
Silicon crystals for steering of high-intensity particle beams at ultra-high energy accelerators

A. Mazzolari, M. Romagnoni

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CRYSTALS TECHNOLOGY AT INFN



Collimation
Beam steering
Innovative radiation sources
Pair production studies
Innovative detectors



Beam steering
Innovative radiation sources
Pair production studies



Beam steering
Innovative radiation sources
Pair production studies




CRYSBEAM
SELDOM

INFN COMPETENCIES

INFN has competencies related to

- Development of innovative ideas and research activities (connected to channeling and related effects)
- Crystals manufacturing and characterization
- Holders manufacturing and characterization
- Goniometry
- Trackers and detectors
- Data analysis
- Design of setups for channeling experiments

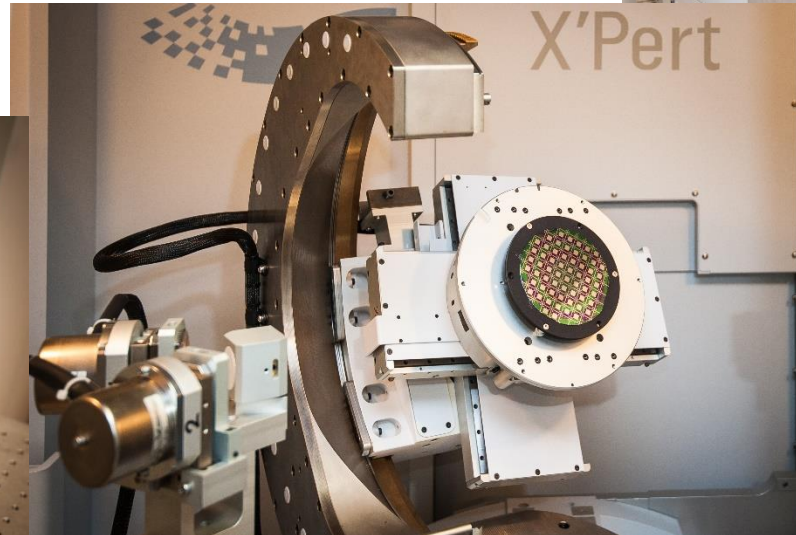
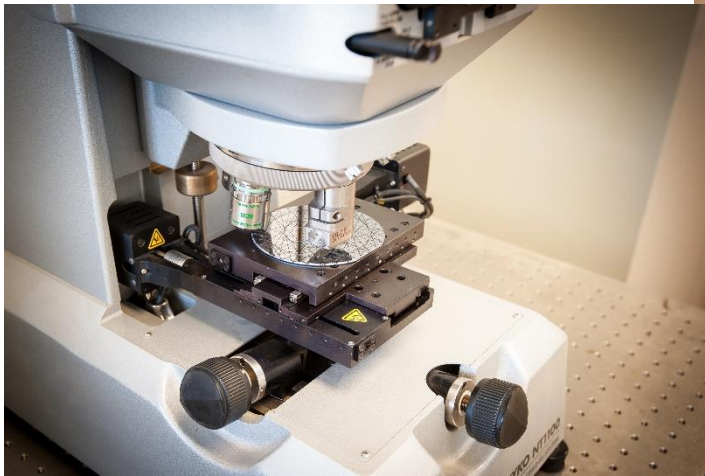


INFN is a scientific agency encompassing a full set of competencies related to studies of coherent effects between charged particle beams and crystals.

INFN INFRASTRUCTURE

Laboratory fully equipped for silicon micro and nanomachining
ISO4 certified clean room (130 m²)

High-resolution x-ray diffraction
Dicing and polishing equipment
White light and Fizeau inteferferometers



INFN INFRASTRUCTURE

Laboratory fully equipped for silicon micro and nanomachining

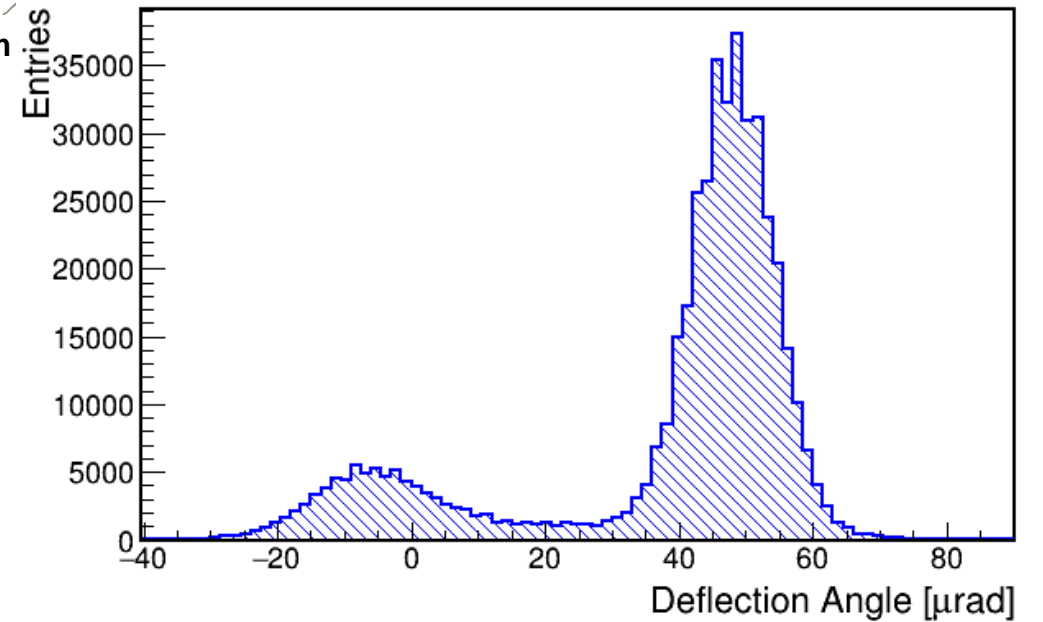
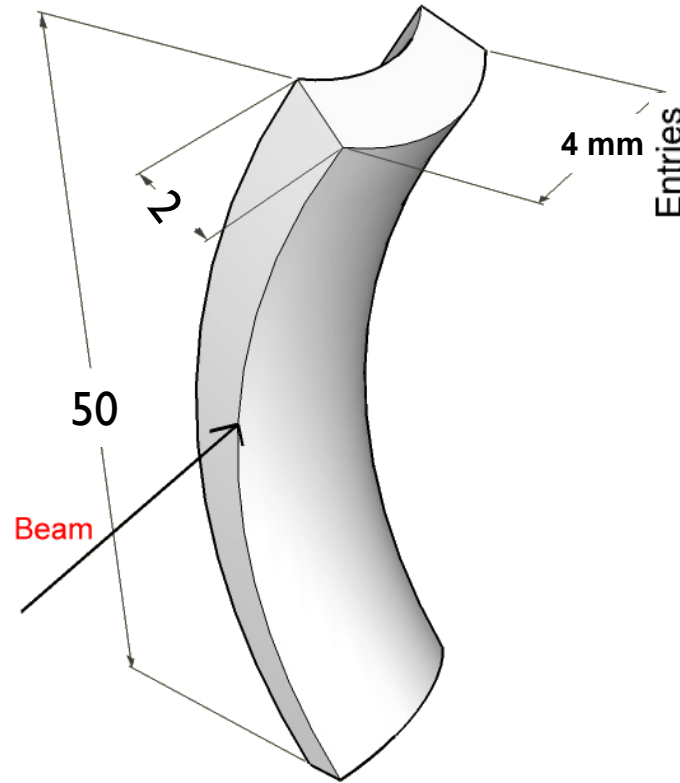
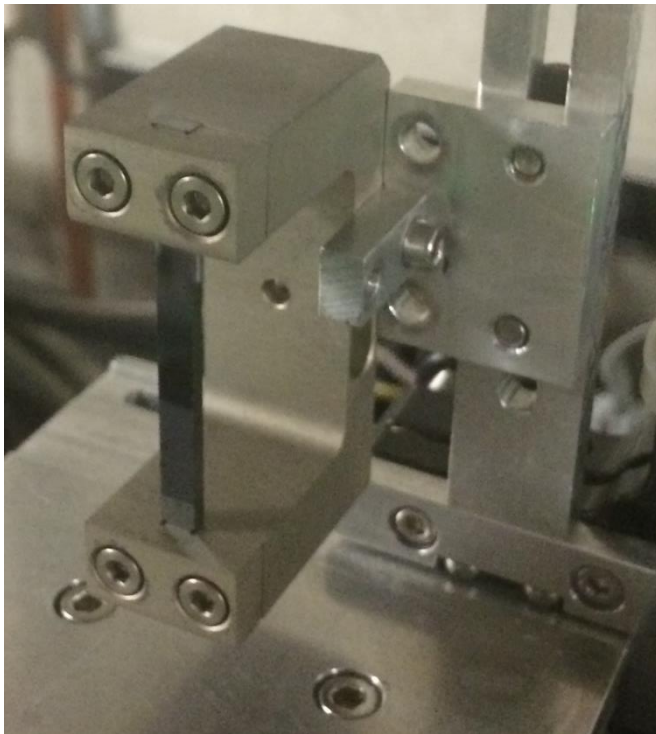
Fotolitography

