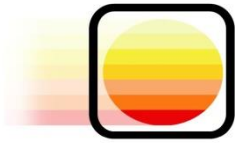

Sensor and
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University of Ferrara

State-of-the-art bent silicon crystals for high-energy charged particle beam collimation

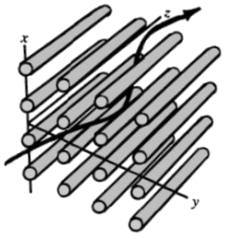
G. Germogli [a], **A. Mazzolari** [a], **V. Guidi** [a], **M. Romagnoni** [a]

[a] Department of Physics and INFN, University of Ferrara, Ferrara, Italy

Sirmione-Desenzano sul Garda, 28-09-2016

Outline

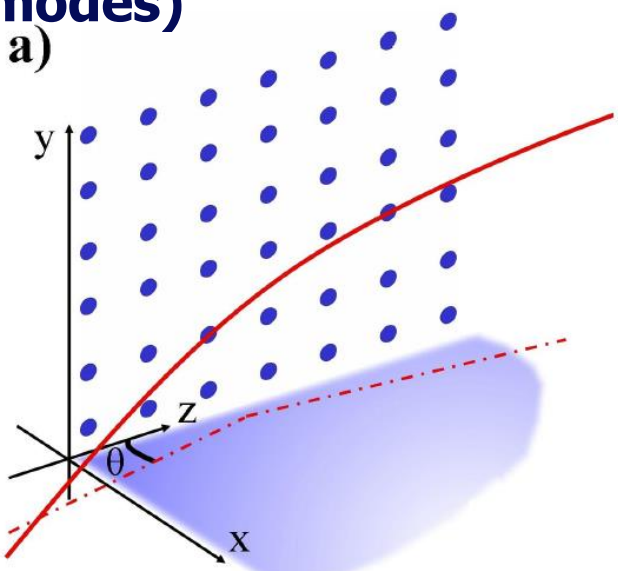
- Crystals in accelerators
  - Coherent interactions in bent crystals
- Crystals for beam collimation
  - Mandatory issues for collimation
  - Manufacturing techniques
  - Bending and characterization

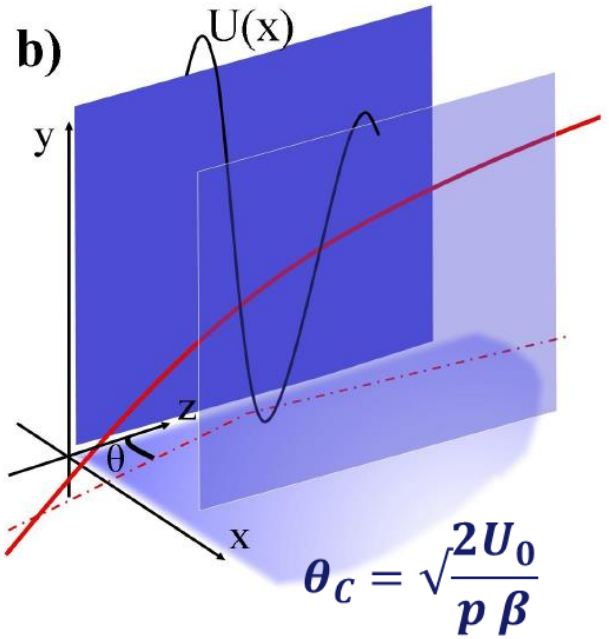


Channeling

Coherent interactions in straight crystals:

Channeling is the confinement of charged particles traveling through a crystal within atomic planes (planar or axial modes)



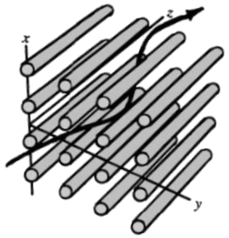


$$\theta_C = \sqrt{\frac{2U_0}{p\,\beta}}$$

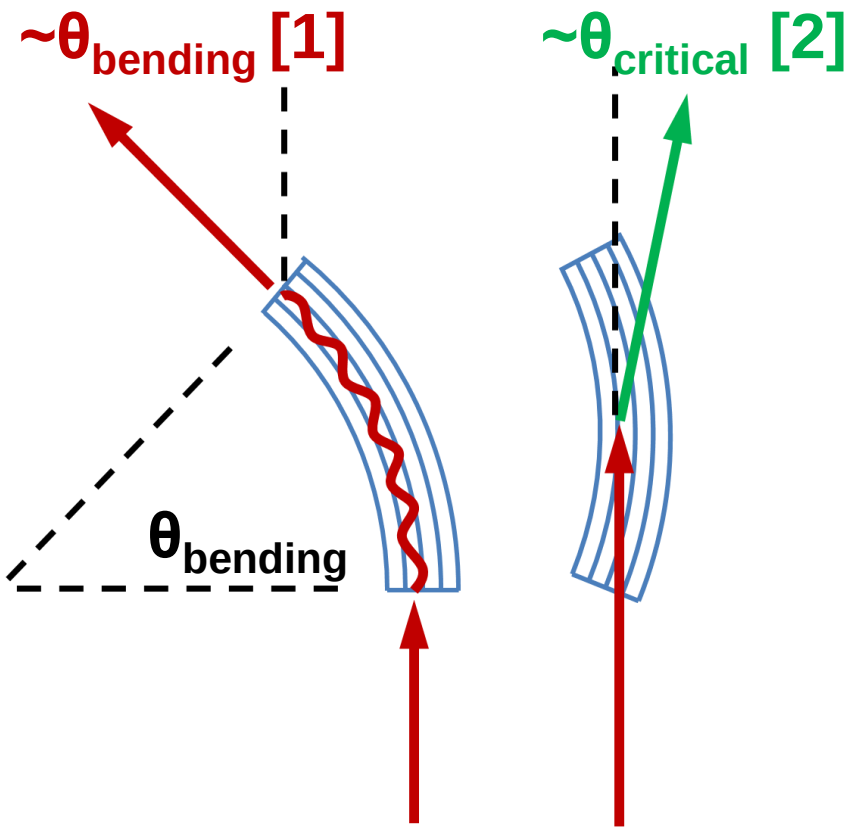
Channeling occurs as the trajectory of particles forms an angle lower than the critical angle θ_{max} [1]

