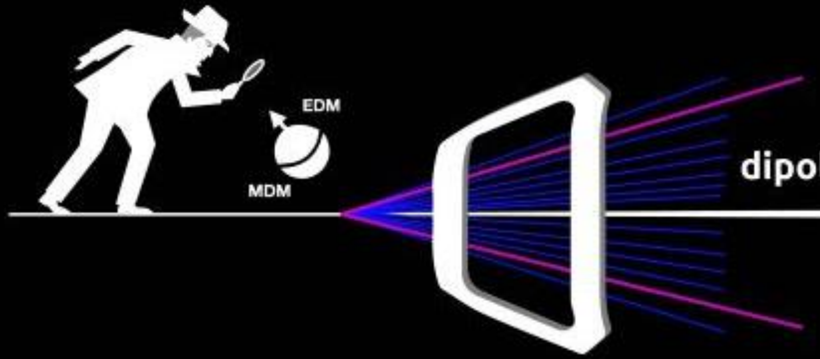
M. Romagnoni

Design, construction and test of bent crystals



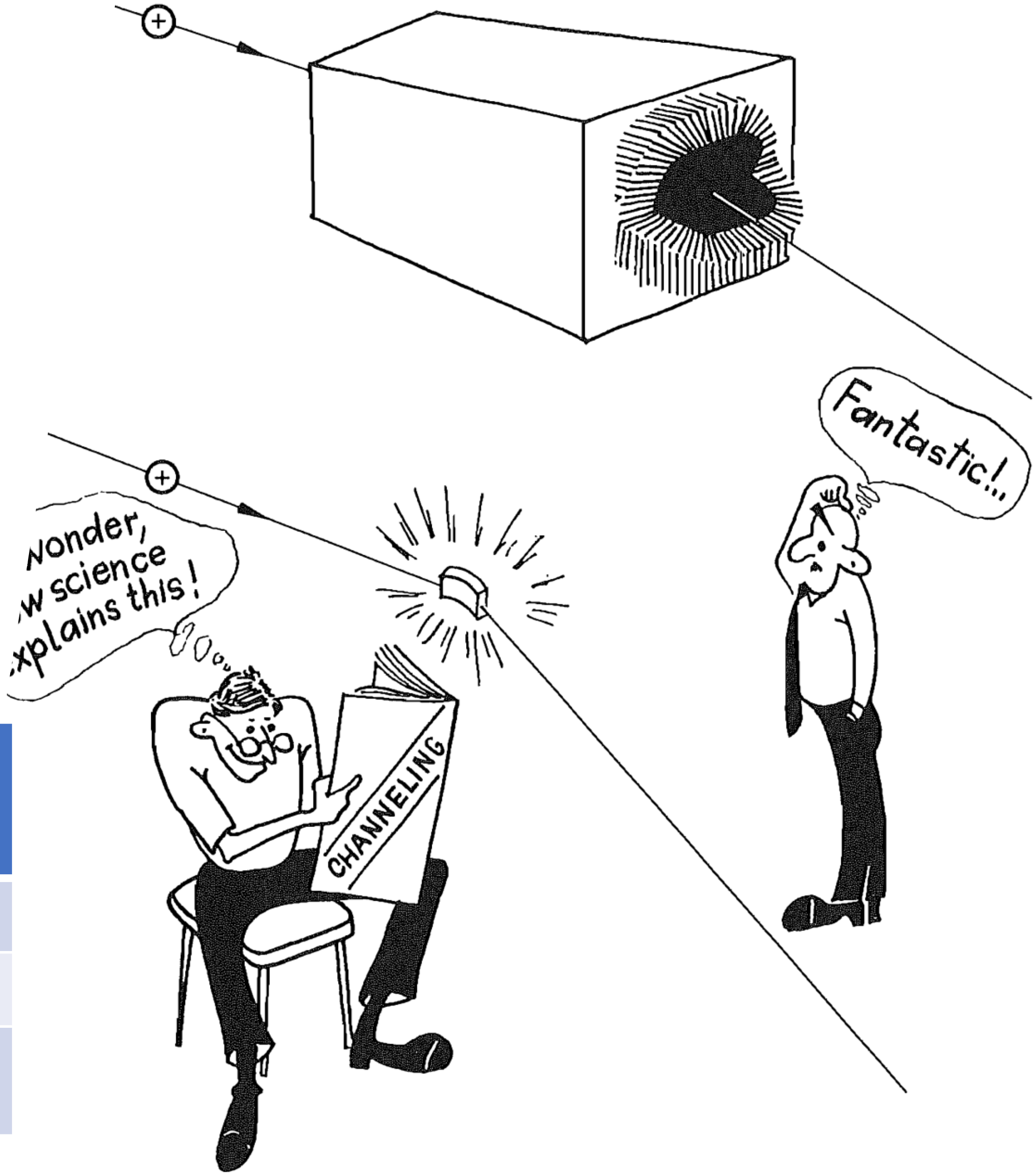
Workshop on electromagnetic dipole moments of unstable particles

3-4 October 2019
Milano, Italy

Beam deflection via channeling

- Charged particles in channeling state follows the bending of the crystal within the critical radius of curvature
- Large deflection power wrt standard magnetic dipole:

Particle energy	Deflection angle	Thickness along the beam	B_{eq} [T]
7 TeV	50 µrad	4 mm	292
7 TeV	150 µrad	12 mm	292
1 TeV	15 mrad	80 mm	625



Bent crystals for beam deflection

Goal	Particle	Energy	Deflection	Thickness
LHC collimation	Ions	6.5 TeV	50 μrad	4 mm
LHC extraction (Crysbeam)	Protons	6.5-7 TeV	Few hundred μrad	Few cm
LHC extraction (SELDOM)	Protons	7 TeV	150 μrad	12 mm
Dipole procession (SELDOM)	Charmed Baryons	~ 1 TeV	15 mrad	80 mm (Si) 50 mm (Ge)

Crystal deflectors already produced in Ferrara

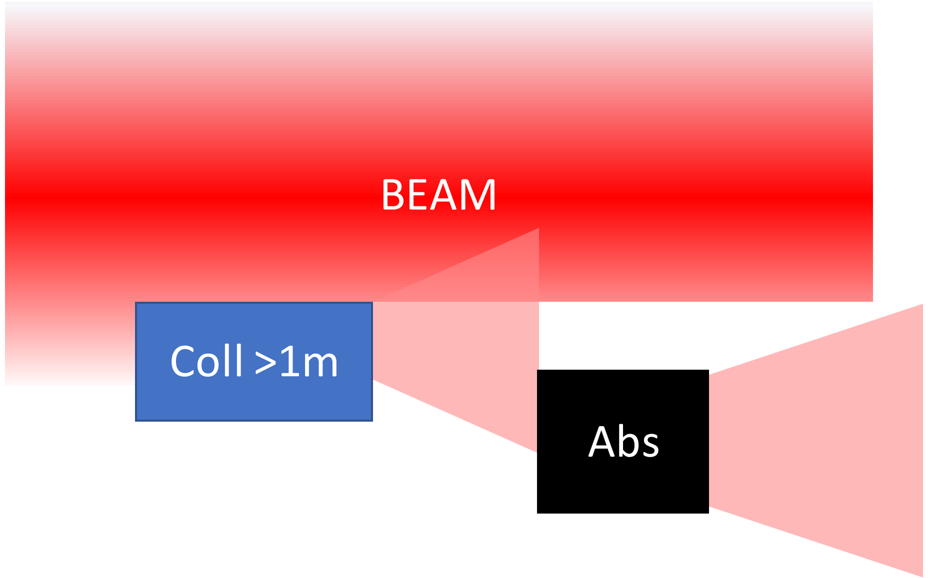
INFN has already produced several crystals deflector in both **Silicon** and **Germanium** exploiting several coherent effects (channeling, volume reflection, mirroring) tested at CERN, SLAC, IHEP and MAMI.