Equipment for silicon chemical etching

Nanoimpringing

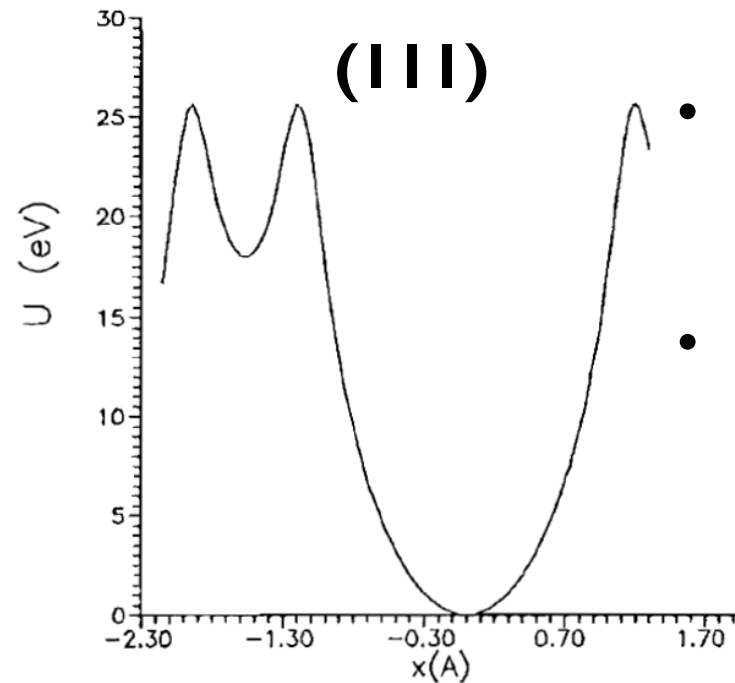
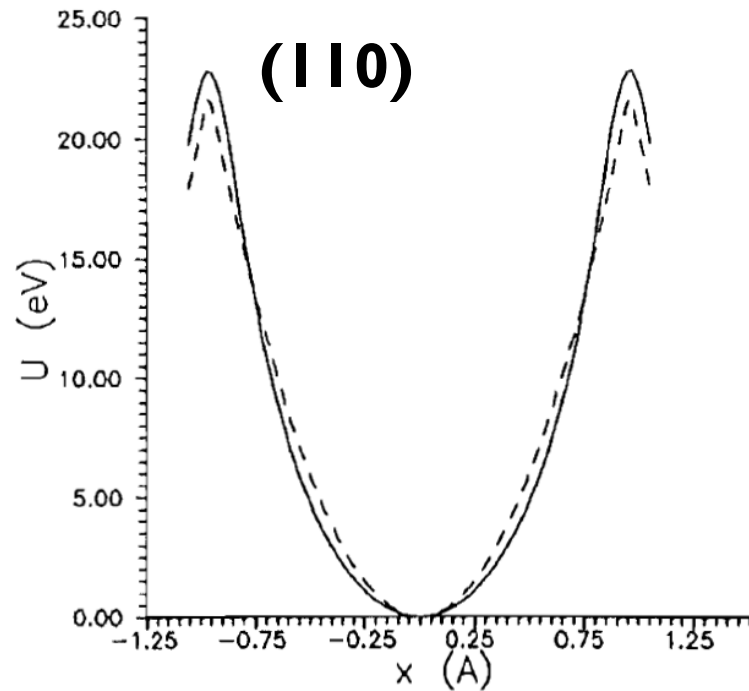


STRIP CRYSTALS FOR THE LHC



A primary bending is mechanically imposed along the 50 mm size.
As a result, «anticlastic bending» manifests along the 4 mm size.

CHOICE OF CRYSTALLINE PLANES



- Comparable depth of potential well
- (110) Planes offers lower nuclear interaction rate

See also W. Scandale et al., Eur. Phys. J. C (2018) 78:505

BRIEF RECAP ABOUT CRYSTALS MANUFACTURING

2006 Manufacturing based on mechanical dicing followed by chemical etching

2007 Manufacturing based on purely chemical methods

2014 Manufacturing of low-miscut crystals (<10 urad)

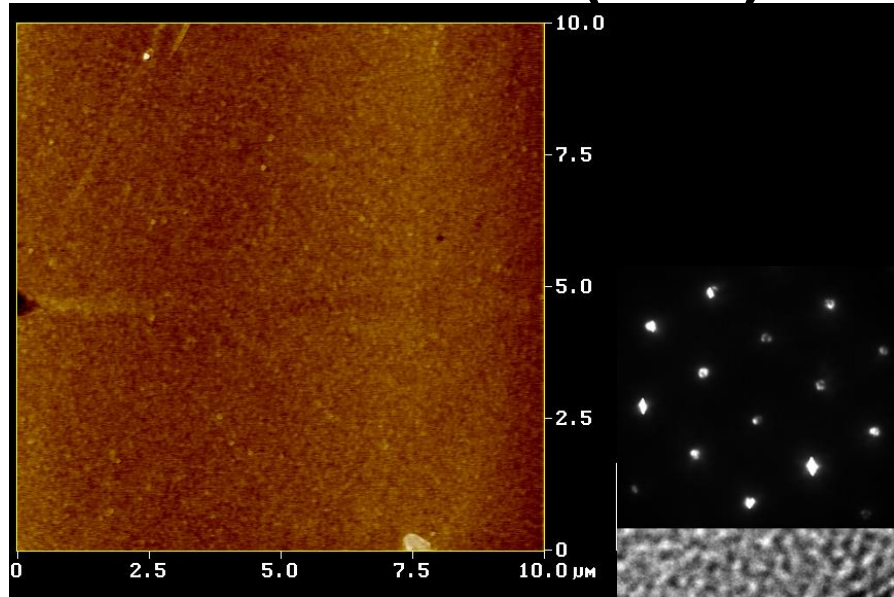
2018 Manufacturing based on mechanical dicing followed by chemical etching and polishing of surface entry face

Manufacturing of ultra low-miscut crystals (<1 urad)

CRYSTAL MANUFACTURING – AFM AND HRTEM –

High-quality surfaces achieved via anisotropic chemical etching

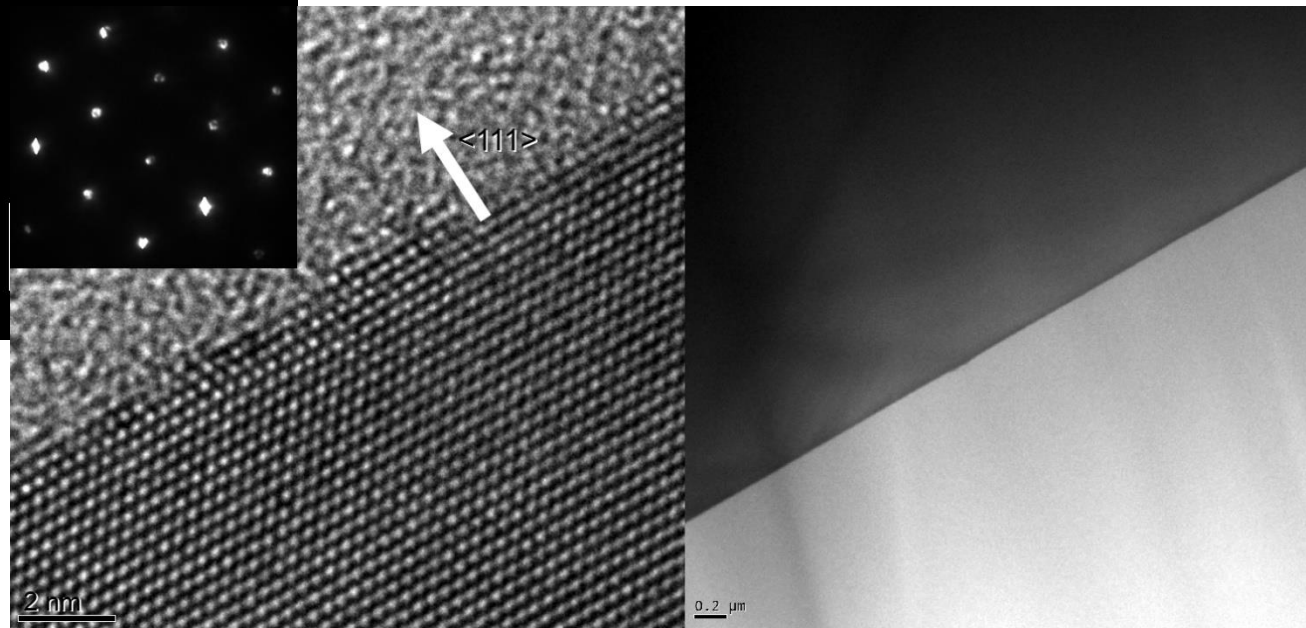
Lateral surface (AFM)



Sub-nm roughness
achieved (0.2 nm)

Entry surface (High Resolution
transmission electron
microscopy).

Zero nm amorphous layer



BRIEF RECAP ABOUT HOLDERS MANUFACTURING

2006 First holders version (in collaboration with IHEP), made of Al7075

2007 FEM-assisted optimization of holder geometry

2008 First prototypes of pre-shaped holders (aluminum)

2013 Request for holders with the following specs:

weight < 90 g

UHV compatible (bakeable)

electron cloud compatible

} → Titanium.

About 90 commercial alloys, most common is «titanium grade 5» (90% Ti 6% Al 4% V)

2014 First generation of titanium grade 5 holders → not compatible with bake-out

2018 Pre-shaped titanium grade 5 holders now fits LHC requirements

CRYSTALS FOR THE LHC

Thickness along the beam: 4.0 ± 0.1 mm

Height < 55 mm.

Weight < 150 g

Channeling plane: (110)

Channeling axis: $\langle 111 \rangle$ or $\langle 110 \rangle$

Miscut for axial channeling: 0 ± 18 mrad

Miscut for planar channeling: < 10 μ rad.

