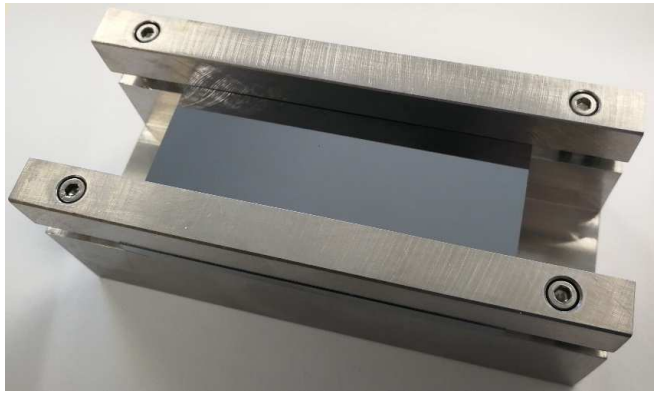
Proposal from N. Neri to the LHCb collaboration

EXPERIMENTAL SETUP @ SPS H8







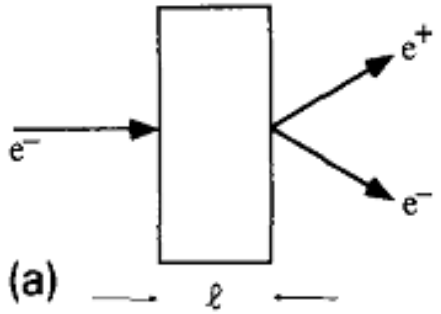
- Positive pion beam @ 180 GeV (H8 beam line).
- Particle tracking telescope to reconstruct particle trajectories (no vacuum pipes between telescopes).
- High resolution goniometer to align the crystal to the beam.
- Crystal offers (111) channeling planes, 8 cm thick along the beam, bending angle 16 mrad.