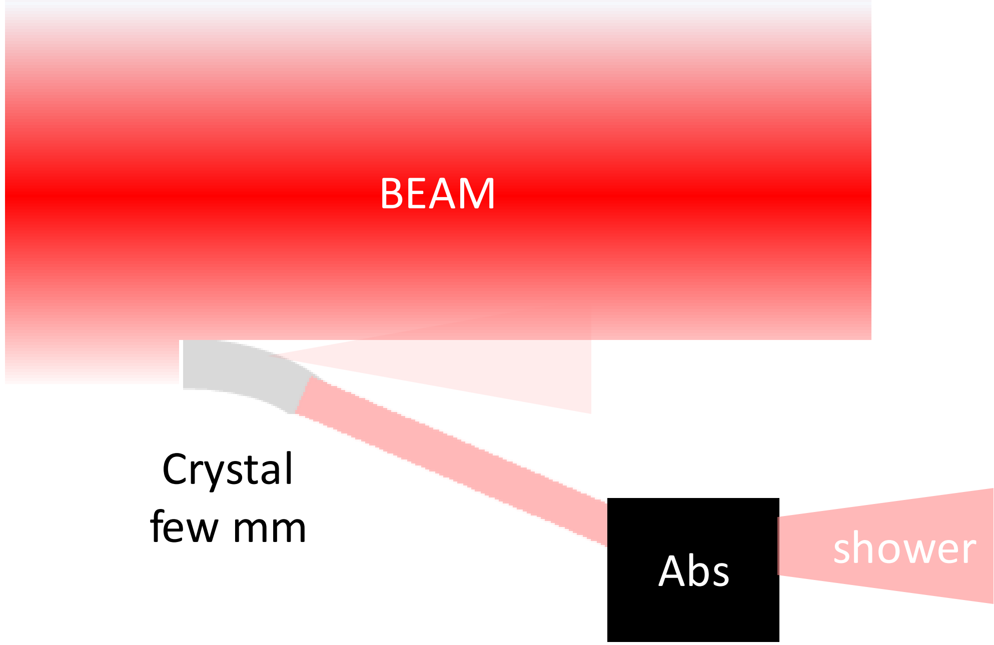
Produced crystal for two ERC project (Crysbeam & Seldom)

Those collaborations involved a wide range of experiment employing both positive and negative charged particles at energies from 2 MeV to 6.5 TeV

Crystal collimation at LHC

- Unavoidably particles diverge from desired trajectory and form **a halo around beam**
- Traditional approach stops the halo with a series of amorphous absorber
- Cons: development of showers in collimators





- Channeled particles in bent crystal while being steered avoid strong scattering: shower development strongly suppressed
- High efficiency in removing halo from beam in controlled manner

Requirements for LHC collimation crystals

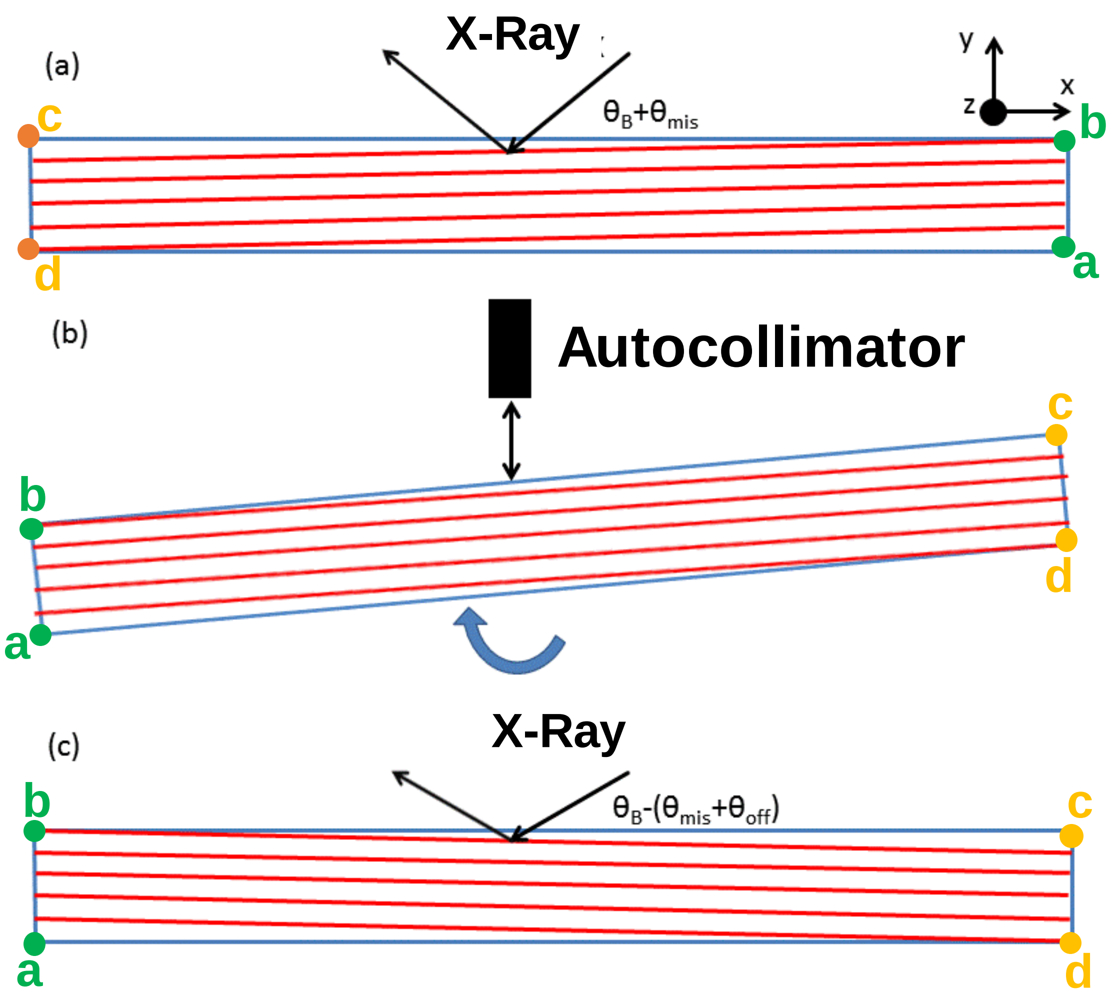
1. Miscut <10 µrad along beam direction
2. In LHC beampipe only few selected material are allowed: Ti gr V was selected for holder
3. Maximization of channeling efficiency to suppress particle loss
4. Deflection 50±2.5 µrad for best performance in LHC machine
5. Torsion < 1µrad/mm to maximize angular acceptance
6. Bake-out thermal process takes place in LHC beampipe

1. Best result in semiconductor industry is 175 µrad (standard 8700 µrad)
2. Poor features for precision machining. Dedicated R&D was carried out.
3. Low dislocation ($<1/cm^2$). Bending radius (80 m): vertical deformation range only 200 nm along 4mm
4. Shape error allowed is 10nm over area of $4x20\ mm^2$
5. Less than 1nm/mm slope along transverse direction
6. Assembly (Ti holder+Si crystal) must be stable after >200°C variation

Sample Production: wafer preparation

- Wafer quality control (before and after processes)
- Measurement of wafer miscut
- Reduction of wafer miscut

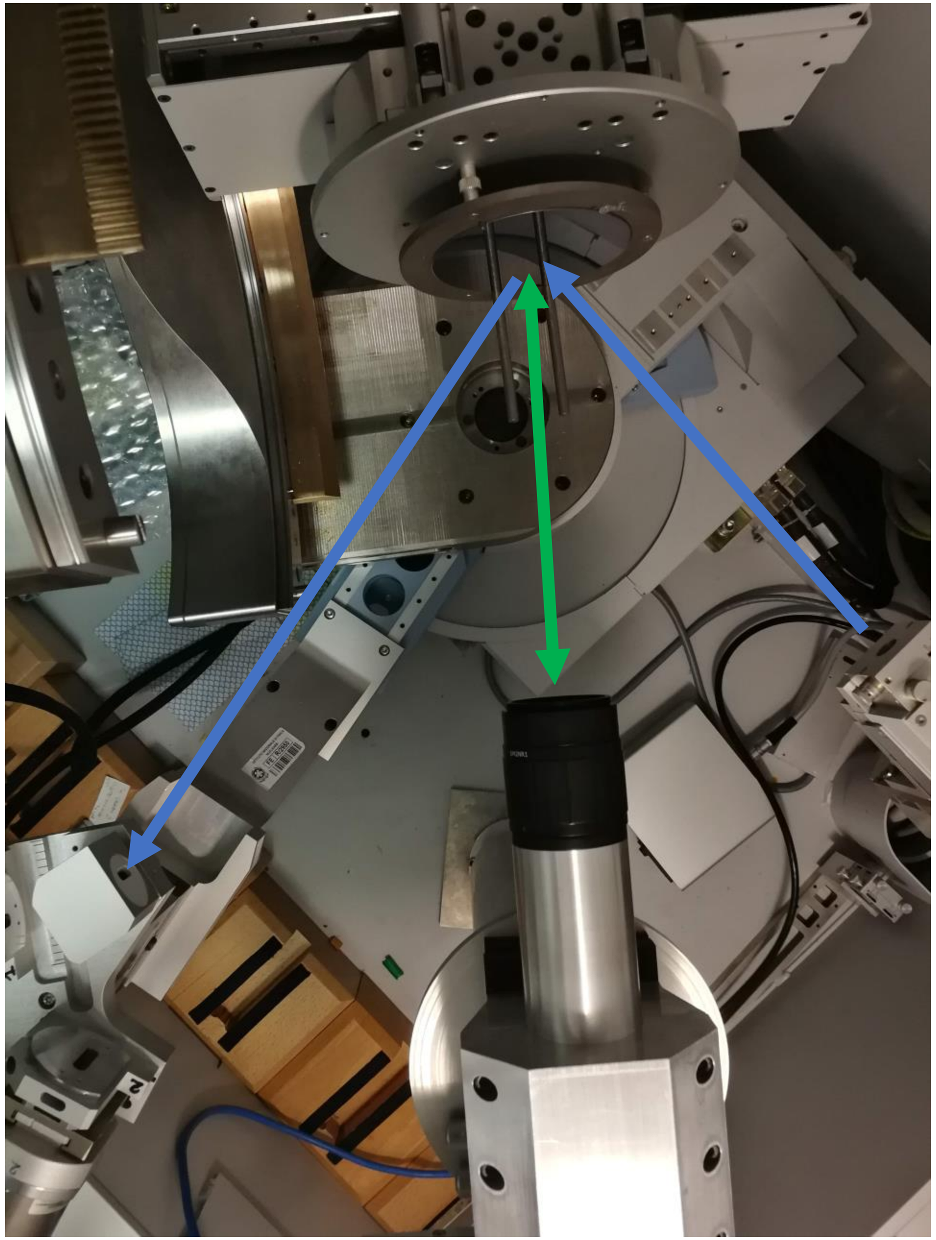
Miscut measurement



Accuracy 1.7 µrad

- Crystal mounted on XRD and oriented diffraction alignment
- Crystal rotated of 180° around y-axis. Bragg reflection lost due to
  - Crystal off-axis
  - Mechanical imprecision during rotation
- Movement compensated through laser autocollimator.
- Bragg reflection found again and miscut determined.