Torsion: < 1 μ rad/mm

Bending angle: 47.5 - 52.5 μ rad

Dislocation density < 1 cm^{-2}

Bake out

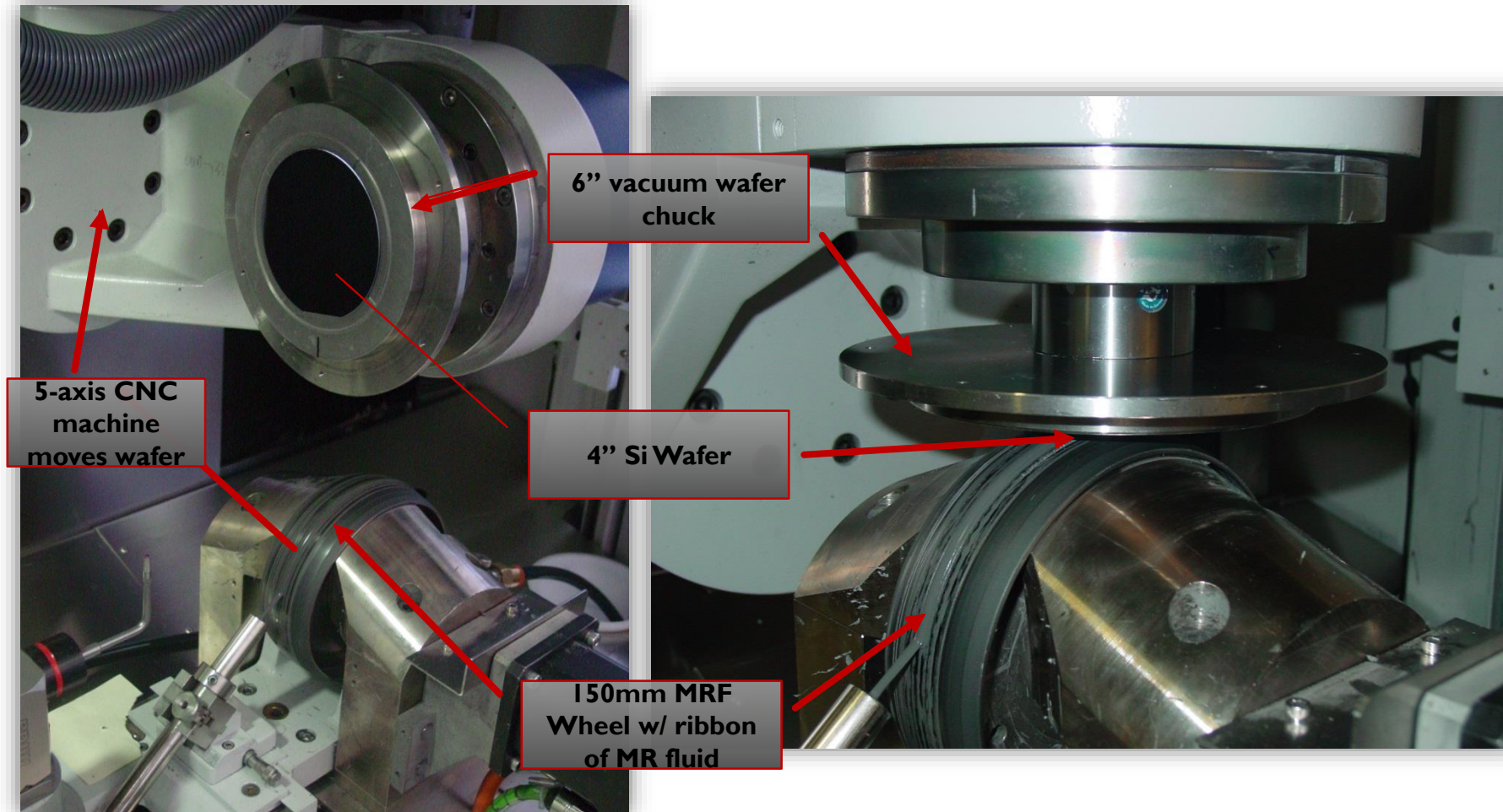
- Bake out temperature = 250°C
- heating ramp = 50°C/h
 - Bake out time = 48h00
 - Number of thermal cycles: 3 at least
- Maximum allowed total outgassing after each bake out: 1×10^{-7} mbar \cdot l \cdot s $^{-1}$

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

CHALLENGING ASPECTS

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

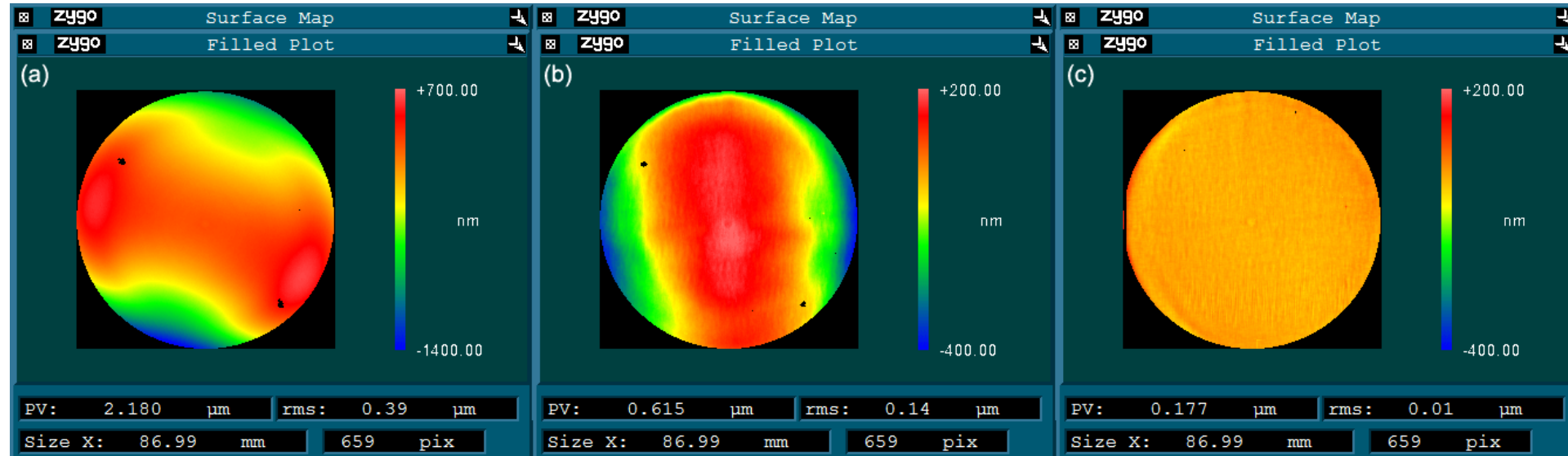
MRF FINISHING



Technique developed for astronomy applications (glasses and ceramics, i.e. amorphous materials)

After a 2 years R&D the technique was adapted to operate on crystalline materials.

MRF FINISHING



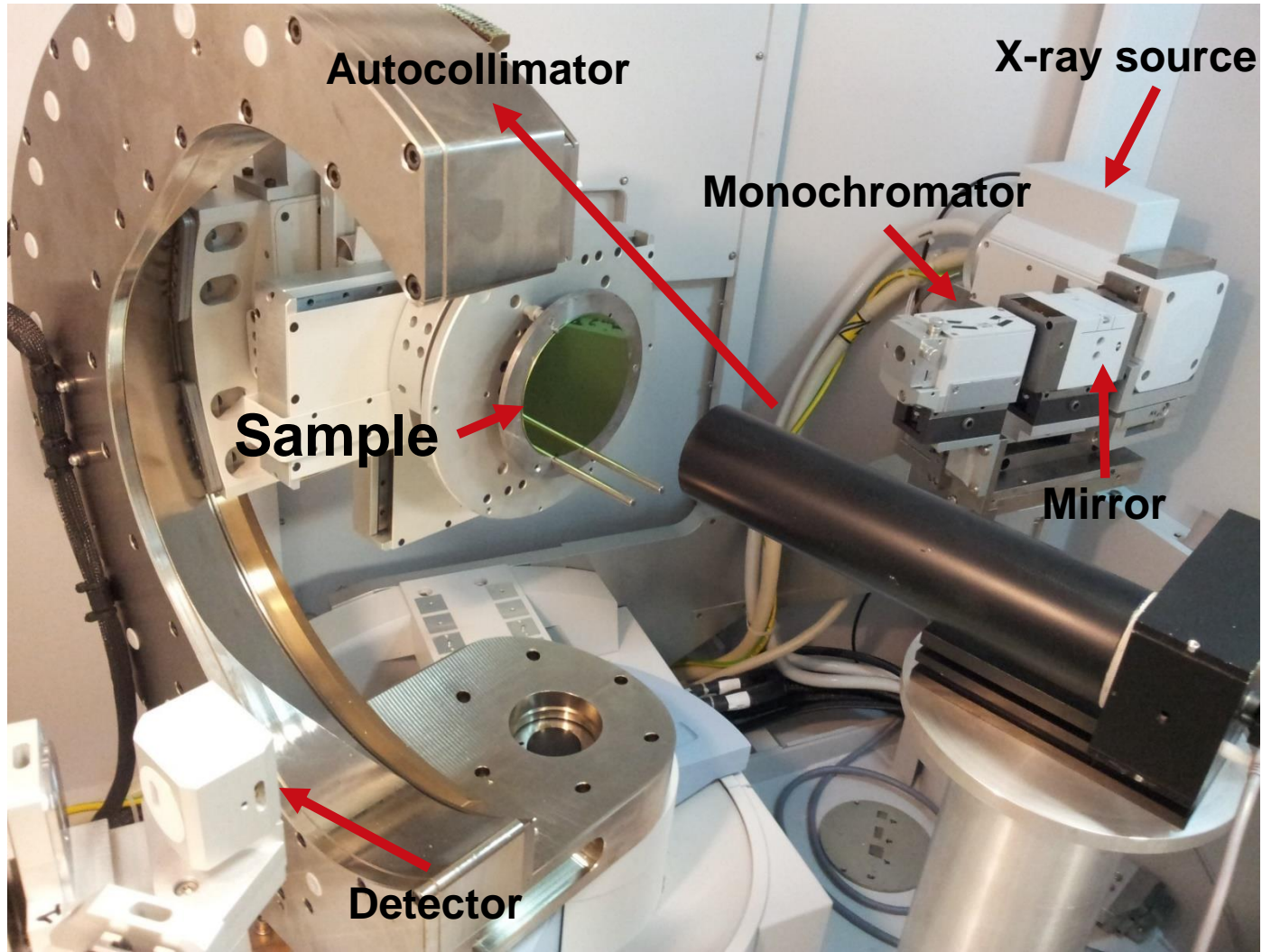
Starting surface
PV 2.18 μm
RMS 0.39 μm

Surface after first treatment
PV 0.615 μm
RMS 0.14 μm

Final surface
PV 0.177 μm
RMS 0.01 μm

- MRF is a deterministic polishing process
- Does not induce any lattice damage
- **Miscut < 1 urad**