U_0: Potential well depth ~Z [22.7 eV for (110) Si]
P, β: Particle momentum and velocity
$\theta_C \approx 20\mu rad$ at $E \sim 100$ GeV

[1] J. Lindhard, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. 34 (1965) 14.



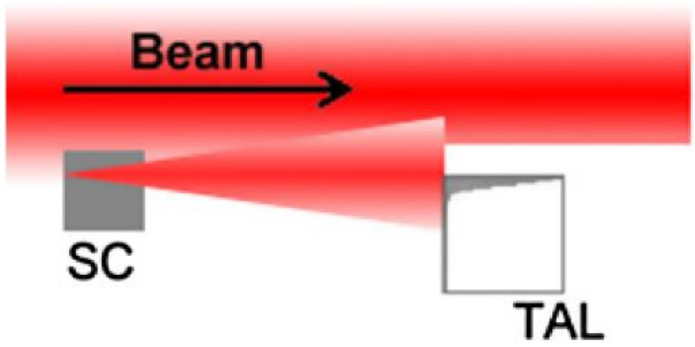
Channeling and volume reflection in a bent crystal



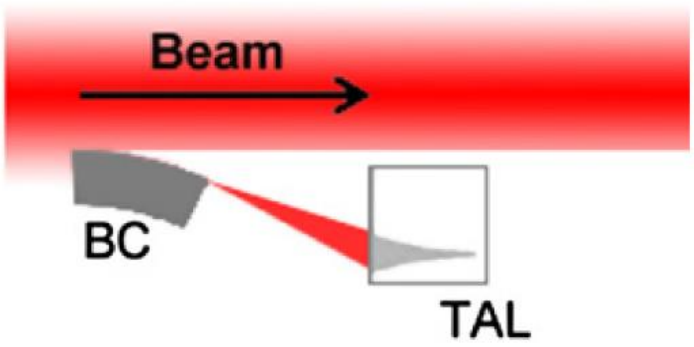
- A **channeled particle** is deflected by an angle equal to the bending angle of the crystal [1].
- A **volume-reflected** particle is deflected by the channeling crytical angle [2].
- Bent crystals can be used in an **accelerator** for:
  - **collimation** and **extraction of particles** from the circulating particle beam;
  - **beam steering**;
  - **radiation** production.
- With short bent crystals (~mm), it is possible to deflect ultra-high-energy particles in CERN (SPS or LHC) with angles (100 μrad – 1mrad) achievable by 1000 Tesla magnets having a similar size.

[1] Tsyganov (1976)
[2] Taratin and Vorobiov (1988)

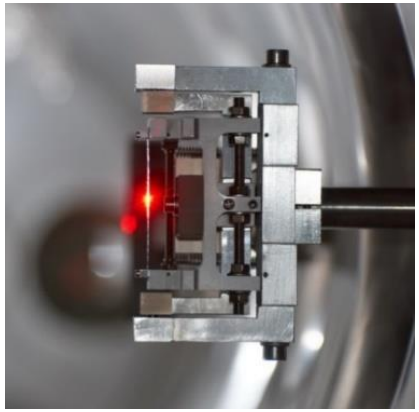
UA9 experiment: Crystal assisted collimation of modern hadron colliders (e.g. LHC)



