Bent Crystals for Spin Precession Experiment at LHC

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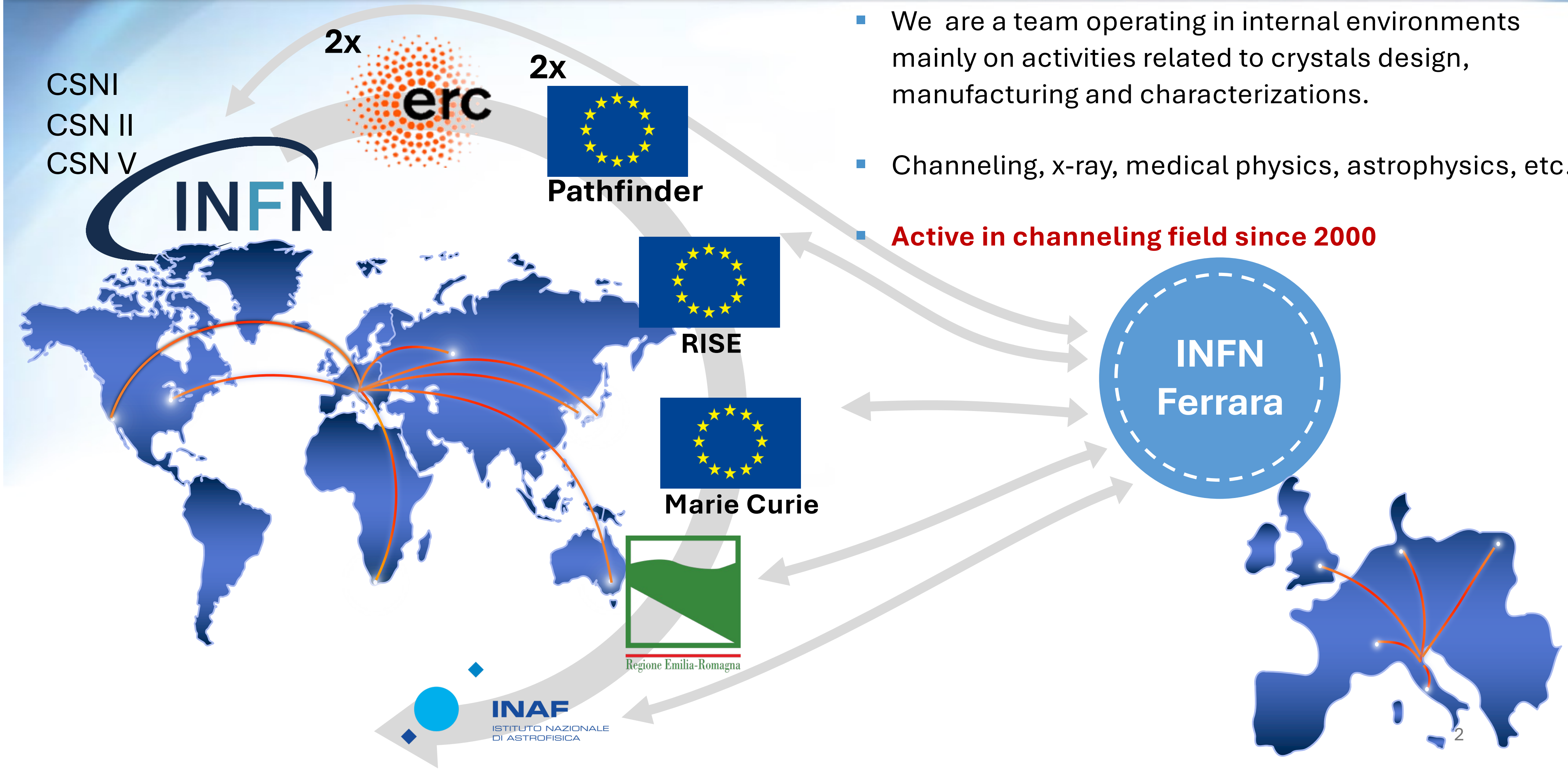
11/09/2025

Relationships

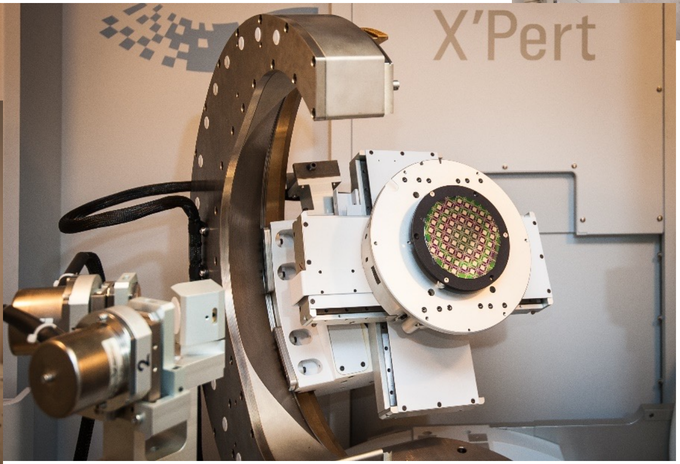
- We are a team operating in internal environments mainly on activities related to crystals design, manufacturing and characterizations.
- Channeling, x-ray, medical physics, astrophysics, etc…
- **Active in channeling field since 2000**

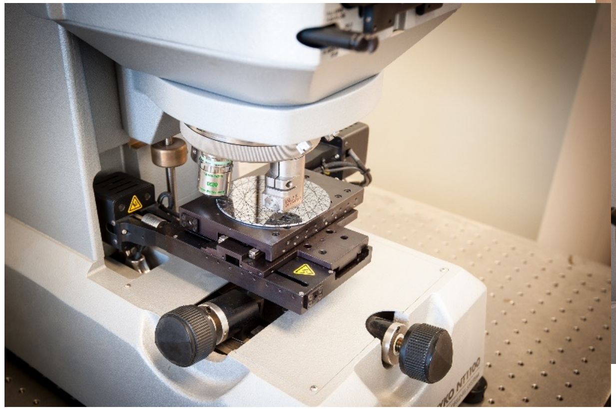


INFN infrastructure

Laboratory fully equipped for silicon micro and nanomachining
ISO4 certified clean room (130 m^2)

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

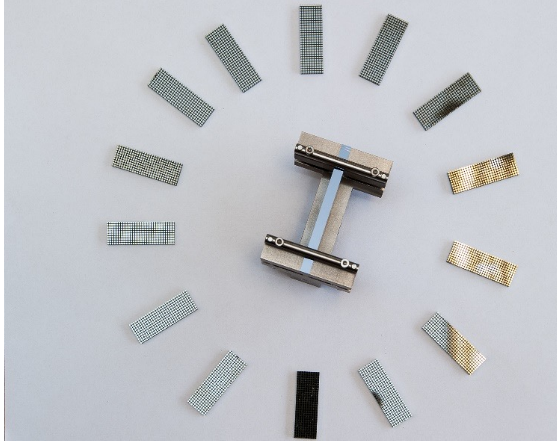


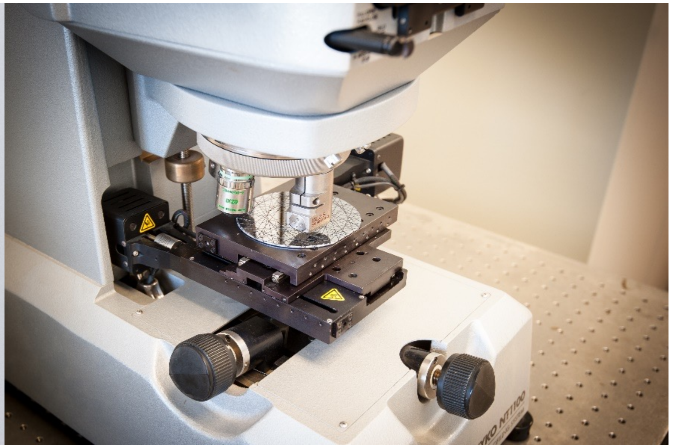


INFN infrastructure

Laboratory fully equipped for silicon micro and nanomachining

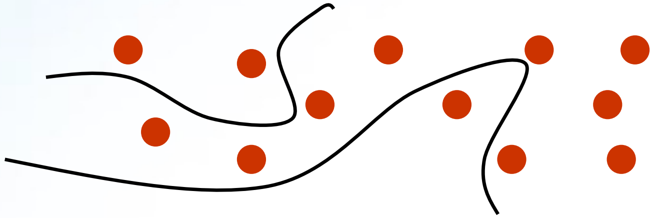
Fotolitography
Equipment for silicon chemical etching
Nanoimpringing



