Bent crystals for large angle deflection of TeV particle beams

Speaker: M. Romagnoni

A. Mazzolari , L. Bandiera, R. Camattari, V. Guidi, G. Cavoto , E. Bagli, D. Casotti, A. Sytov

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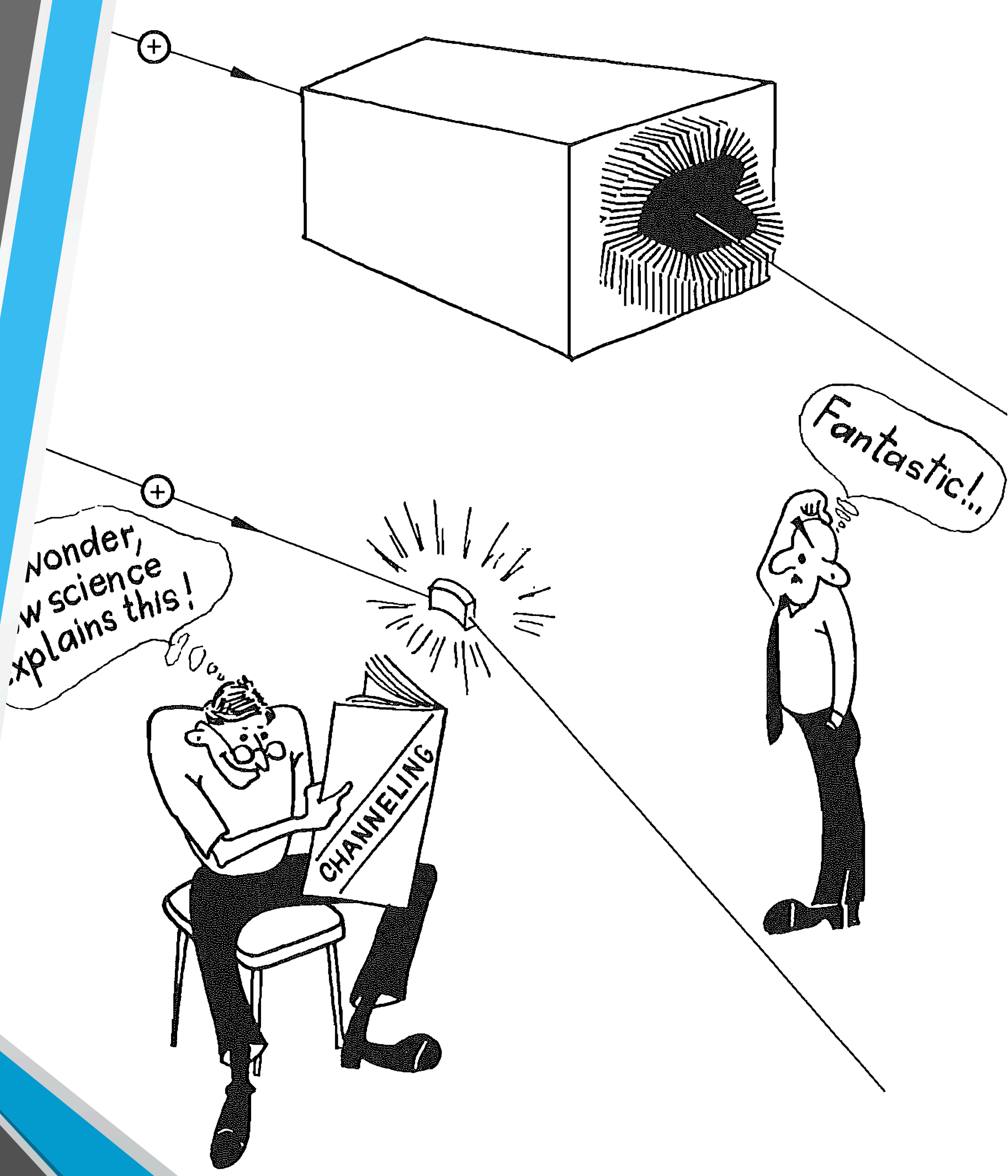
Beam deflection via channeling

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

Sample code	B_{eq} [T]	Deflection angle	Thickness along the beam
PL05	590	1.5 mrad	55
PL07	160	420 µrad	55
Prototypes Holder	500-670	11.5-16mrad	80



Crystal deflectors already produced in Ferrara

INFN has already produce several crystals deflector exploiting coherent effects (such as channeling volume reflection and mirroring) at a range of energy with collaboration with research team at CERN, SLAC and IHEP.

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

Future possibilities:

LHC 6.5 TeV beam extraction (Crysbeam)

- Beam energy: 6.5 TeV
- Deflection angle: 1 mrad
- Radius of curvature: ~100 m

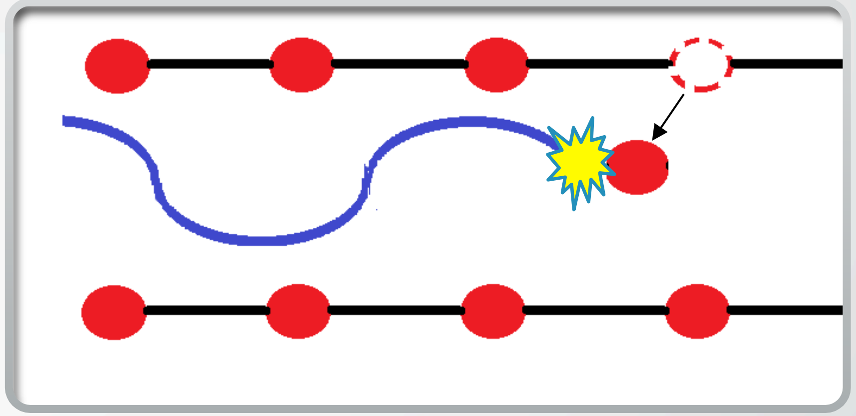
Heavy baryon EDM & MDM studies (SELDOM)