INNOVATIVE POSITRON SOURCE

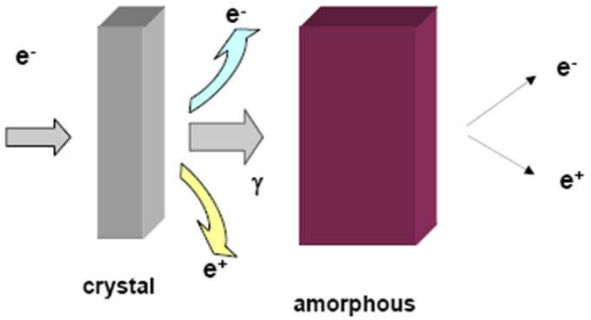
INNOVATIVE POSITRON SOURCE

Positron source using channeling in a tungsten crystal

X. Artru [a], V.N. Baier [b], R. Chehab [c,*], A. Jejcic [d]



KEK 7 GeV

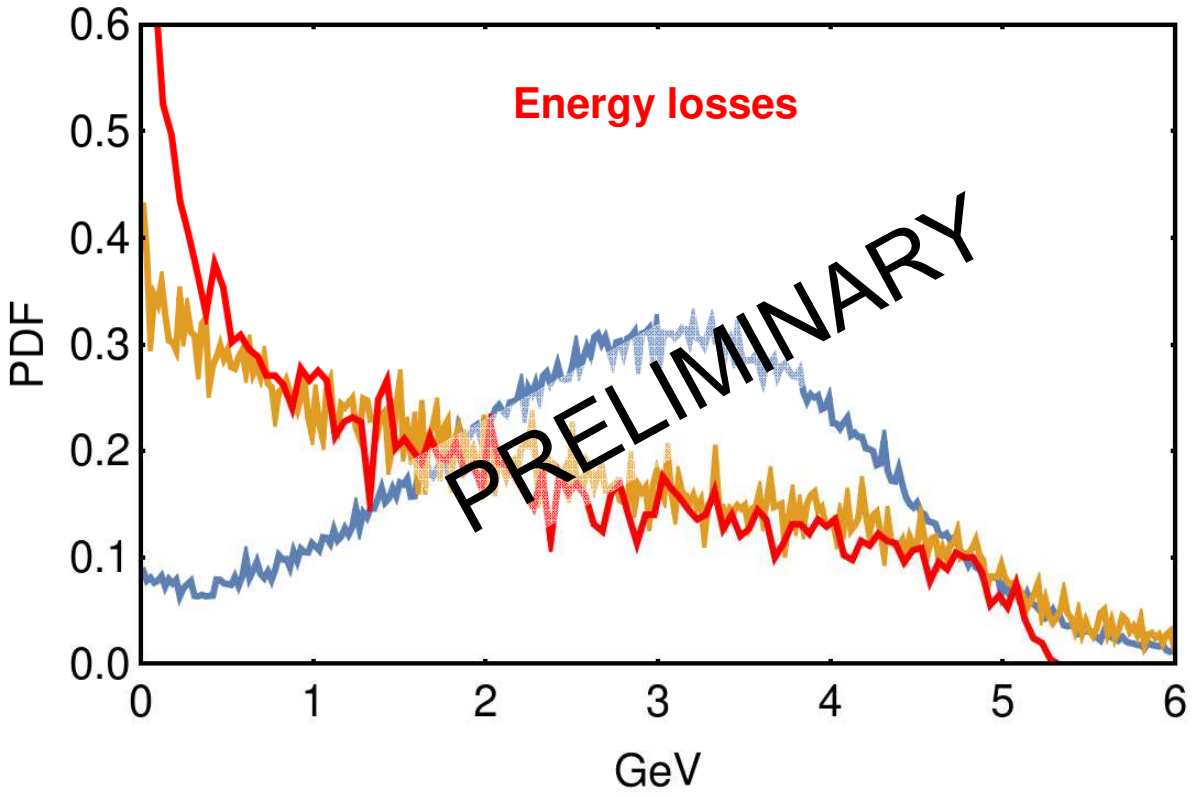


(a) Solution attractive because both processes, channeling photon production and pair creation, occur in the same medium.

(b) Hybrid source may be of interest since the amorphous target in which pairs are produced can be heated more.