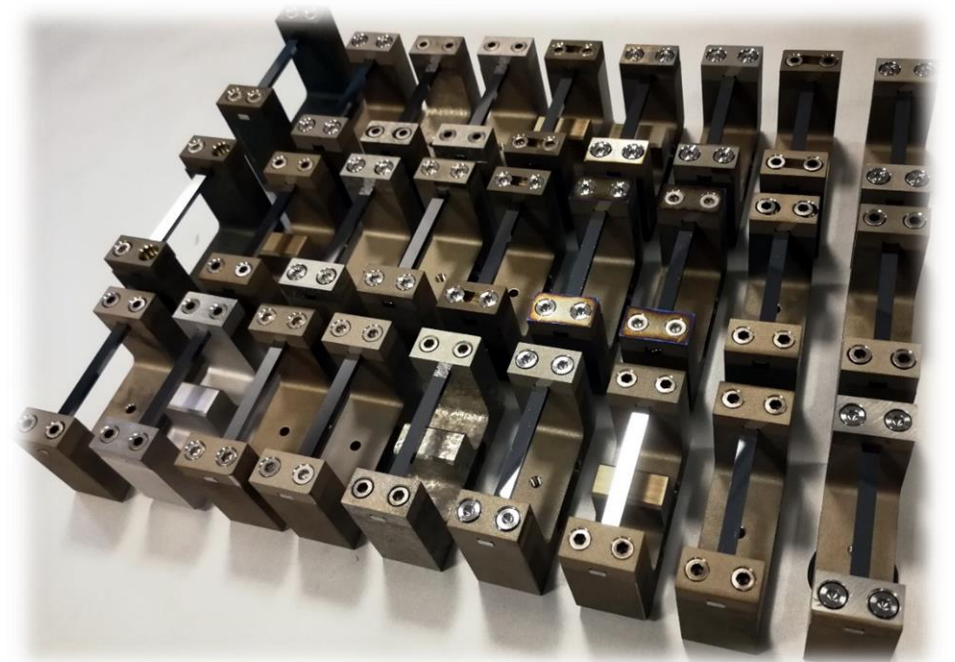
MISCUT REDUCTION



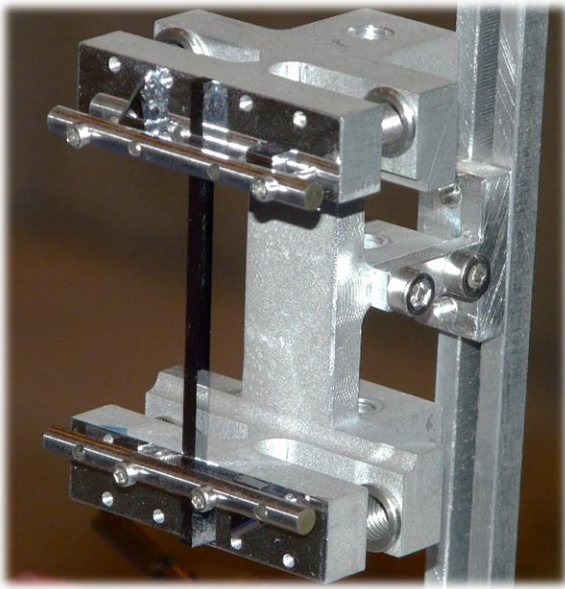
- High resolution x-ray diffractometer (PANALYTICAL)
- Miscut: angle between optical surface and atomic planes
- Requested miscut $< 10 \mu\text{rad}$.

RECENTLY DEVELOPED CRYSTALS

- Developed «pre-shaped» holders made of titanium grade 2 and grade 5.
- High-resolution x-ray diffraction characterizations: analysis of correlation
- Investigated thermal stability of holders+crystal assembly.
- Crystals for the LHC



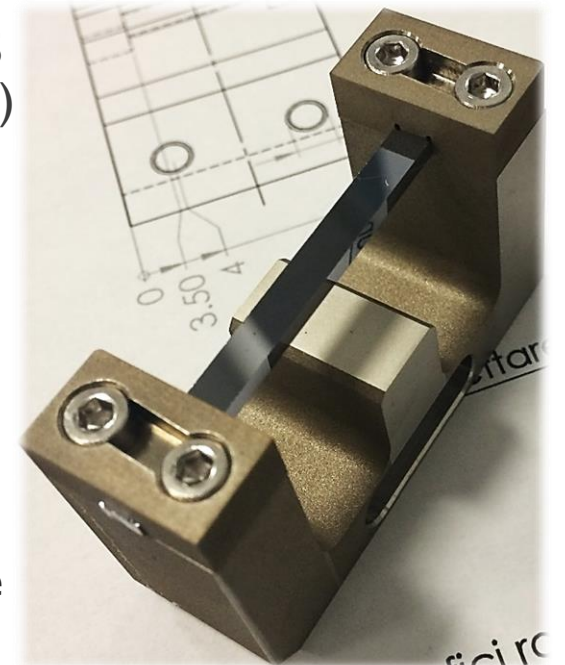
PRE-SHAPED HOLDERS



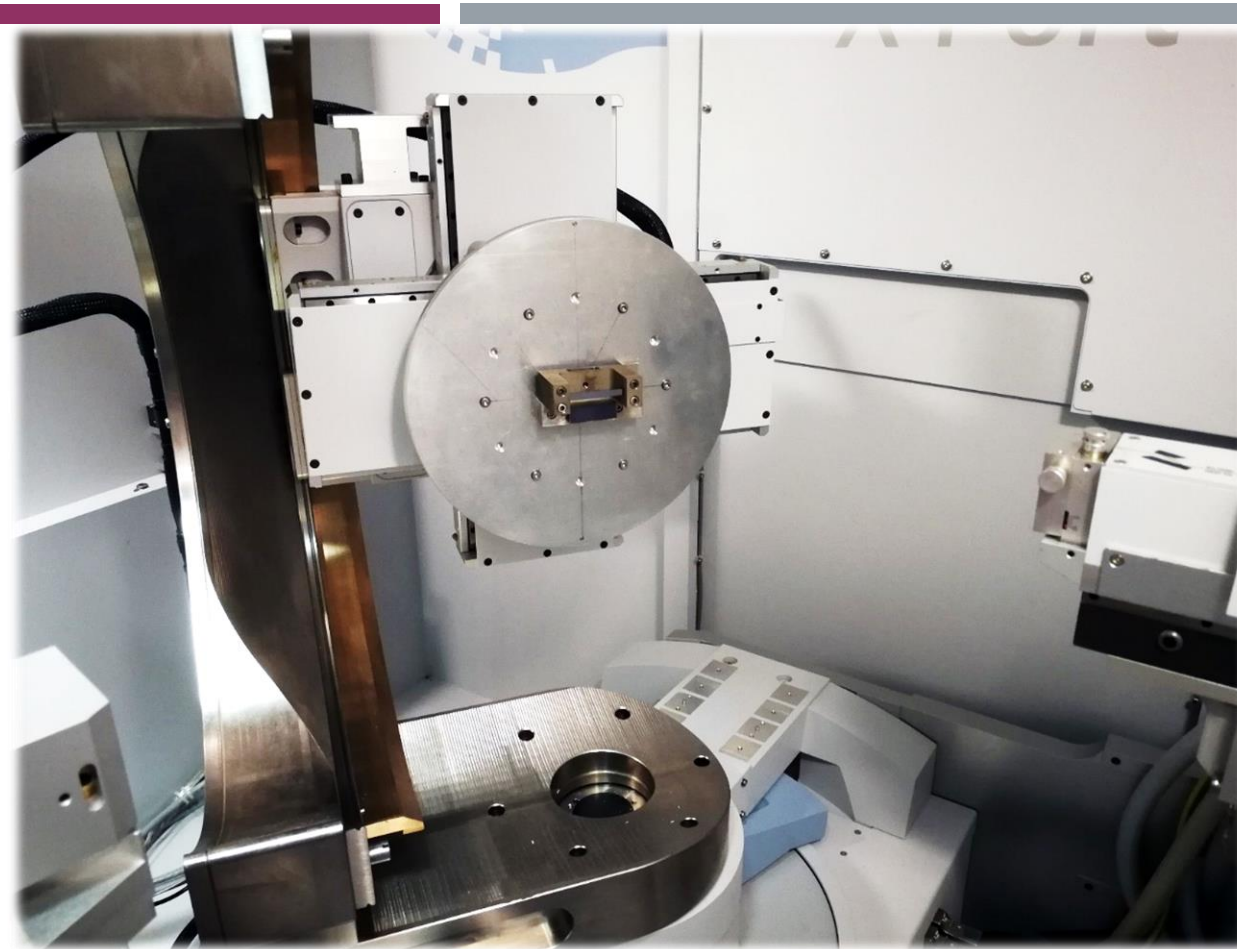
A pre-shaped holder manufactured in 2011 for UA9. Holder was made from aluminium and torsion correction mechanism still used. Base for development of current holders.

- Ultra-high precision machining provides holders with crystal-supporting surfaces inclined at a proper angle to impart to the crystal the desired deformation.
 - At first step, the holders are manufactured with approaches typical of conventional precision mechanics.
 - selected holders are treated with super-finishing techniques to adjust surface inclinations.
- Approach already developed for crystals installed in the SPS and for studies of multiple-volume reflections (~2010÷2015)
- Design is now revisited:
 - holders made of titanium grade 2 and grade 5 (previous version was made of aluminium).
 - removed torsion-adjustment mechanism.