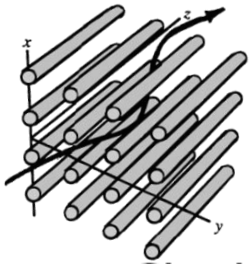
Common collimation scheme

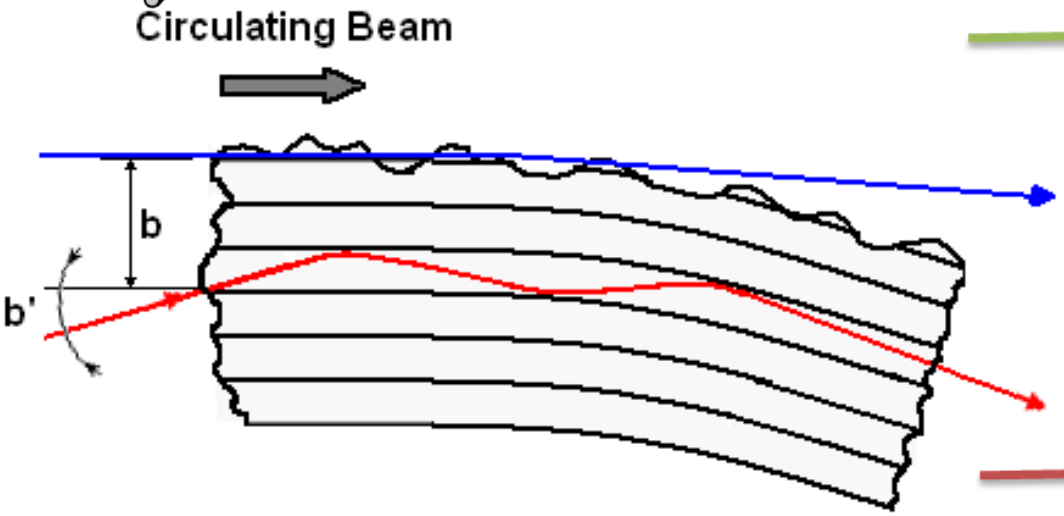


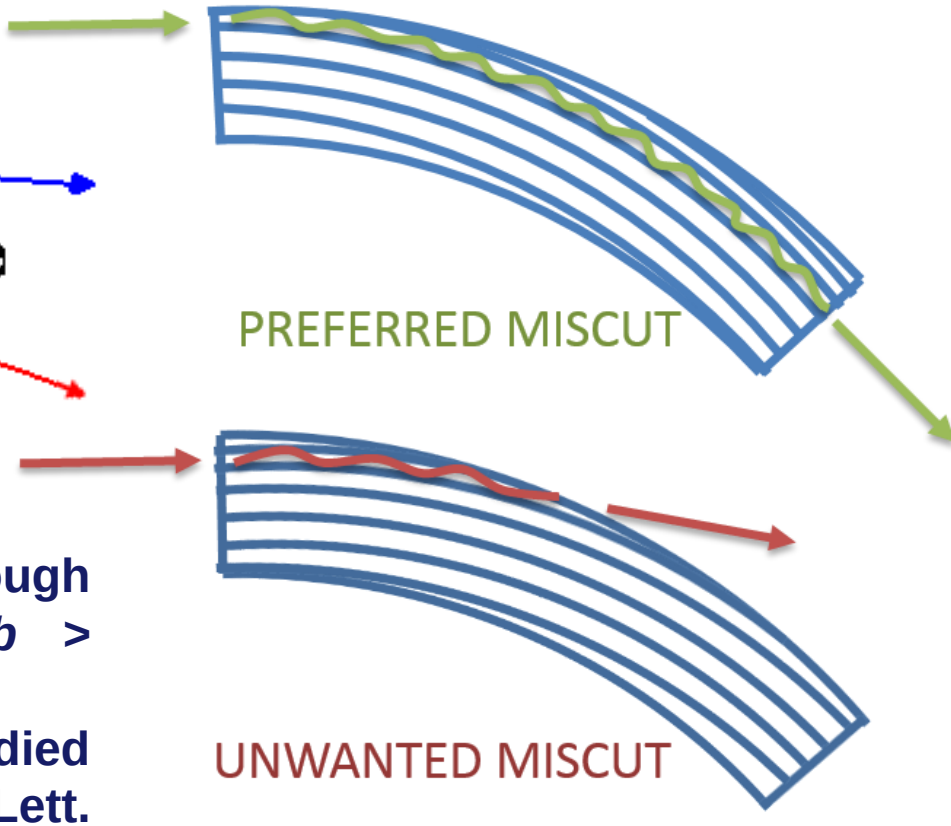
Crystal-assisted collimation



Surface requirements for collimation







- **Impact parameter *b* must be large enough to overcome imperfections (i.e. *b* > surface roughness R_A)**
- **The effect of miscut was recently studied by the UA9 collaboration: (e.g. Phys. Lett. B 714 (2012) 231)**