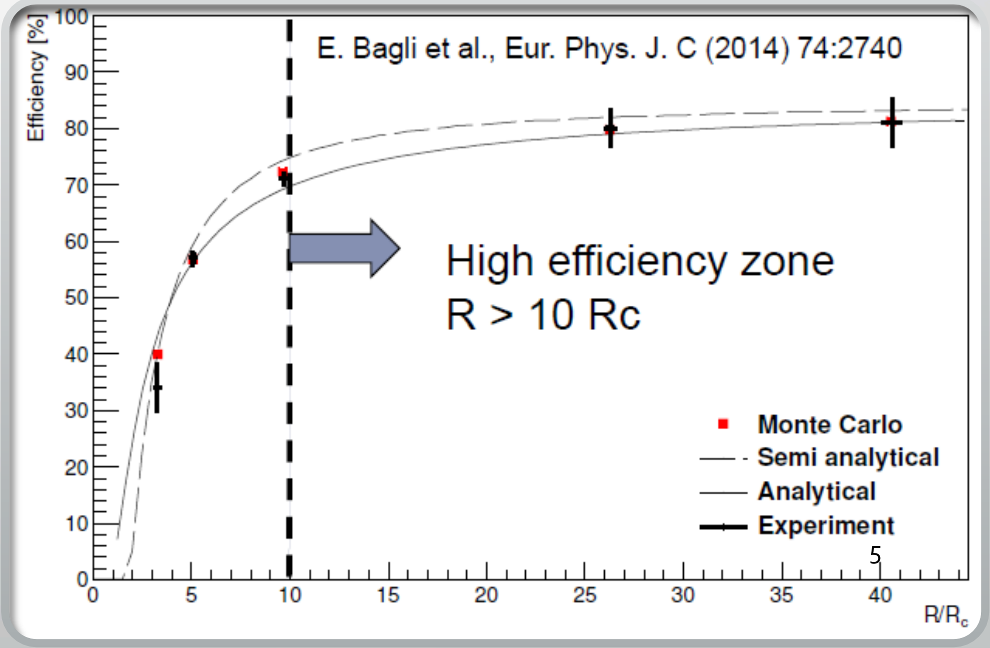
- Beam energy ~1 TeV
- Deflection angle 13-16 mrad
- Maximum length ~8 cm (quick particle decay)

Novel prototypes crystal deflector

- High crystalline quality
- To increase channeling efficiency the radius of curvature should be as large as possible
- High precision and control of the crystal shape along all the trajectory

- Only Si or Ge crystal should be used
- The thickness along the beam is several cm, hence secondary curvatures can no longer be employed efficiently
- Processes of preparation must follow strict condition



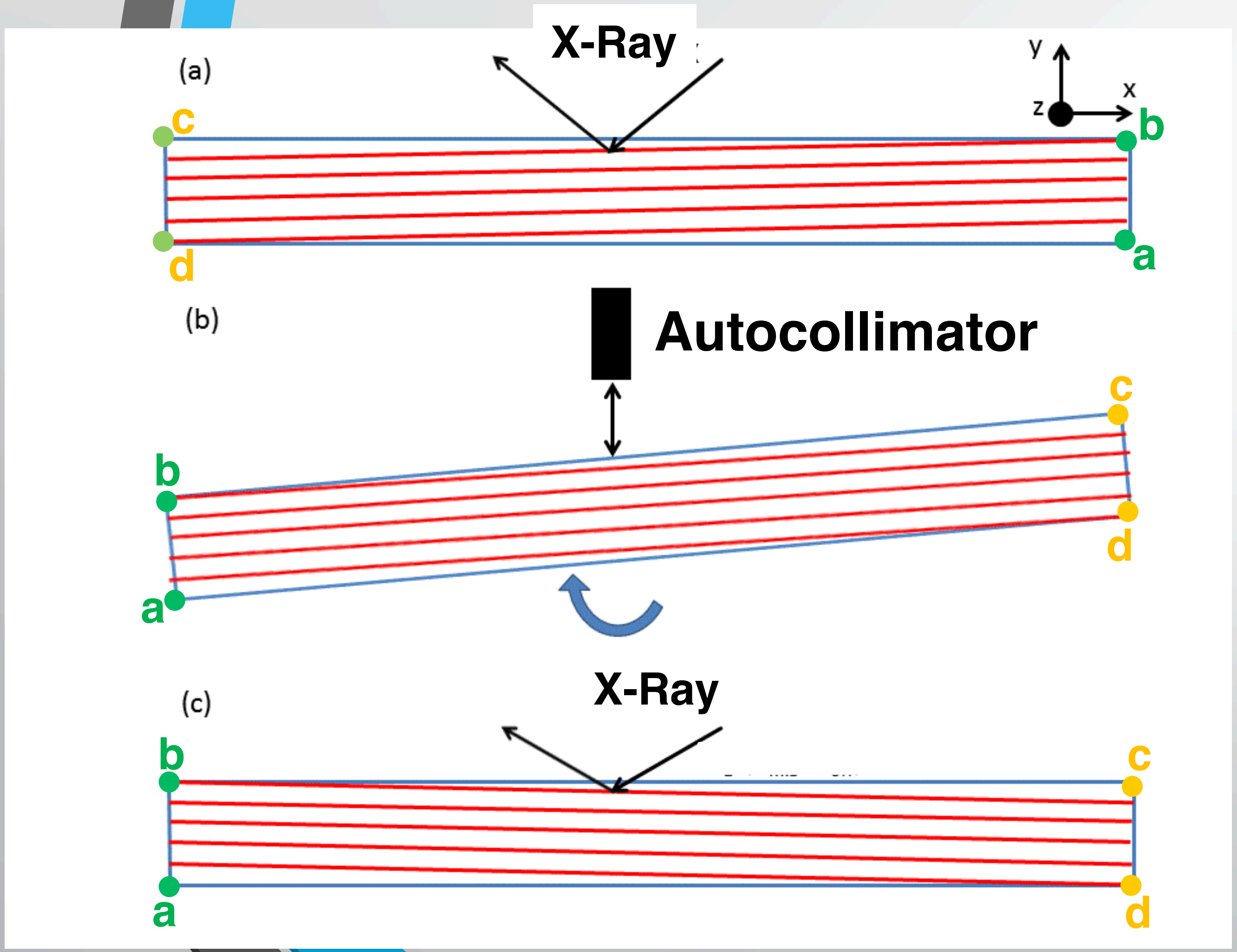


Sample Production

Sample production requires a series of step :

- Measure of wafer miscut
- Reduction of wafer miscut
- Precise cut of sample with dicer
- Removal of cut damaged area
- Cleaning of sample
- Mounting of the sample in clean condition (if a holder is needed)
- Precise characterization of the curvature obtained