Recent test at KEK NIMB 402 (2017) 58 with a <111> W crystal

INNOVATIVE POSITRON SOURCE



Data taking running at DESY

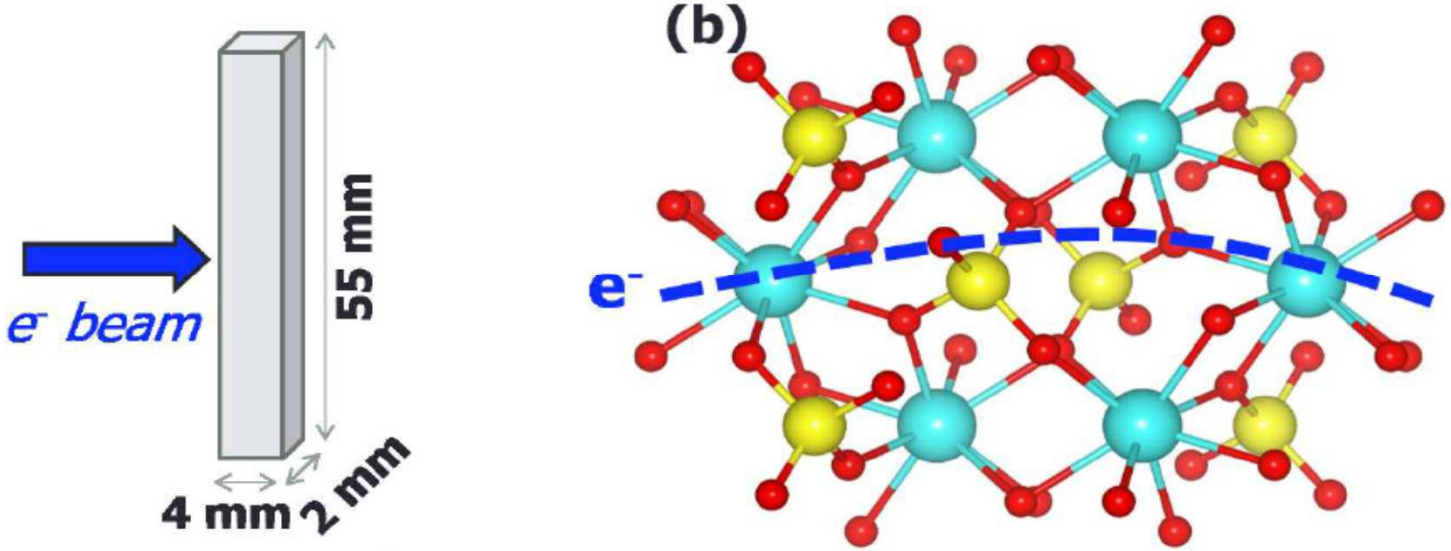
W crystal 2.3 mm thick

W [100] 7x7x2.3 mm3
axial experimental
amorphous experimental
amorphous Geant4

INNOVATIVE DETECTORS

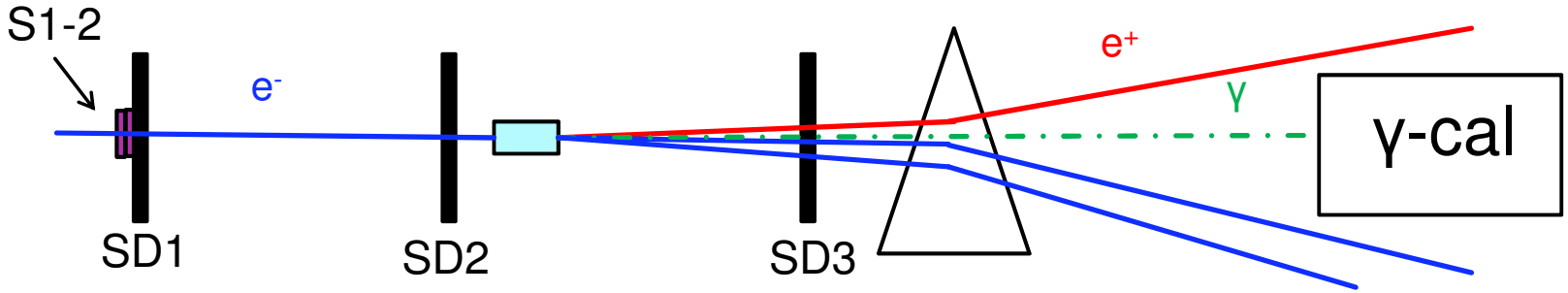
SCINTILLATING CRYSTALS

Structural characterization of PWO single crystal by x-ray diffraction showed scheelite type structure (tetragonal, a=5.456, c=12.020 Å).

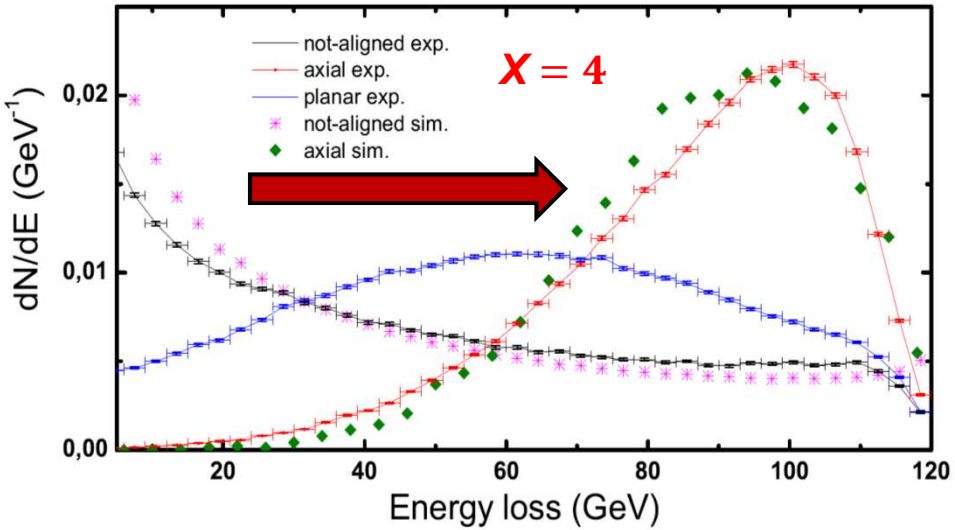


A 2x55x4 mm^3 strip-like PWO crystal with the largest faces oriented parallel to the (100) planes was selected for the experiment. **4 mm length** along the beam direction corresponds to about **0.45 X_0**.