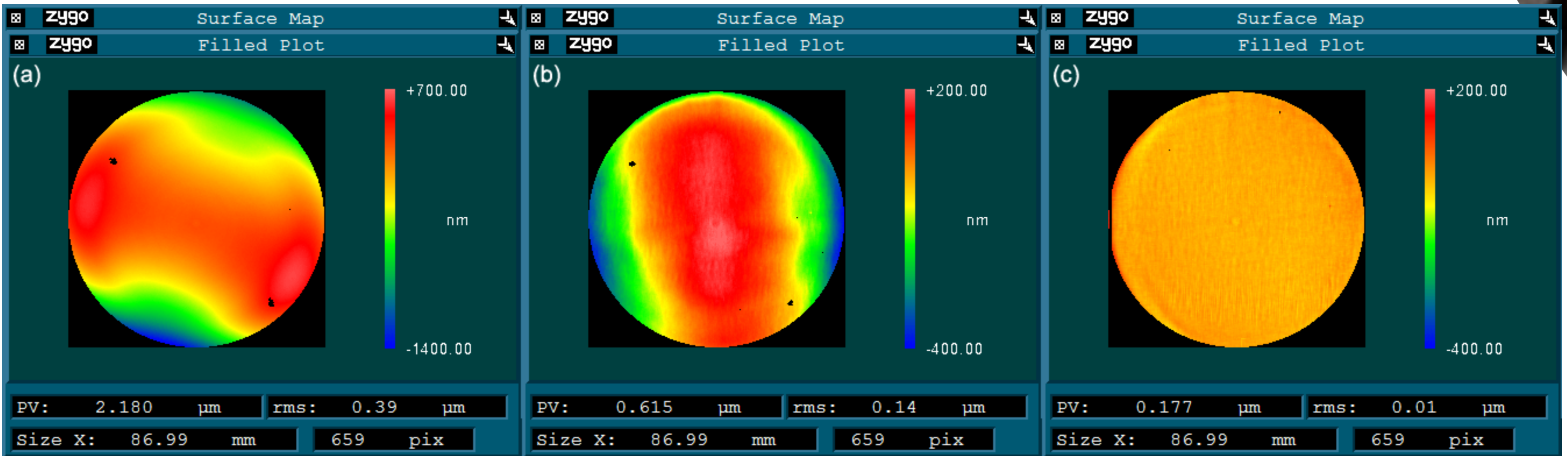
Set-up



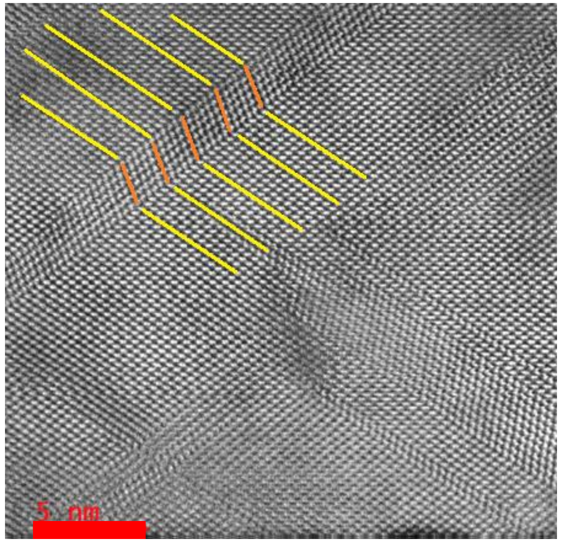
Miscut reduction

In order to correct the miscut, material must be removed from the crystal along precise direction with precise gradient resolution (**≤ 1 nm/mm**)

Achieved miscut ≈2 µrad
Almost two order of magnitude lower than best result of semiconductor industry

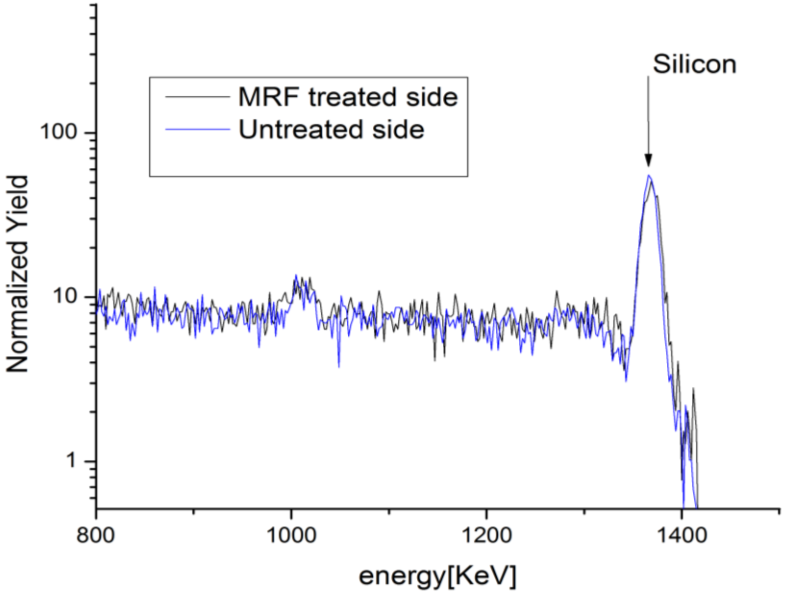


Wafer quality



- Dislocation cause local dechanneling and large area stress field
- Only best samples out of silicon and germanium wafer produced are selected

RBS measurement in channeling mode performed before and after MRF showed no sign of crystal degradation



Sample Production: crystal fabrication

Precise cut of sample with dicer

Removal of cut damaged area

Cleaning of sample

Sample cutting

Mechanical cutting with diamond dicing saw.

DISCO dicing saw DAD 3220 allows to perform cut with 0.001 mm lateral resolution and 0.01° angular resolution

Wafer up to 6inches and 5mm thickness can be cut

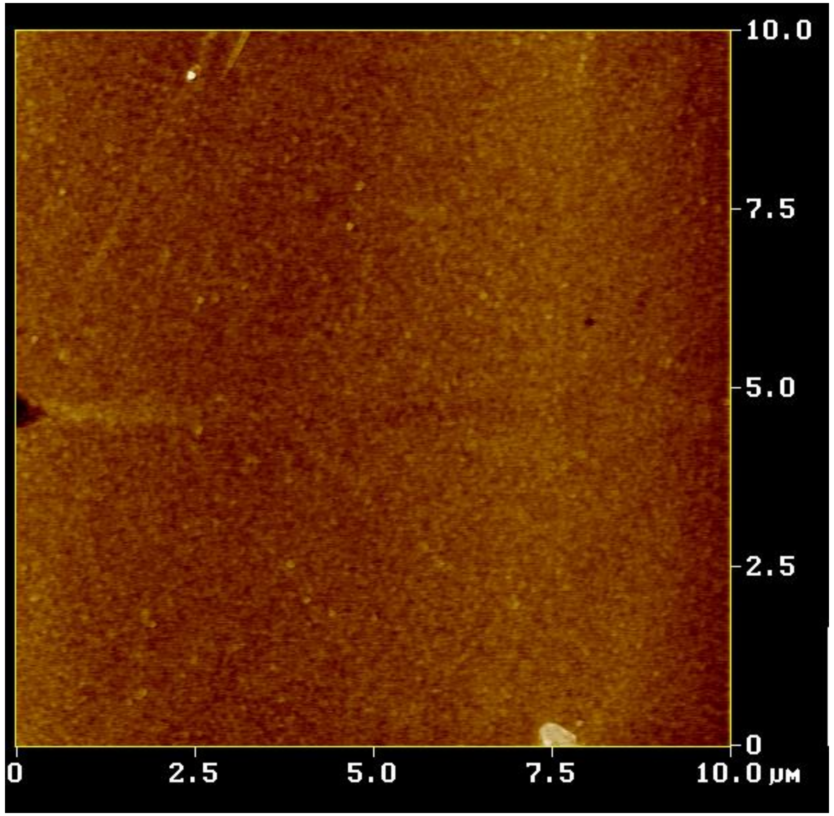
Cutting damage removal & sample cleaning

Chemical mechanical polish is performed on samples cut faces to remove damage for cutting