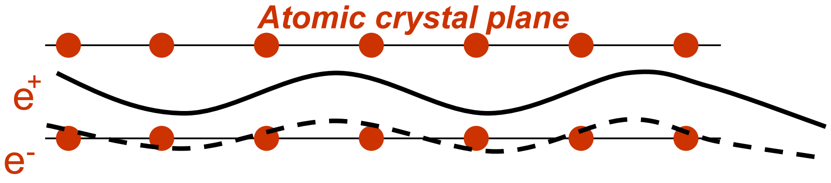


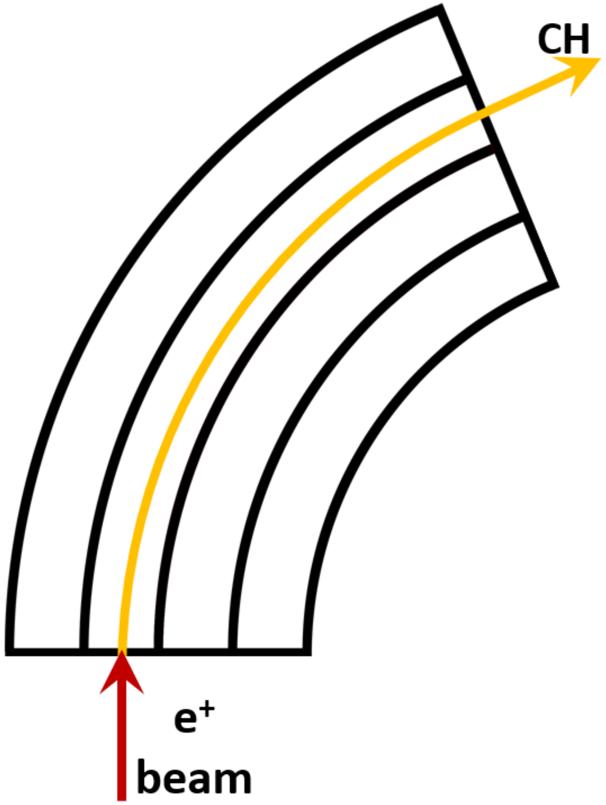
CHANNELING IN BENT CRYSTALS

@ Amorphous:

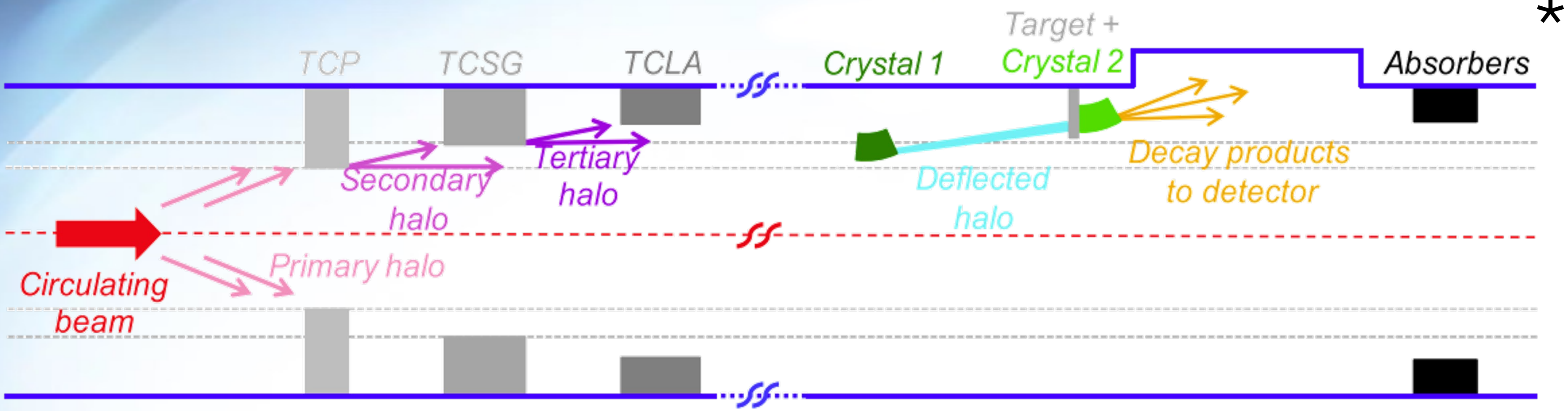


@ Planar channeling





Experimental scheme



A first «short» crystal is used to extract the circulating beam halo

Extract beam hits a target generating short-living particles

A second «long» crystal collects a fraction of generated particles and channel them inducing spin precession

*D. Mirarchi et al., Eur. Phys. J. C (2020) 80 :929

Crystals for beam extraction

Thickness along the beam: 4.0±0.1 mm

Height < 55 mm.

Weight < 150 g

Channeling plane: (110)

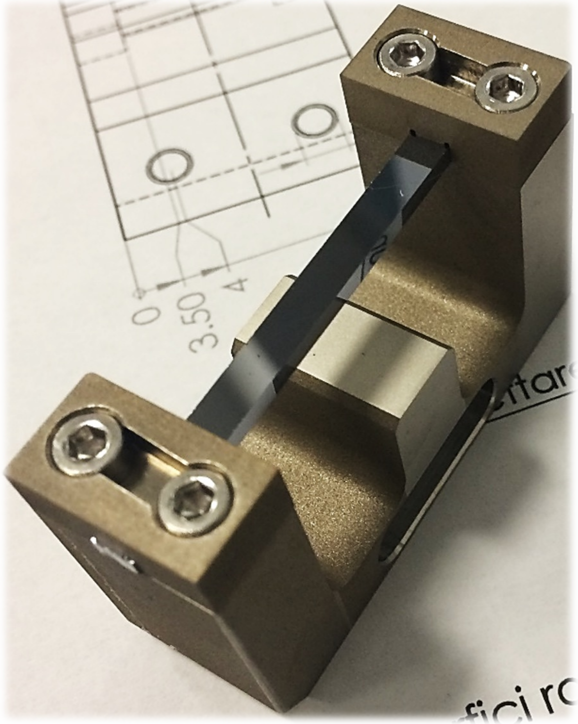
Channeling axis: <111> or <110>

Miscut for planar channeling: < 10 μrad.