Miscut measure

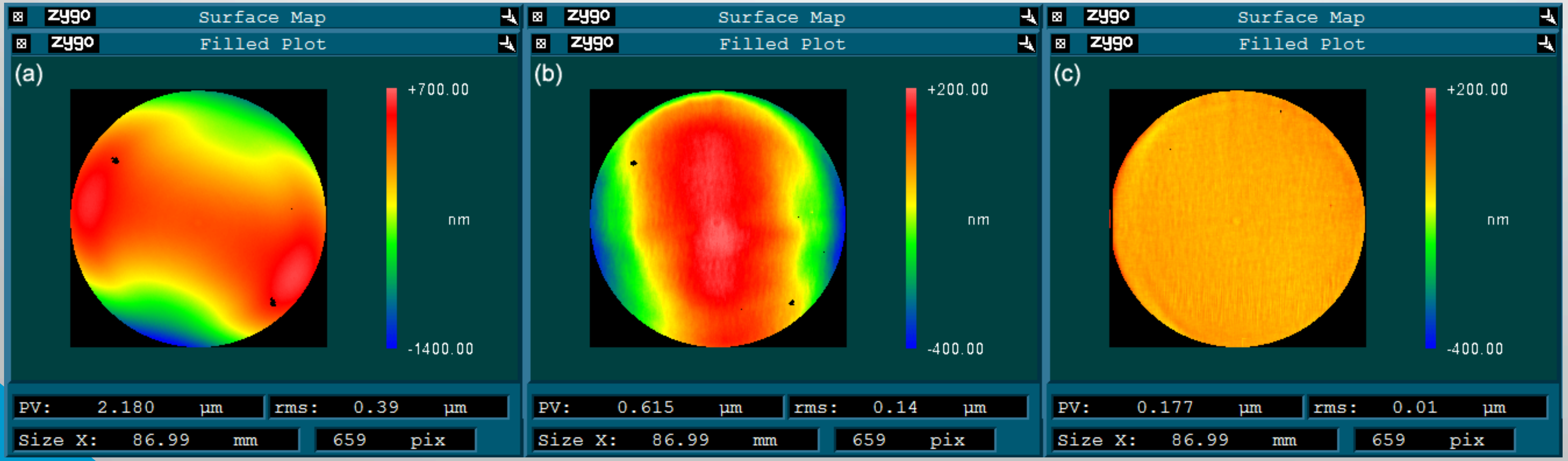


- Crystal mounted on HRXRD and oriented in order to excite Bragg reflection
- Crystal rotated of 180°around y- axis. Bragg reflection lost due to
  - Crystal off-axis
  - Rotational stage mechanical plays
- Mechanical plays compensated through autocollimator.
- Bragg reflection found again and miscut determined.
- **Accuracy: ~2 μrad!!**

Miscut reduction

In order to correct the miscut, material must be removed from the crystal along precise direction with a precise gradient (≤ 1 nm/mm) resolution and without damaging the lattice:

- Magneto-rheologic
- Ion polishing



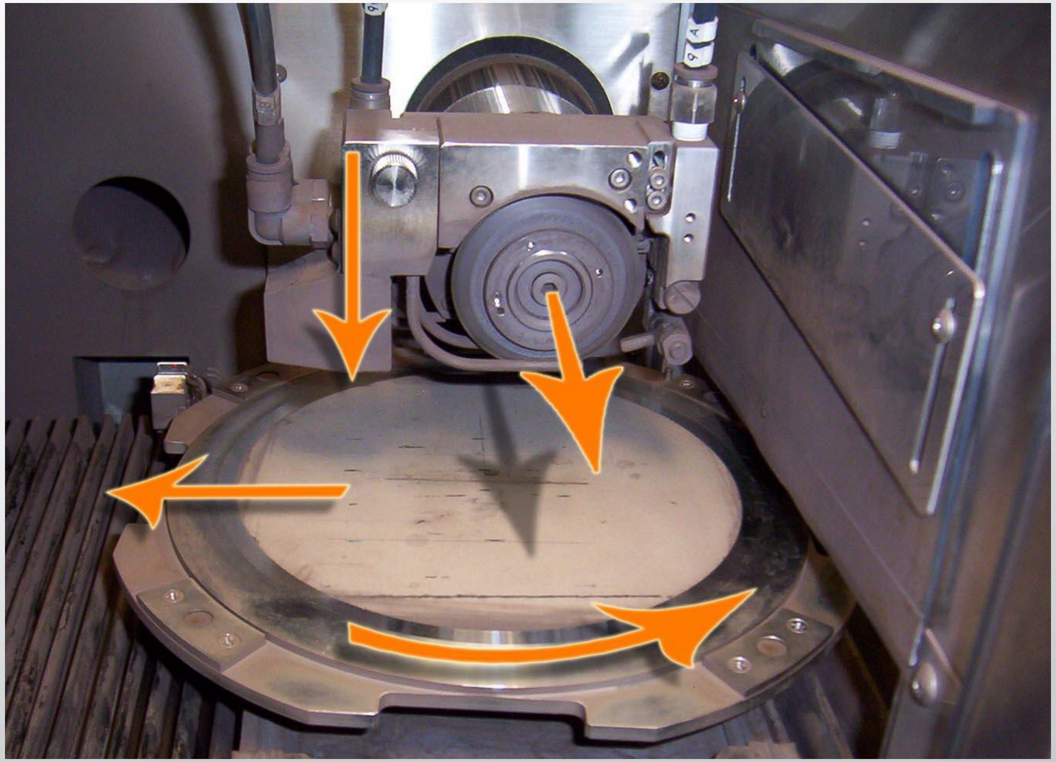
Sample cutting

The sample with suitable shape must be cut from the wafer.

Cutting process is done by mechanical cutting with diamond dicing saw.

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

Wafer within 6inches and 5mm thickness can be cut



Lattice damage removal

The dicing saw cut allows to freely select any crystallographic orientation (or offset), but leaves a damaged layer of material in the material. This layer must be removed in order to achieve high channeling efficiency. This can be achieved

- By chemical etching on the surfaces: in which case the wafer surface must be protected with chemically resistance wax or by SiN deposition on the wafer prior the cut
- Lapping process

Cleaning procedure of the sample

The sample must be in high cleaned condition. This is extremely important in order to avoid unwanted effect in the final curvature of the sample.

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

The whole process is performed in clean room environment in order to avoid further dust contamination.