RADIATED ENERGY LOSS



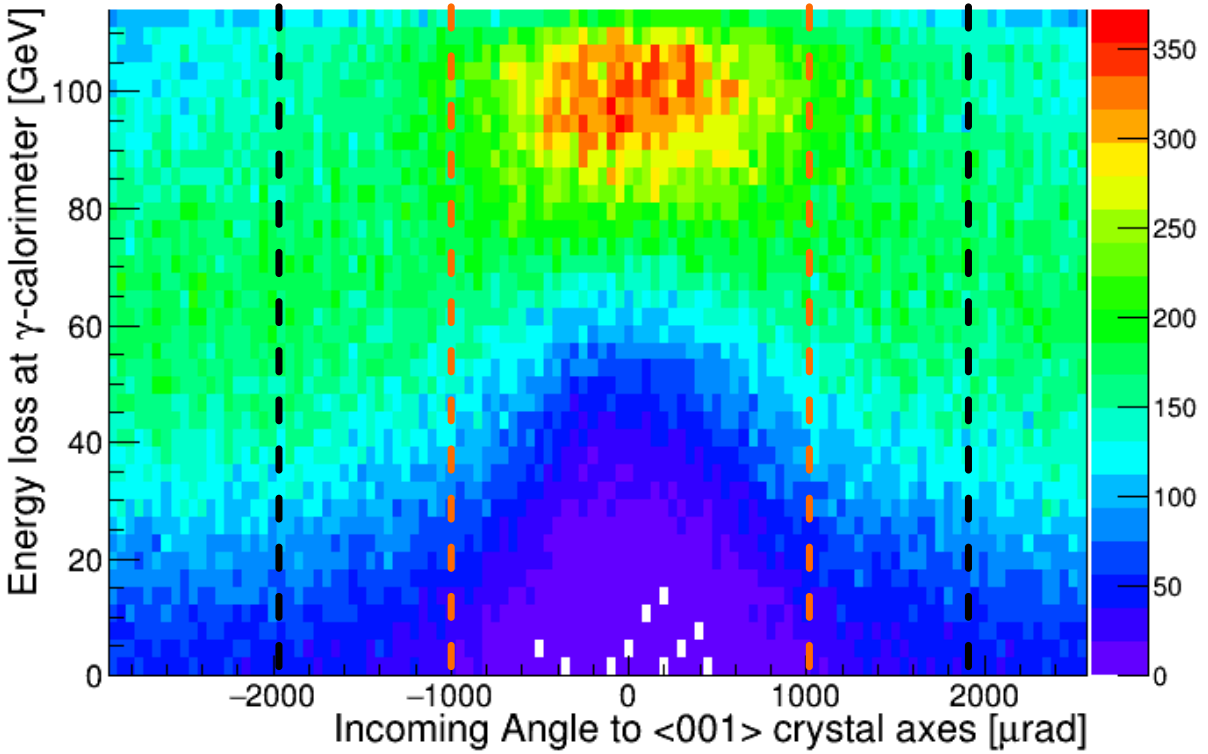
We selected single events on SD1-2 and collected the energy loss at the gamma-calorimeter.



Mean energy loss in photons:
~ 40 GeV not-aligned;
~ 85 GeV axial.

Strong reduction of X_0 in the oriented cases.