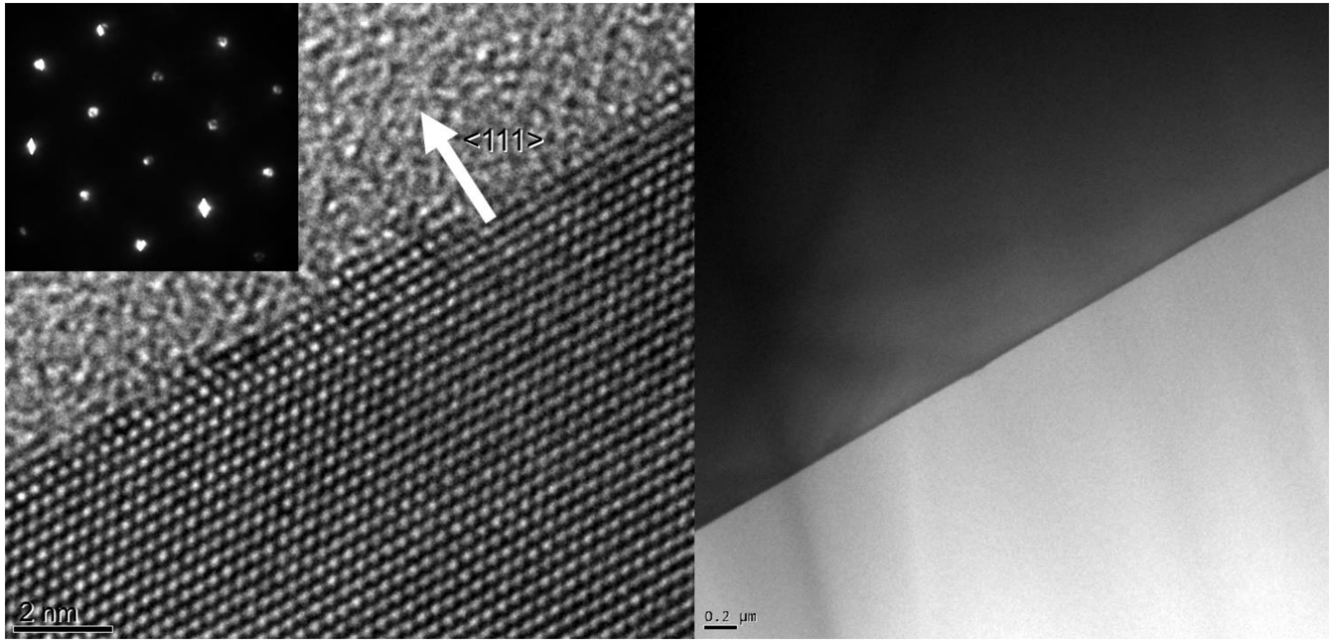
Finishing chemical wet etching and cleaning are performed in clean room ISO4 certified, in order to avoid contamination and dust particles.

The process of cleaning is performed in mega sound tank with filtered demineralized water and are dried with clean air flux.

Control of damage removal



- High Resolution transmission electron microscopy shows no amorphous layer
- AFM measured sub-nm roughness (0.2 nm)



Sample Production: bending & characterization

2D: imaging of the sample surface shape by optical interfermetry

1D: direct measurement of plane curvature along one direction using x-ray diffraction

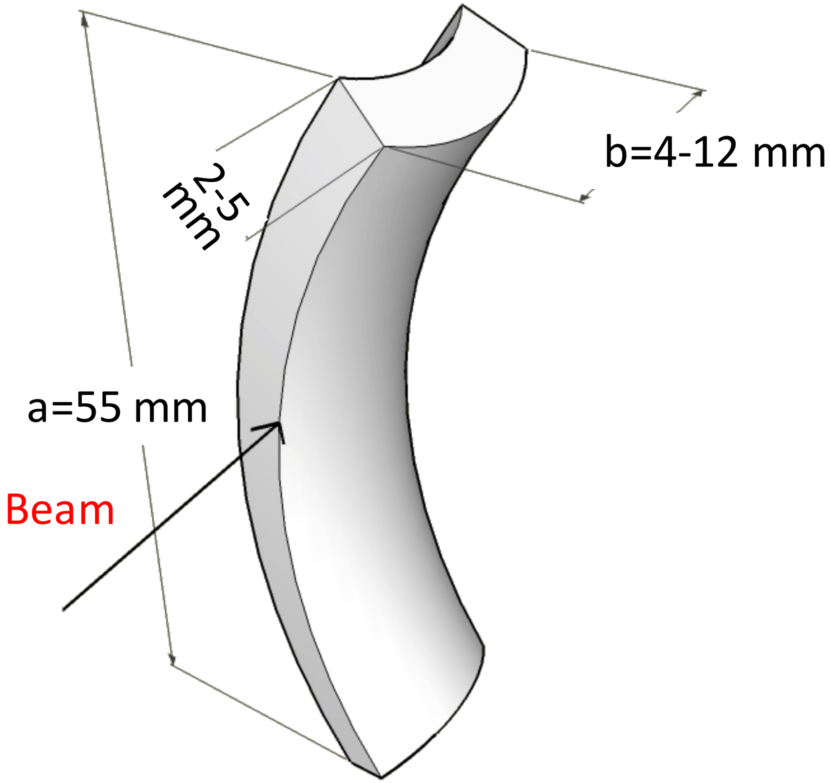
Verification of thermal stability after bake-out cycle

Elastic theory for crystal bending

- Anticlastic curvature is an elastic reaction from bending momentum, perpendicular direction and opposite sign. Available for every crystal orientation →(110) selected

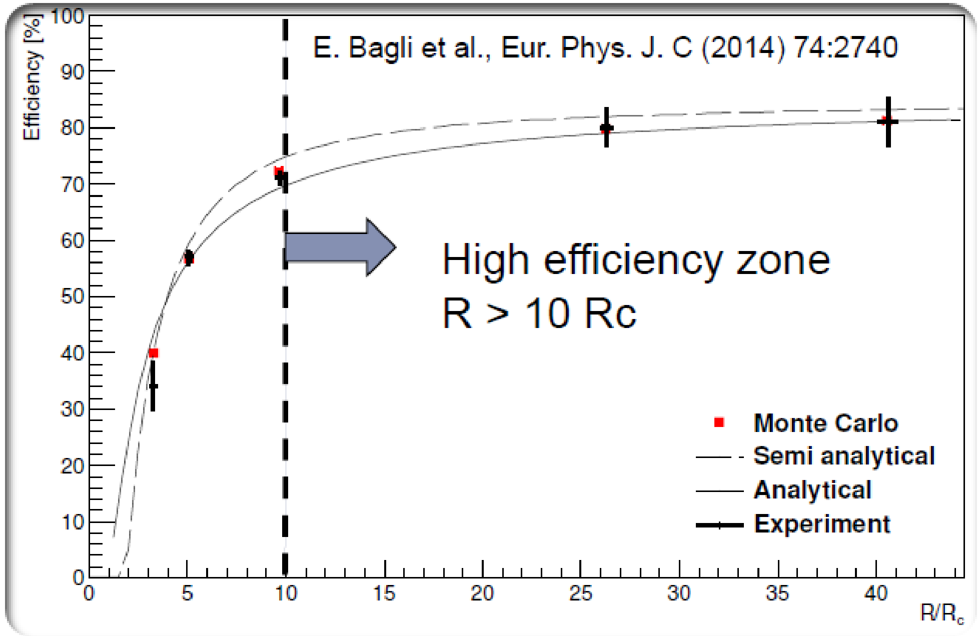
- Anticlastic curvature lower than primary one by Poisson ratio factor →**enhanced control** over anticlastic deformation by acting on primary one

- Effect limited for short anticlastic length wrt primary curvature length (not suitable for curvature several cm long)



Bending radius homogeneity

- High efficiency deflection for radius > 10 critical value
- To maximize channeling efficiency and minimize crystal length, radius value at beginning of high efficiency plateau was selected
- curvature must be controlled: local increase of curvature could decrease deflection efficiency



Interferometric characterizations

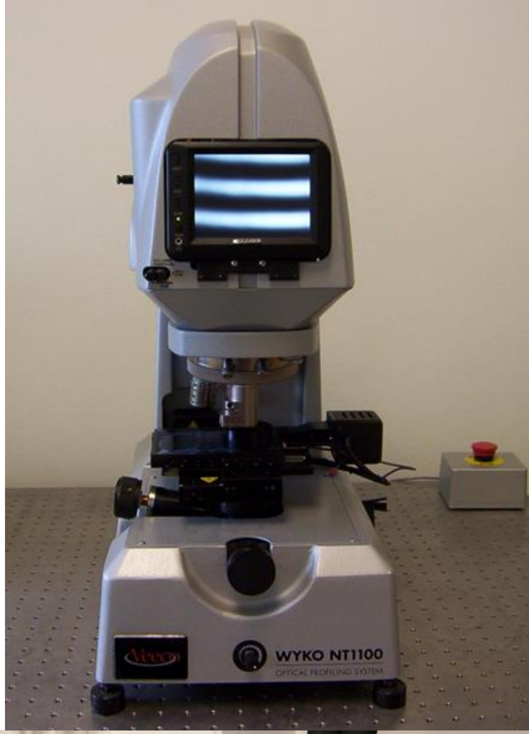
- Optical interferometry performs fast characterization with **sub-nanometric** vertical resolution

- Curvature can be calculated from surface shape

- Two instrument:

