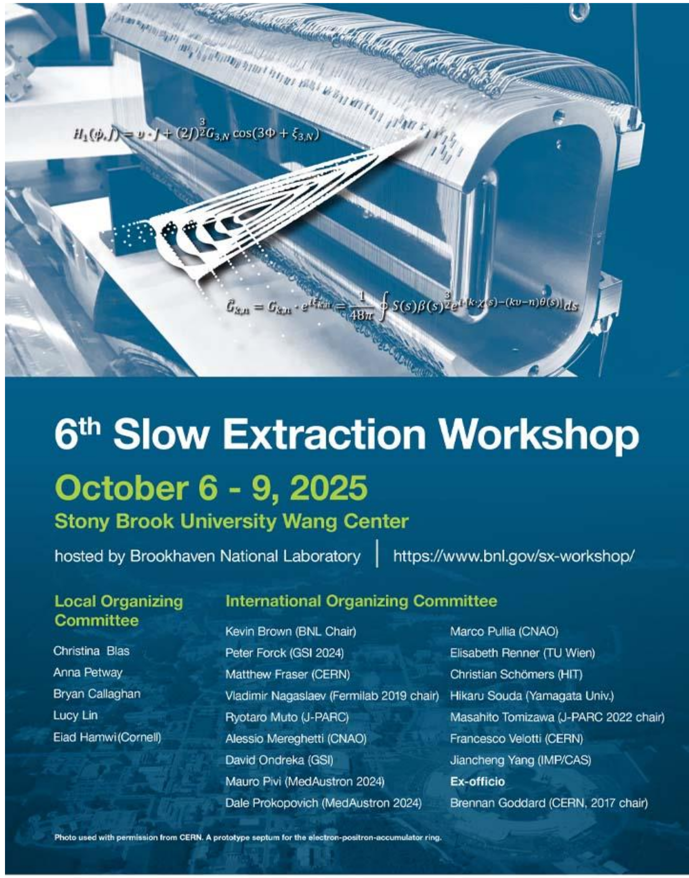
DEVELOPMENT OF BENT CRYSTALS FOR SLOW EXTRACTION

Vincenzo Guidi and Marco Romagnoni
on behalf of Ferrara team



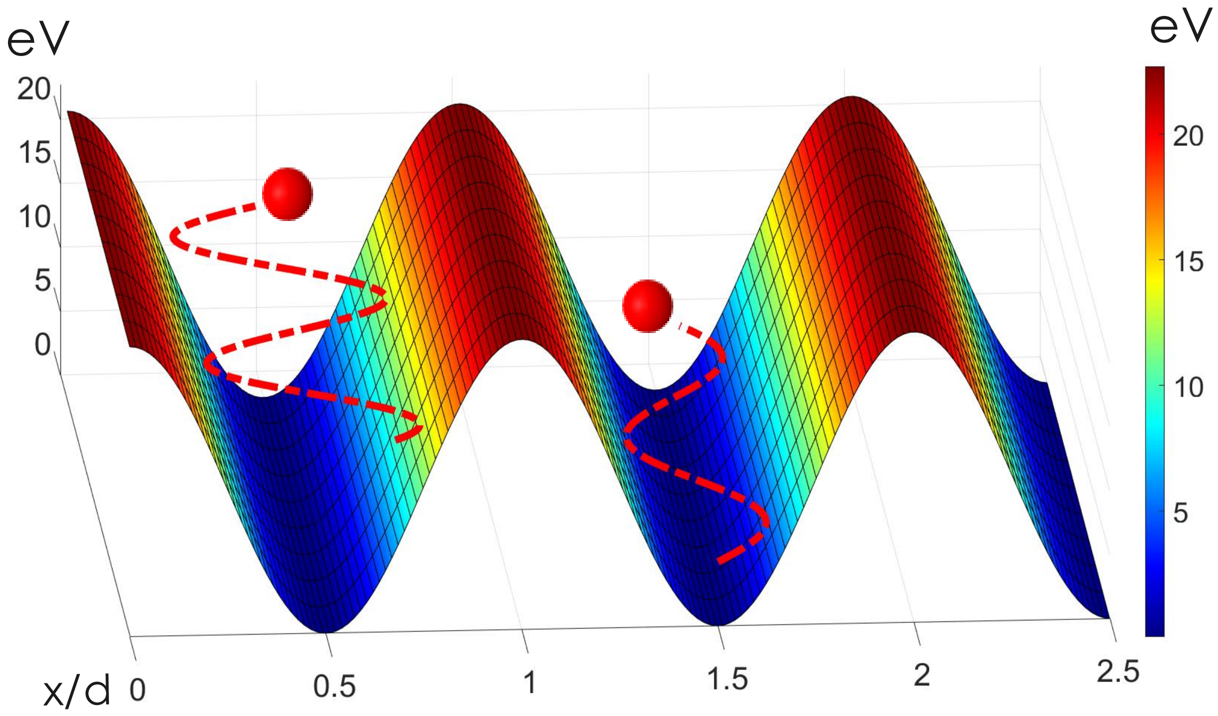
In streaming from Ferrara (Italy), October 8th, 2025

OUTLINE

- Brief introduction on crystal channeling
- Crystal design and fabrication
- Bent crystal characterization
- Conclusions and future plans

CHANNELING IN CRYSTALS

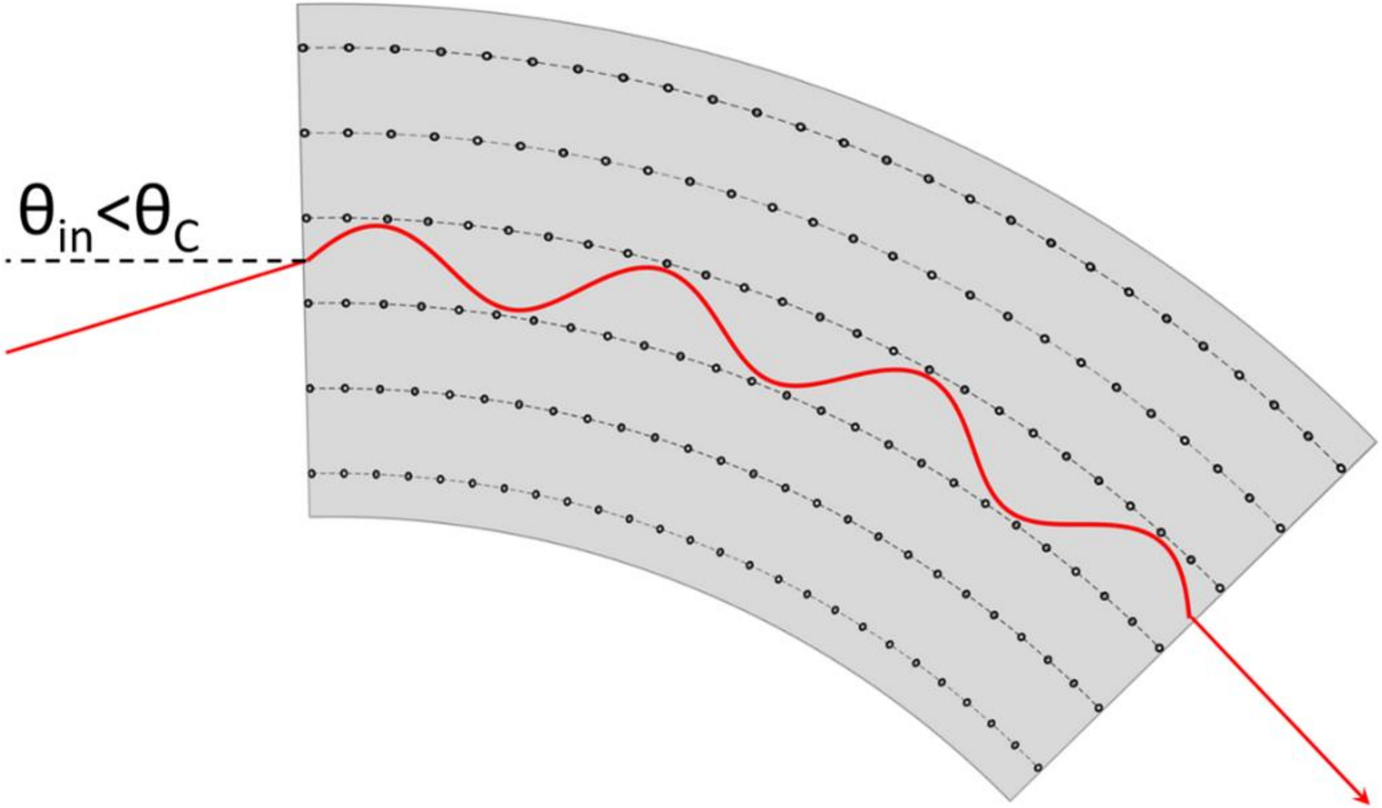
- As a charged particle enters a crystal slightly atilt with respect to atomic planes, channelling takes place mainly due to:
- Small scattering angle
- Repeated periodic scattering against nuclei at nearly the same impact parameter



It builds up a continuous strong static potential (≈**GeV/cm**), which can trap (channel) and guide positive particles between two adjacent atomic planes within a critic angle $\sqrt{(2U_0)/(pv)}$

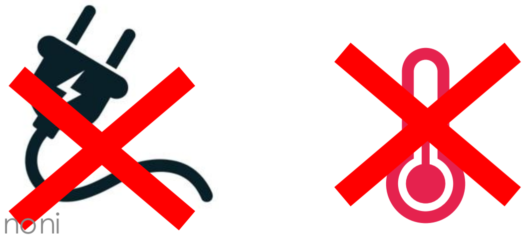
CHANNELING IN BENT CRYSTALS

- Channeled particle follows the curvature of the lattice plane
- A bent crystal can act as a sort of waveguide for channeled particle, steering them at angle depending on its geometry



CHANNELING IN BENT CRYSTALS

- Channeled particle follows the curvature of the lattice plane
- A bent crystal can act as a sort of waveguide for channeled particle, steering them at angle depending on its geometry
- **Large steering power can be obtained in few millimeters of crystal**, equivalent to that of hundreds of Tesla magnetic dipole