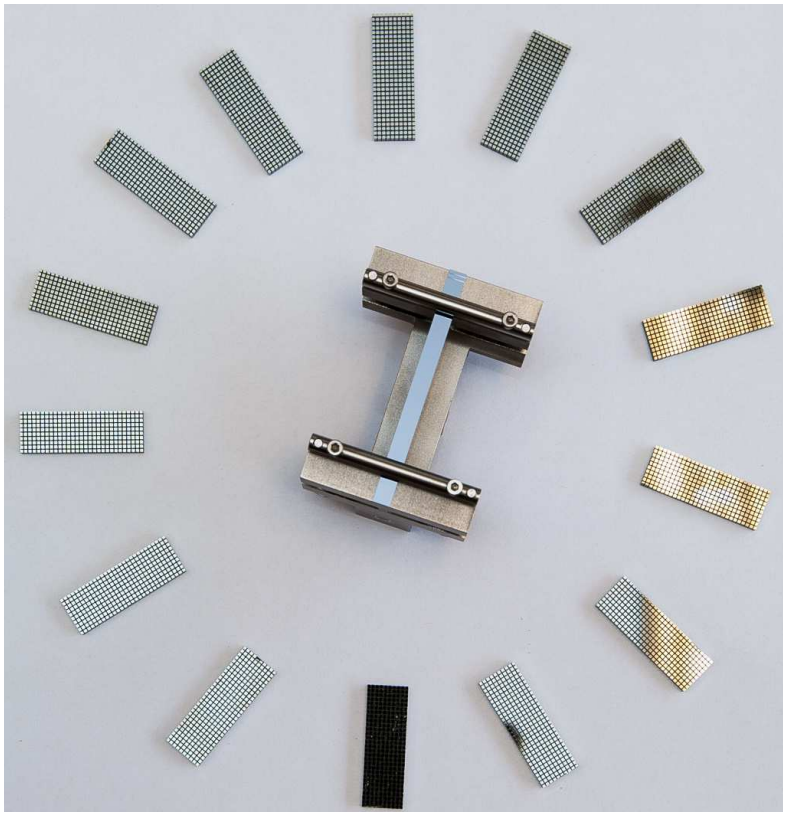
ANGULAR ACCEPTANCE OF RADIATION ENHANCEMENT



The axial influence is strong in **±1 mrad** angular range and it is maintained up to almost **±2 mrad** (±0.1 deg)

INFN INFRASTRUCTURES

INFN FACILITIES



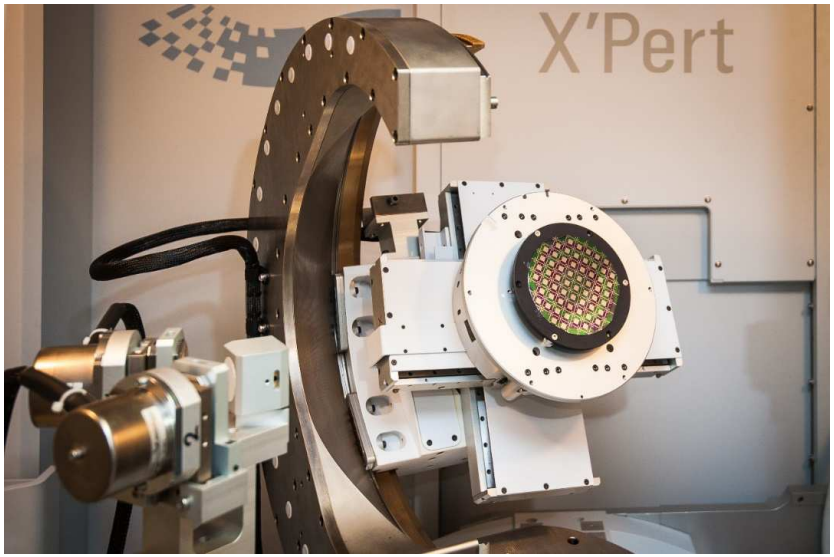
INFN owns a complete infrastructure for manufacturing and characterization of bent and not bent crystals for applications at high-energy particles accelerators.