Torsion: < 1 μrad/mm

Bending angle: 50-55 μrad

Dislocation density < 1 cm^2

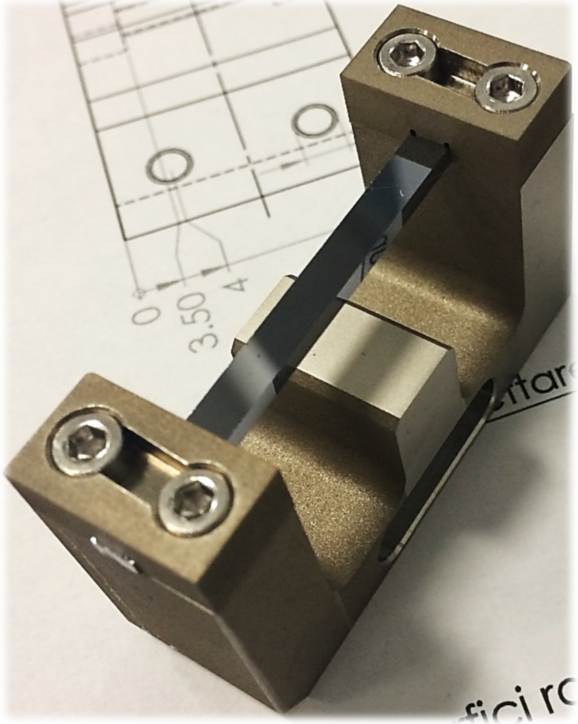


Specifications defined in collaboration with CERN

Crystals for beam extraction

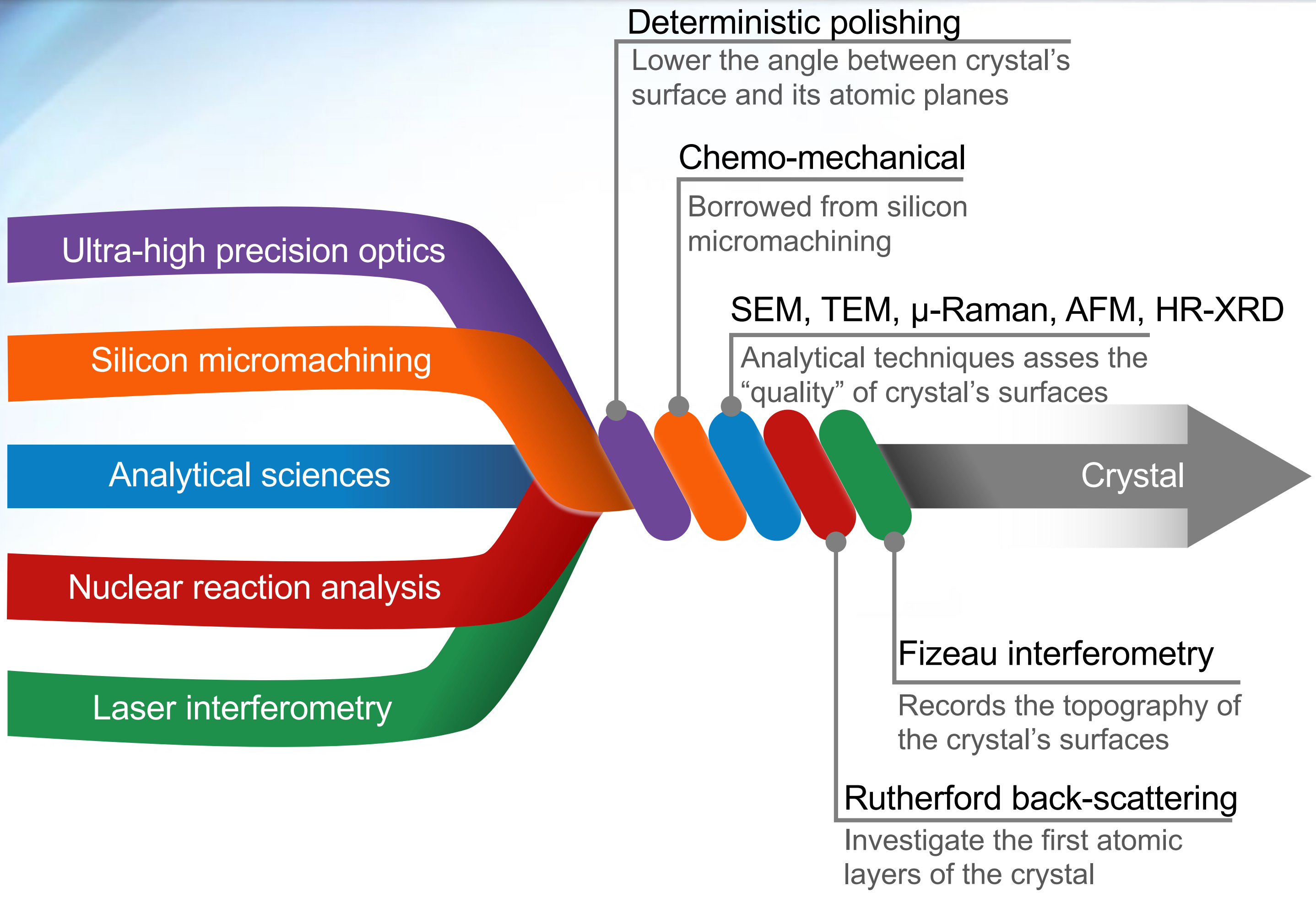
Bake out

- 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}



Specifications defined in collaboration with CERN

Crystals for extraction – “classic” approach –



Ultra-high precision optics

Silicon micromachining

Analytical sciences

Nuclear reaction analysis

Laser interferometry

Deterministic polishing
Lower the angle between crystal’s surface and its atomic planes

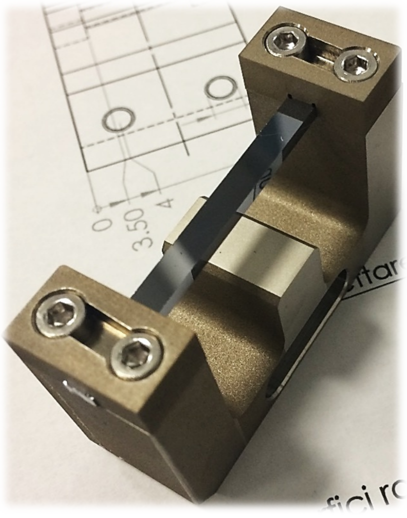
Chemo-mechanical
Borrowed from silicon micromachining

SEM, TEM, µ-Raman, AFM, HR-XRD
Analytical techniques asses the “quality” of crystal’s surfaces

Crystal

Fizeau interferometry
Records the topography of the crystal’s surfaces

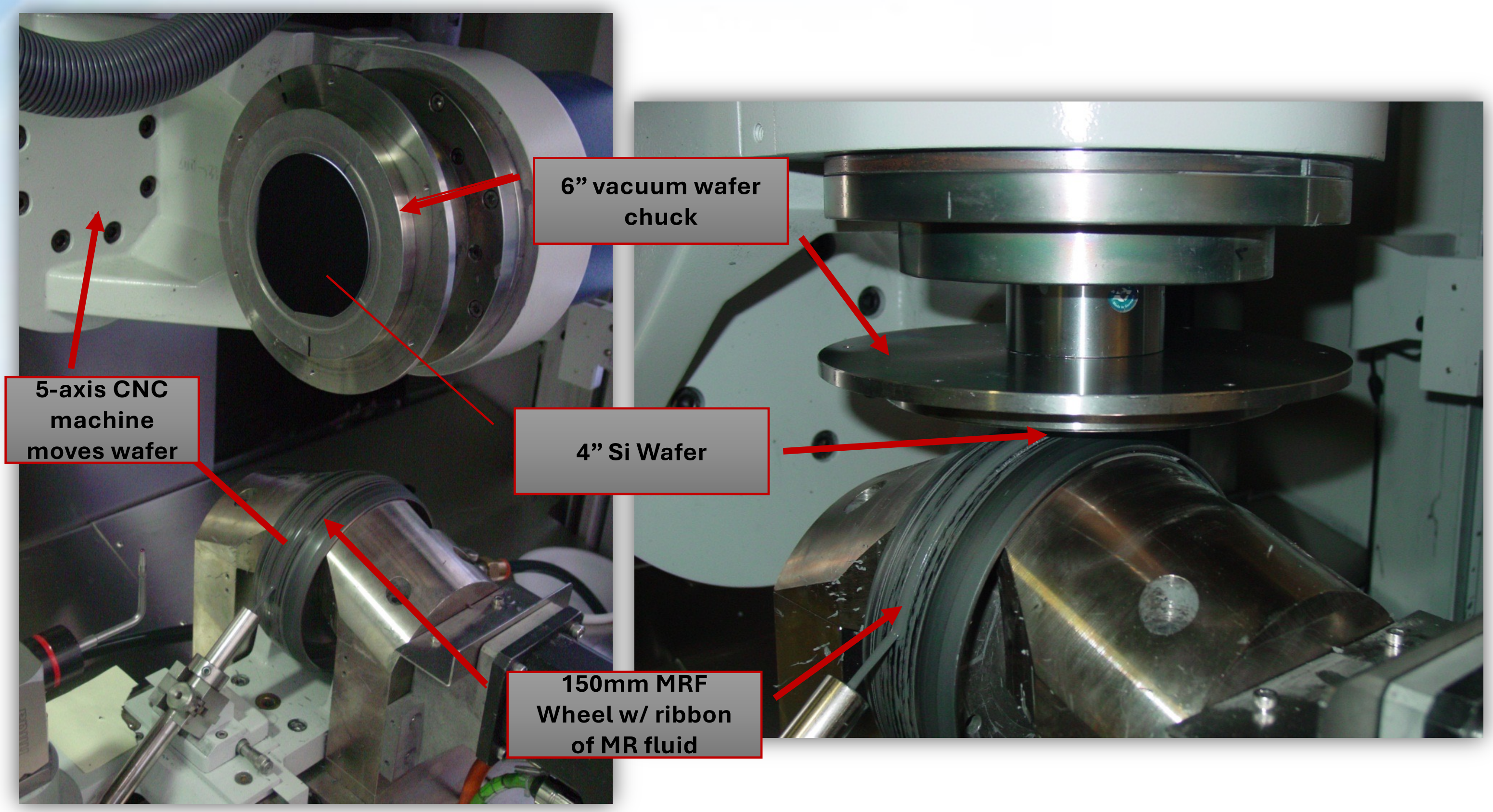
Rutherford back-scattering
Investigate the first atomic layers of the crystal



Challenging aspects

- ✓ Planar miscut: < 10 μrad→ MRF finishing
- ✓ Torsion: < 1 μrad/mm → ultra precise machining and assembly.
- ✓ Bending angle: 50-55 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.