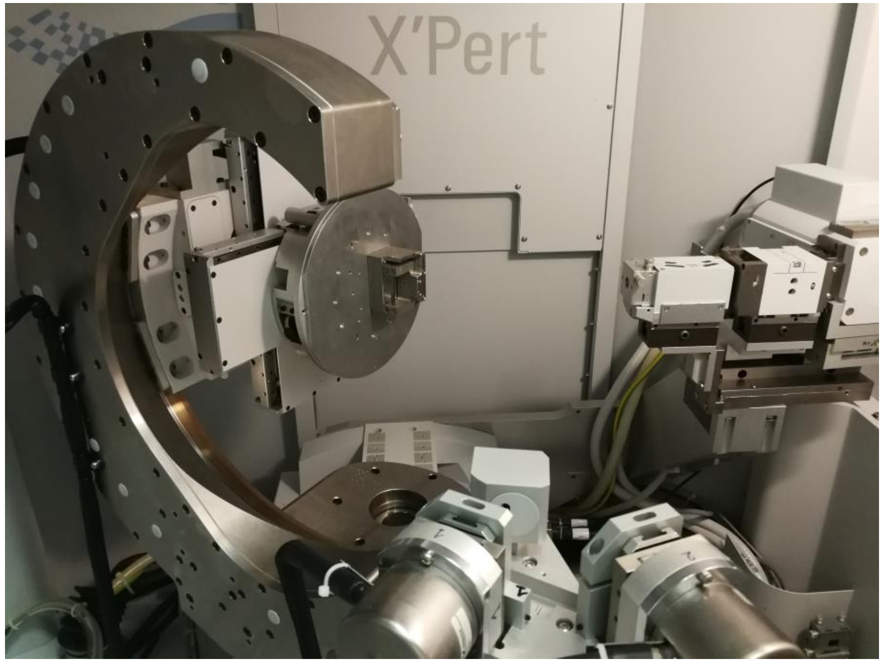
  1. White light interferometer weeko NT1100: narrow field of view (max 4x4 mm^2), large magnification (up to 100x)

  2. Laser interferometer Zygo Verifire HDX: large field of view (150 ø mm), max lateral resolution 0.044mm

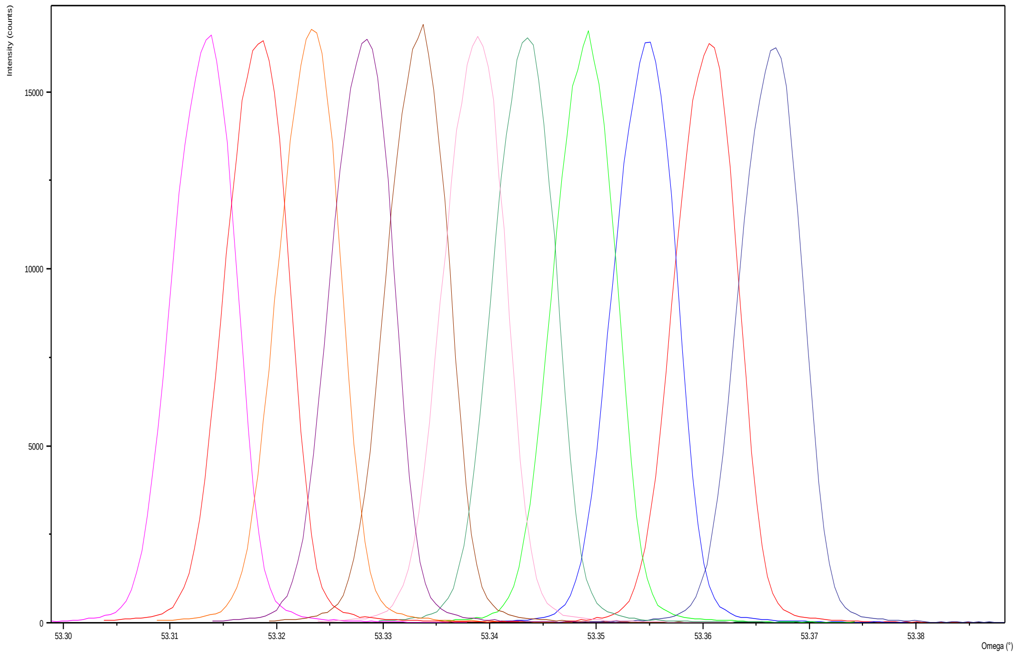


X-Ray characterization @ Ferrara

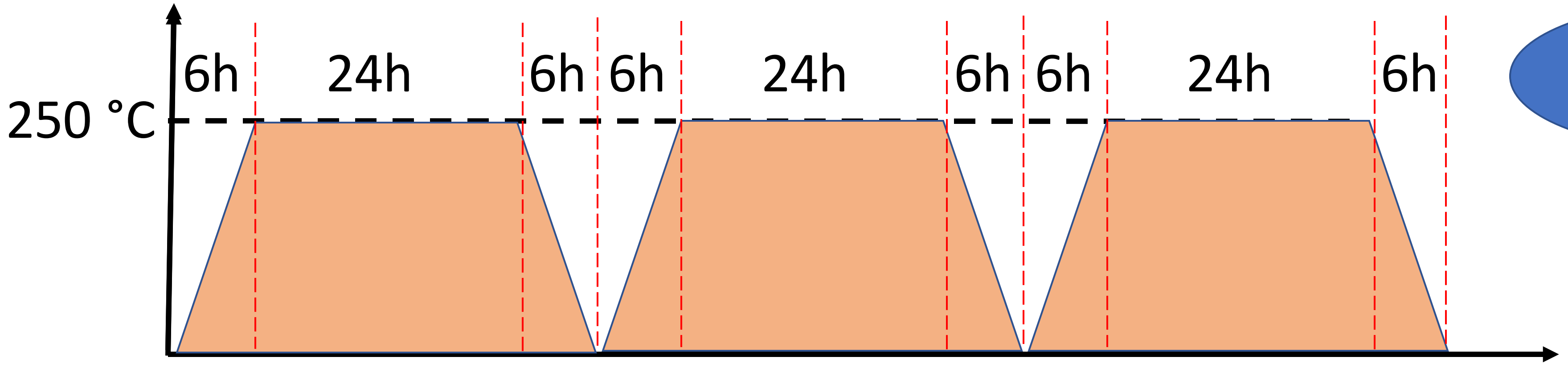
HRXRD with monochromatic 8.14 KeV beam (Cu $K\alpha_1$).
7 axis handling. Goniometer with angular resolution 1.7 μrad



RCs are acquired along a direction, the angular shift corresponds to the tilt of crystal plane

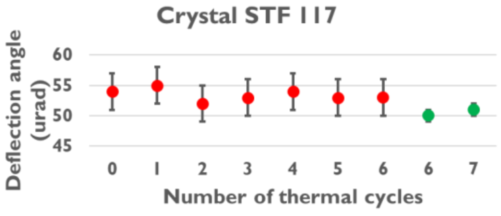


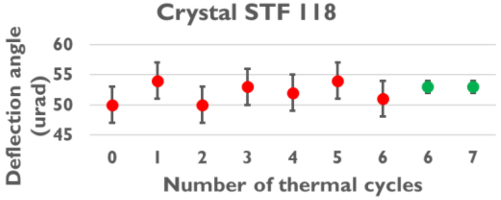
Samples	High resolution x-ray diffraction	Channeling	Consistency
STF47	33±2	35±2	YES
STF48	144±2	142±2	YES
STF49	247±3	246±2	YES
STF50	142±5	143±2	YES
STF51	33±2	33±2	YES
STF70	56±2	55±2	YES
STF71	60±5	62±2	YES
STF99	119±3	120±2	YES
STF100	67±6	63±2	YES
STF101	170±6	165±2	YES
STF102	45±3	42±2	YES
STF103	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

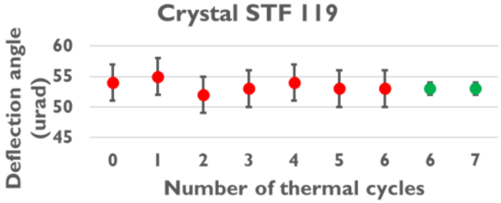


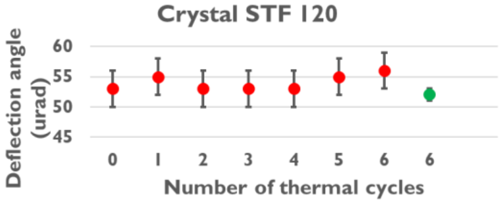
10^{-6} mbar

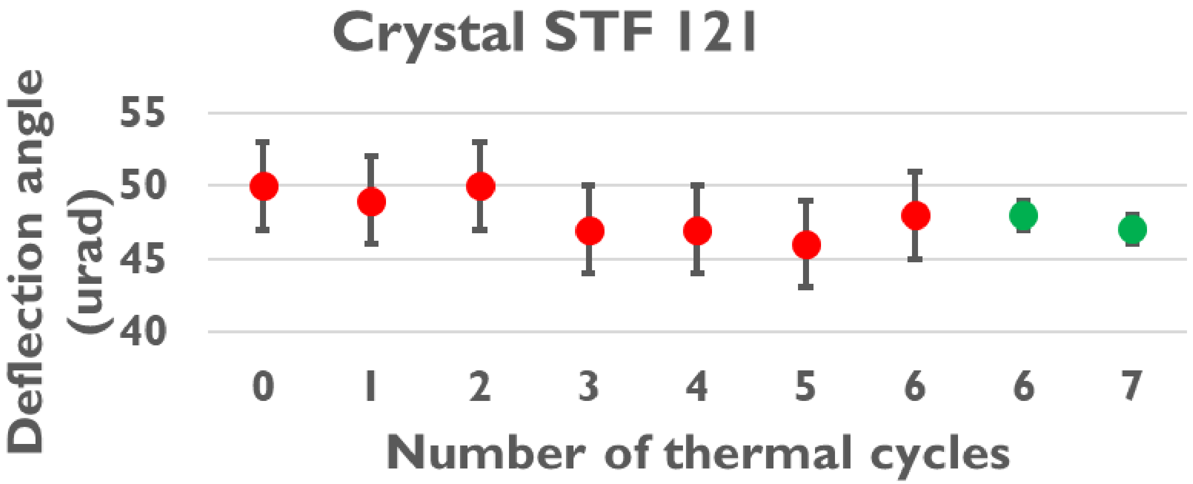
Although different expansion coefficient, crystal and holder maintain perfect mounting within µm