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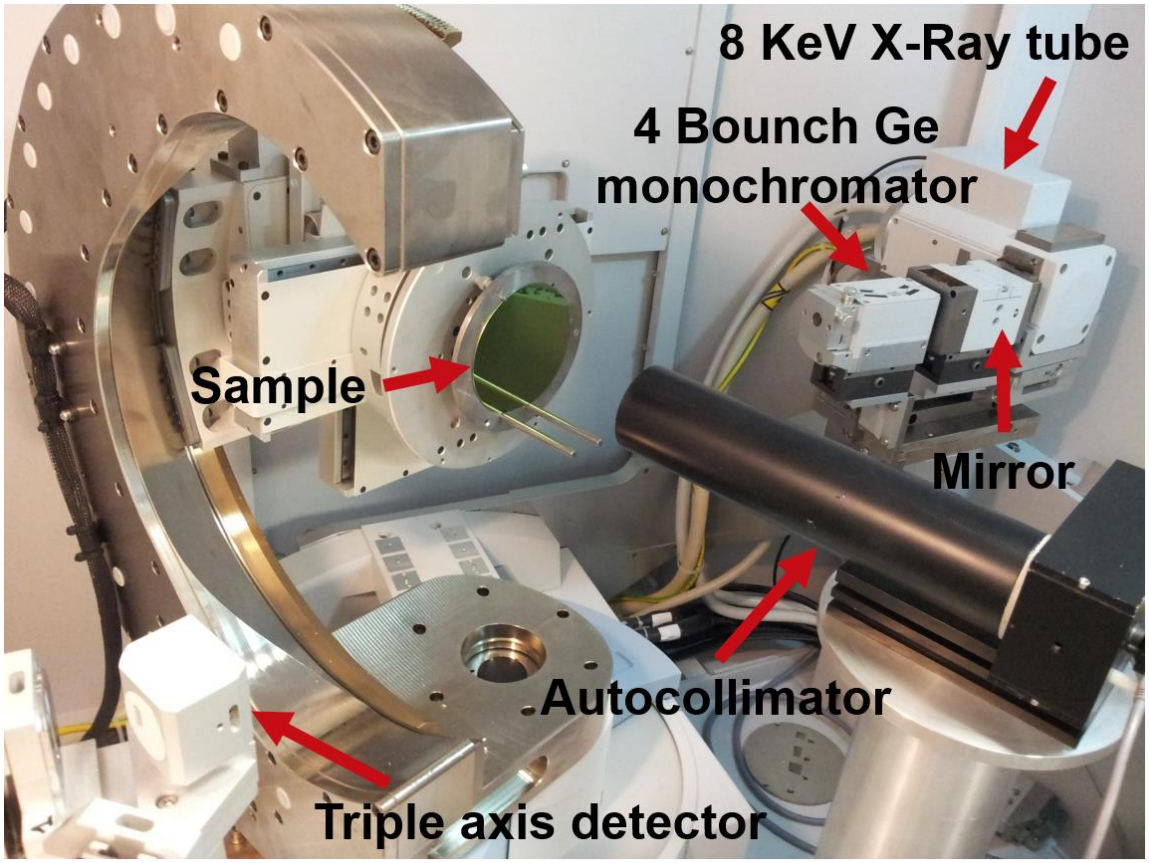
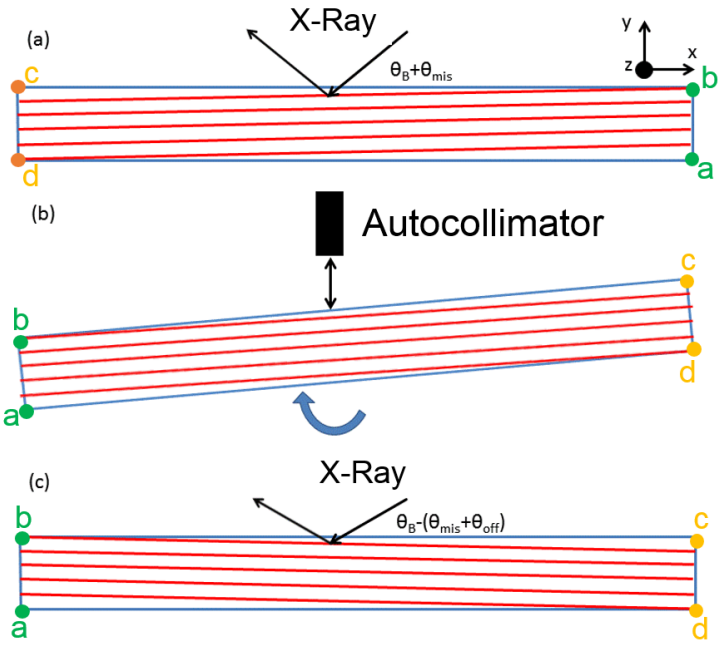
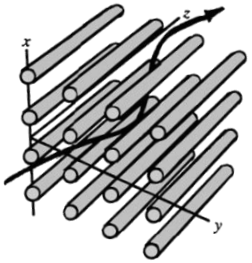
Miscut precise measurement

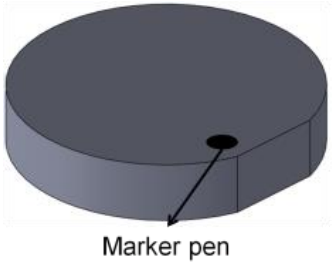


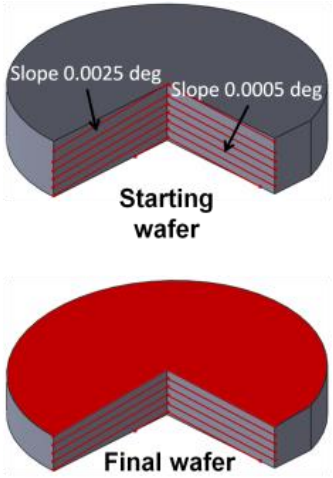


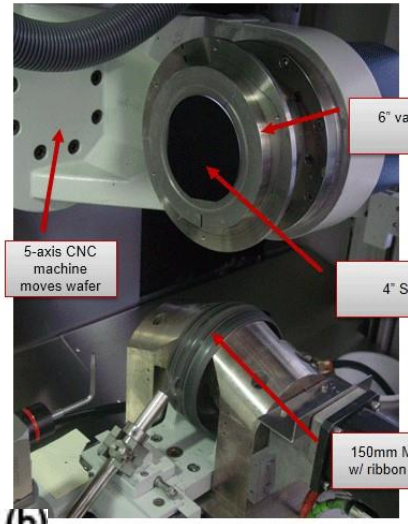
Miscut measurement (x-rays diffraction + autocollimator)