Characterization techniques

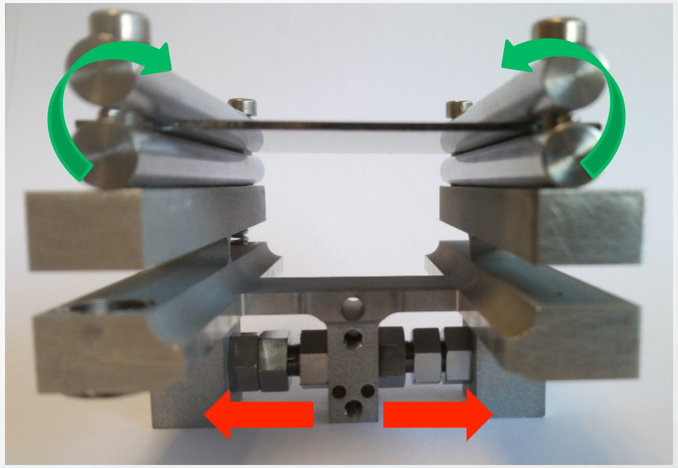
- Optical analysis of the surface shape with interferometer Veeco NT-1100 at Sensor and Semiconductor Laboratory in Ferrara
- Map of lattice curvature with HRXRD Panalytical XpertPro in Bragg configuration at Sensor and Semiconductor Laboratory in Ferrara
- Measure of curvature in the bulk by Rocking Curve of 140 keV x-rays in Laue configuration at ID11 beamline of ESRF.

Long crystal produced

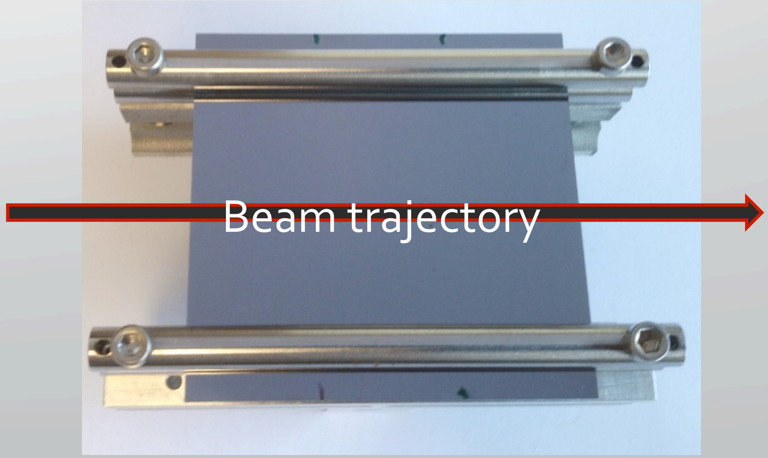
Code	Year of production	Bending method	Thickness along the beam [mm]	Crystal thickness [mm]	Bending angle [mrad]
PL01	2015	Adjustable Holder	20.0	0.5	0.28
PL02	2015	Adjustable Holder	28.8	0.5	0.29
PL02-b	2015	Adjustable Holder	23.8	0.5	1.83
PL03	2016	Adjustable Holder	56.8	1	0.32
PL04	2016	Nitride deposition	20	0.3	0.28
PL05	2016	Surface Plasticized	55	1	1.5
PL07	2017	Surface Plasticized	55	2	0.42
PL08	2017	Adjustable Holder	56.8	1	0.72
PL09	2017	Adjustable Holder	20	0.5	1.07
PL10-a	2017	Adjustable Holder	79.8	1	3.45
PL10-b	2017	Adjustable Holder	79.8	1	8.87
PL10-c	2018	Adjustable Holder	79.8	1	10.92

Adjustable Holder

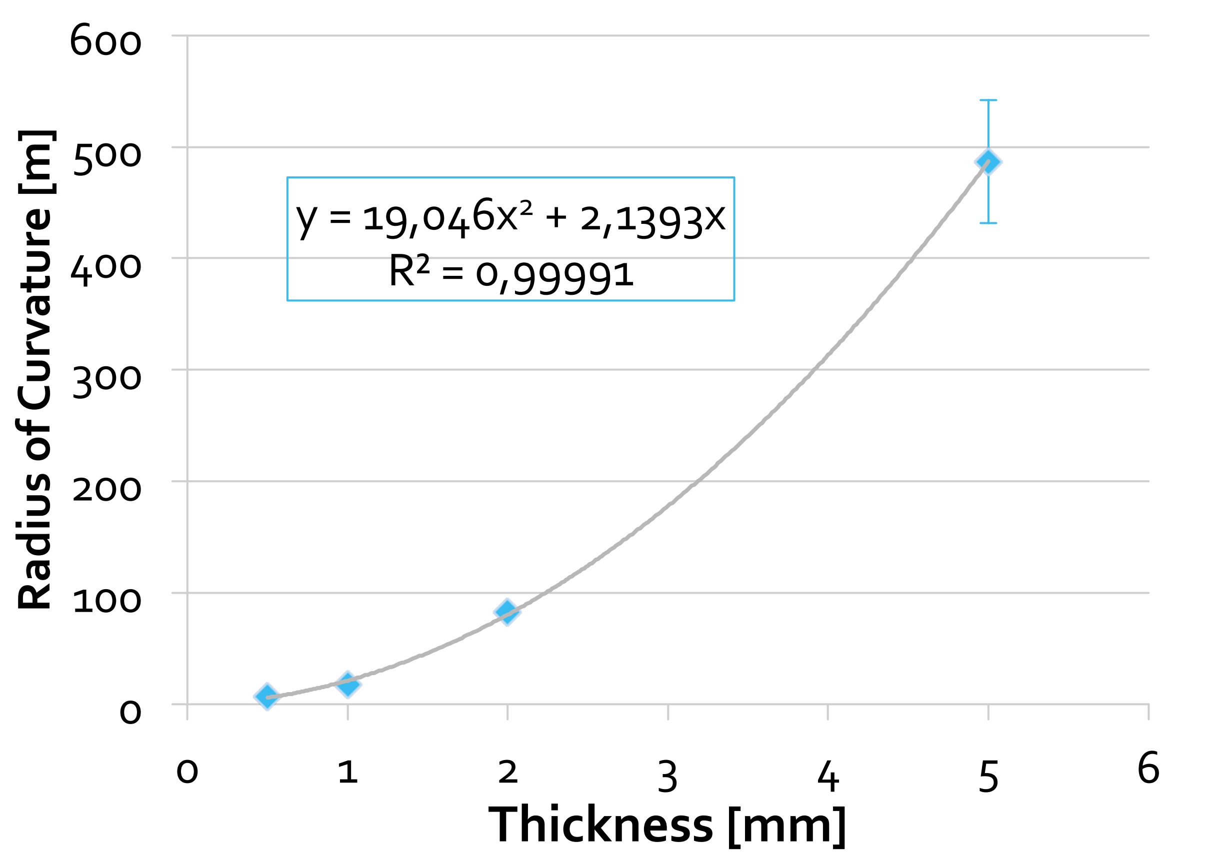
- The holder is deformed by a screw system in order to impose curvature on the crystal mounted on it