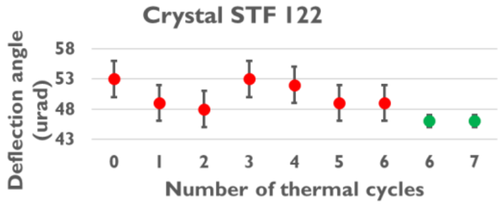


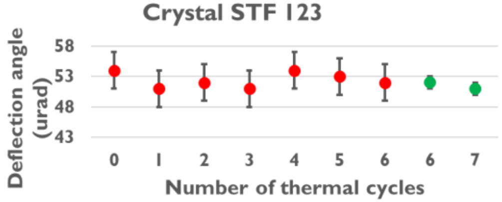


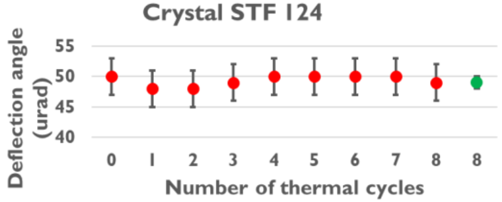


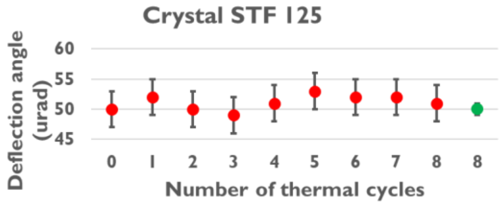


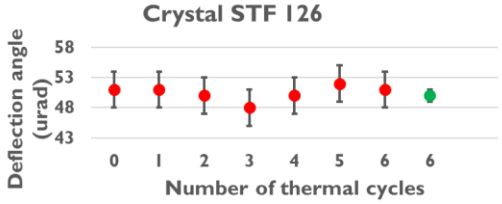






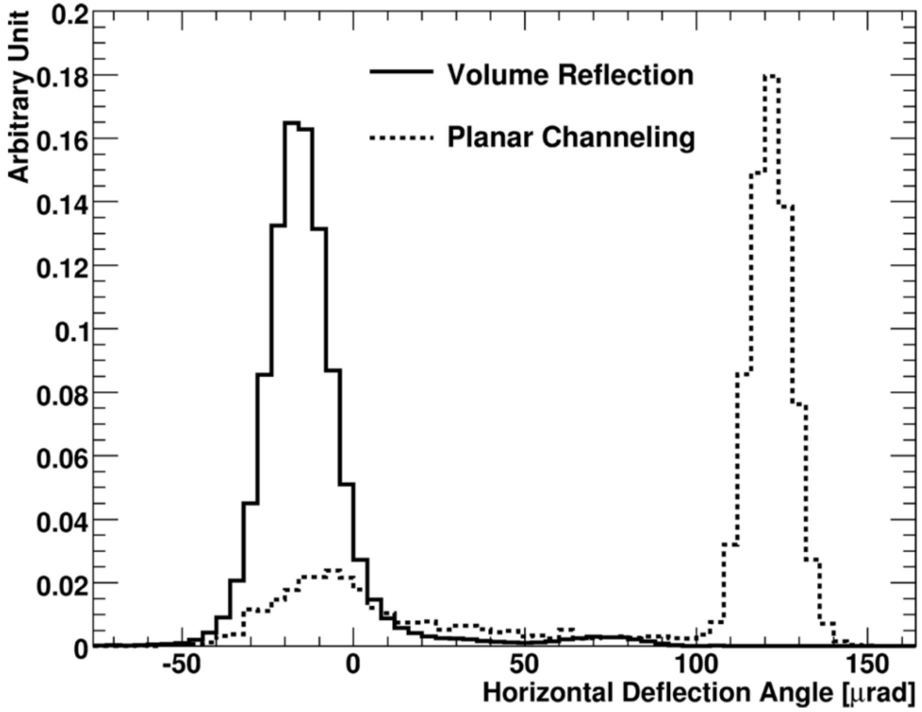


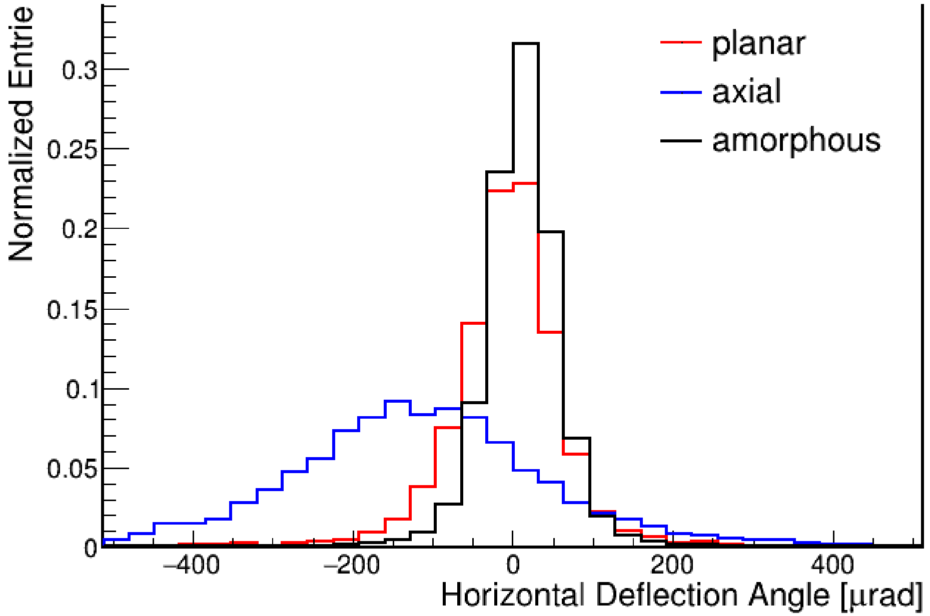




Germanium Crystals

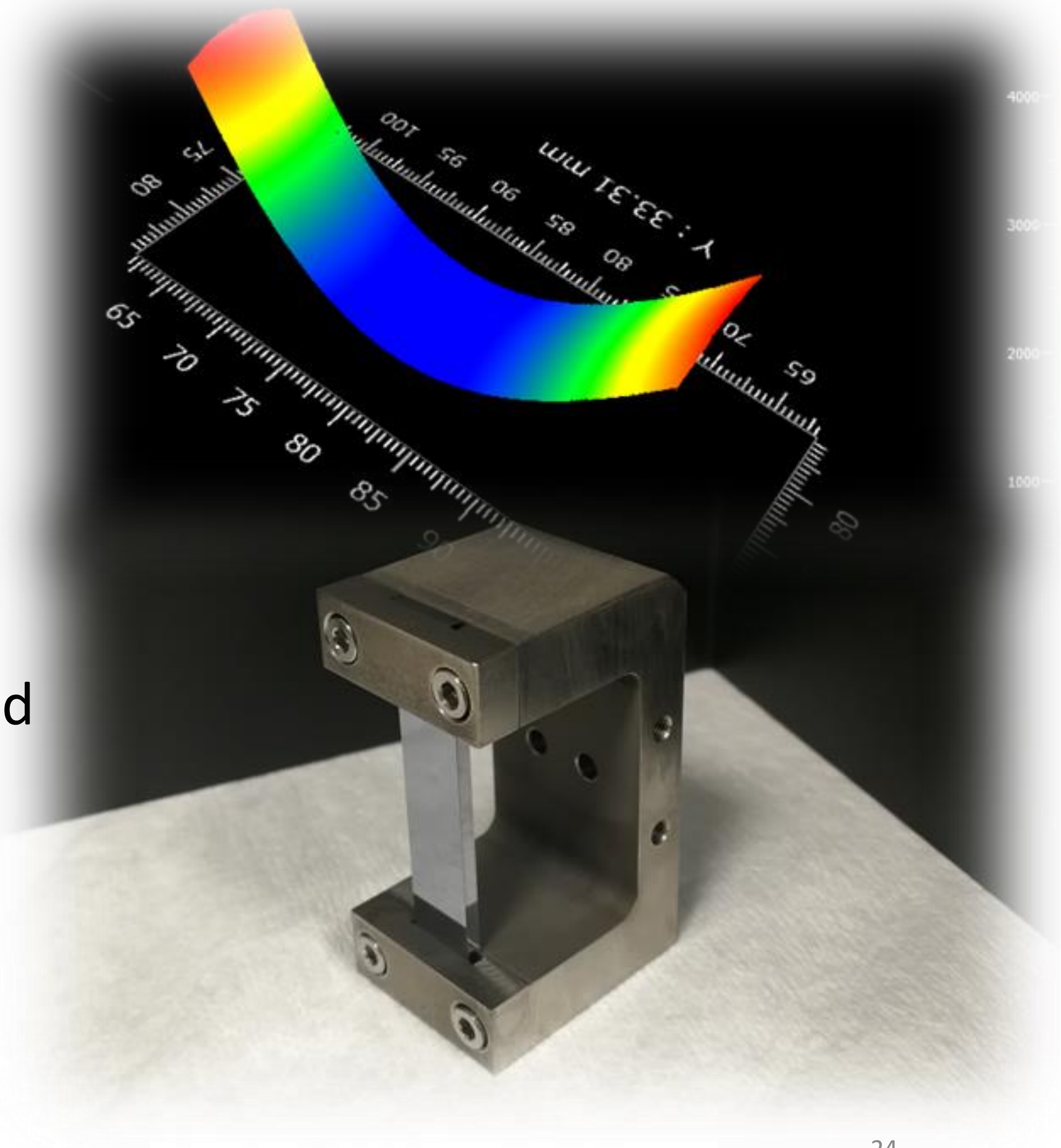
- Efficient channeling deflection was obtained with germanium crystal
- Germanium can be obtained with high level of lattice perfection (only one provider up to now, x10 cost wrt Si)
- Germanium has same crystal structure as silicon (diamond like FCC), but have deeper potential **higher channeling efficiency**
- Use of Germanium required special procedure for cut damage removal and careful handling of sample in every step of the production process