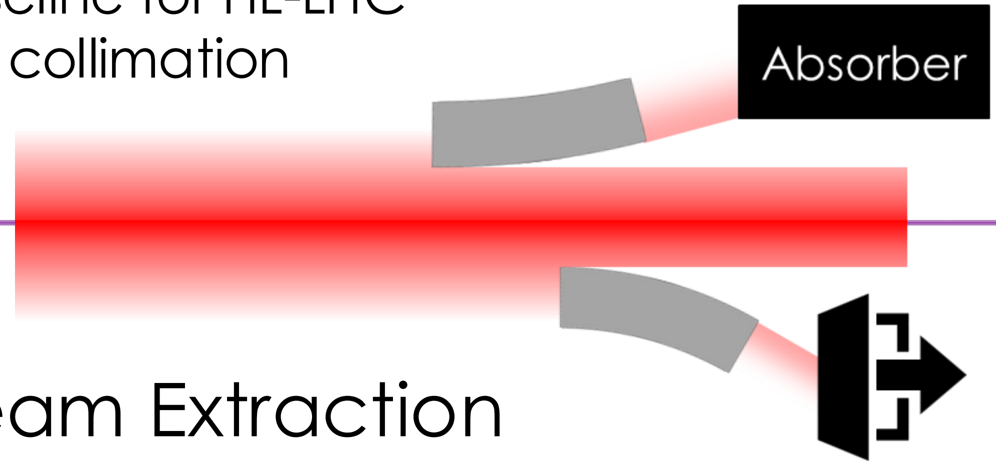


Energy (GeV)	Deflection (μrad)	Size (mm)	Equivalent dipole (T)
6500	50	4	276
0.855	1500	0.015	285
20.53	400	0.06	456
2000	14000	70	1134

BENT CRYSTAL APPLICATIONS

Beam Collimation

With crystal high control of beam halo separation from primary beam
Baseline for HL-LHC
ion collimation

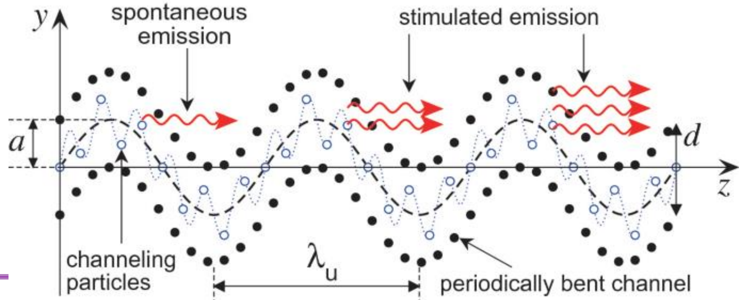


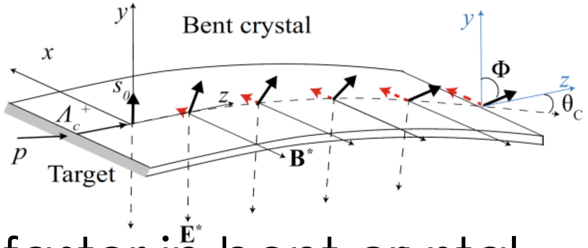
Beam Extraction

Surgical redirection of a beam portion, towards a precise location in the machine or in an external facility

Novel radiation sources

For channeled light particles (e^+/e^-) enhanced photon emission



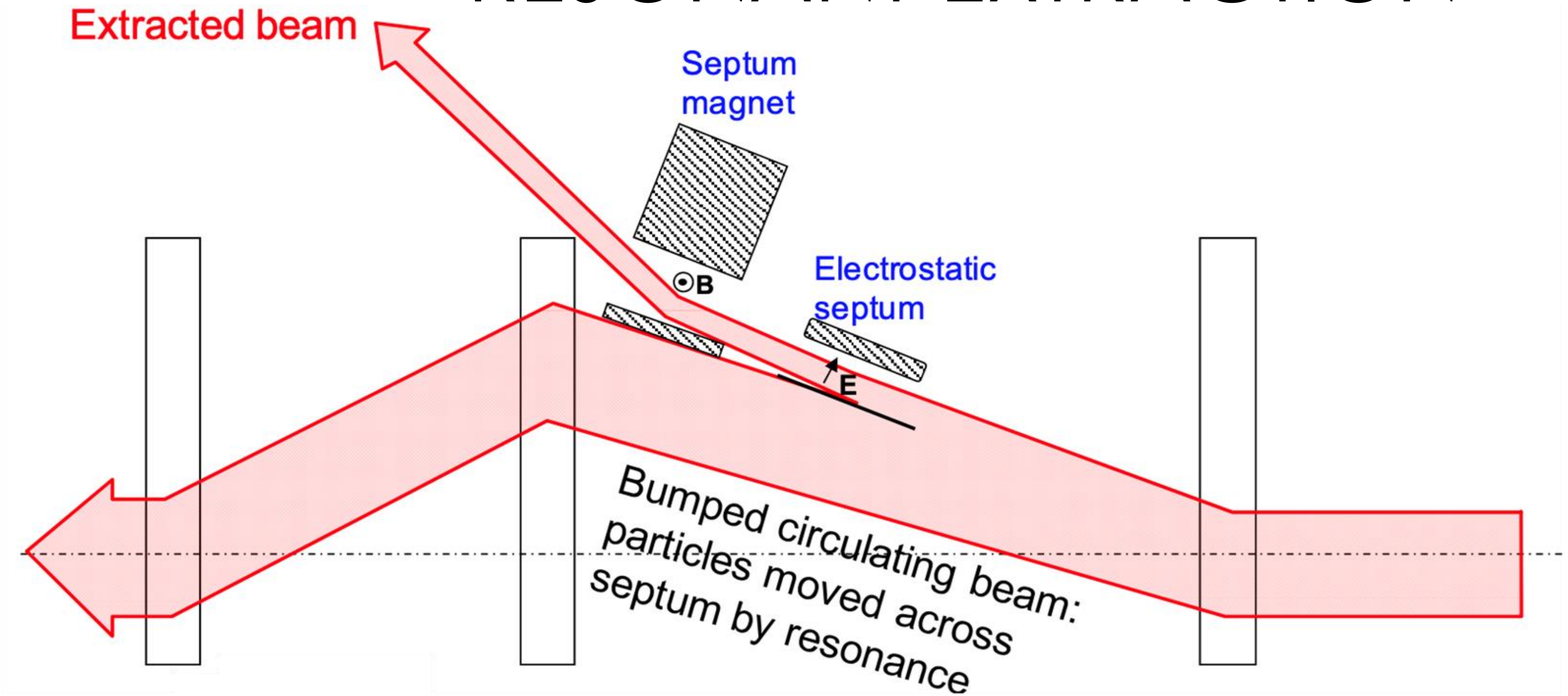


Spin precession

Spin precession much faster in bent crystal wrt existing dipole magnets→EDM & MDM study of fast decaying particles

SEPTUM MAGNET FOR SLOW RESONANT EXTRACTION

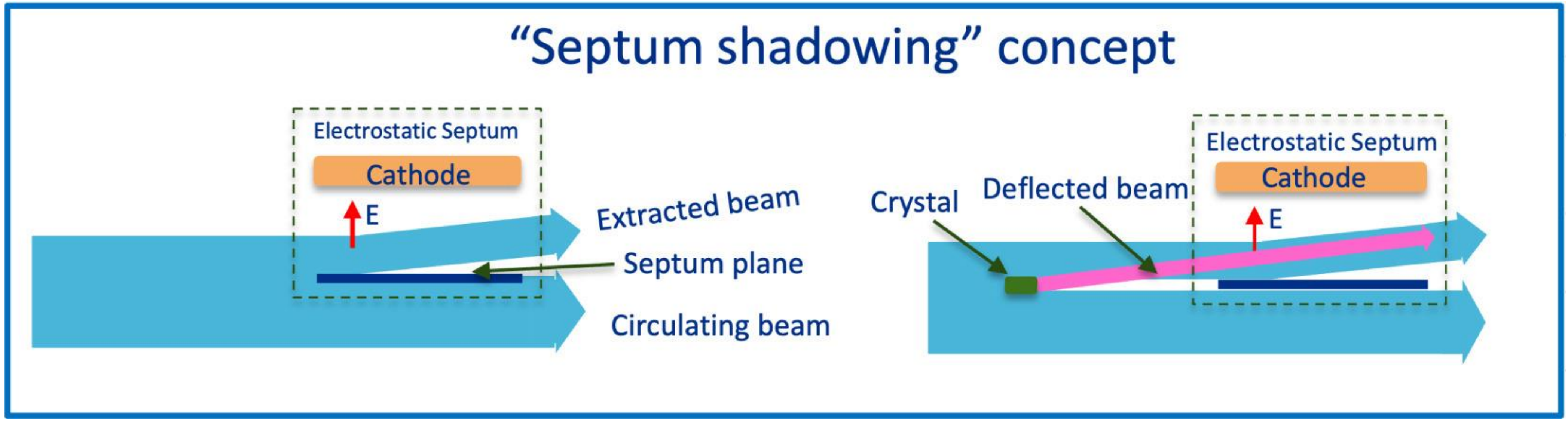
- Resonance is driven by sextupoles
- Largest oscillating particles are captured by the septum magnet yielding extraction
- A fraction of the particle beam interact with the matter in the septum and generates losses



Slow extraction by crystal extraction was pioneered at CERN by F.M. Velotti, F.M., Esposito, et.al. Septum shadowing by means of a bent crystal to reduce slow extraction beam loss. *Physical Review Accelerators and Beams*, 22, 093502.