A pre-shaped holder for LHC. Holder is made of titanium. Flexure for torsion adjustment have been removed.



| Crystal | Deflection angle (μrad) | | Consistency |
|---------|--------------------------------------|--------------|-------------|
| | High resolution x-ray diffraction | Channeling | |
| STF47 | 33 \pm 2 | 35 \pm 2 | YES |
| STF48 | 144 \pm 2 | 142 \pm 2 | YES |
| STF49 | 247 \pm 3 | 246 \pm 2 | YES |
| STF50 | 142 \pm 5 | 143 \pm 2 | YES |
| STF51 | 33 \pm 2 | 33 \pm 2 | YES |
| STF70 | 56 \pm 2 | 55 \pm 2 | YES |
| STF71 | 60 \pm 5 | 62 \pm 2 | YES |
| STF99 | 119 \pm 3 | 120 \pm 2 | YES |
| STF100 | 67 \pm 6 | 63 \pm 2 | YES |
| STF101 | 170 \pm 6 | 165 \pm 2 | YES |
| STF102 | 45 \pm 3 | 42 \pm 2 | YES |
| STF103 | 52 \pm 5 | 54 \pm 2 | YES |
| STF104 | 95 \pm 5 | 91 \pm 3 | YES |
| STF105 | 49 \pm 3 | 50 \pm 2 | YES |
| STF106 | 42 \pm 2 | 42 \pm 2 | YES |
| STF107 | 56 \pm 2 | 56 \pm 2 | YES |
| STF110 | 52 \pm 3 | 54 \pm 2 | YES |
| STF110 | 56 \pm 10 | 62 \pm 2 | YES |
| STF112 | 64 \pm 3 | 63 \pm 2 | YES |
| STF113 | 46 \pm 3 | 45 \pm 1 | YES |
| STF114 | 52 \pm 3 | 52 \pm 1 | YES |
| STF117 | 53 \pm 3 | 50 \pm 1 | YES |
| STF118 | 52 \pm 3 | 53 \pm 1 | YES |
| STF119 | 54 \pm 3 | 52 \pm 1 | YES |
| STF120 | 54 \pm 3 | 52 \pm 1 | YES |
| STF121 | 48 \pm 3 | 48 \pm 1 | YES |
| STF122 | 50 \pm 3 | 46 \pm 1 | YES |
| SFT123 | 52 \pm 3 | 52 \pm 1 | YES |
| PL08 | 715 \pm 30 | 706 \pm 2 | YES |
| PL09 | 1040 \pm 50 | 1067 \pm 2 | YES |

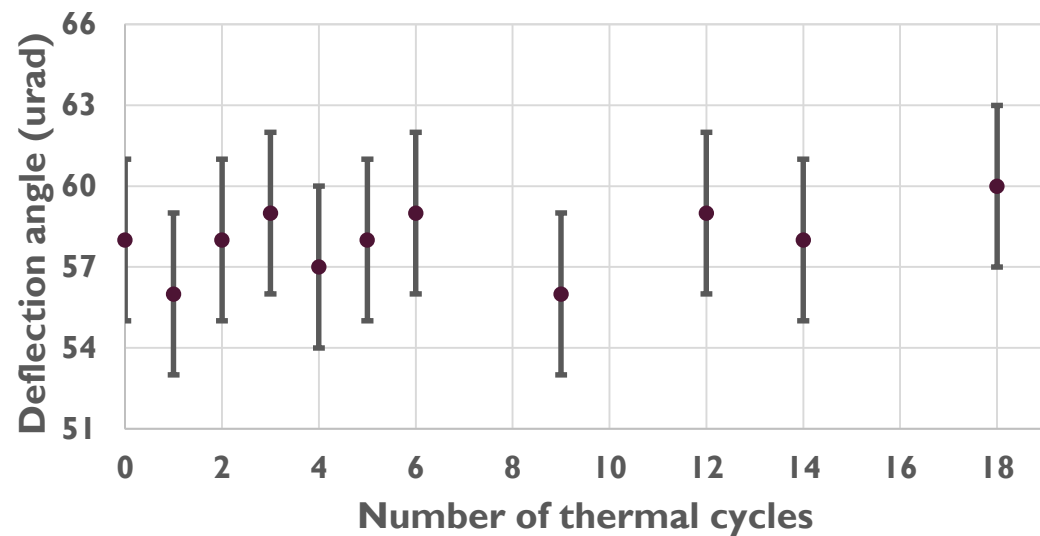


Determinantion of crystal bending angle with high-resolution x-ray diffraction and channeling of high-energy particles are in good agreement.

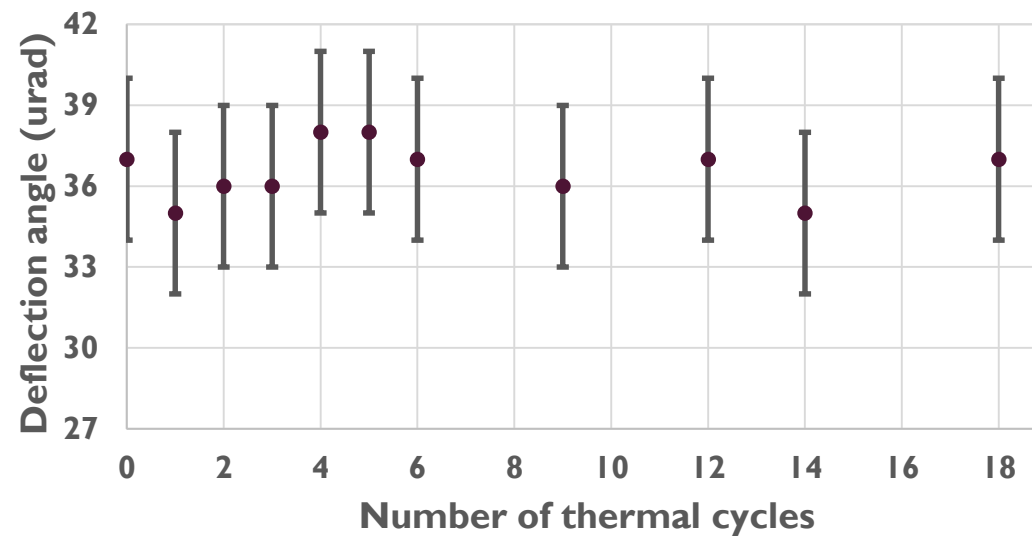
HOLDERS THERMAL STABILITY

Crystal bending angle is measured through high-resolution x-ray diffraction before and after thermal cycles for 4I holder+crystals assemblies.