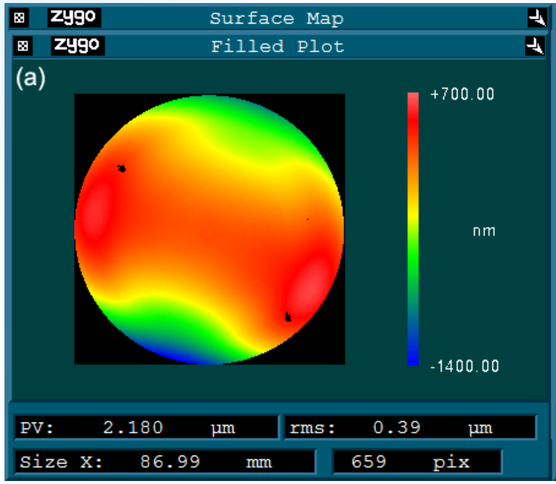
MRF finishing



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

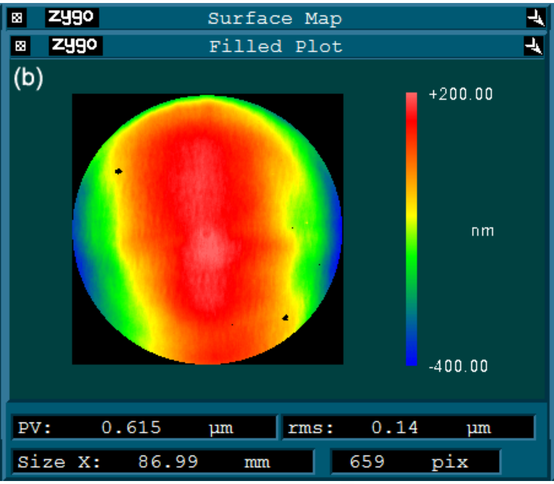
After a 2 years R&D the tecnique was adapted to operate on crystalline materials.

MRF Finishing



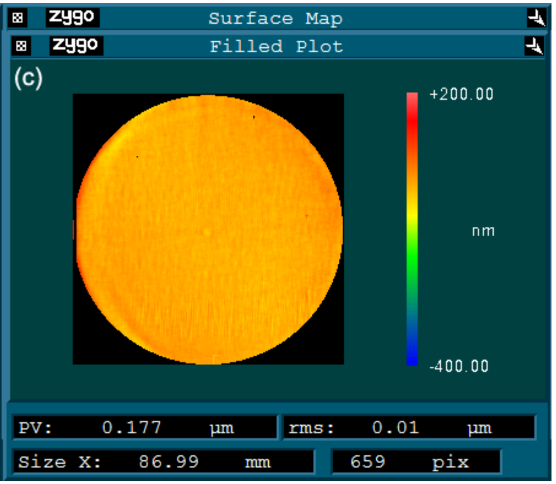
PV: 2.180 µm rms: 0.39 µm
Size X: 86.99 mm 659 pix

Starting surface
PV 2.18 um
RMS 0.39 um



PV: 0.615 µm rms: 0.14 µm
Size X: 86.99 mm 659 pix

Surface after first treatment
PV 0.615 um
RMS 0.14 um

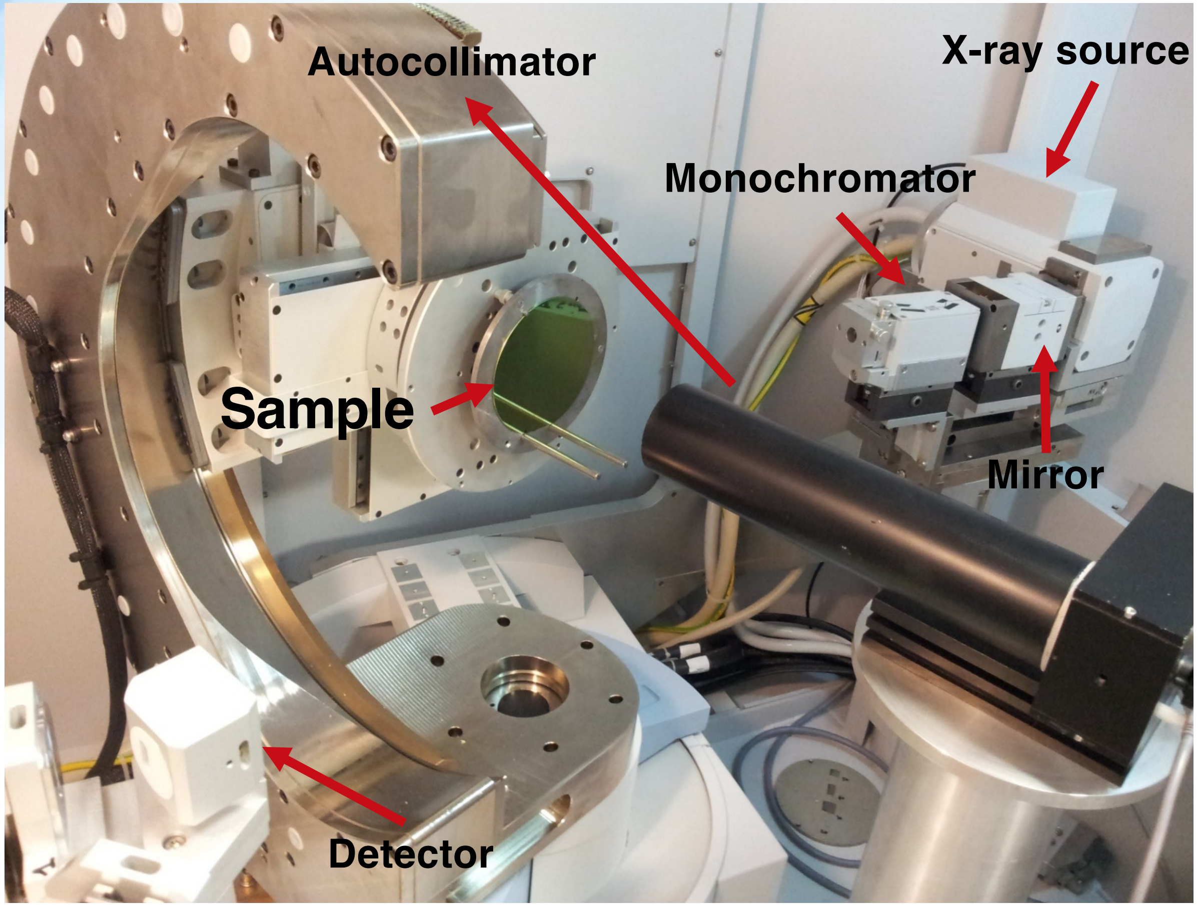


PV: 0.177 µm rms: 0.01 µm
Size X: 86.99 mm 659 pix

Final surface
PV 0.177 um
RMS 0.01 um

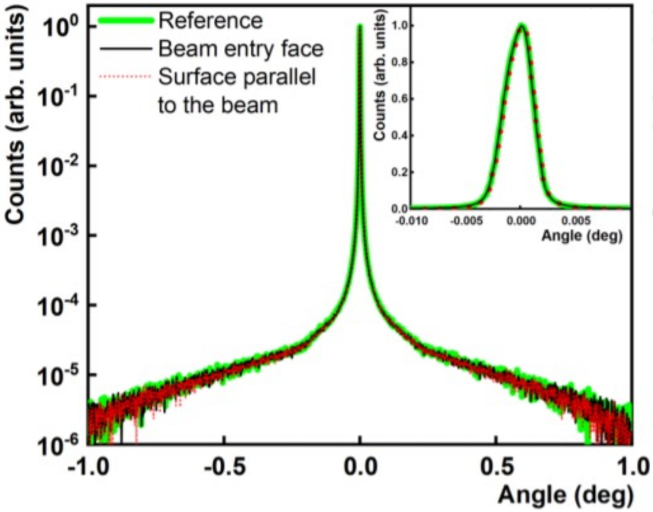
- MRF is a deterministic polsihing process
- Does not induce any lattice damage
- Miscut < 1 urad