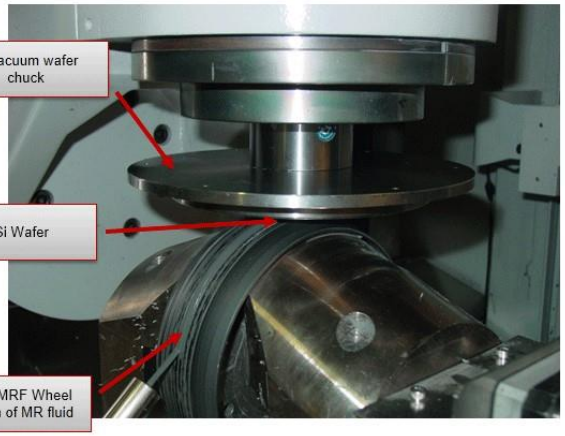


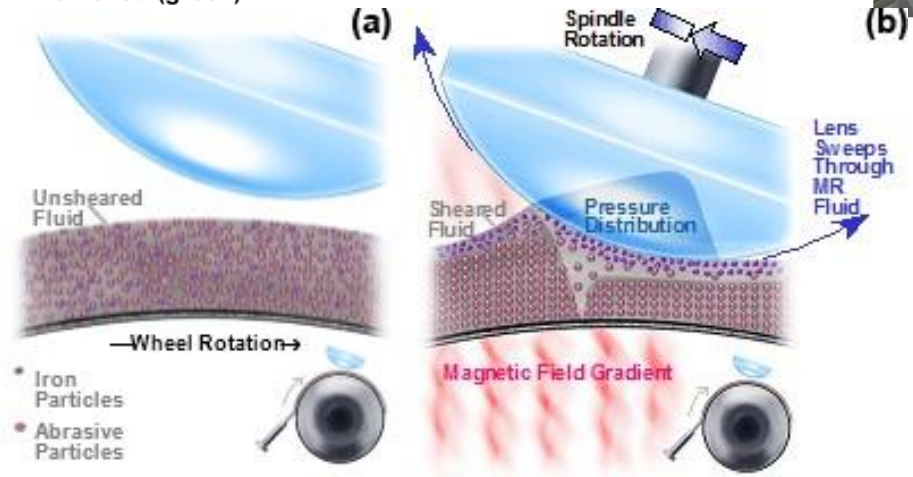
Miscut reduction via Magnetorheological Finishing (MRF)







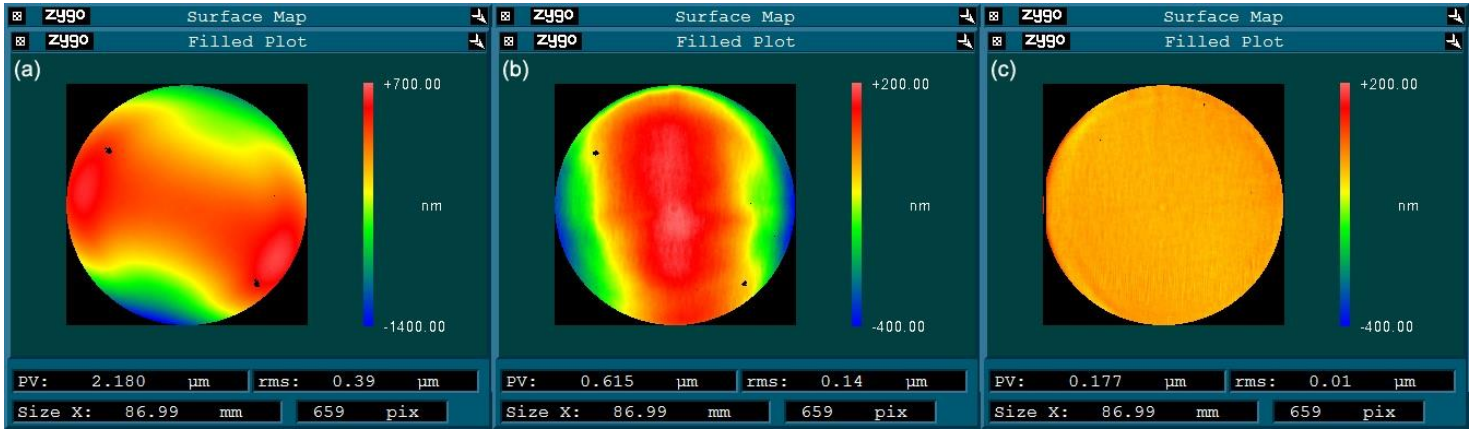




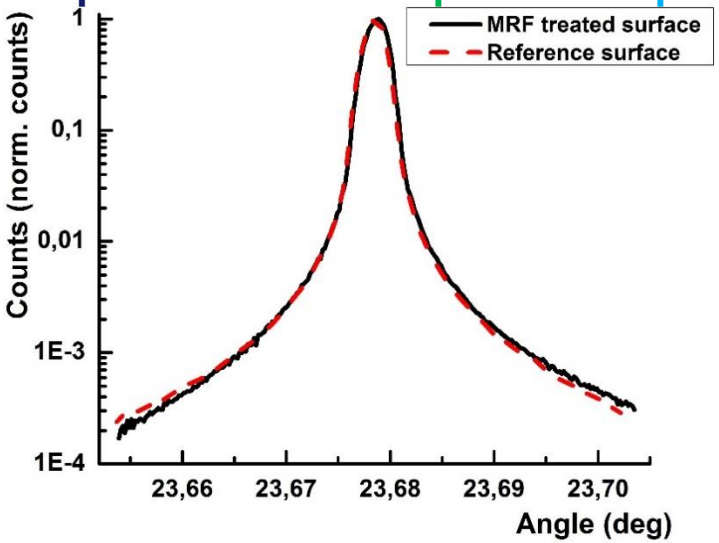
- **Best «pre-selected» wafer had a miscut of (73 ±2) µrad**
- **MRF treatment allowed the reduction of miscut down to (5 ±2) µrad**