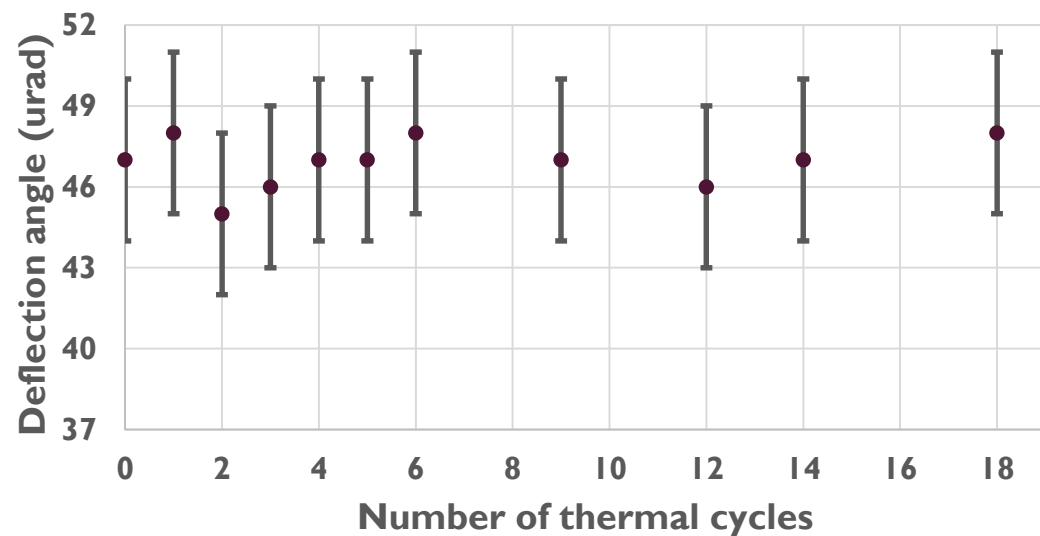
Crystal #1



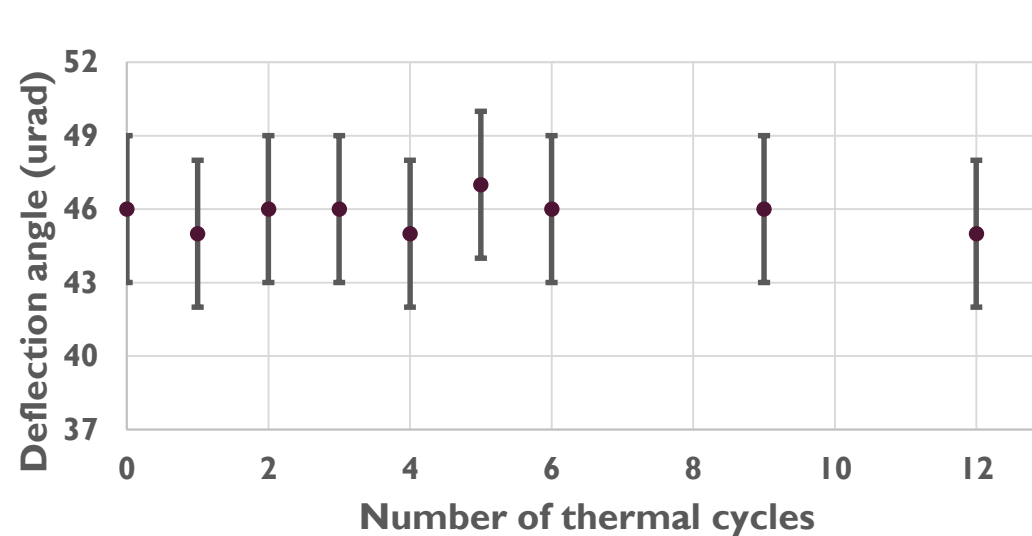
Crystal #2



Crystal #3

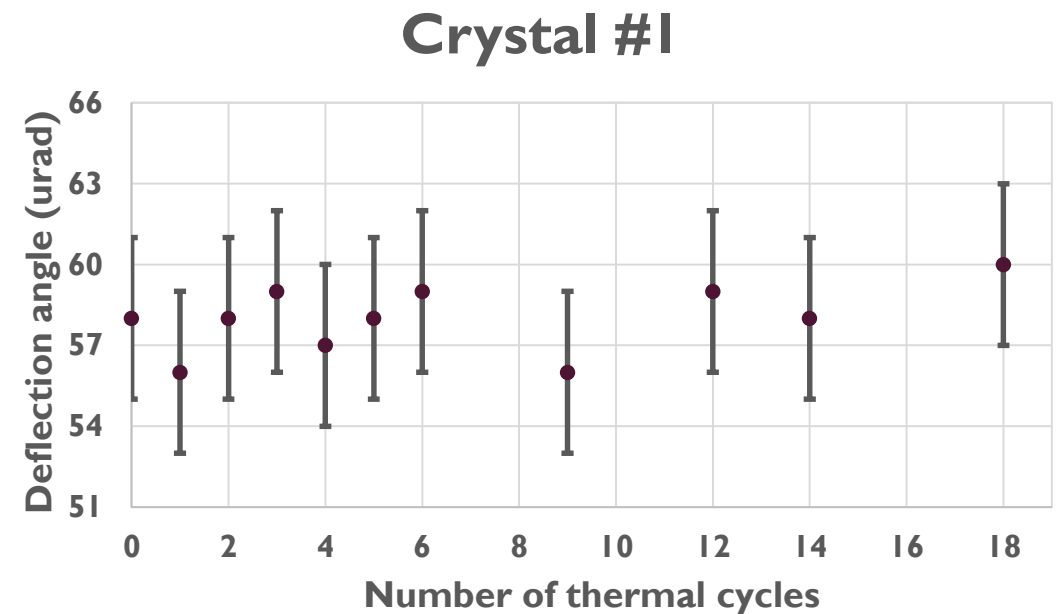


Crystal #4



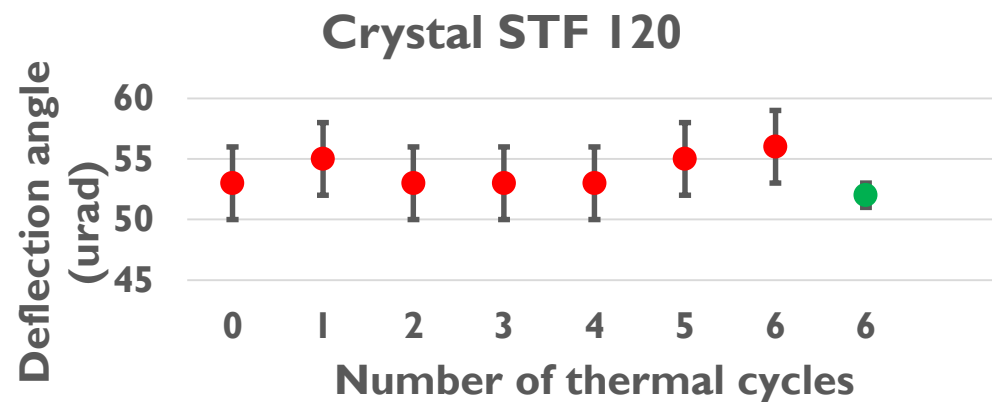
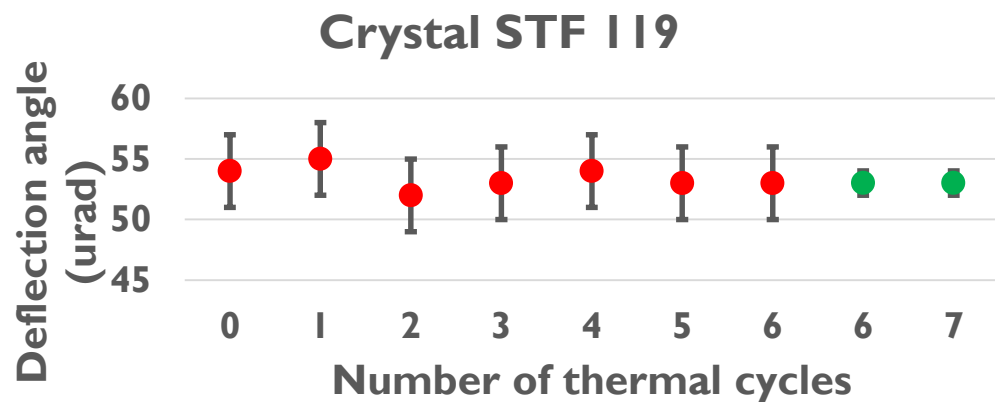
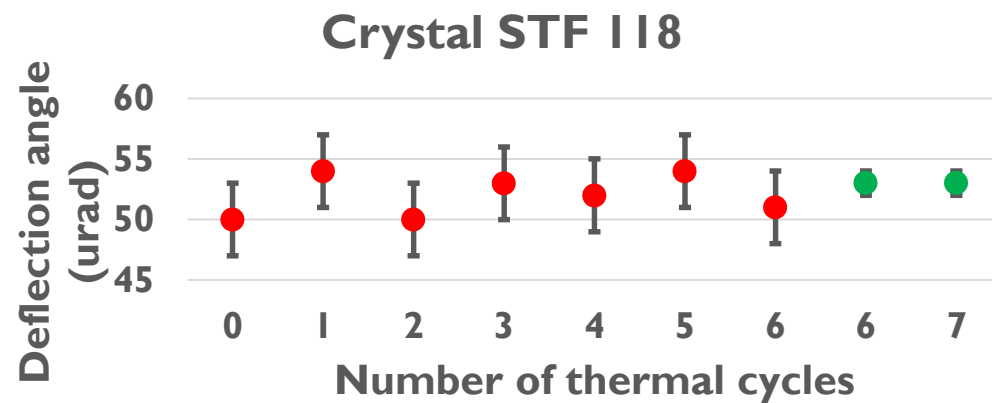
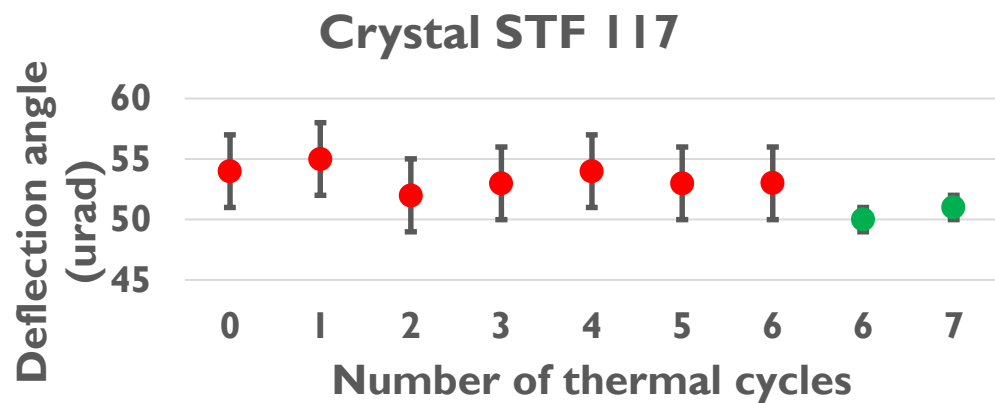
HOLDER STABILITY VS BAKE-OUT: CONCLUSIONS

- Manufactured 41 holders (31 titanium grade 2+10 titanium grade 5).
- 41 holders subjected to bake-out thermal cycles. Performed a total of 243 thermal cycles.
- For all the cases crystal bending angle is stable.



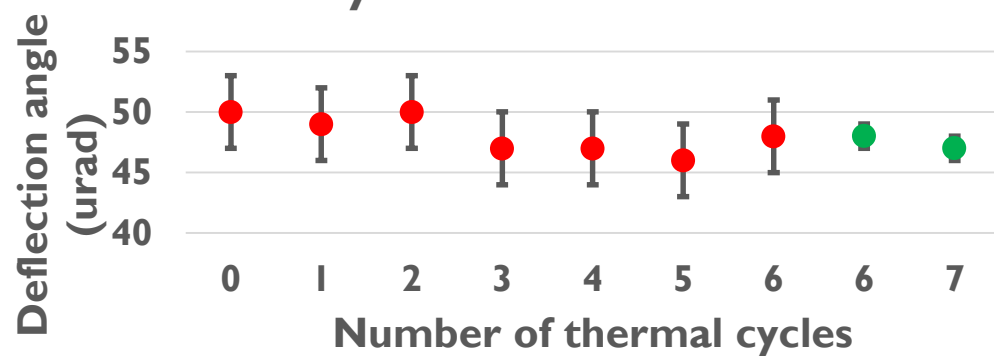
Newly developed holders (both titanium grade 5 and titanium grade 2) are thermally stable with respect to bake-out cycles.