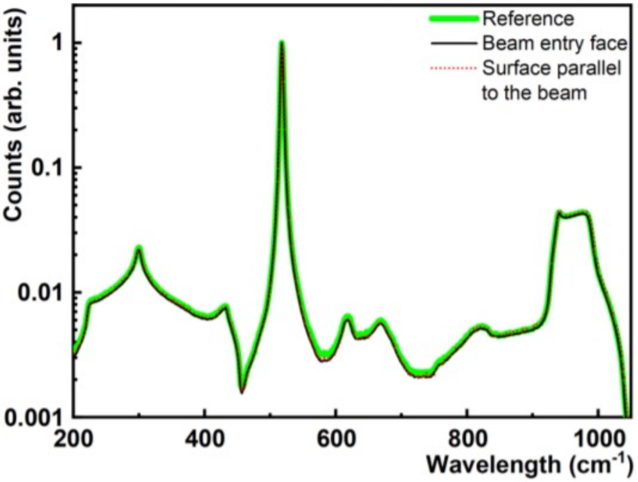
Miscut reduction

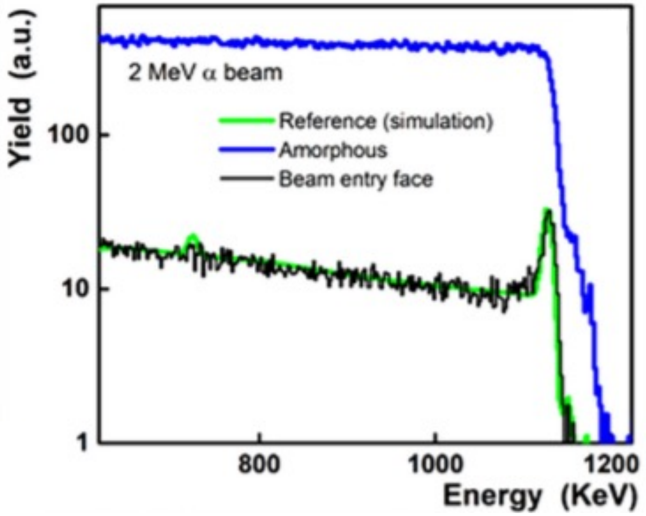


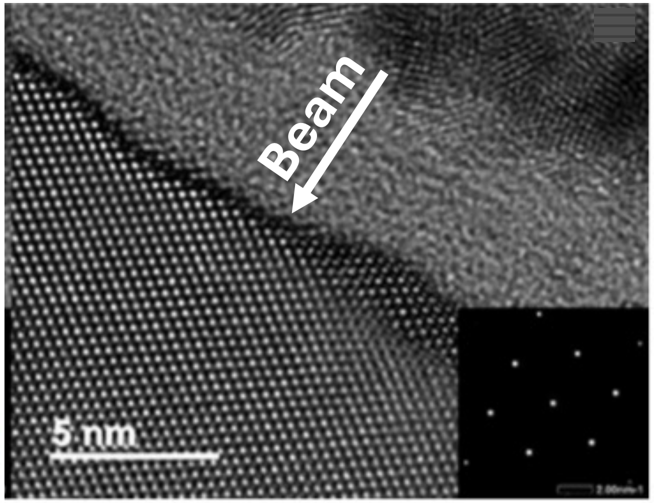
- High resolution x-ray diffractometer (PANALYTICAL)
- Miscut: angle between optical surface and atomic planes
- Requested miscut < 10 µad.

Crystals for extraction – “classic” approach –





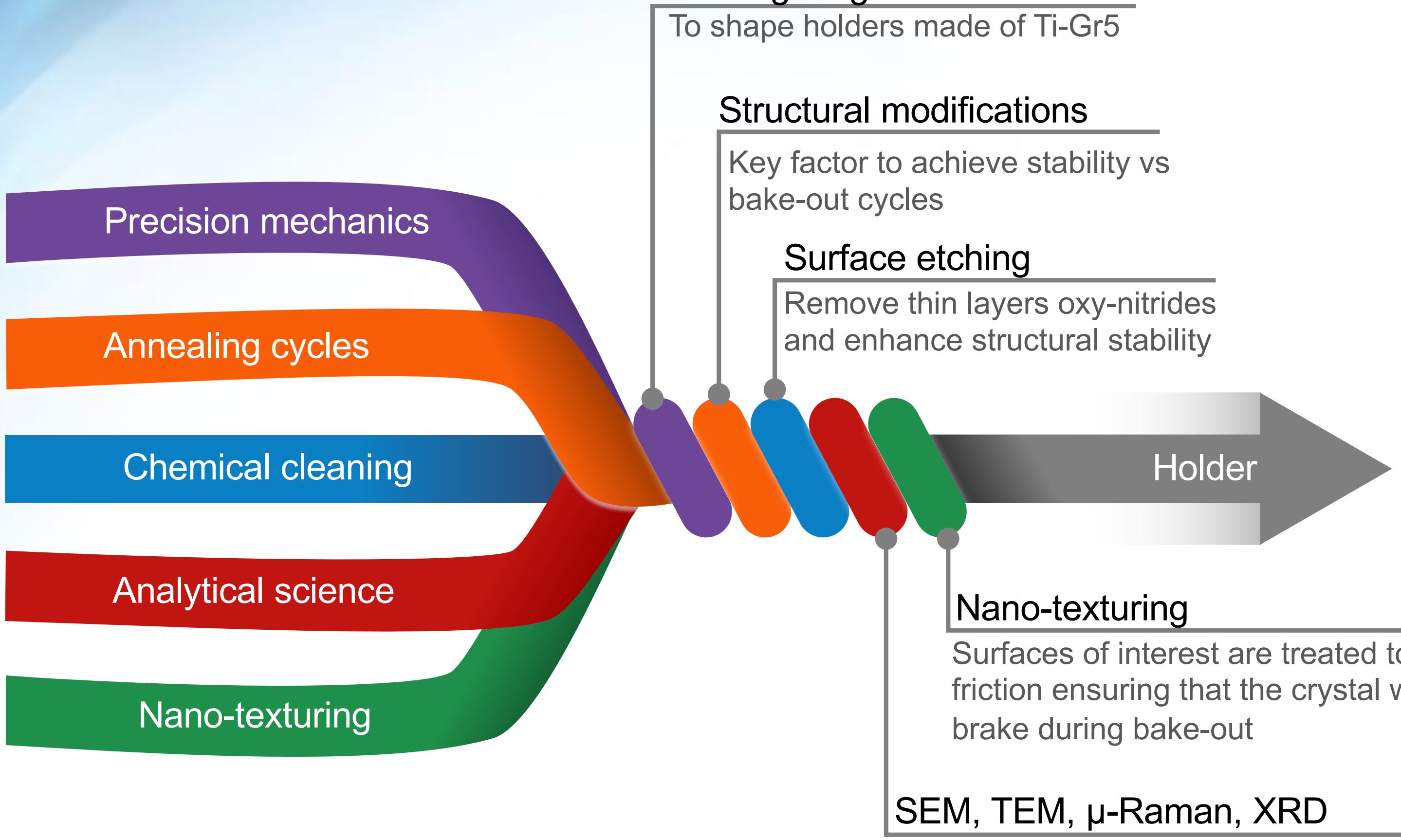




A. Mazzolari et al., Phys. Rev. Research 3, 013108

- Essential to have surfaces free from sub-surface lattice damage: a dedicated manufacturing process have been established
- A large set of characterization techniques is exploited to validate the manufacturing process.
    - HR-XRD probe up to few tens of microns
    - μ-raman (probe up to few microns)
    - RBS-Channeling (probe up to few hundred nm)
    - TEM (probe the first atomic layers)
- Only HR-XRD in house, other characherizations are outsourced.

Crystals for extraction – “classic” approach –



Precision mechanics

Annealing cycles

Chemical cleaning

Analytical science

Nano-texturing

Holder

EDM figuring

To shape holders made of Ti-Gr5

Structural modifications

Key factor to achieve stability vs bake-out cycles

Surface etching

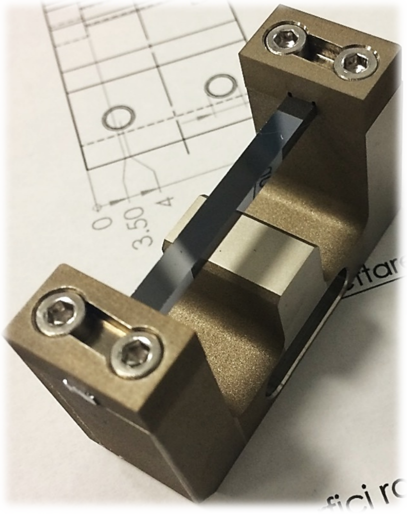
Remove thin layers oxy-nitrides and enhance structural stability

Nano-texturing

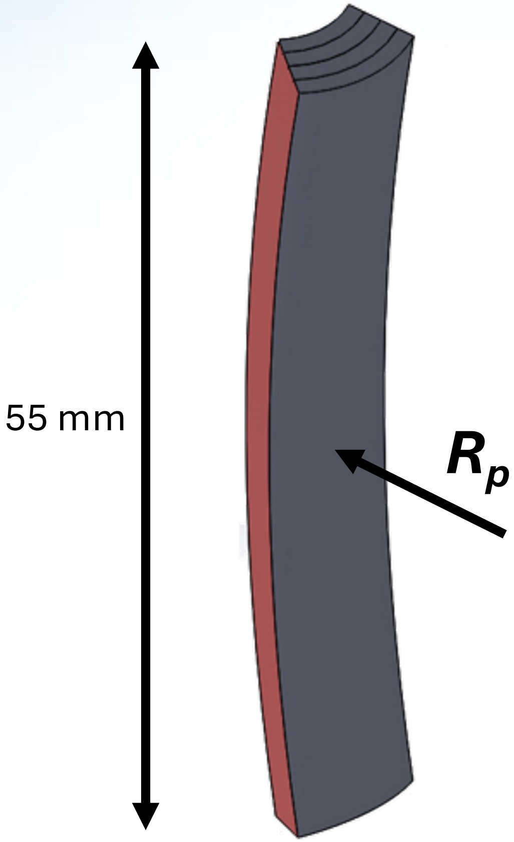
Surfaces of interest are treated to tune friction ensuring that the crystal will not brake during bake-out