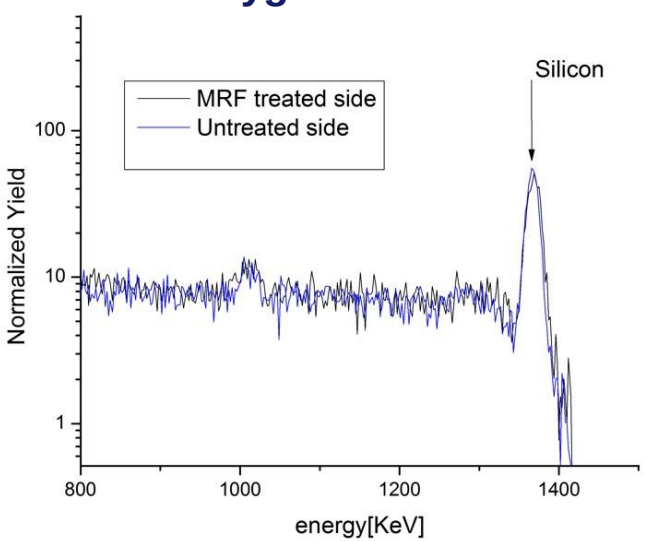
MRF provided by QED Technologies (USA)

Characterization of MRF-treated Si wafer surface



Flatness improved from 0.39 µm to 0.01 µm (measured with Zygo interferometer by QED)



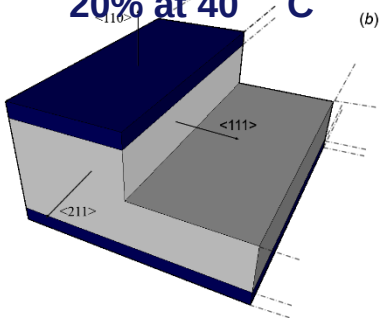


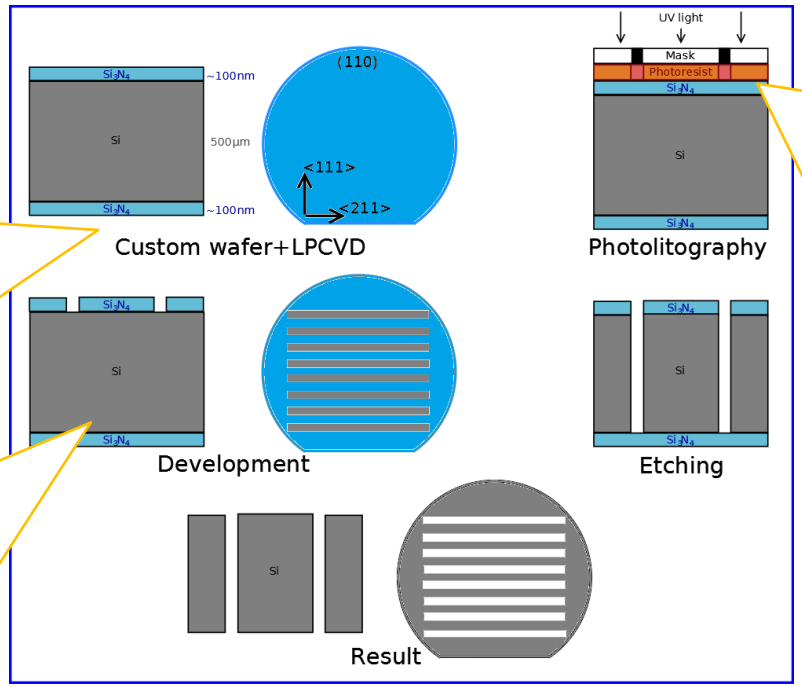
Surface quality preserved (checked with high-resolution x-rays diffraction and Rutherford back scattering in channeling mode at LNL Legnaro)

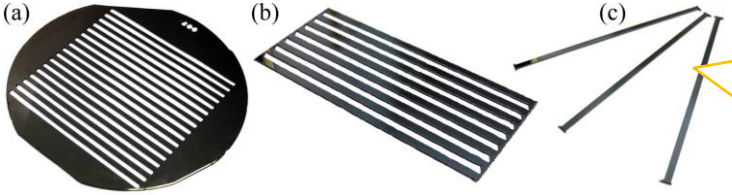
Strip crystals fabrication

LPCVD deposition of silicon nitride thin layer

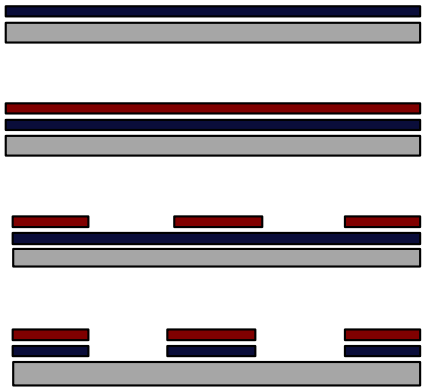
Anisotropic etching: Etching rate on different silicon planes for KOH 20% at 40 ° C