CRYSTALS FOR THE LHC

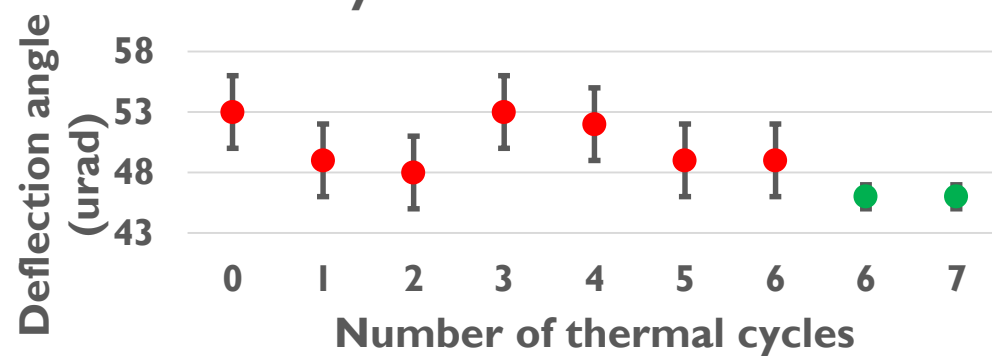


CRYSTALS FOR THE LHC

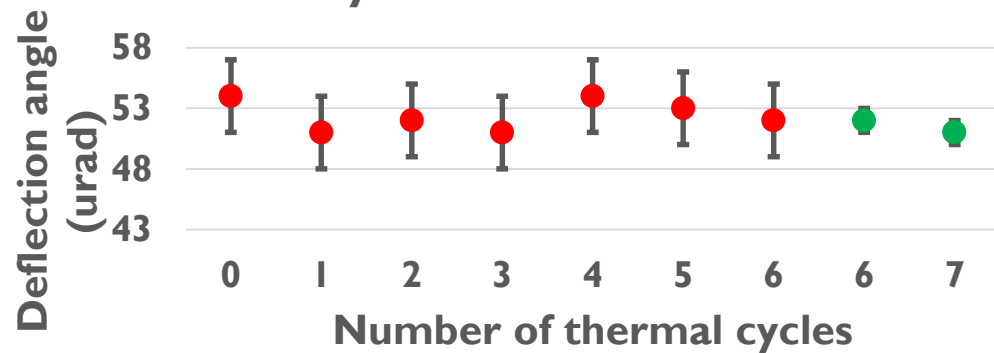
Crystal STF 121



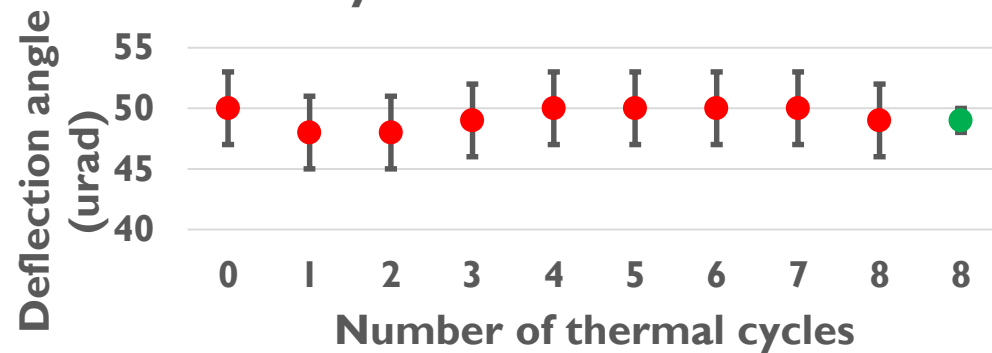
Crystal STF 122



Crystal STF 123

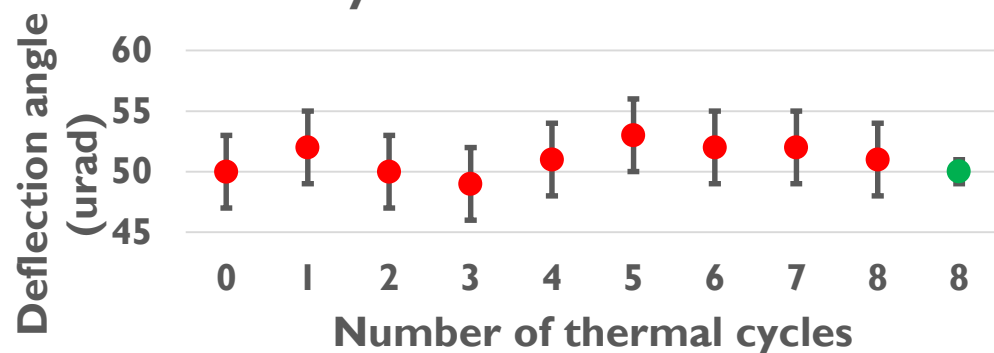


Crystal STF 124

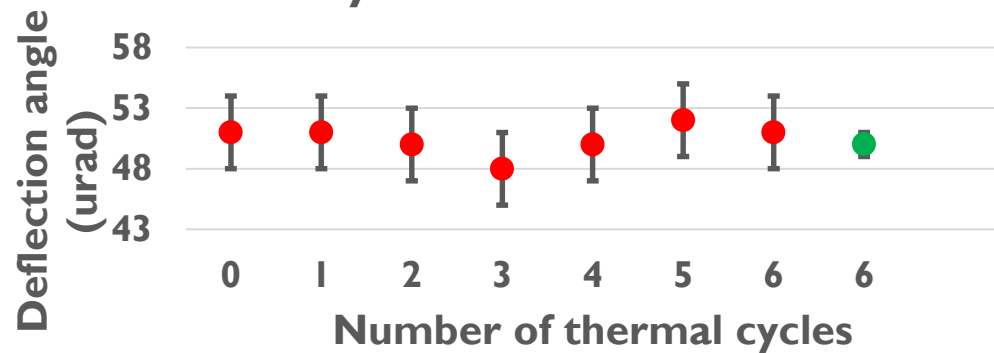


CRYSTALS FOR THE LHC

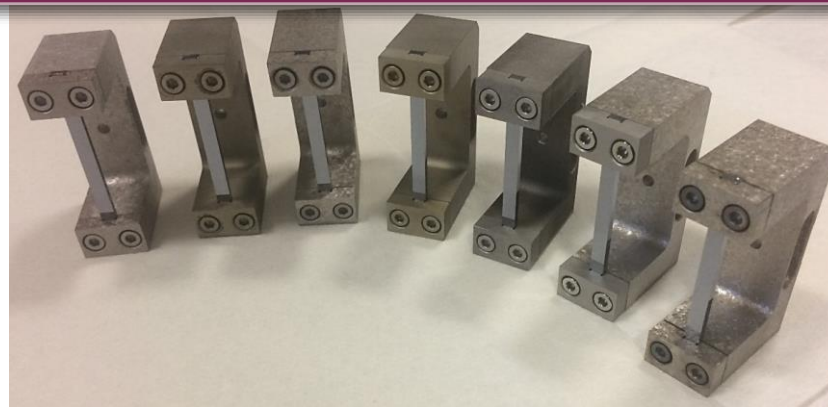
Crystal STF 125



Crystal STF 126

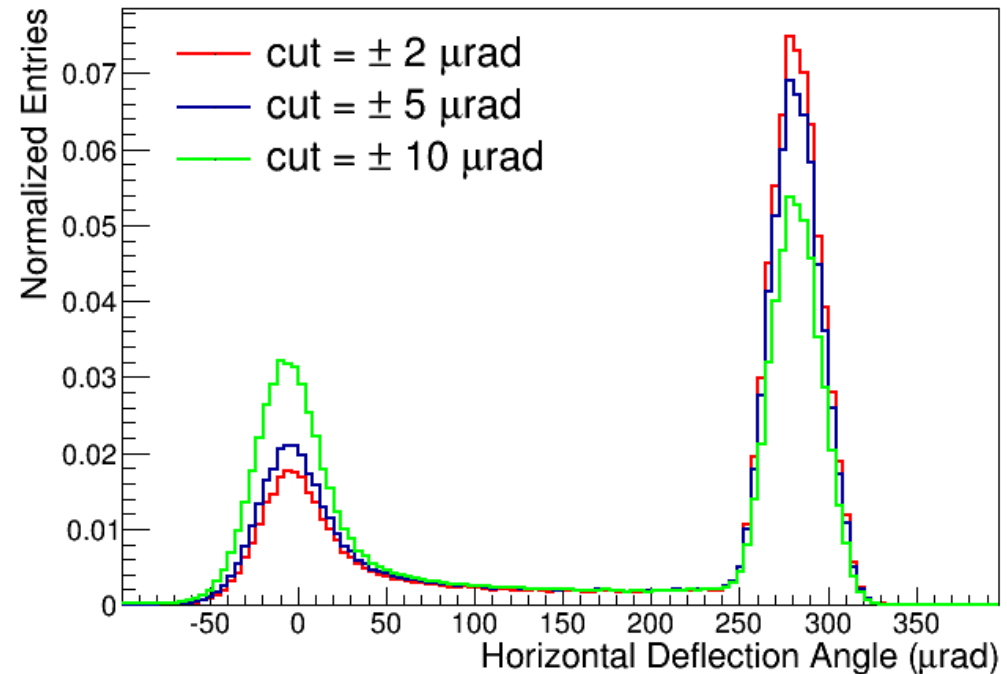
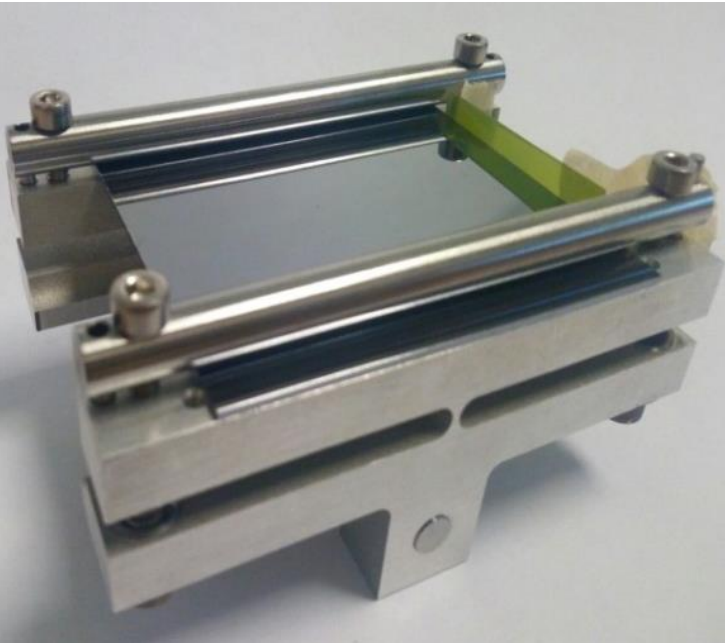


| Crystal code | Bending angle | Miscut | Bakeable |
|--------------|---------------|--------|----------|
| STF117 | 51±1 | 6±1 | YES |
| STF118 | 53±1 | 6±1 | YES |
| STF119 | 53±1 | 6±1 | YES |
| STF120 | 52±1 | 6±1 | YES |
| STF121 | 47±1 | 6±1 | YES |
| STF122 | 46±1 | 6±1 | YES |
| STF123 | 51±1 | 6±1 | YES |
| STF124 | 49±1 | 6±1 | YES |
| STF125 | 50±1 | 6±1 | YES |
| STF126 | 50±1 | 6±1 | YES |