Crystal for beam extraction

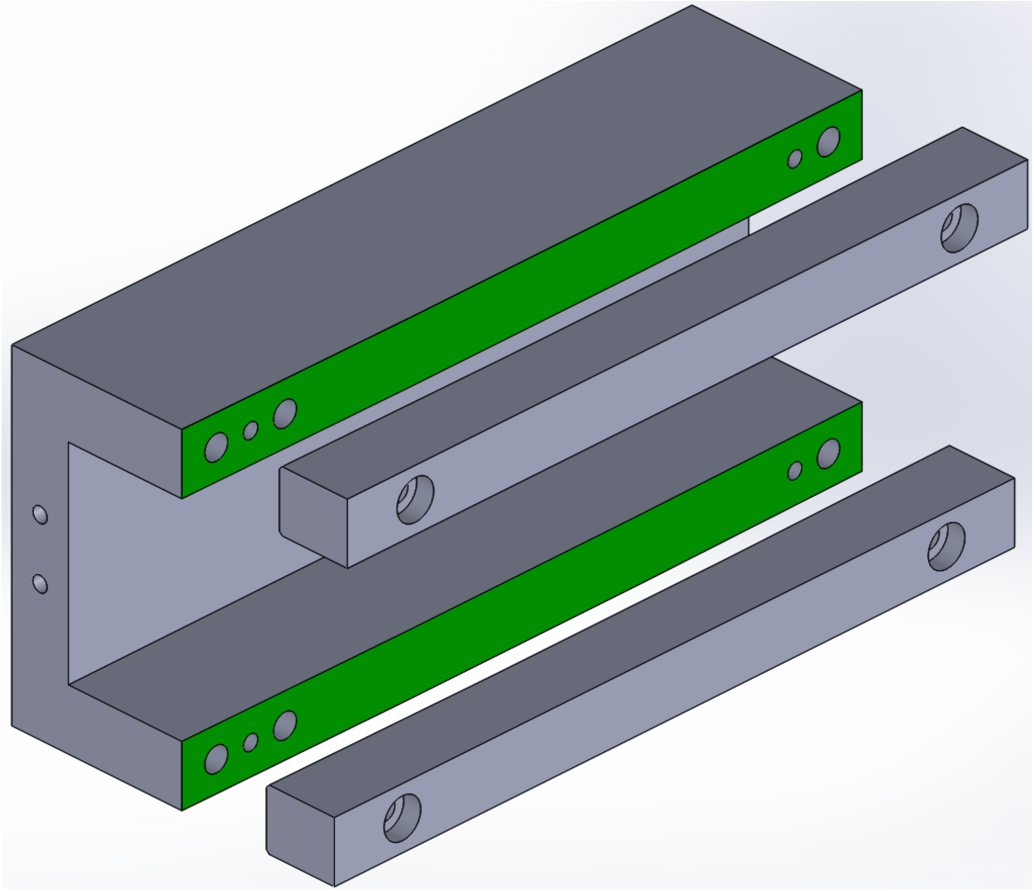
- Particles deflected by channeling form a well collimated beam along precise direction
- Deflected beam instead of being absorbed can be exploited
- Larger angular kick than for simple collimation: 150 µrad →**adaptation from collimation scheme possible**



Holder for MDM & EDM precession

- 80 cm length along the beam makes impossible anticlastic curvature approach: **only primary curvature** possible
- Challenge: controlled curvature over sample with **x20 size** wrt LHC crystals.

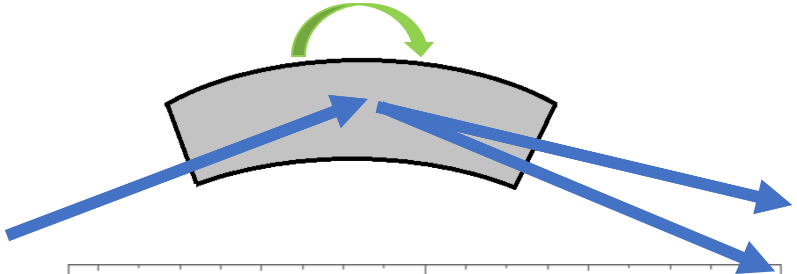
- No intrinsic limit on maximum curvature or maximum thickness (within material elastic limit). **5mm** thick sample already produced
- Can be easily employed with different material (i.e. Germanium)

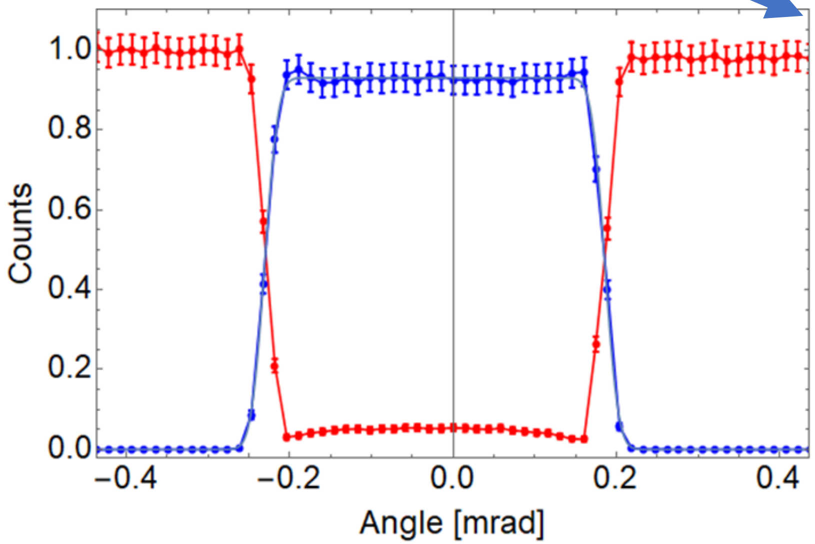


X-Ray characterization @ external facilities

ESRF beamline ID11 provides high intensity monochromatic x-ray **microbeam**. Energy range from few tens KeV up to 140 KeV.