- Exploited secondary curvature created by elastic reaction to the bending momentum (green arrows)

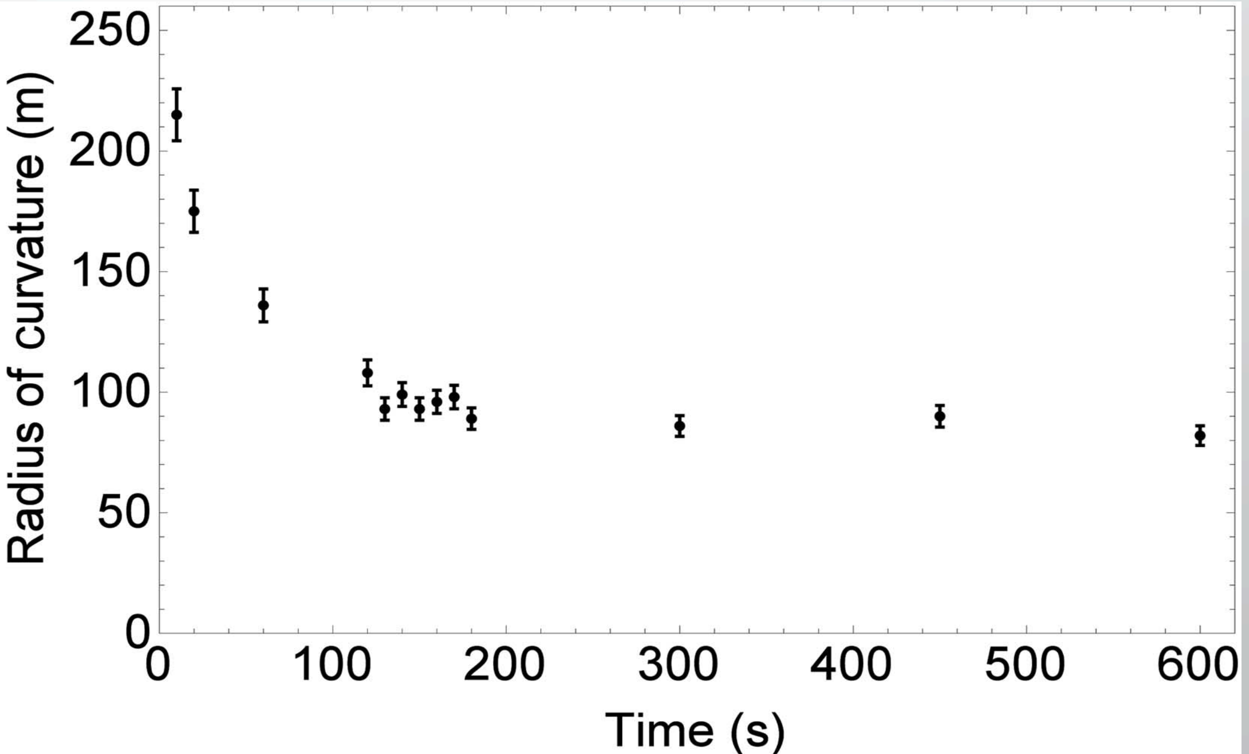


Self-standing crystal



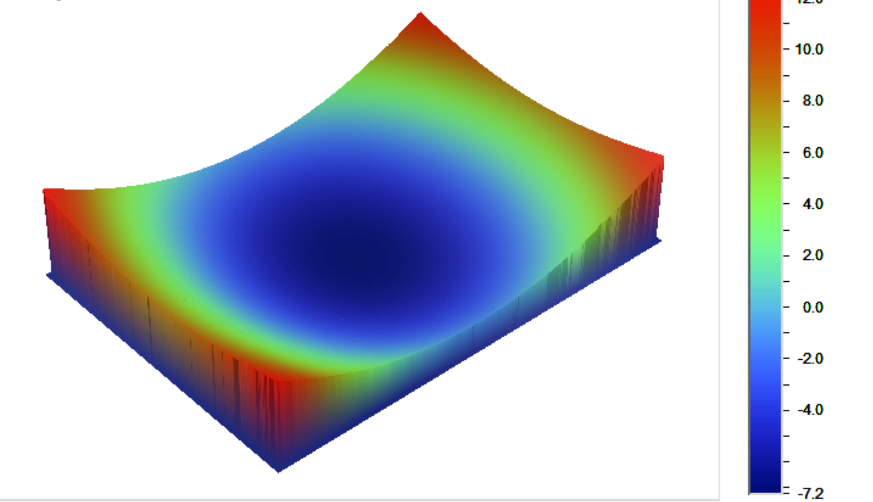
Sample Thickness	Radius of curvature
0.5 mm	6.2±0.7 m
1 mm	21±2 m
2 mm	80±3 m
5 mm	500±50 m

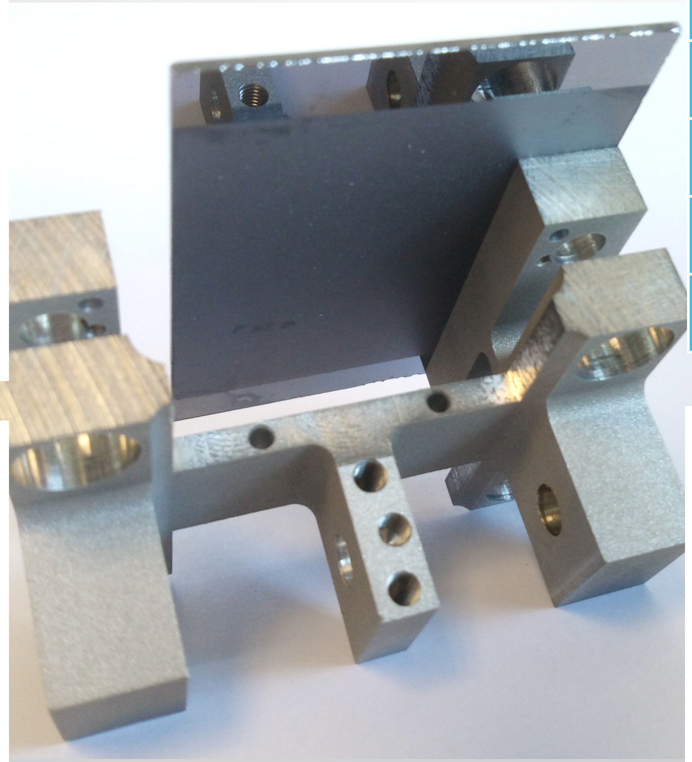
Controlled plasticization of the superficial layer of the crystal to create stress inside the sample. Such layer acts like a tensile film on the sample, imposing a spherical curvature