BEAM SHADOWING WITH A BENT CRYSTAL

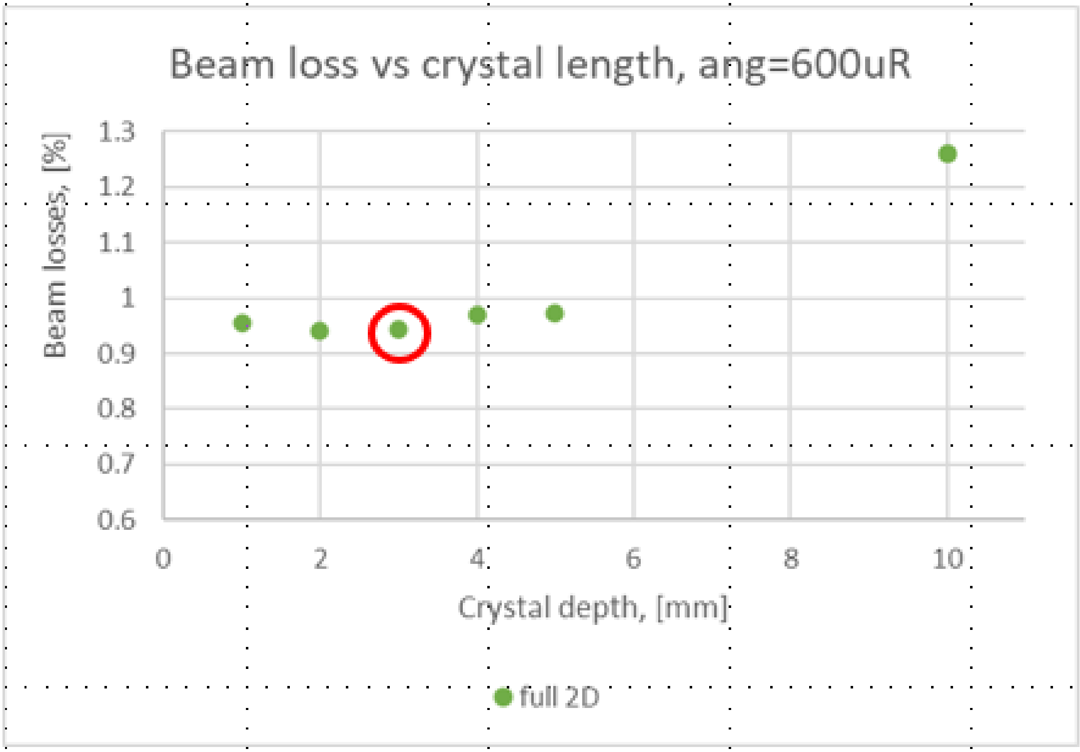
- An upstream bent crystal aligned wrt the beam deflect incoming particles
- The crystal ”shadows” the septum plane
- Tested at SPS for 400 GeV proton
- Feasible also for 8 GeV proton of Mu2e beam

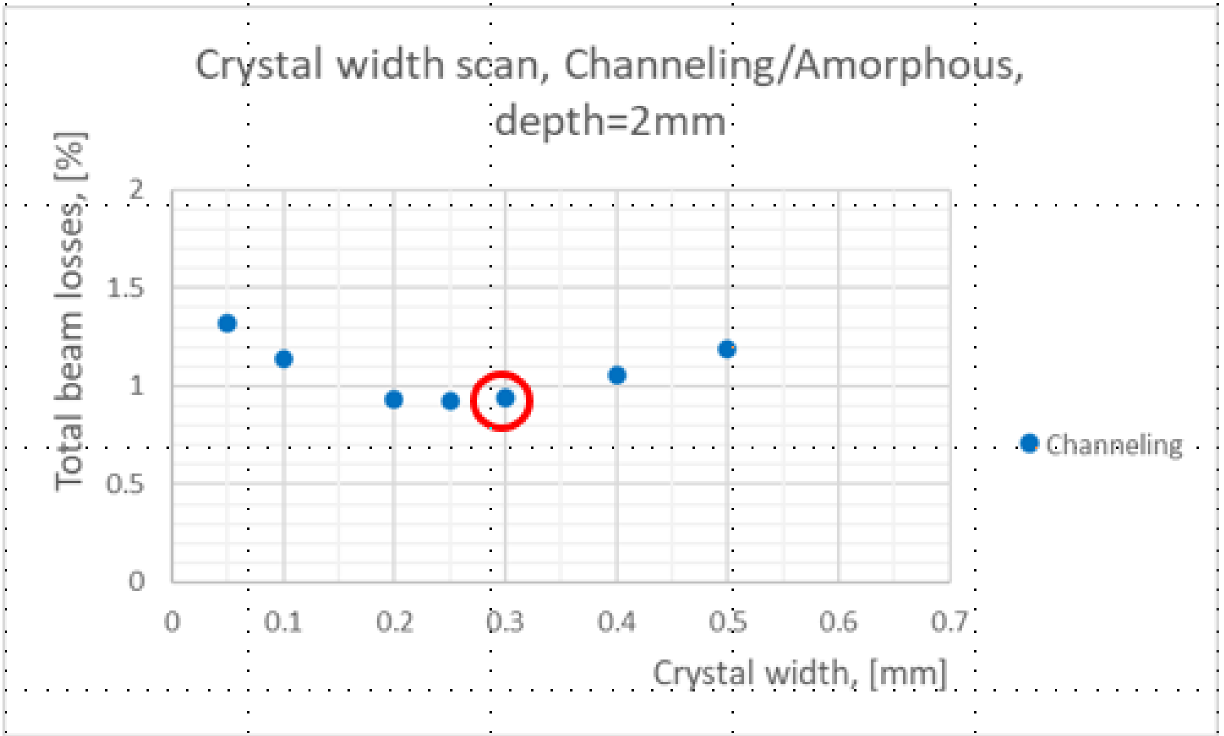


S. Miscetti and Mu2e Collaboration. "Status of the Mu2e experiment." Nucl. Instrum. Methods Phys. Res. (2025): 170257.

SIMULATION OF BEST CRYSTAL CONDITION

Beam losses from interaction of beam with the septum can cause high level of radiation and consequent limitation to beam intensity





Courtesy of Vladimir Nagaslaev (FNAL)

DESIGN PARAMETERS

Deflection Angle	300-600 μrad
Crystal Thickness along the beam	3 mm
Crystal Width across the beam	300±20 μm
Crystal Torsion	<10 μrad/mm
Distance between crystal and holder	>10 mm
Crystal height free of clamping	>30 mm
Holder Material	Stainless steel
Bake-out cycle	No need

- Crystal fabrication at our clean-room facility

- Crystal fabrication at our clean-room facility

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SAMPLE FABRICATION

Prime-material quality control

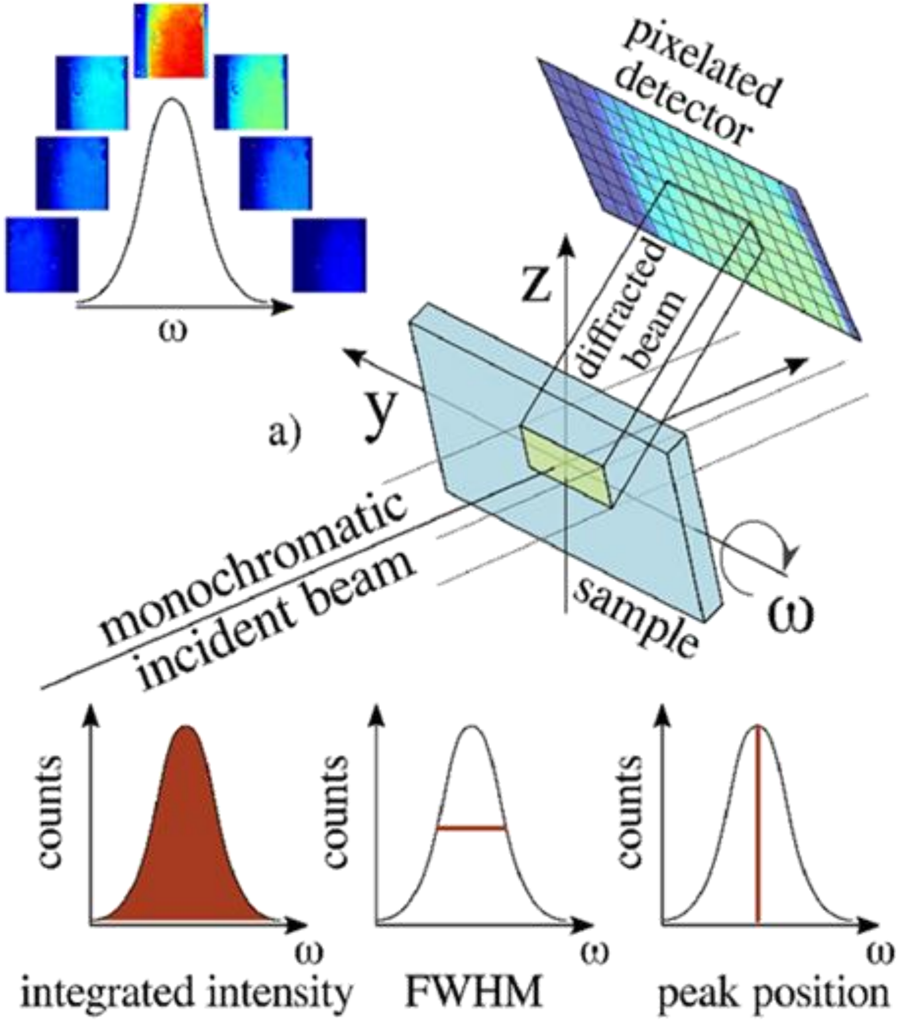
Sample shaping

Mechanical bending

Bending characterization

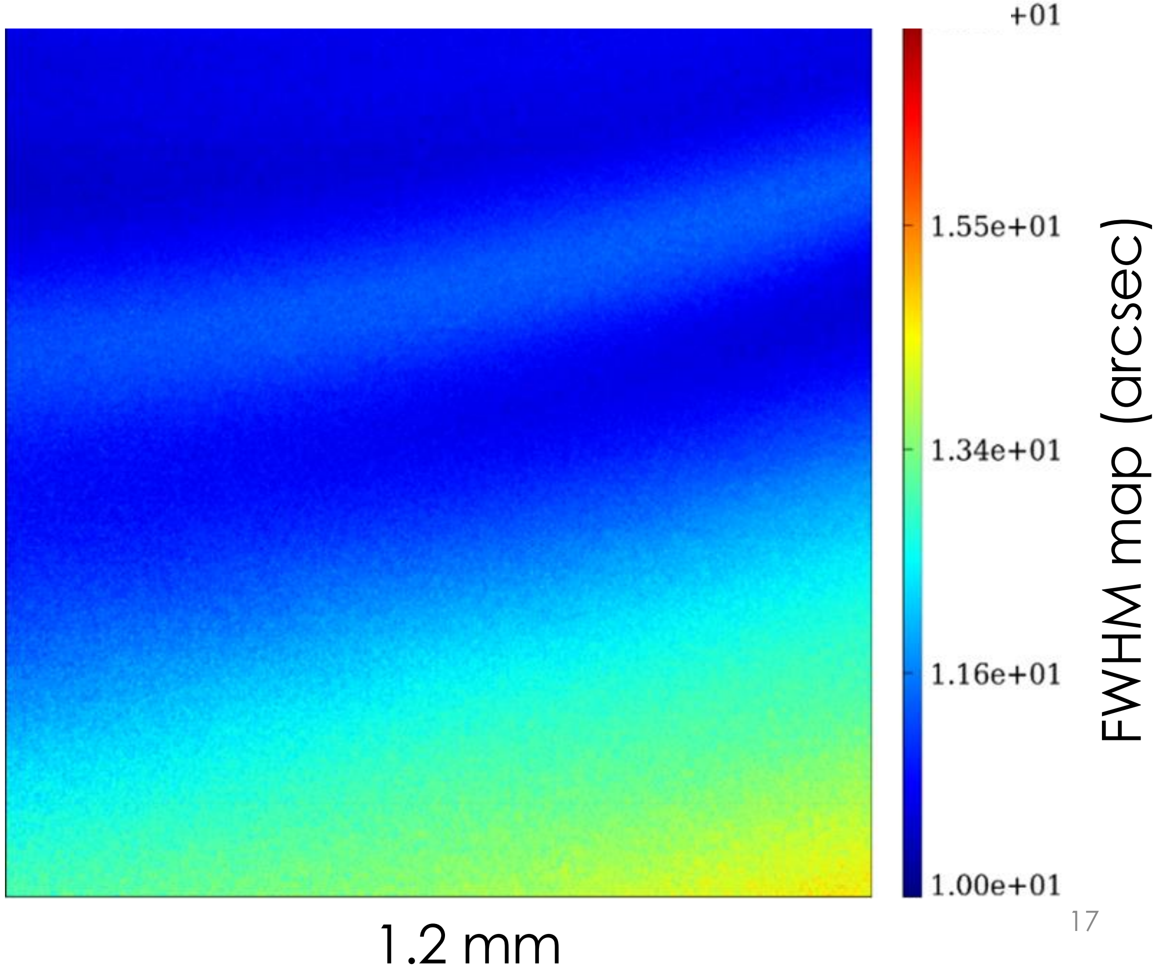
WAFER QUALITY ASSESSMENT

- For high channeling efficiency, lattice quality is mandatory
- X-ray topografy is powerful technique for crystal lattice characterization:
  - Crystalline quality
  - Lattice parameter variation
  - Curvature, strain
  - Defects