Measuring angular spread of a RC diffracting thought bent plane. Curvature acquired in a single measurement





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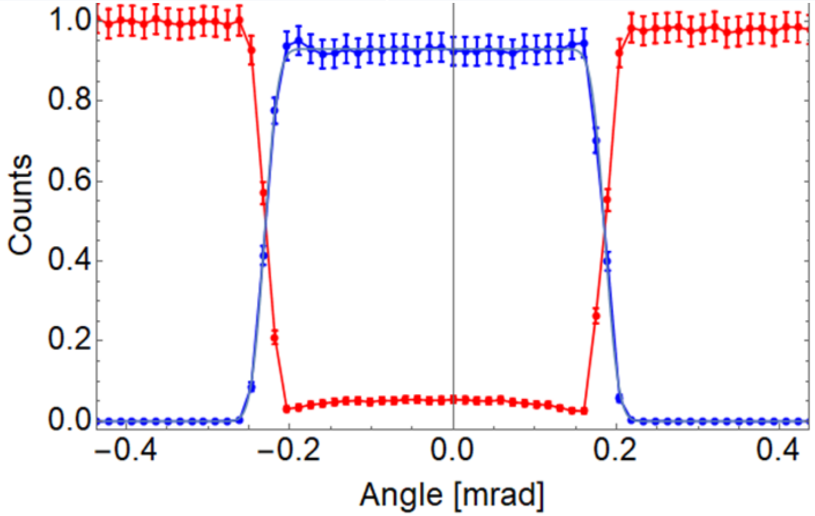
Deflection ESRF	Defection HRXRD
1570±10 µrad	1550±20µrad
420±10 µrad	430±10µrad



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180 GeV π^+ : 419±2 μrad

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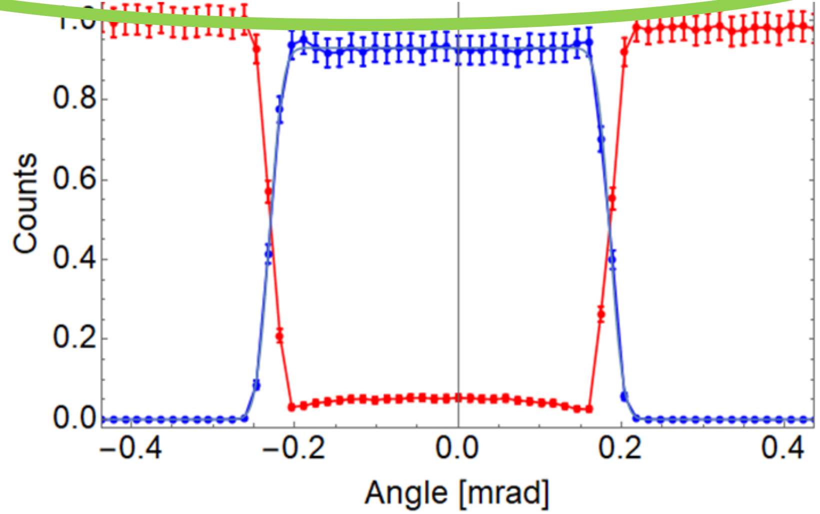
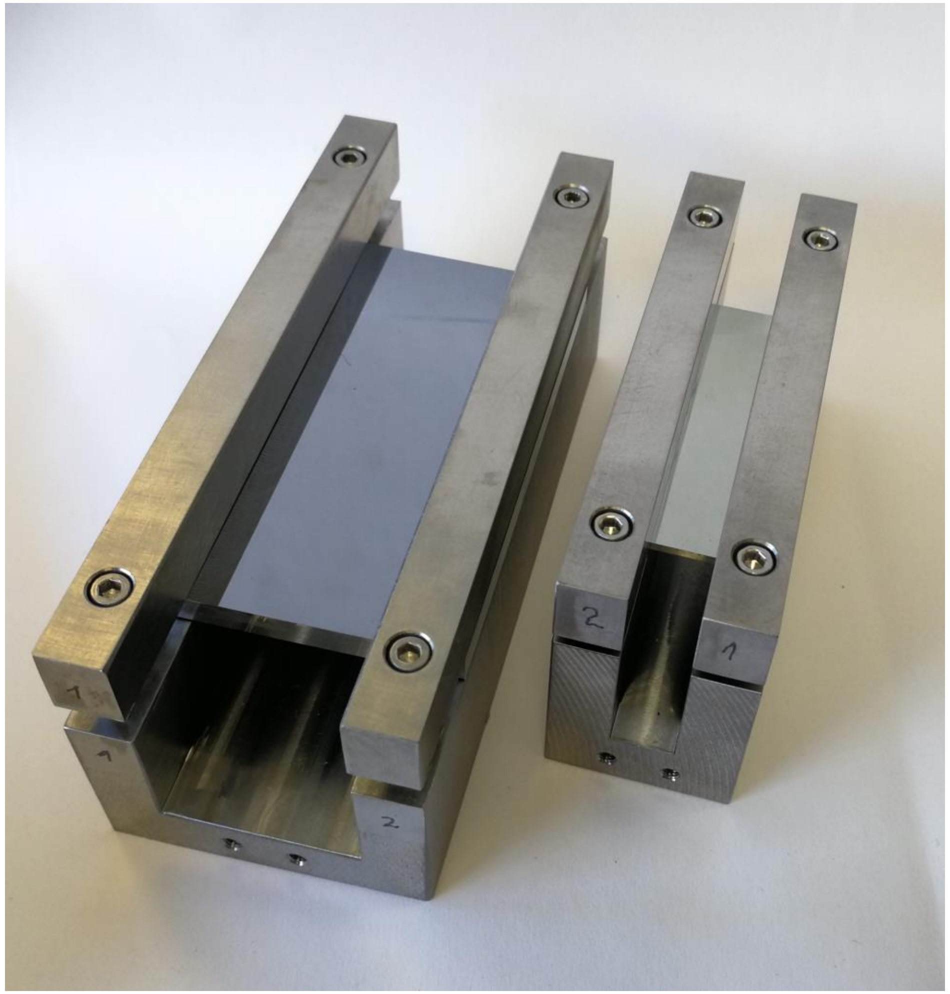


Sample produced

#sample	Deflection (HRXDR)	Spin precession Λ_c^+	Spin precession Ξ^+
1	11.53 mrad	-1.51 rad	16.72 rad
2	15.93 mrad	-2.09 rad	23.10 rad
3	11.66 mrad	-1.53 rad	16.91 rad
4	14.35 mrad	-1.88 rad	20.81rad
5	13.74 mrad	-1.80 rad	19.93 rad
6	13.95 mrad	-1.83 rad	20.23 rad
7	12.26 mrad	-1.61 rad	17.78 rad
8	15.83 mrad	-2.08 rad	22.96 rad
9	14.90 mrad	-1.96 rad	21.61 rad



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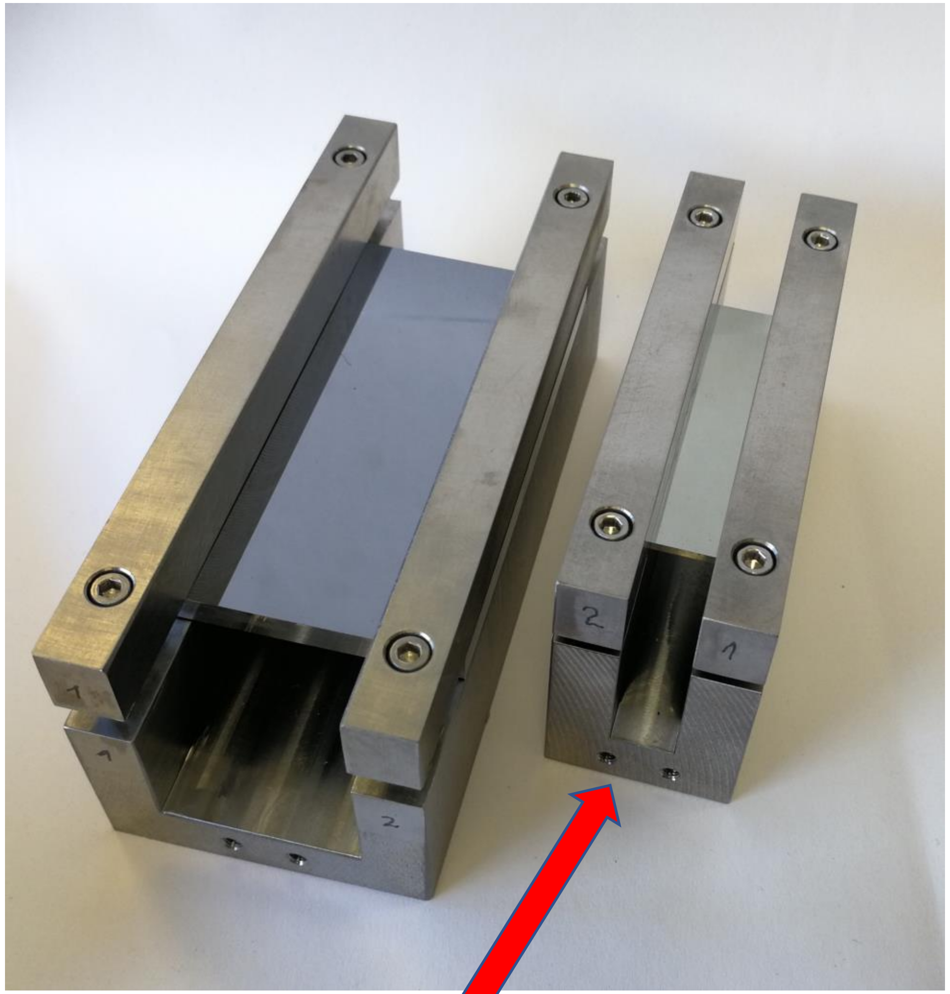

Germanium crystal prototype!!

Conclusion

High control over miscut achieved by combination of ultra-precise finishing techniques and x-ray diffractometry aided by laser autocollimator: **up to almost two order of magnitude** better than semiconductor industry best result (>4000 wrt standard)

Bent crystal shape is controlled with interferometry and x-ray, **nanometric scale precision** geometry in macroscopic object (10^5 larger!!!) reached

Mechanical holder tested to **withstand LHC vacuum environment and bake-out** have been successfully produced

First prototypes of long crystal for spin precession produced, state of art INFN know-how in crystal bending solid base for future development

Employ of Germanium crystal for highly efficient ultrarelativistic particle channeling deflection: **exclusive of INFN**

Thank you for your attention!