INFN is the only wordwide agency with full capabilities for

- Crystals design and manufacturing
- Design and setting up of complex experimental setup to study coherent interactions between charged particle beams and crystals
- Setting up of data taking and data analysis
- Papers writing and handling

We are willing to collaborate with any worldwide agency.

INFN FACILITIES



High resolution x-ray diffraction

- Measurement of crystals perfection in terms of micut angle, dislocation density
- Characterization of crystals deformational state (bending angle, torsion)

INFN FACILITIES

Optical photolitography and chemical etching are basic tools for crystals shaping

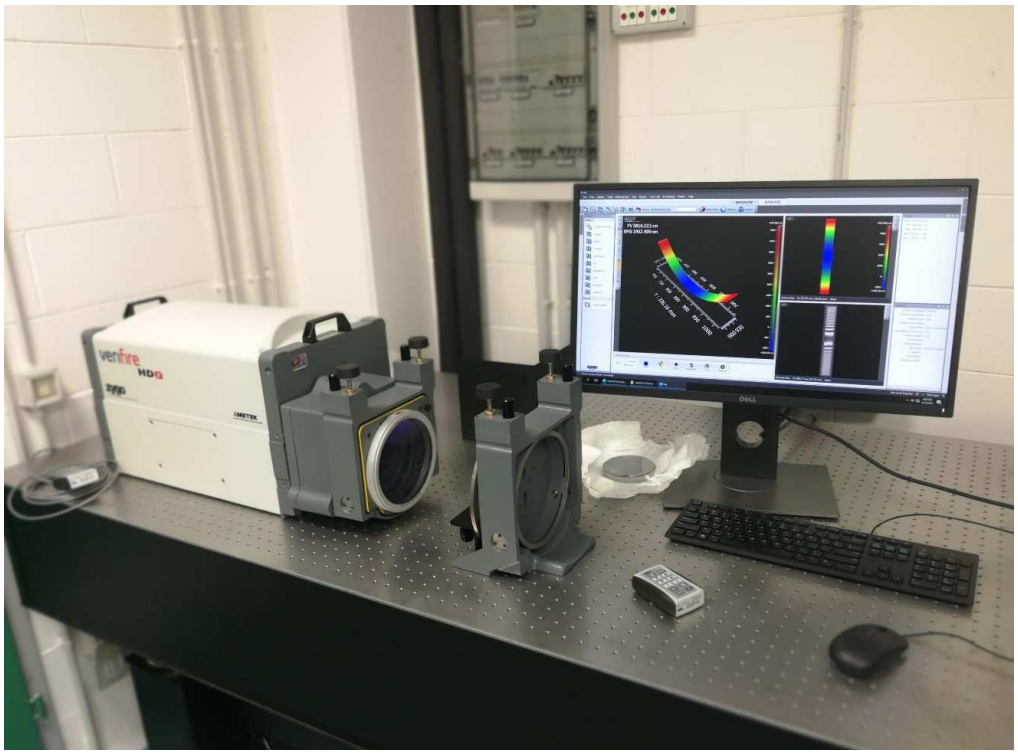
- Coater and spinner units
- Chemical web benches
- Equipment for silicon wafers and pieces cleaning before and after chemical machining.

MECHANICAL DICING

Mechanical dicing is used to shape crystals such as germanium or others which can not be chemically-machined.

- Dicing recipes optimized for low lattice damage
- Chemical etching removes lattice damage after dicing operations.

HIGH RESOLUTION INTERFEROMETRY



- Zygo Verifire HDX laser interferometer was recently installed at Ferrara Laboratories
- Great increase of the field of view: 150 Ø mm in a single acquisition
- High lateral resolution thanks to 50x digital magnification
- Nanometric resolution

CONCLUSIONS

- Efficiency of steering of particle beams assisted by crystals raised from a few % to almost 100%, reaching its theoretical limit.
  - Collimation and extraction of LHC circulating beam
  - New physics!
- Coherent interactions as innovative sources of e.m. radiation
  - Experiments at CERN, DESY, MAMI, SLAC lines
- Future applications to study new physics
- We are ready for new collaborations