Prototype: PL05

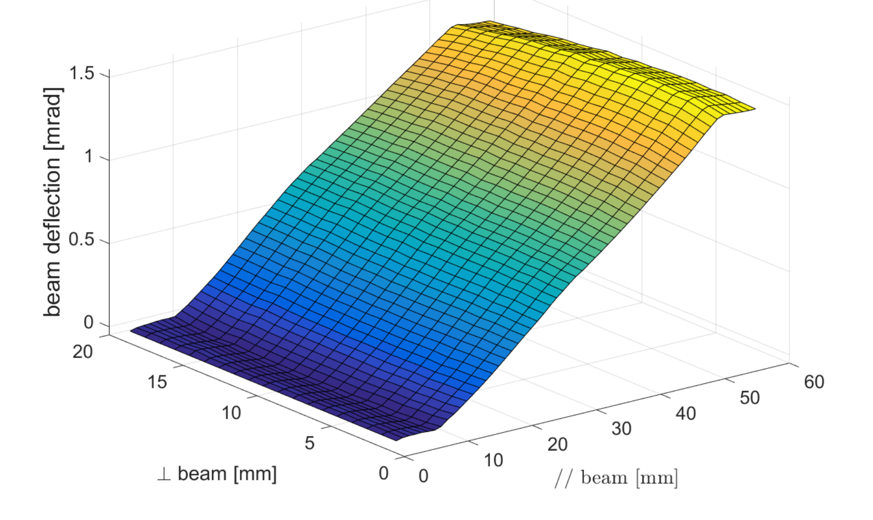
Optical characterization



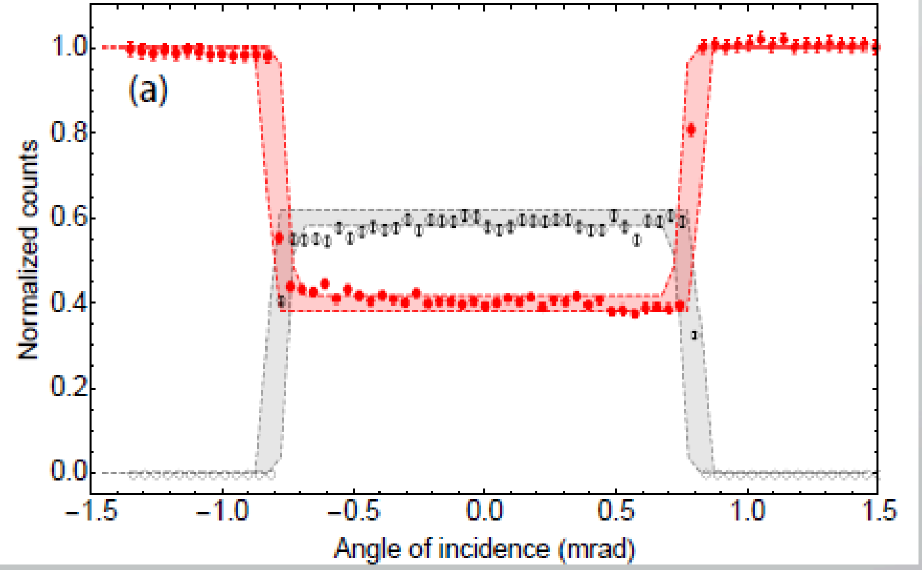


Thickness along the beam	55 mm
Crystal thickness	1 mm
Channeling planes	(111)
Channeling Axis	<110>
Deflection HRXRD (Bragg)	1550± 20 μrad
Deflection Interferometer	1530 ± 20 μrad
Deflection ESRF (Laue)	1570 ± 10 μrad