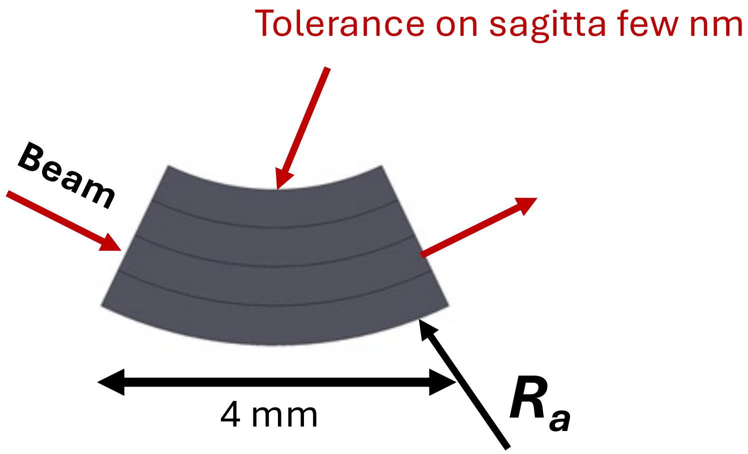
SEM, TEM, μ-Raman, XRD

Assessment of the correct ratio between alpha and beta alloy phases, key factor for stability vs bake-out cycles, assessment of correct nano-texturing



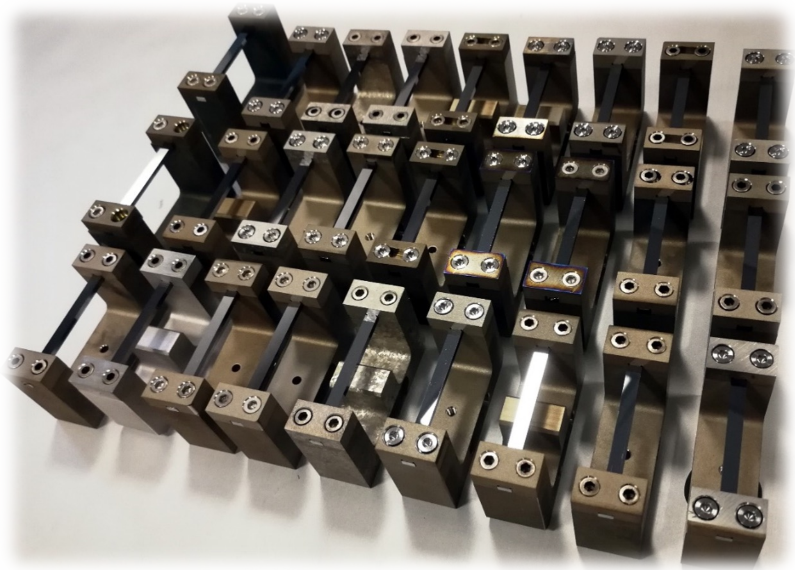
Anticlastic deformation





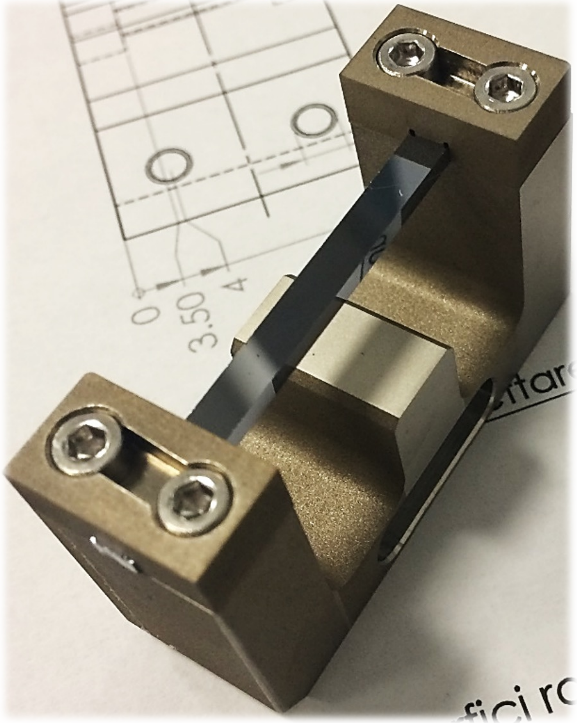
Innovative benders

- 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



Innovative benders

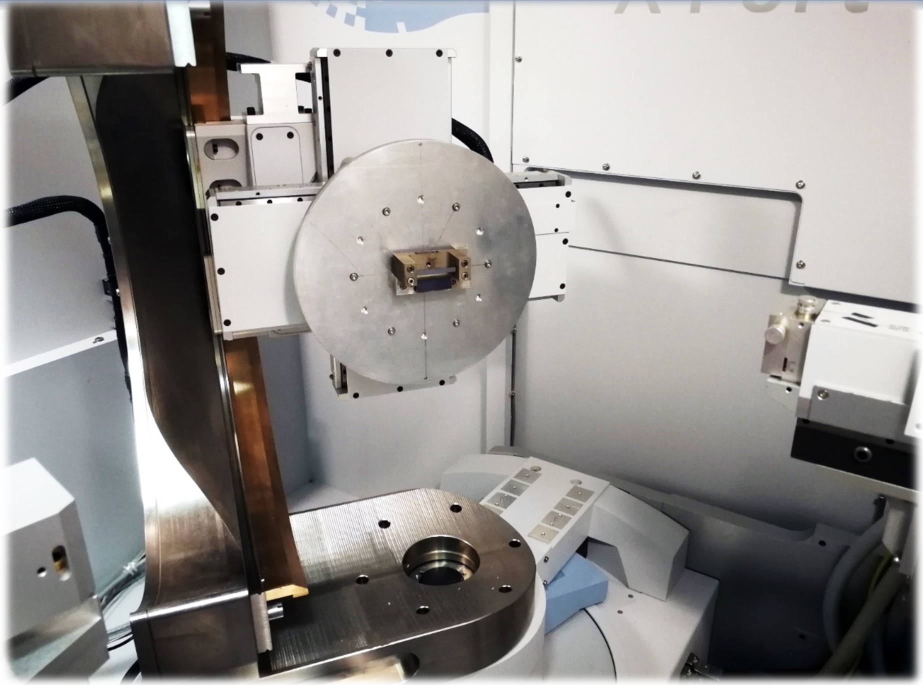
- Ultra-high precision machining provides holders with crystal-supporting surfaces inclined at a proper angle to impart to the crystal the desired deformation.
  - At first step, the holders are manufactured with approaches typical of conventional precision mechanics.
  - selected holders are treated 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.

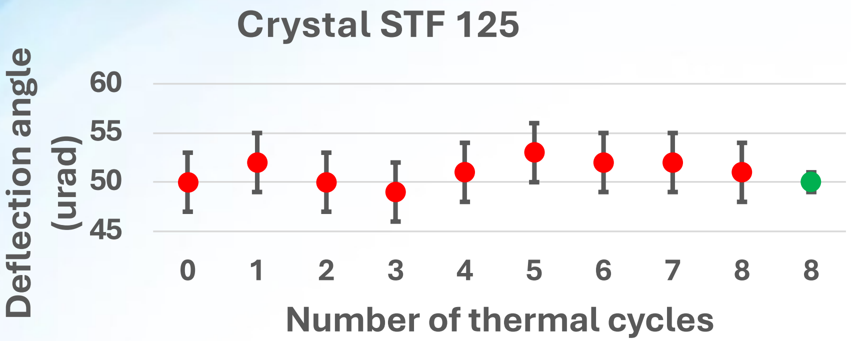
X-ray lab measurement of bending angle

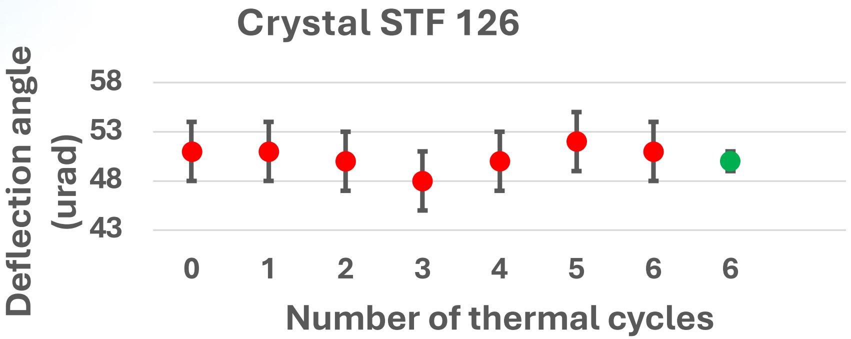
	Deflection angle (μrad)		
Crystal	High resolution x-ray diffraction	Channeling	Consistency
STF47	33±2	35±2	YES
STF48	144±2	142±2	YES
STF49	247±3	246±2	YES
STF50	142±5	143±2	YES
STF51	33±2	33±2	YES
STF70	56±2	55±2	YES
STF71	60±5	62±2	YES
STF99	119±3	120±2	YES
STF100	67±6	63±2	YES
STF101	170±6	165±2	YES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