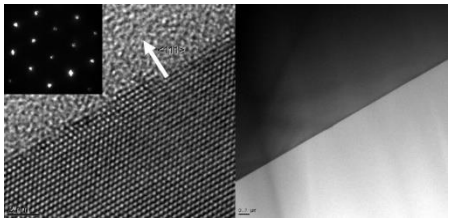




Silicon nitride patterning

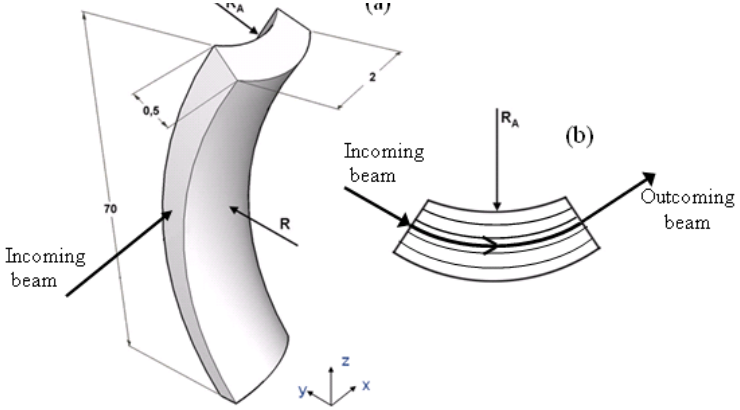


Crystalline surfaces

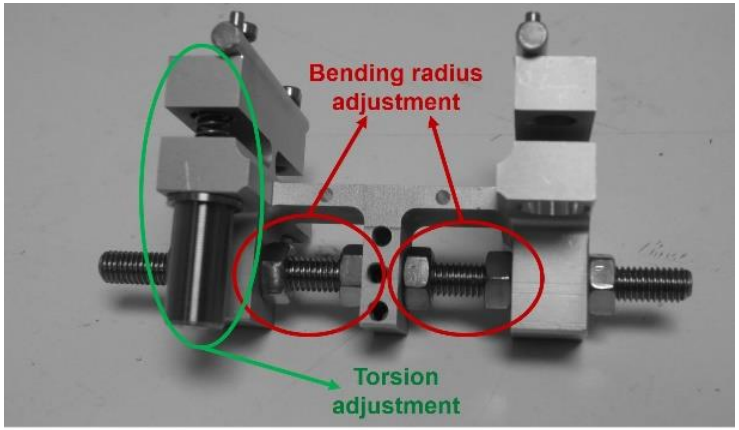


[1] S. Baricordi et al., Journal of Physics D: Applied Physics 41 (24), 245501
[2] S. Baricordi et al., Applied Physics Letters 91 (6), 061908

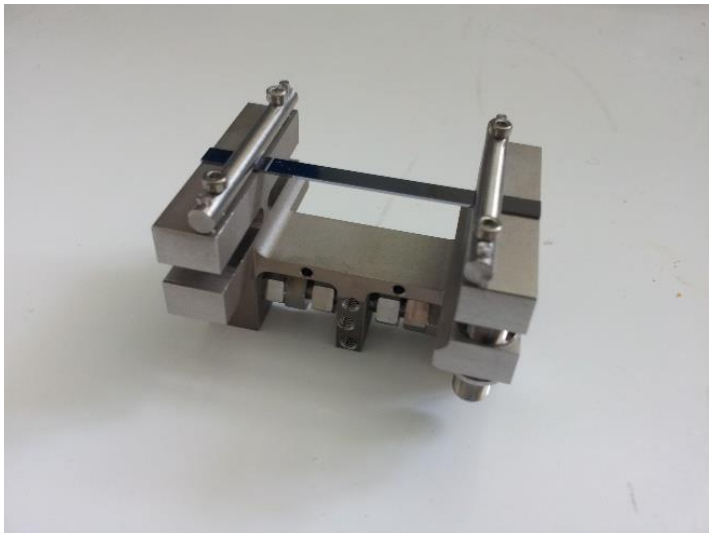
Strip crystals bending



Anticlastic deformation used to deflect particle beam



Mechanical bending holder



Bent strip crystal

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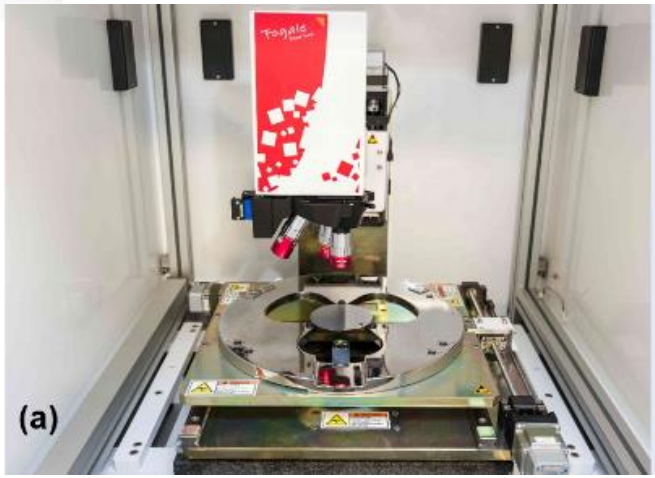
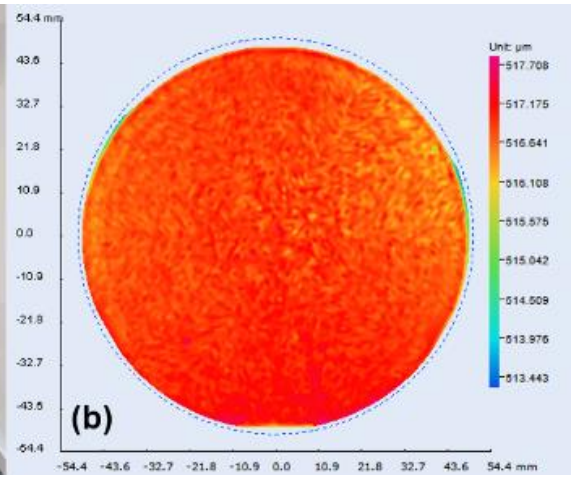
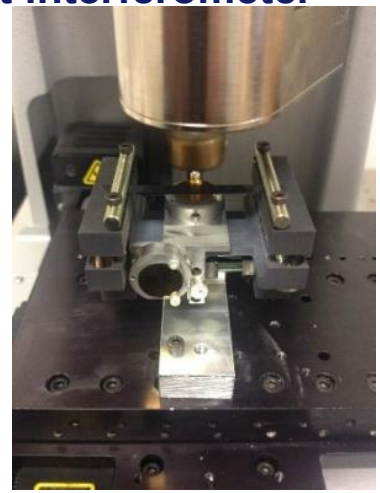
Morphological characterization