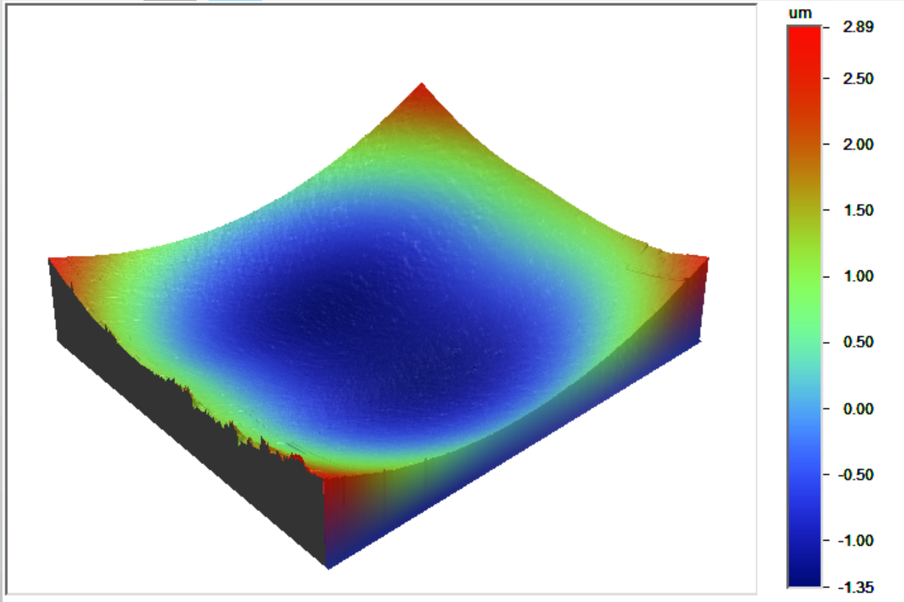
HRXRD characterization

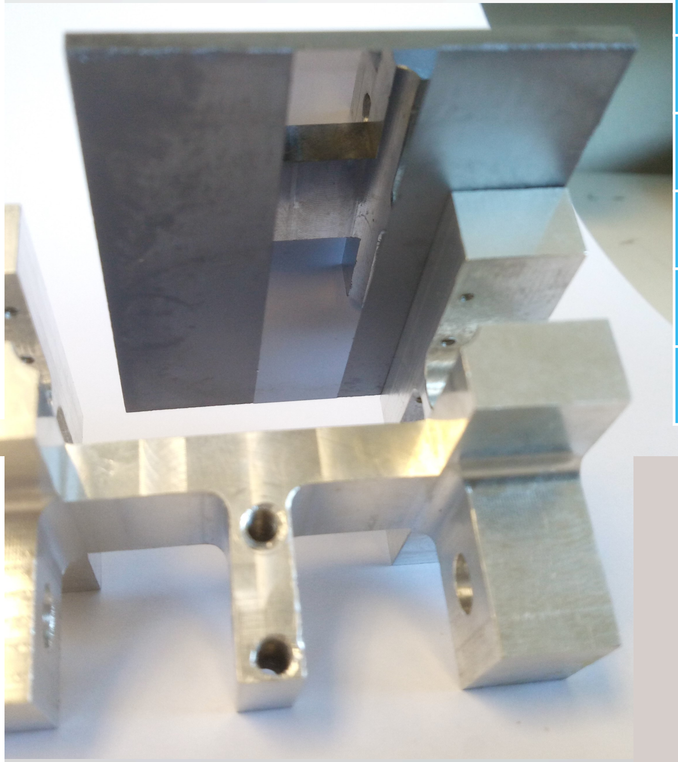


ESRF characterization

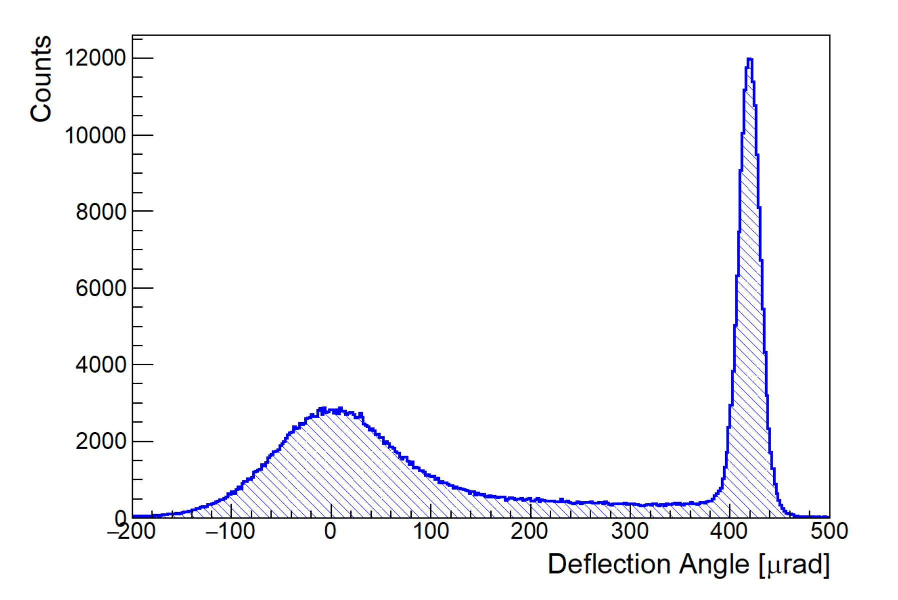


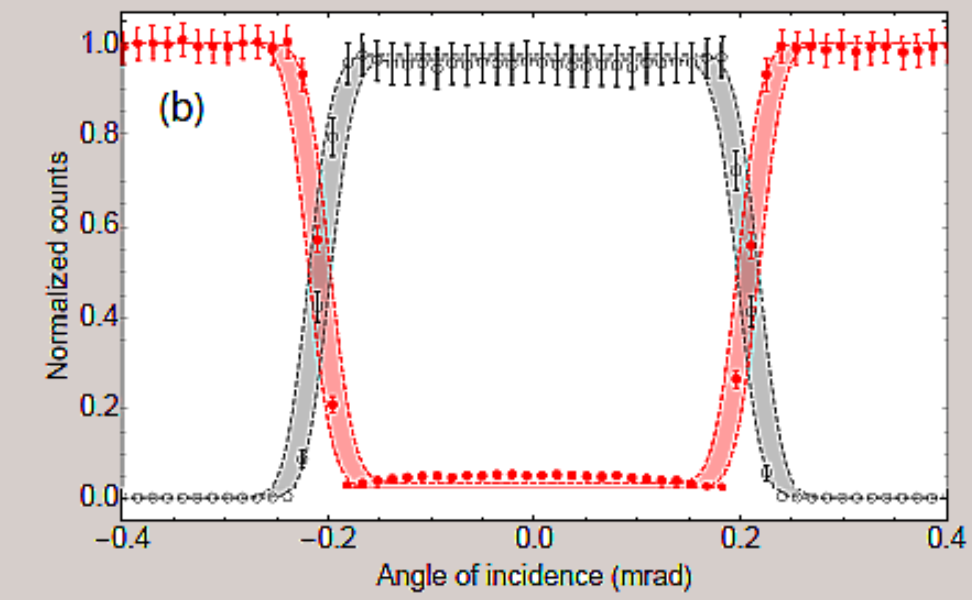
Prototypes: PL07





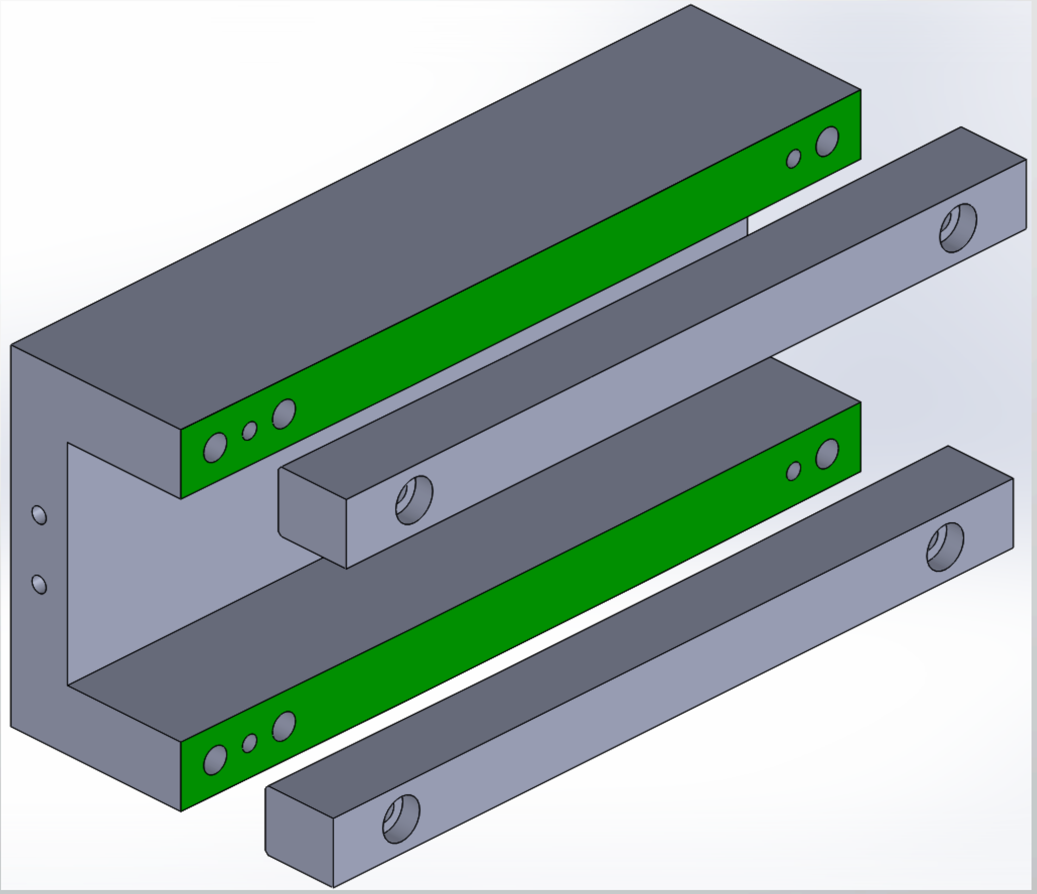
Thickness along the beam	55 mm
Crystal thickness	2 mm
Channeling planes	(111)
Channeling Axis	<110>
Deflection Interferometer	430 ± 10 μrad
Deflection ESRF (Laue)	420 ± 10 μrad
Deflection π^+ @ 180 GeV	419 ± 2 μrad