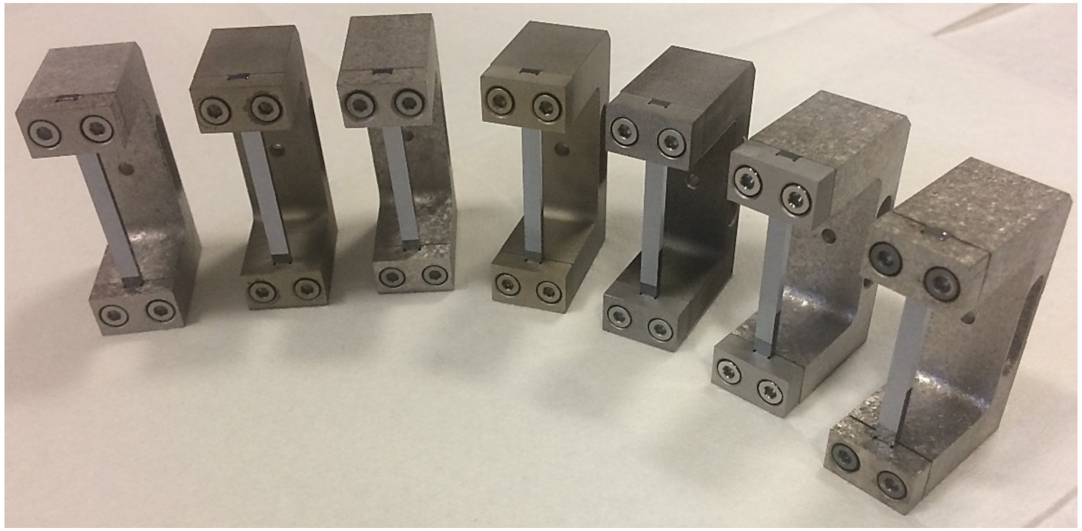


Determinantion of crystal bending angle with high-resolution x-ray diffraction and channeling of high-energy particles are in agreement.

CRYSTALS FOR THE LHC

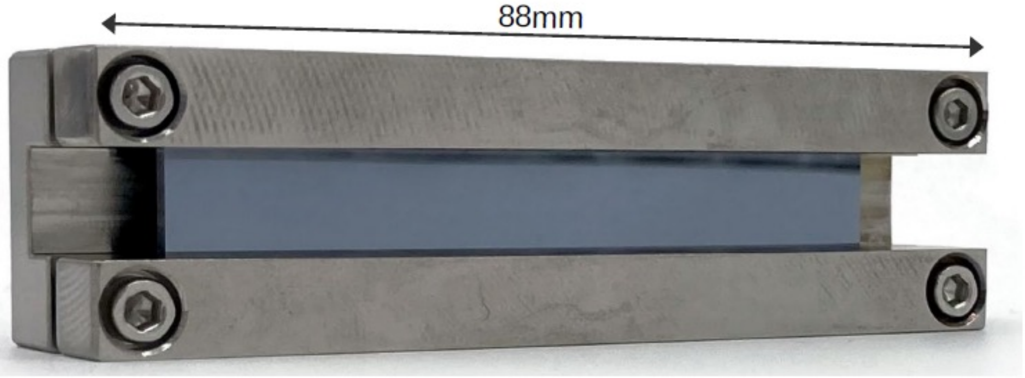






Long crystal

Property	Specification
Material	Silicon
Crystal length along the beam, L_C	70±5 mm
Minimal thickness in bending (vertical) direction, H_C	2±0.1 mm
Minimal width in horizontal direction, W_C	8±0.1 mm
Channelling plane	<110>
Channelling axis	<111> or <110> or <100>
Miscut for planar channelling	< 100 mrad
Torsion	< 200 mrad/mm
Nominal bending angle	7.0 mrad
Bending radius, R_{nom}	10 m
Acceptable bending angle range	6.0 – 7.5 mrad
Minimum curvature radius across crystal length	10 m
Single-pass channelling efficiency at 180 GeV	> 20 %
Single-pass channelling efficiency at 400 GeV	> 28 %
Miscut for axial channelling	0 mrad ± 0.5 mrad
Dislocation density	< 1 / cm^2



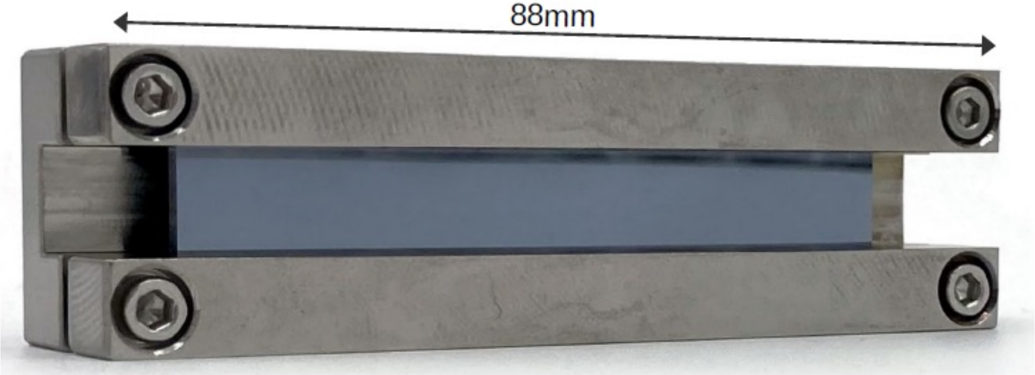
Specifications defined in collaboration with CERN

Manufacturing of «long» crystals

Manufaturing and characaterization approach similar to the one used for «short» crystals.

Special care must be paid to uniformity of bending radius.

Mechanical imperfections and bending approach results in non-uniform bending radius.



Non-uniformities of bending radius

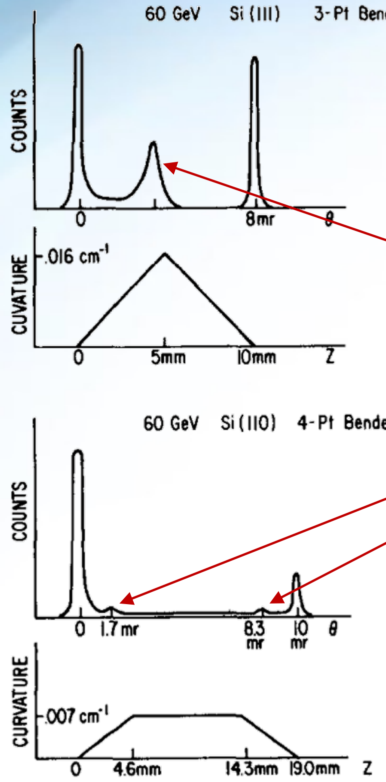
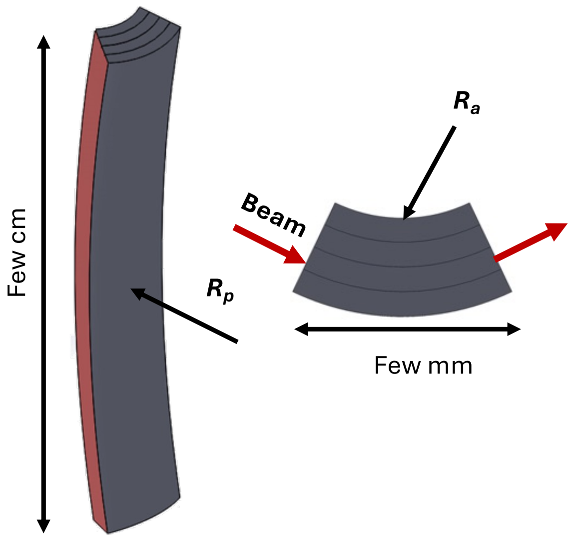


Fig. 2. Fermilab data taken from refs. [7] and [8]. Fig. 2a shows the data for the three point jig, 60 GeV/c and the {111} planes of Si and fig. 2b data from the four joint jig, 60 GeV/c and the {110} planes of Si. In each case the curvature as a function of z is shown. The θ and z coordinates are related by $\theta = \int_0^z \kappa(\xi)\mathrm{d}\xi$. The counts have not been normalized, so a direct comparison of (a) and (b) is not possible.