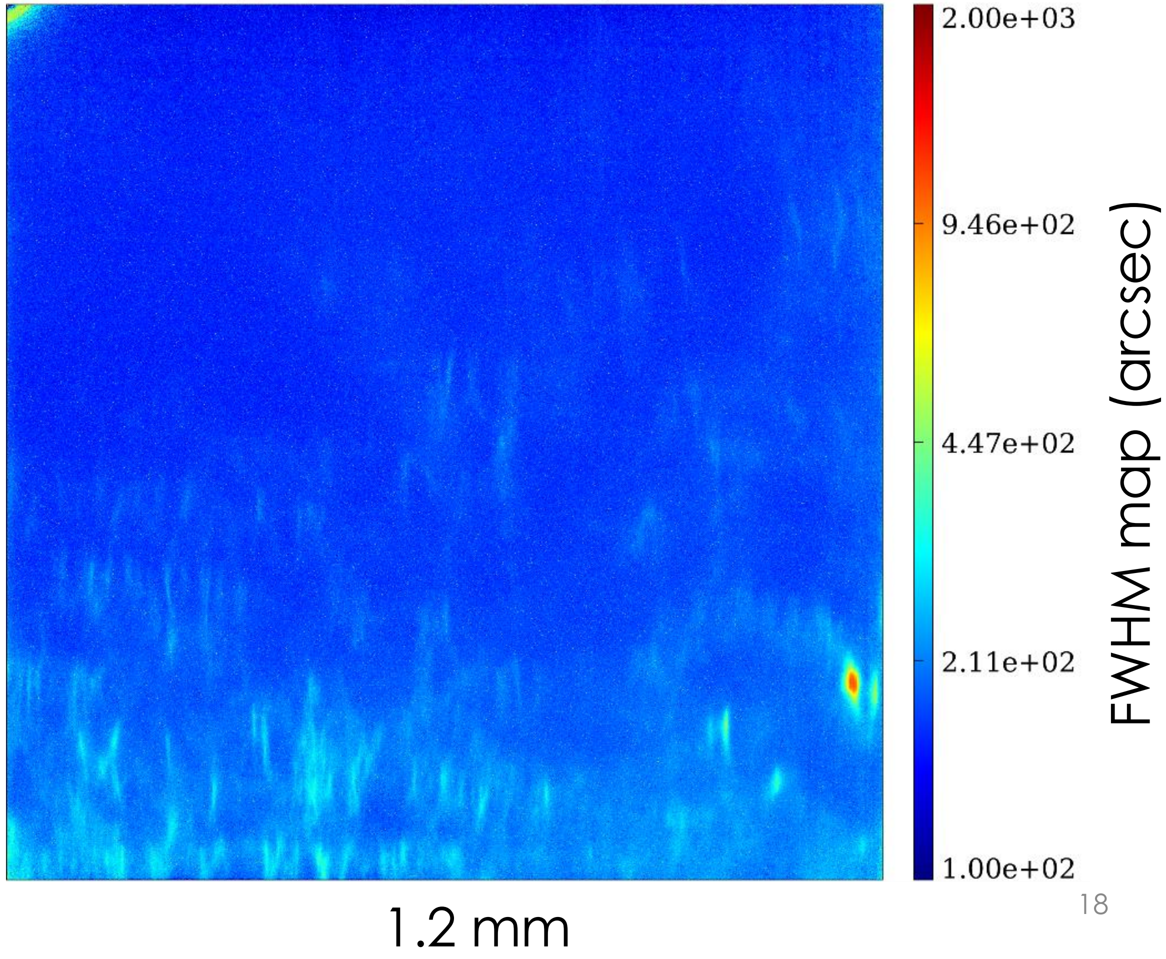
WAFER QUALITY ASSESSMENT

- X-rays topography (performed at ESRF) allows detecting defects in the bulk of the crystal
- Selected silicon wafers exhibited no dislocation



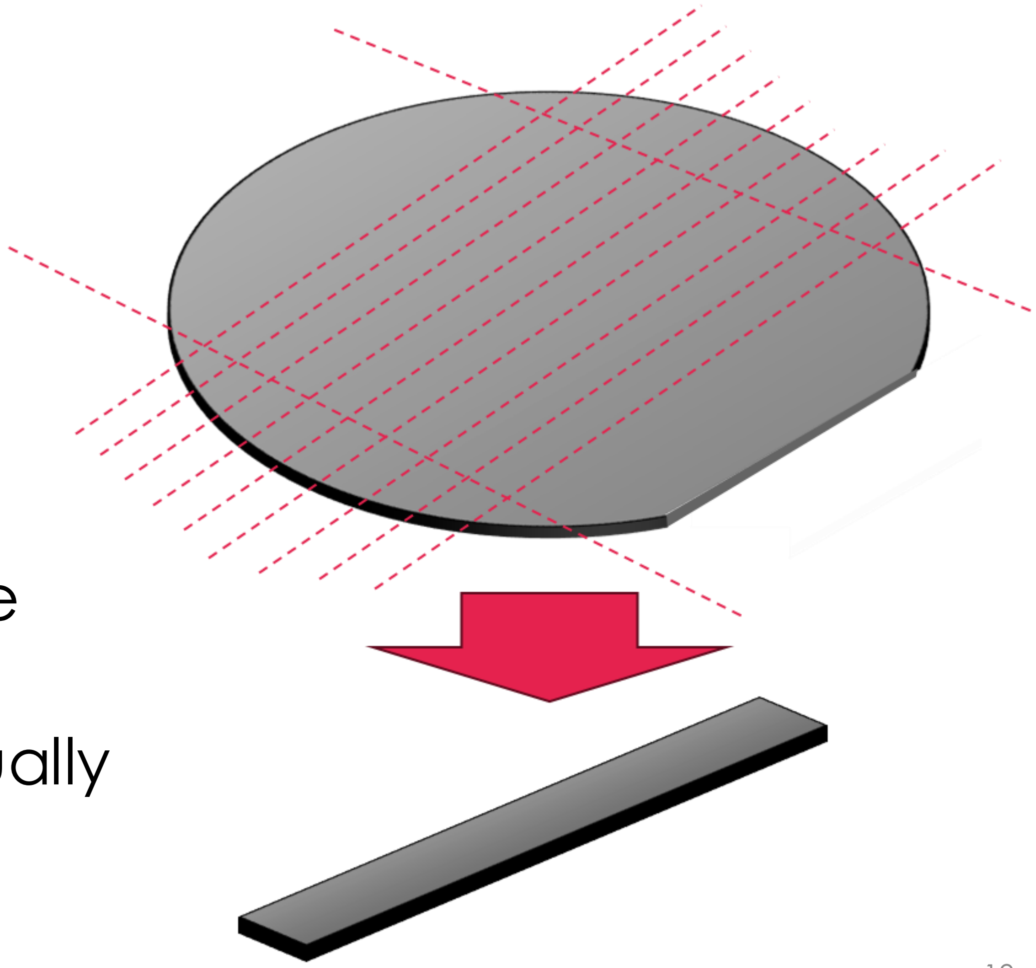
WAFER QUALITY ASSESSMENT

- X-rays topography (performed at ESRF) allows detecting defects in the bulk of the crystal
- Selected silicon wafers exhibited no dislocation
- For comparison we show a faulted sample