New mechanical holder configuration

- The holder surfaces follows a cylindrical profile, the crystal clamped on the holder takes up the same bending radius.
- No intrinsic limit on maximum curvature achievable (within material elastic limit)
- Can be easily employed with different material (i.e. Ge)
- Curvature was imposed on 5mm thick samples



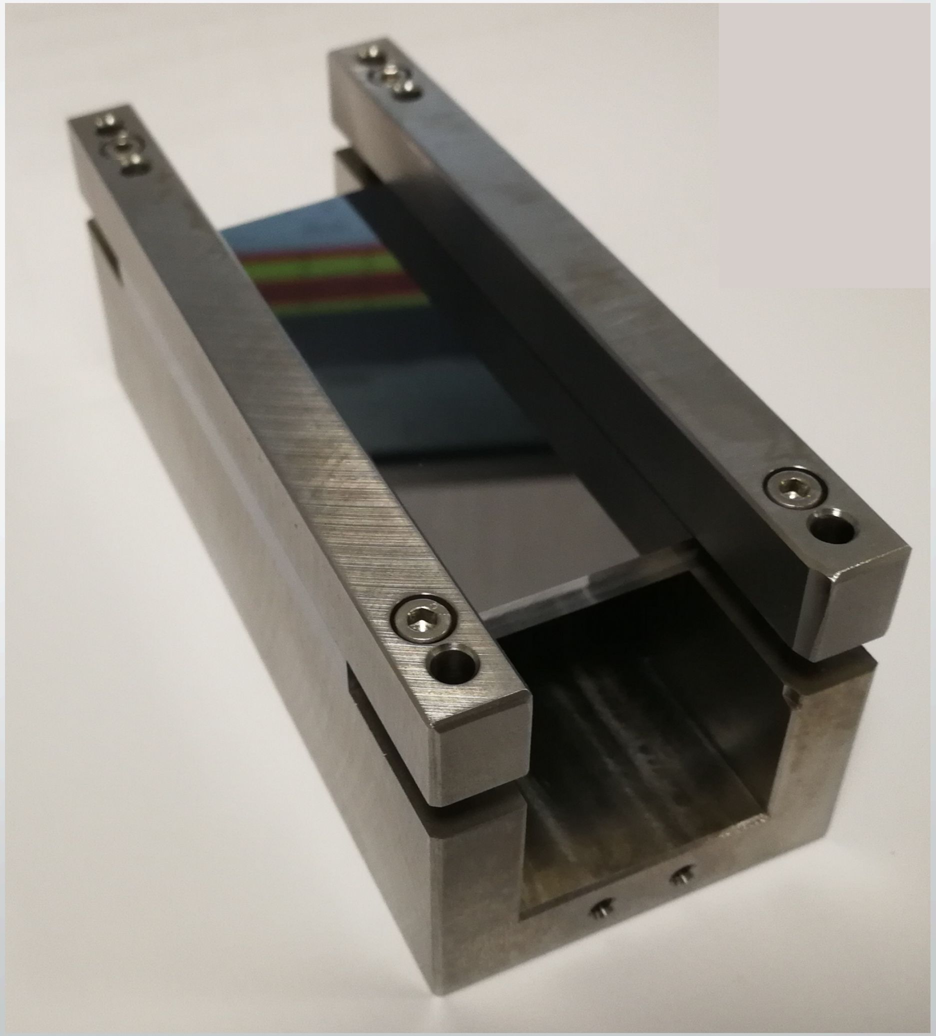
Ultra precise finishing

The challenge is not merely the total deflection angle, but the precise control of the crystal shape in each point. The mechanical holder must be manufactured with severe constrains such as:

- smoothness of the contact surface
- Precise shape
- Coplanarity of the two contact surfaces

Sample produced

#sample	Deflection (HRXDR)	Spin precession Λ_c	Spin precession Ξ
1	11.53 mrad	-1.5 rad	4.5 rad
2	15.93 mrad	-2.1 rad	4.7 rad
3	11.66 mrad	-1.5 rad	4.7 rad
4	14.35 mrad	-1.9 rad	2.3 rad
5	13.74 mrad	-1.8 rad	1.4 rad
6	13.95 mrad	-1.8 rad	1.8 rad
7	12.26 mrad	-1.6 rad	5.5 rad
8	15.825 mrad	-2.1 rad	4.5 rad



Future improvements

- Test of thermal stability, simulating the bake-out process at LHC with vacuum oven
- Testing different type of curvature for holder profile (higher order polynomial, free curve geometries) in order to increase uniformity of the bending radius
- Testing new materials for crystals (Ge) and holders (Ti).
- Investigation of new technologies for miscut reduction process (SPDT, FJP…)

Conclusion

Self standing crystals:

- Self standing curvature seems well suited for crystal up to 2mm thickness
- Well suited for different size of samples production (if crystal thickness in not changed).

Mechanical Holder:

- Production of first prototypes for new holder design, featuring large deflection angle for very thick (5 mm) crystals

Thank you for your attention!