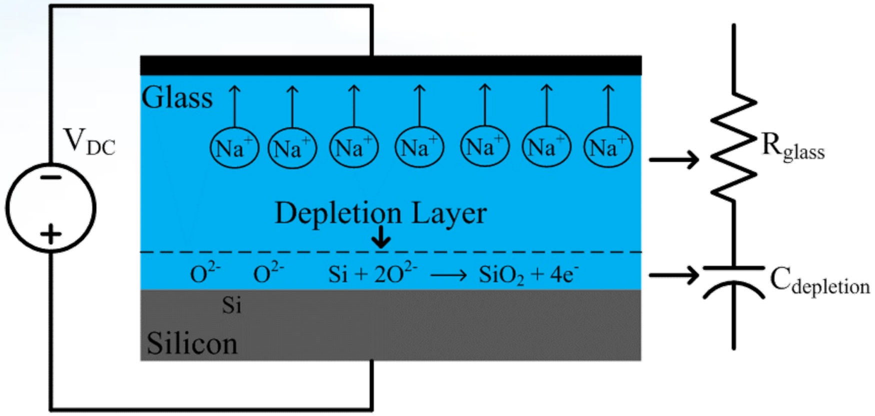
Effects of non uniformities in the bending radius were already observed in pioneering experiments at Fermilab (60 GeV, protons)

- Particles dechanneled in regions of «small» radius
- Issue was solved introducing «anticlastic deformation» (initially by IHEP, later refined at INFN).
- Due to requirement of high aspect ratio, this approach can not be used for «long» crystals



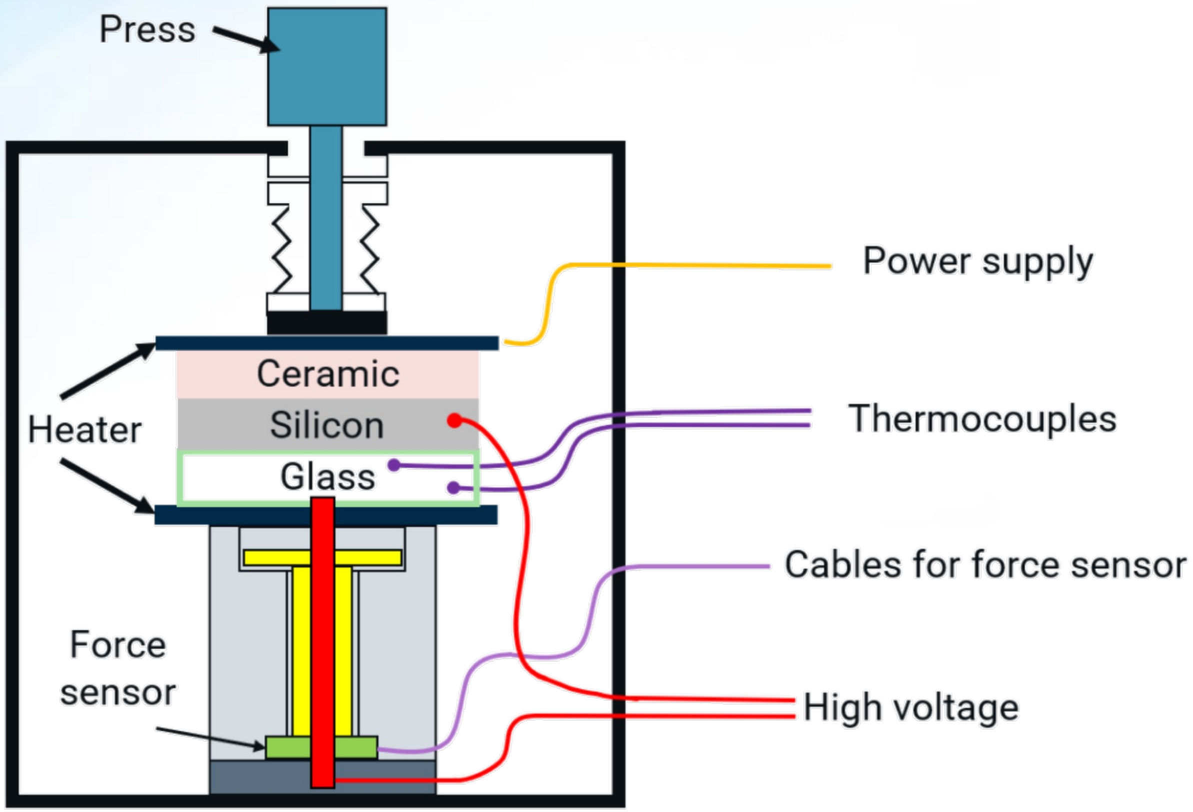
Ellison et al., NIMB 2 (1984) 9-12

«Bonding anodico»



- Anodic bonding is a technique to seal silicon and glass without using an intermediate layer.
- A clean wafer surface and atomic contact between the substrates is required for anodic bonding.
- Bonding takes as the temperature is increased to just below the glass transition temperature of glass, followed by applying electric potential of few kV.
- The oxides dissociate. Alkali ions are driven into the glass, resulting in an oxygen-rich layer at the interface with the silicon. Oxygen ions are driven into the silicon surface by the electric field resulting in the formation of silicon dioxide.

Apparatus for anodic bonding



Crystal pressed between glass and a counter-die.

- Pressure
- Temperature
- Electric field

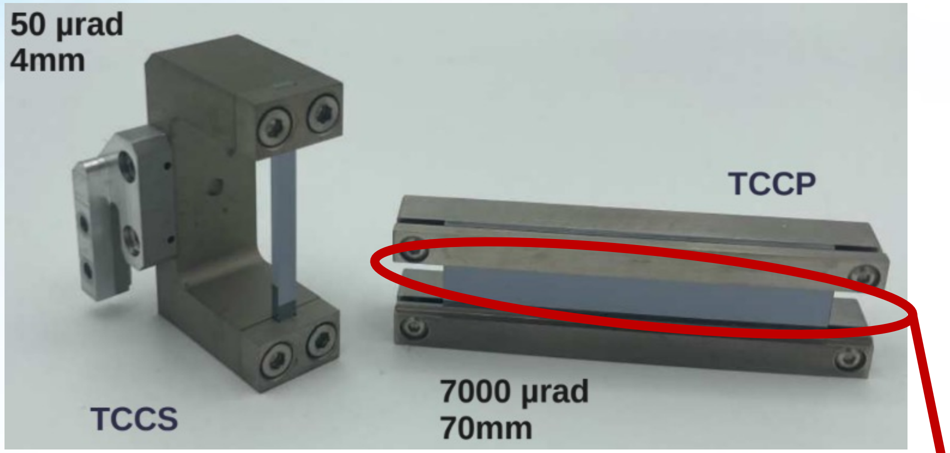
Innovative bent crystals based on anodic bonding

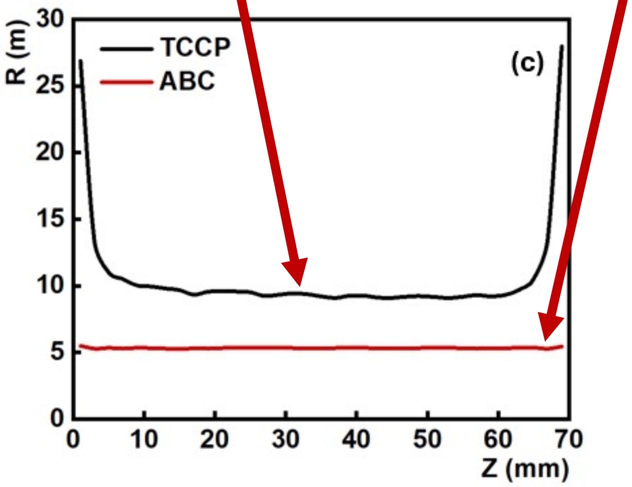
Current technology

To be installed in the LHC

Most recent development

To be further developed





Conclusions

- Protocol for manufacturing and characterization of «short» and «long» bent crystals is well established
- Crystals for collimation of LHC fully operational
- Crystals for TWOCRYST being installed
- Future developments will rely on anodic bonding