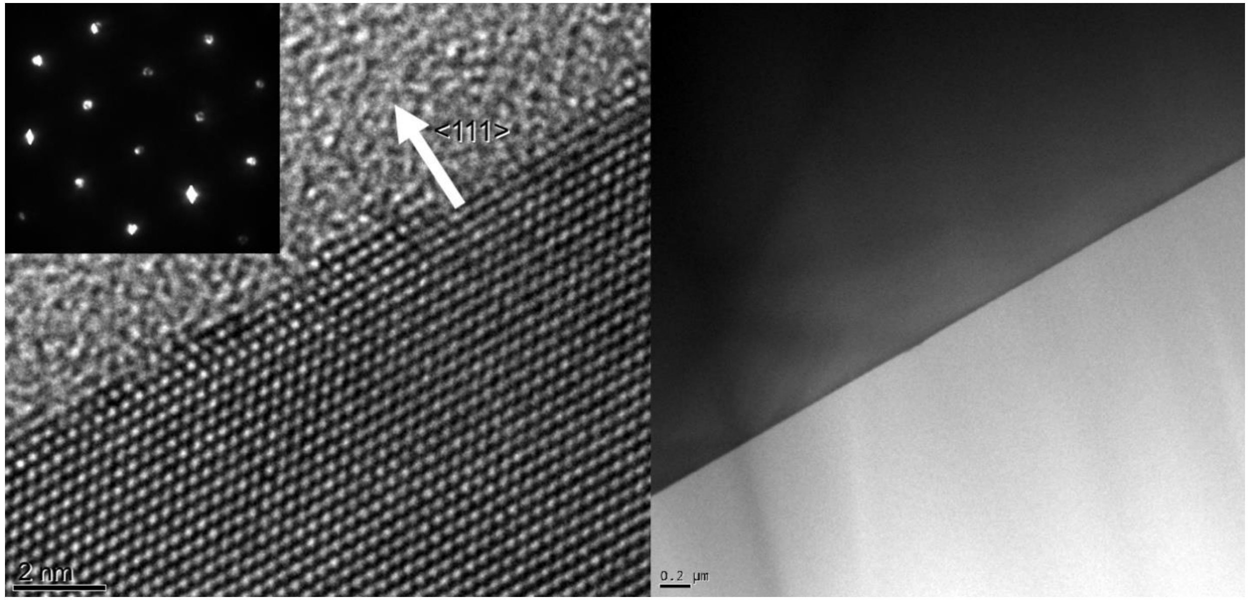


SAMPLE PREPARATION

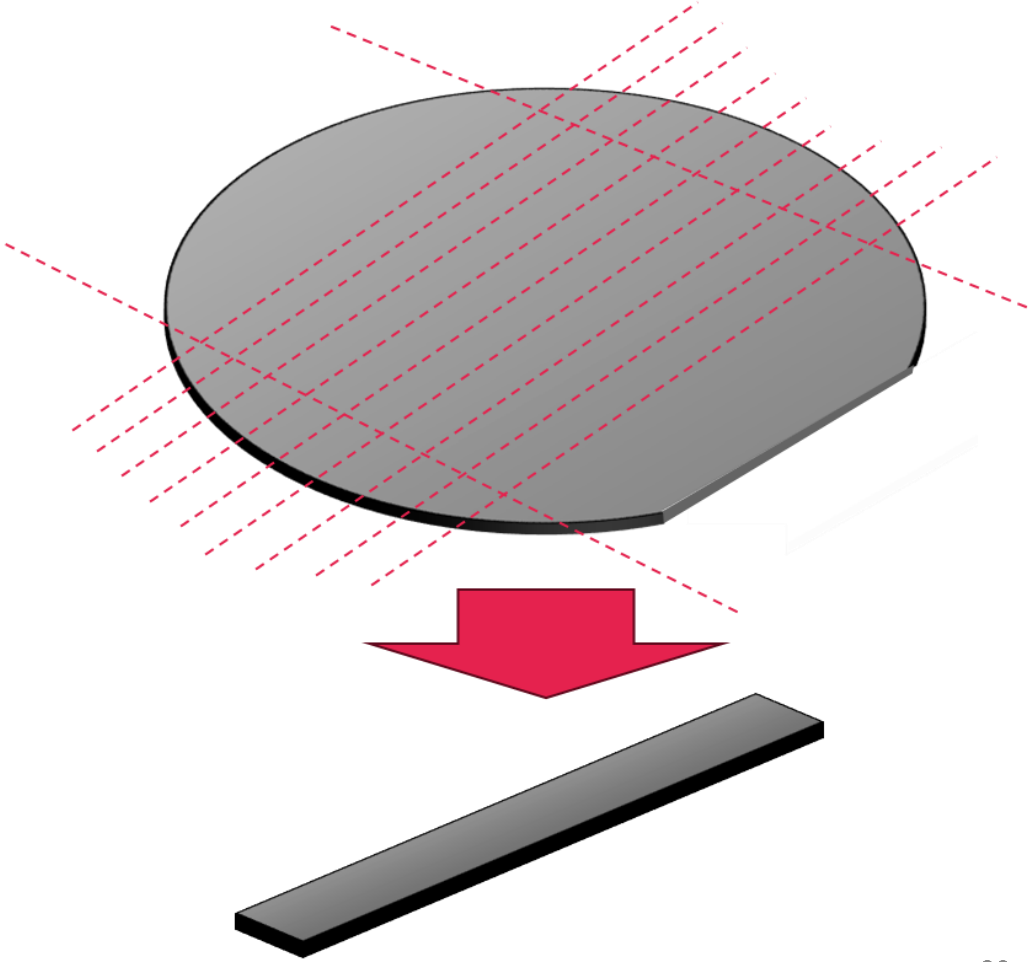
- Starting from a wafer, samples with parallelepiped shape are achieved
- Shaping was done with dicing blades bonded with micro-diamonds
- Micrometric precision can be achieved
- Etching of cut surfaces to get rid of crystalline imperfections as a result of the cut
- The entry faces for the beam are eventually lapped



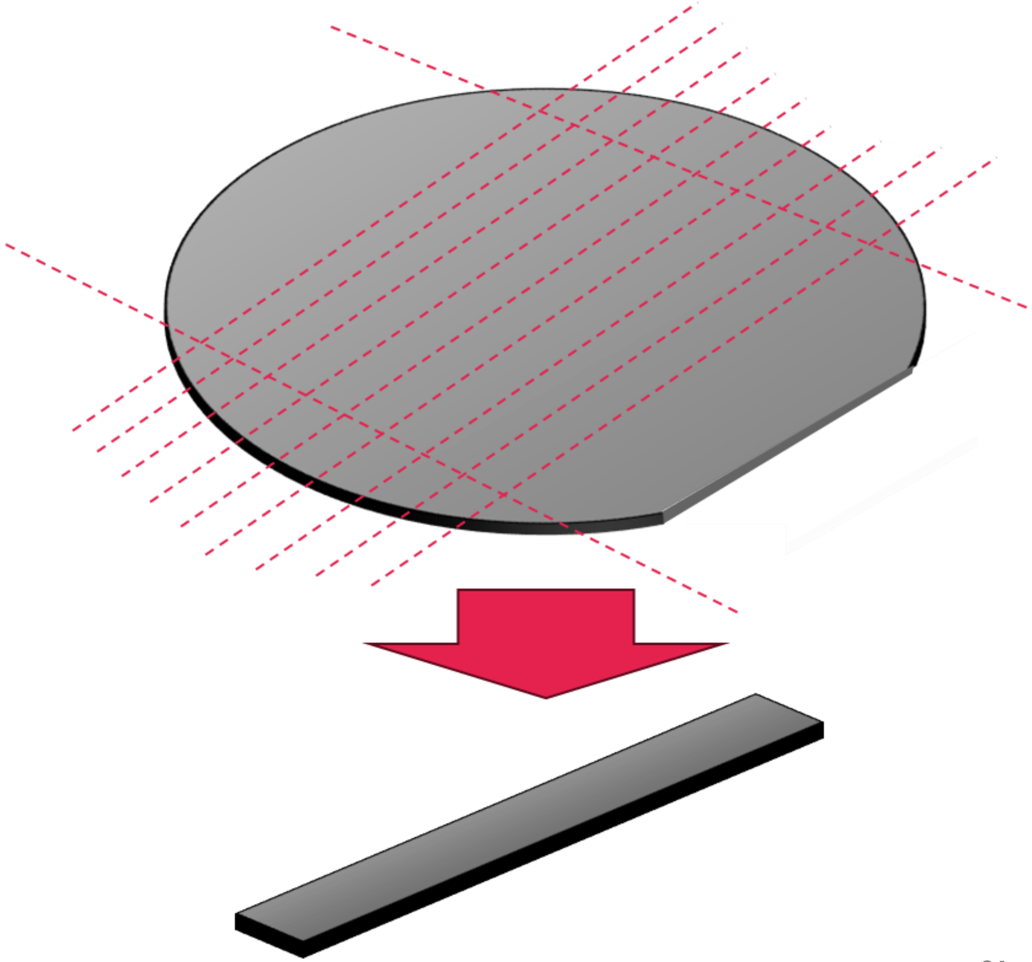
SAMPLE PREPARATION



HR-TEM image of the crystal edge

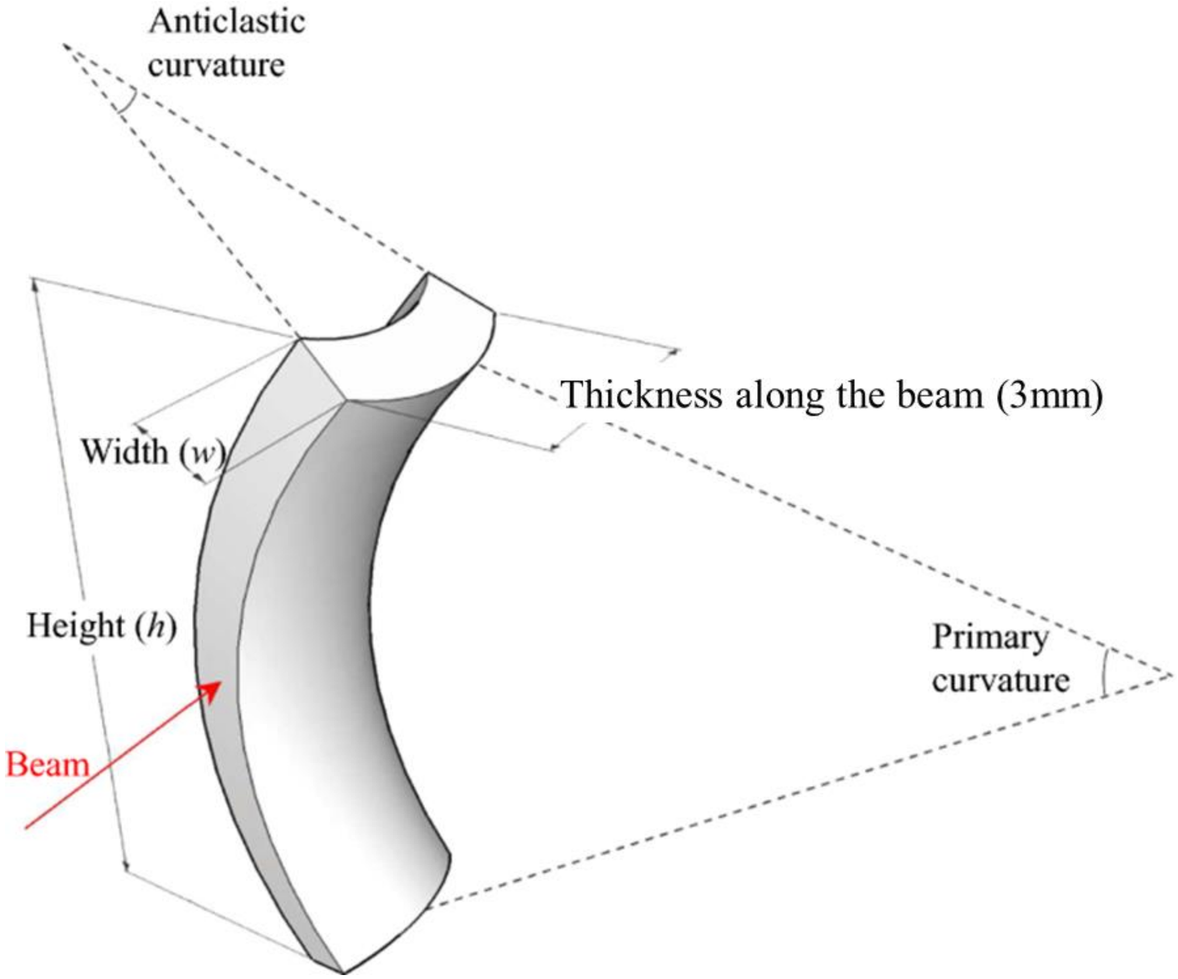


SAMPLE PREPARATION



CRYSTAL BENDING SCHEME

- Secondary anticlastic curvature occurs spontaneously in all materials
- Advantages:
  - thin crystal width
  - Crystal clamped at edges of the crystal, namely far from the beam
  - large and uniform bending achievable