CRYSBEAM EU PROJECT

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



Deflection $\sim 0.3 \text{ mrad}$

Need of a crystal bent at $\sim 1 \text{ mrad}$, bending radius $\sim 80 \text{ m}$

SELDOM EU PROJECT

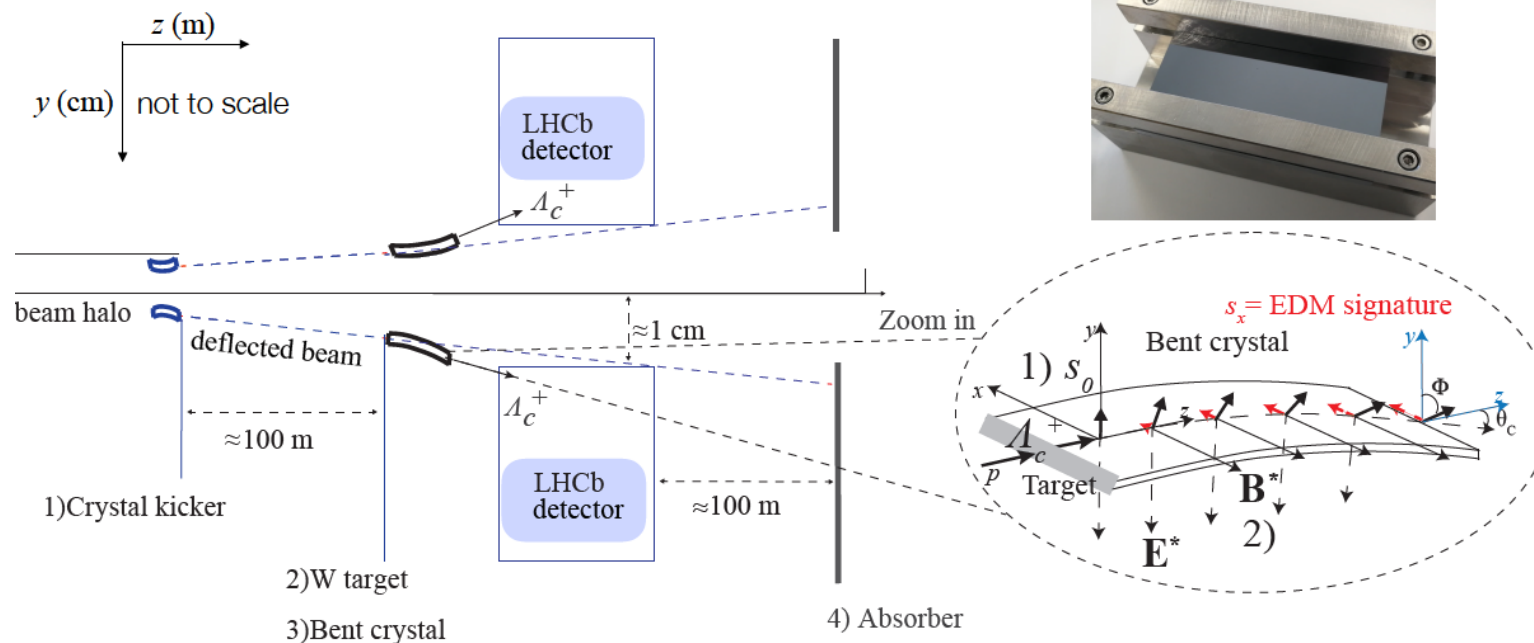
Novel fixed-target experiment at LHC for charm baryons



European Research Council
Established by the European Commission

P.I. Nicola Neri

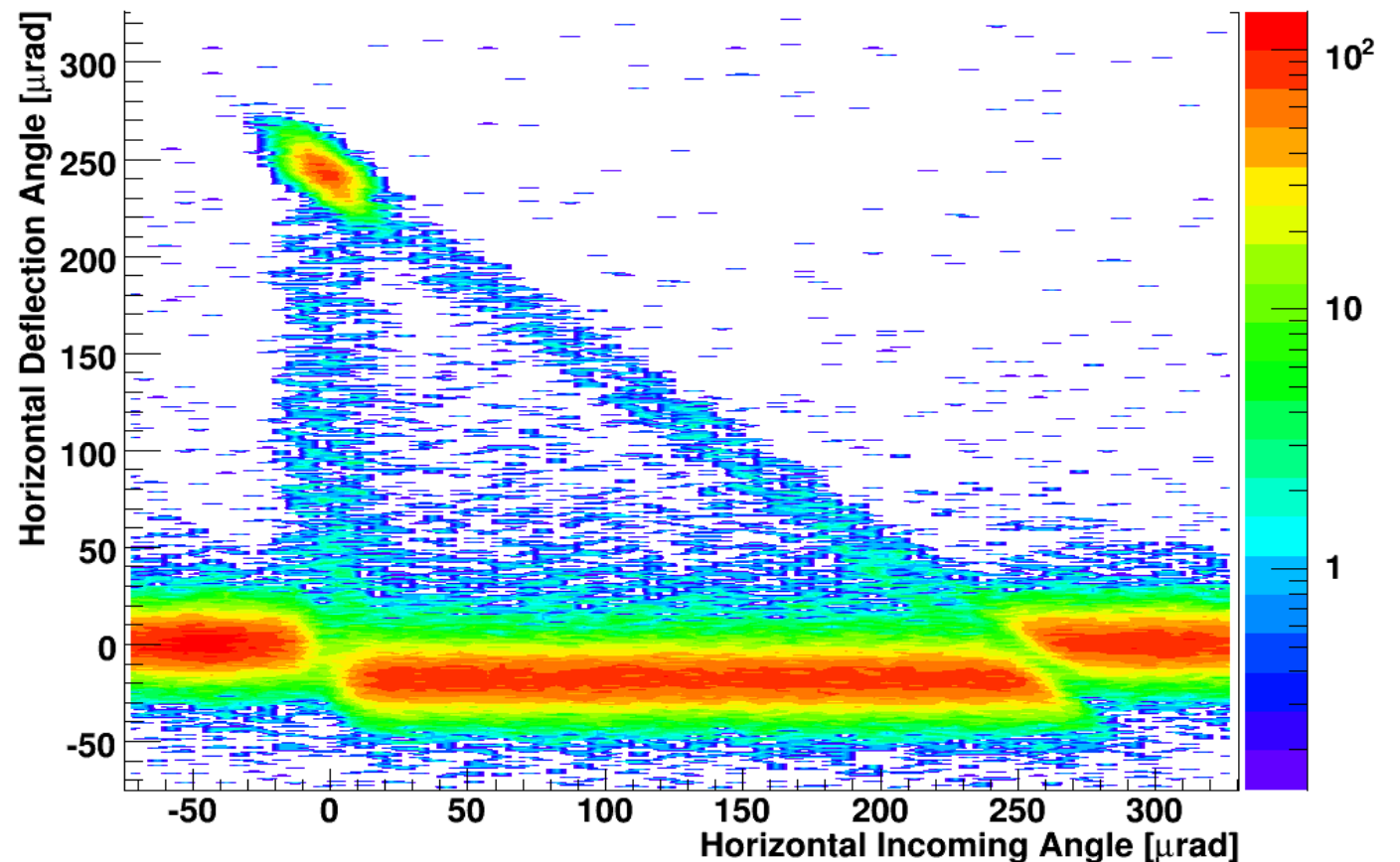
- EDM/MDM from spin precession of channeled baryons in **bent crystals**



p extraction Λ_c^+ polarised production channeling spin precession **event reconstruction**

GERMANIUM CRYSTALS

- We own the technology to machine also germanium crystals
- Mechanical machining
- Chemical etching for lattice damage removal



MOST RECENT DEVELOPMENTS

- Crystals with miscut less than 1 urad
- Assessed a correlation between x-ray and particle measurements
- Thanks to the experience already gained in development of holders for the SPS, pre-shaped holders made of titanium (grade 2/grade 5) are now available
- Holders/crystals assembly are now bakeable to 250 °C
- Tight requirement on bending angle can be routinely satisfied
- Recent progresses on torsion reduction

CONCLUSIONS

- INFN owns the expertise, technical resources, manpower to perform channeling experiments at any worldwide facility.
- Established a protocol for manufacturing of crystals free from crystalline defects.
- Possibility to deliver crystals with miscut lower than 1 urad.
- Developed a protocol to manufacture crystals matching requirements for installation in the LHC.
- Possibility to realize germanium crystals
- Possibility to realize cm-thick uniformly bent crystals