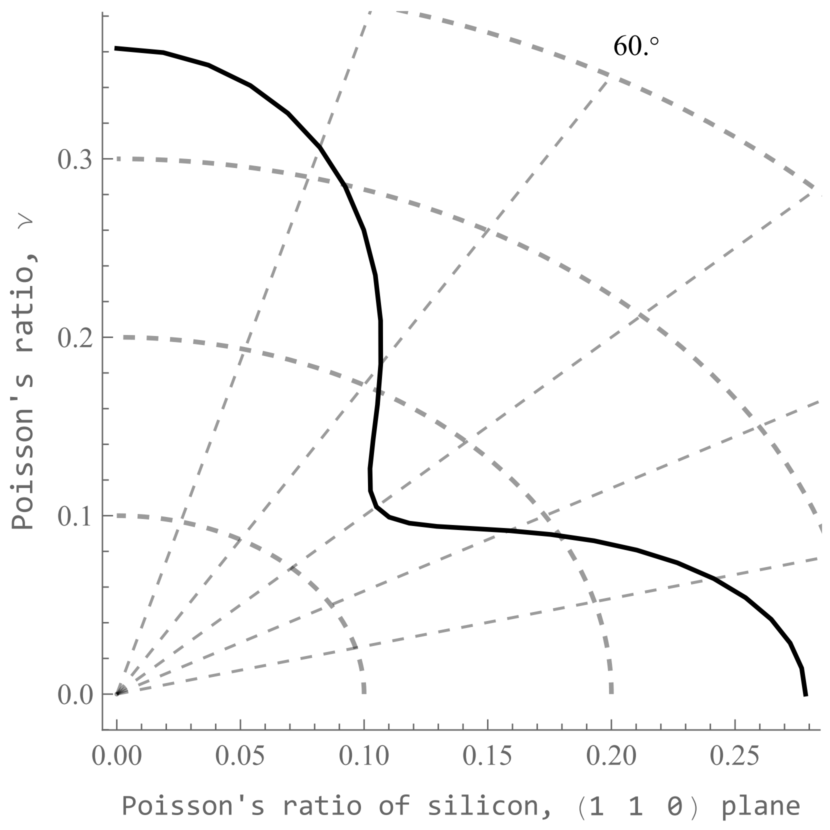
CRYSTAL BENDING SCHEME

- In order to achieve deflection 300-600 μrad with crystal thickness along the beam of 3 mm, the anticlastic radius of curvature is

$$R_A = \frac{3000\mu m}{600\mu rad} = 5m$$

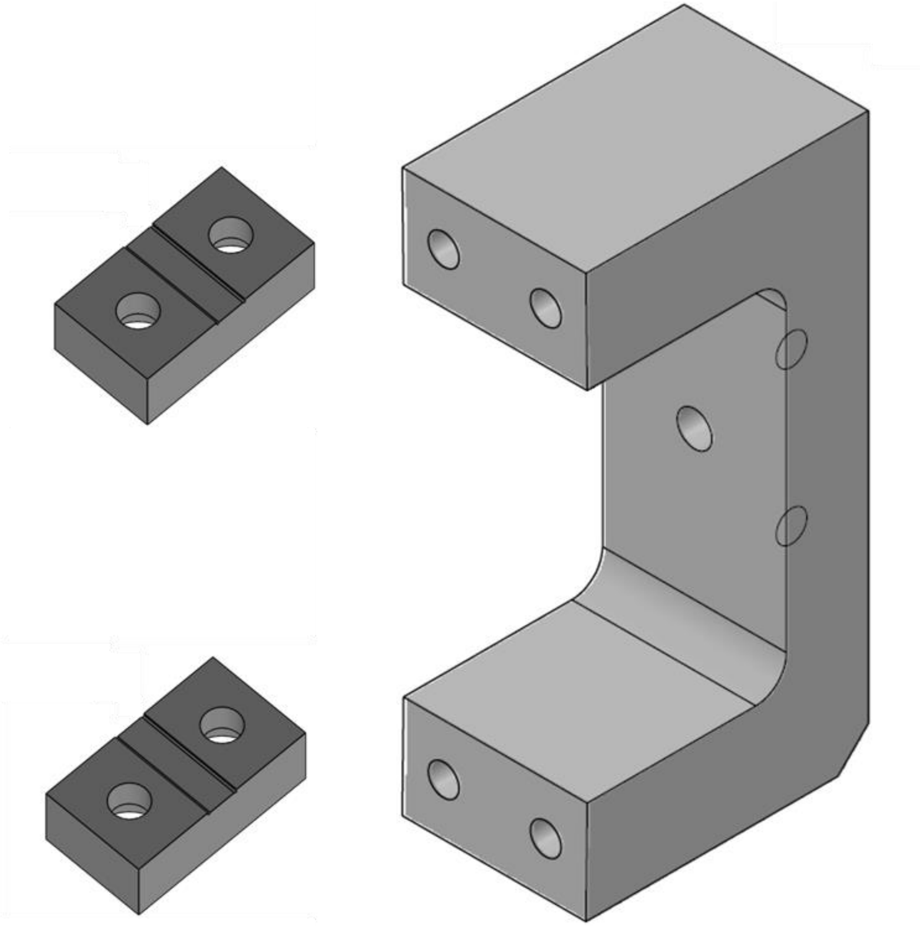
- Thus, the primary bending radius holds

$$\frac{R_P}{R_A} = Poisson\ Ratio = 0.2786 \rightarrow R_P = 1.39m$$



CRYSTAL HOLDER

- Holder designed with inclined support surfaces
- The angle of inclination is obtained with high precision using Electrical Discharge Machining
- The crystal sample is mounted and forced into arched position at R_p=1.39 m curvature radius.

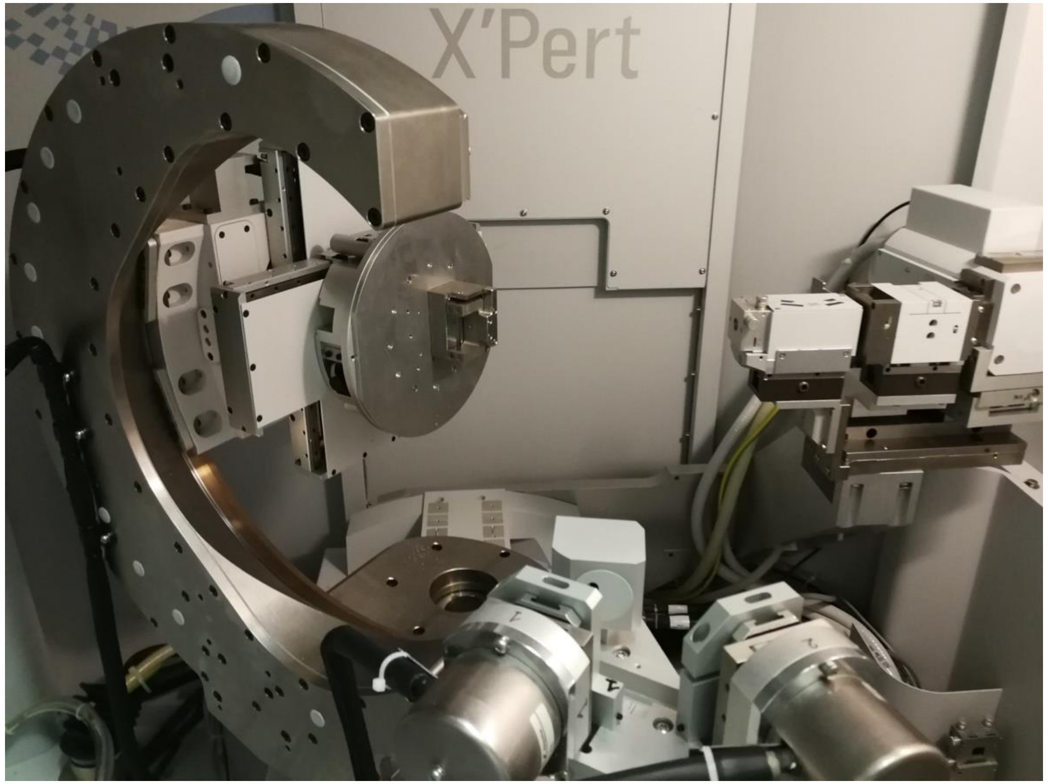


CRYSTAL HOLDER

- Holder designed with inclined support surfaces
- The angle of inclination is obtained with high precision using Electrical Discharge Machining
- The crystal sample (0.3x3x55mm^3) was mounted and forced into arched position with radius of curvature R_p=1.39 m

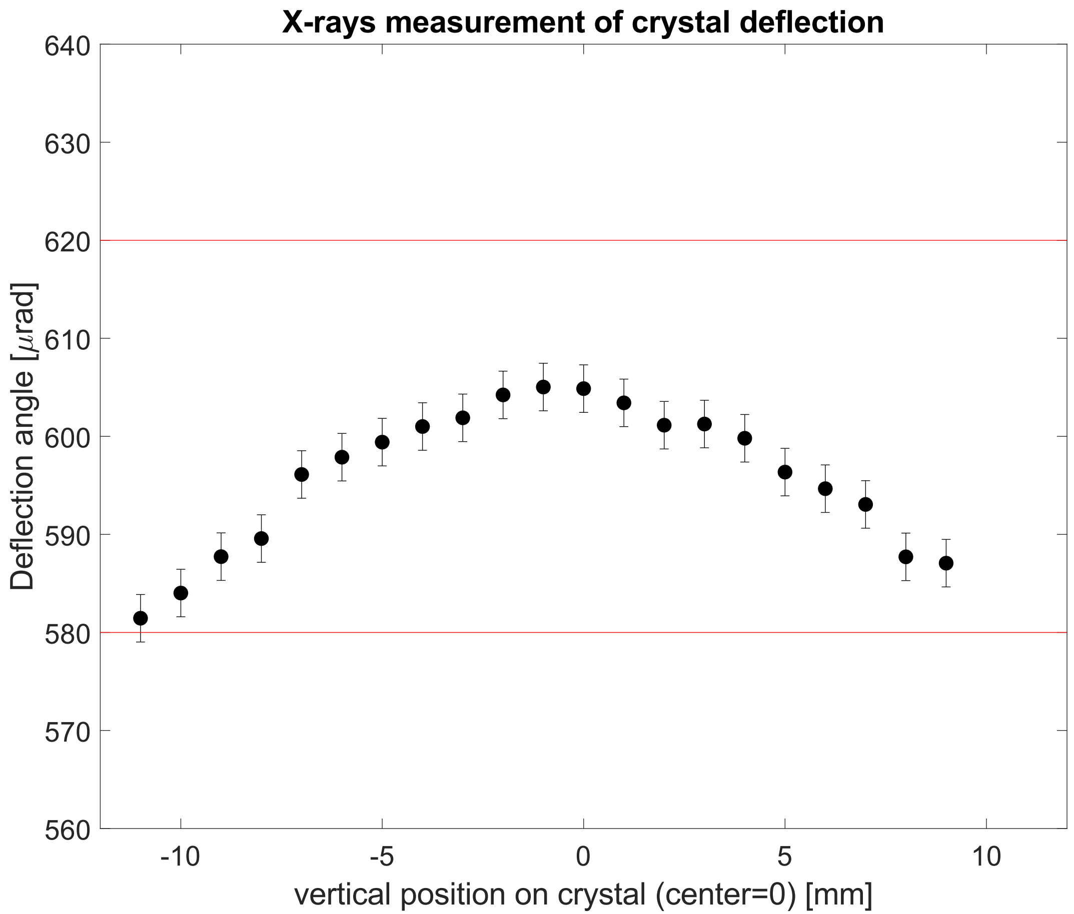
X-RAYS CHARACTERIZATION

- Direct measure of lattice planes curvature can be achieved via x-rays diffraction
- In Ferrara Labs, a Panalytical X'Pert PRO MRD XL High Resolution diffractometer is used
- Measure of local orientation of lattice planes with 0.0001° resolution
- Angular shift allows to reconstruct the curvature along a direction



CURVATURE CHARACTERIZATION

- Measured deflection at different positions along the vertical size of the crystal
- First measurements show values within acceptance
- Further improvement may achieve still more homogeneous curvature

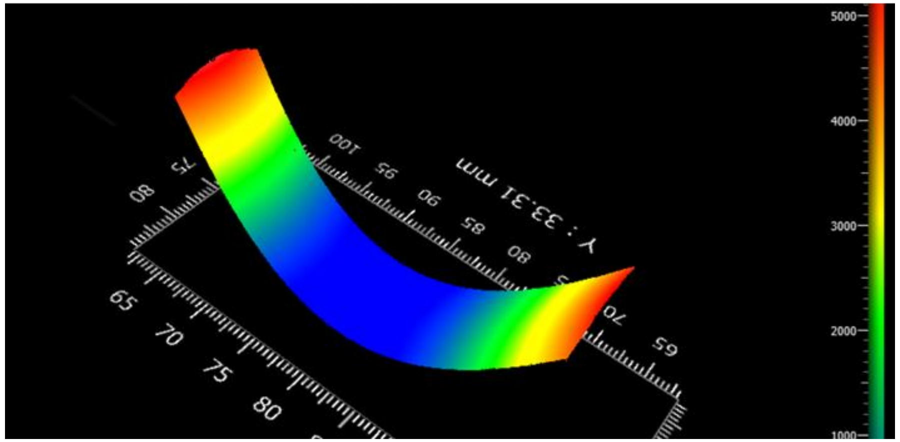


OPTICAL INTERFEROMETRY CHARACTERIZATION

- Characterization of curvature is of utmost importance for control of the channeled particle deflection

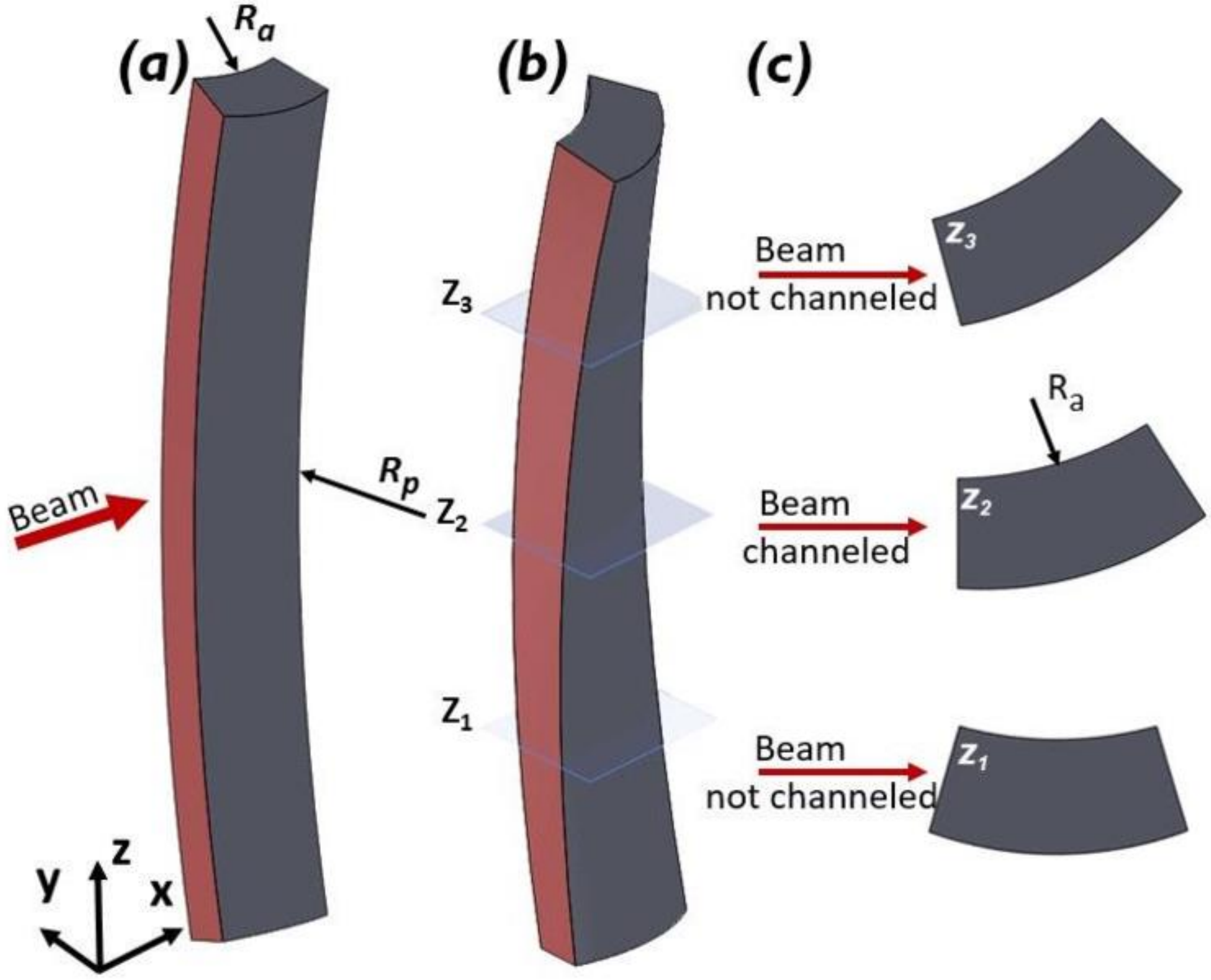
- 2-D measurement of surface profile can be achieved with nanometric precision with interferometric profilometer

- In Ferrara 2 instruments are available:
  - Zygo VeriFIRE HDX, for measure of large sample in 1-shot measurses
  - Zygo NexView NX2, high resolution in small field of view



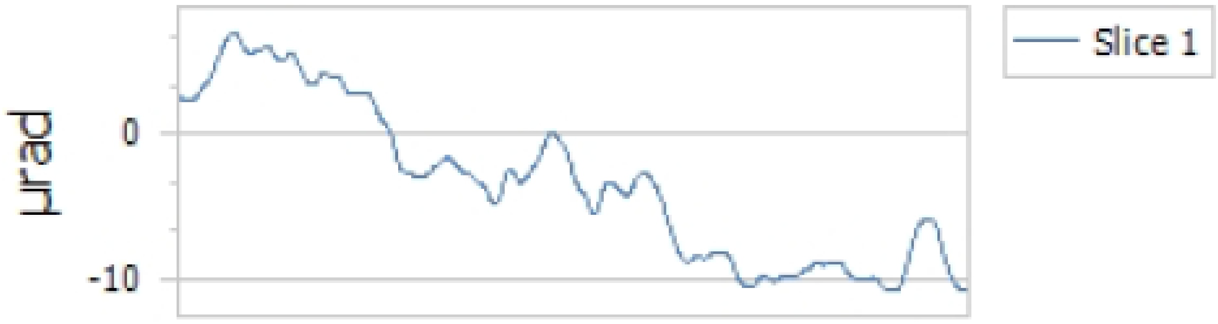
EFFECT OF TORSION

- When flexed, a crystal may be subjected to torsion
- Torsion changes alignment between crystal and beam along the vertical direction, decreasing the total channeling efficiency
- X-rays diffraction allows measure of torsion, <10 μrad/mm is compatible with good steering efficiency



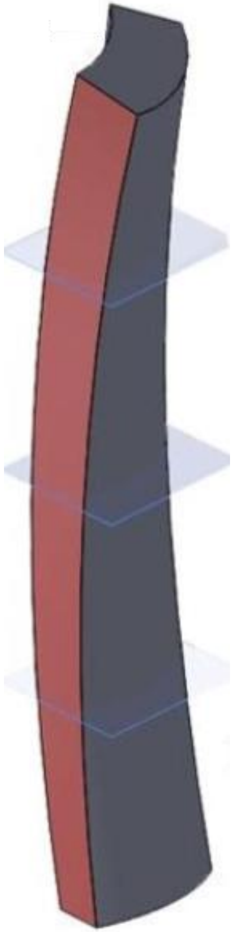
TORSION CHARACTERIZATION

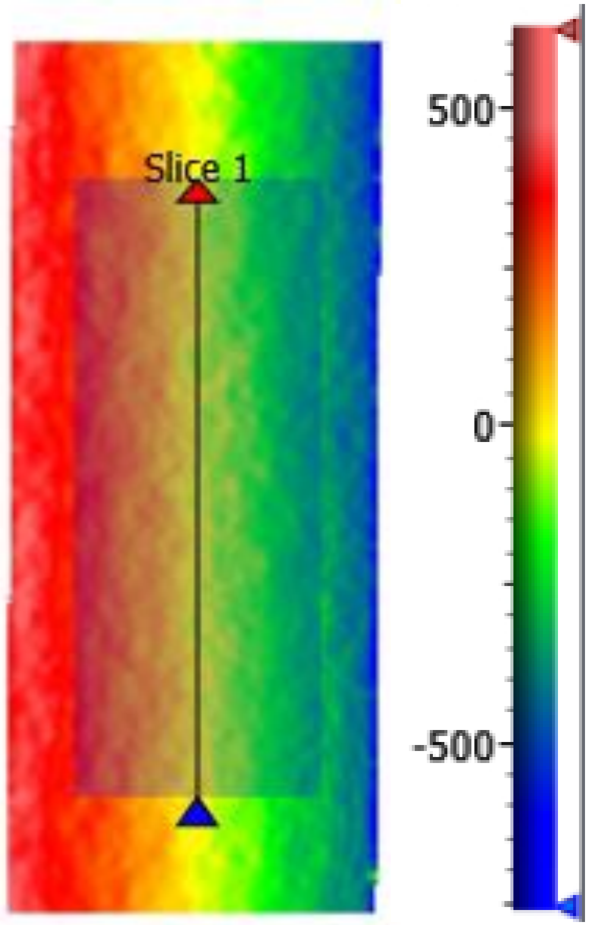
- Final goal is torsion ≤10 μrad/mm
- The optical characterization estimate ~5μrad/mm



-500 μm

+500 μm





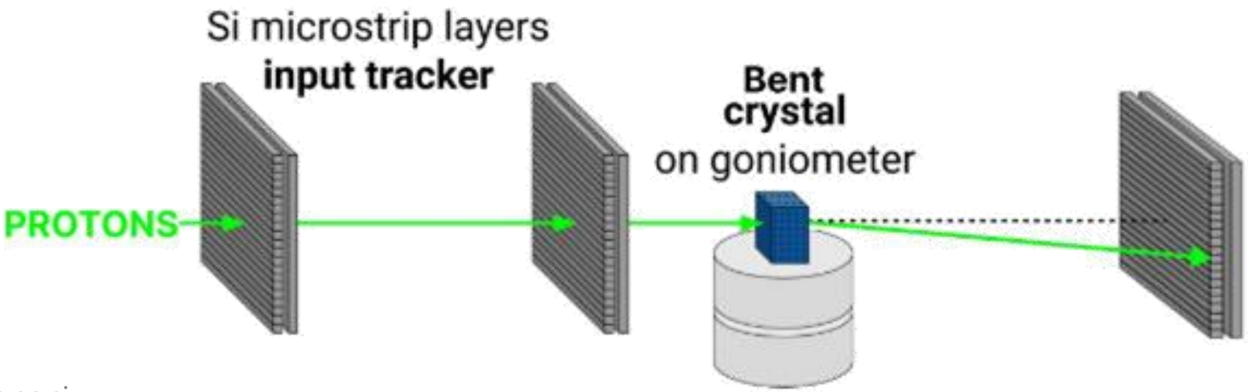
μm

PARAMETER VERIFICATION

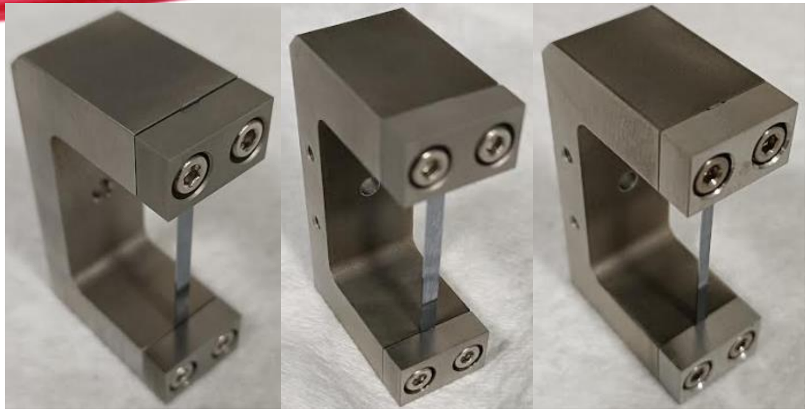
Deflection Angle	300-600 μrad	✓
Crystal Thickness along the beam	3 mm	✓
Crystal Width across the beam	300±20 μm	✓
Crystal Torsion	<10 μrad/mm	✓
Distance between crystal and holder	>10 mm	✓
Crystal height free of clamping	>30 mm	✓
Holder Material	Stainless steel	✓
Bake-out cycle	No need	✓

ON-BEAM CHARACTERIZATION

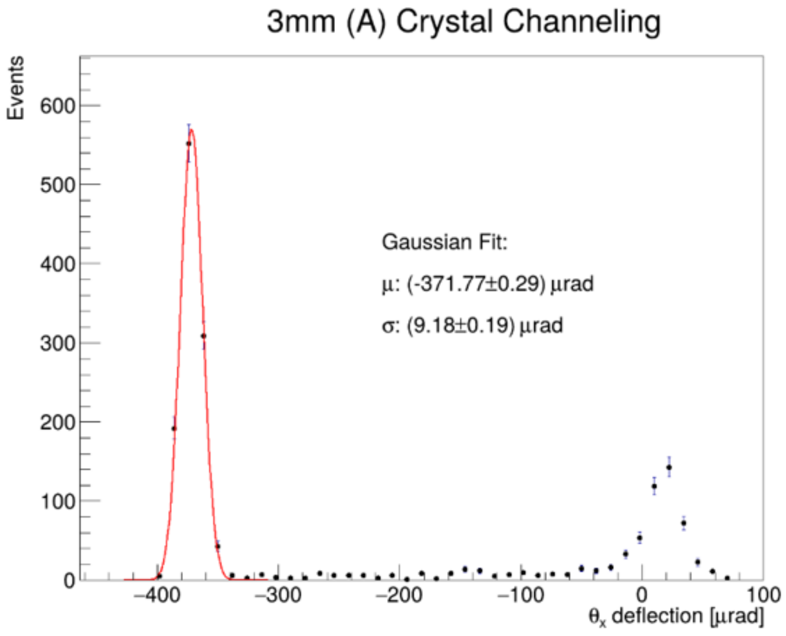
- Beamtime was granted as secondary user at H8 beamline of CERN-SPS North Area from July 30th through August 6th, 2025.
- High quality hadronic beam with particle momentum of 180 GeV/c
- Silicon-strip tracker and DAQ by University of Insubria and high-resolution goniometer from University of Padua.

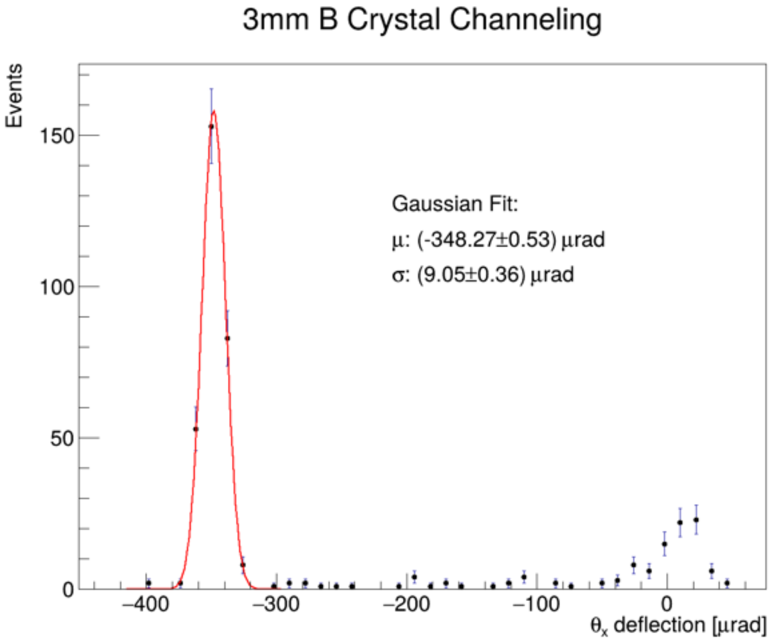


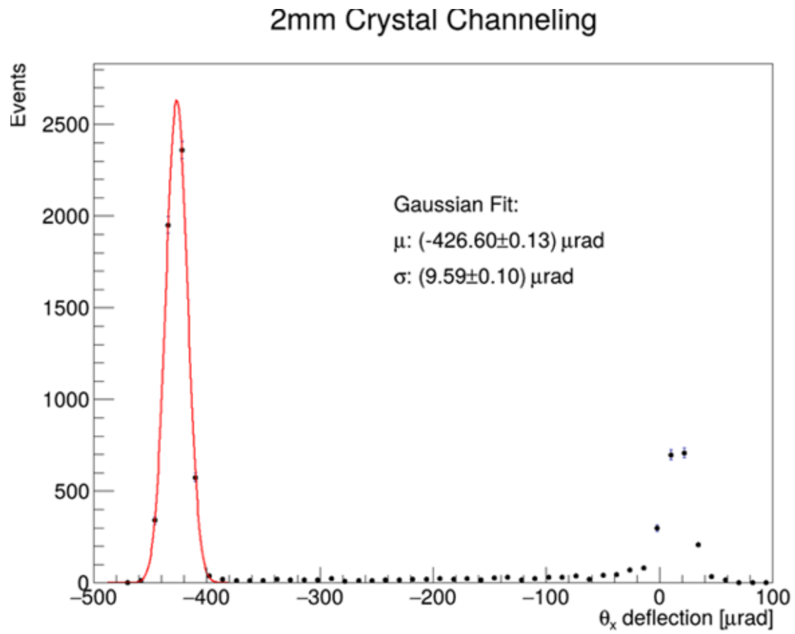
ON-BEAM CHARACTERIZATION



Sample	Deflection (μrad)	Torsion (μrad/mm)
3mm_A	370±50	<5
3mm_B	370±50	<5
2mm	430±50	<5
Goals	450±150	<10







CONCLUSIONS AND FUTURE PLANS

- Mitigation scheme for beam losses through shadowing technique with bent crystal for Mu2e operation
- Prototypes fabricated and characterized
- On-beam characterization in next months
- Samples ready to be dispatched

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Thank you for your attention