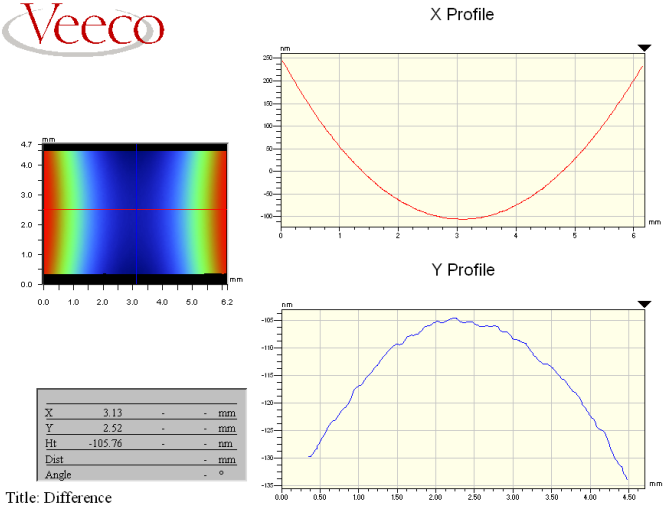
FOGALE TMAP 4 Infrared (IR) light interferometer



Thickness measurement

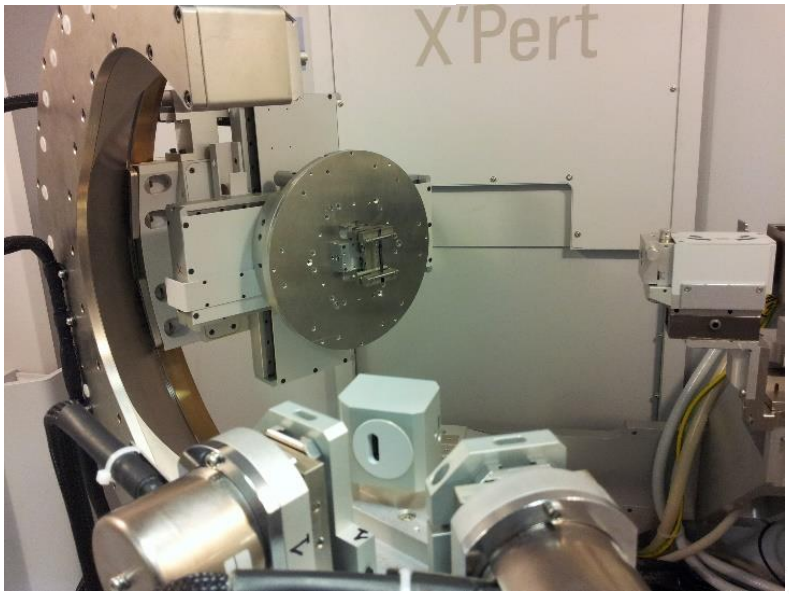


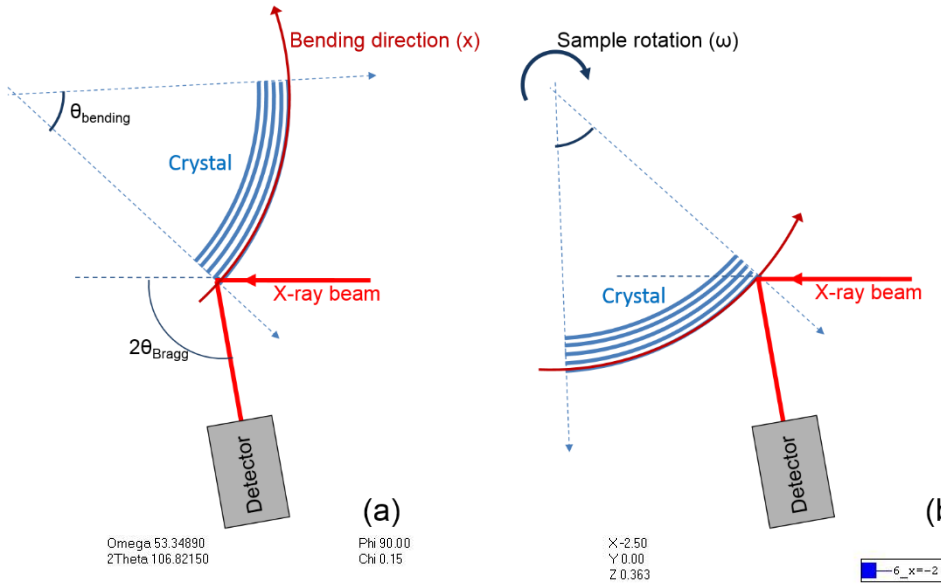
Veeco NT1100 white light interferometer



Curvature measurement and torsion reduction

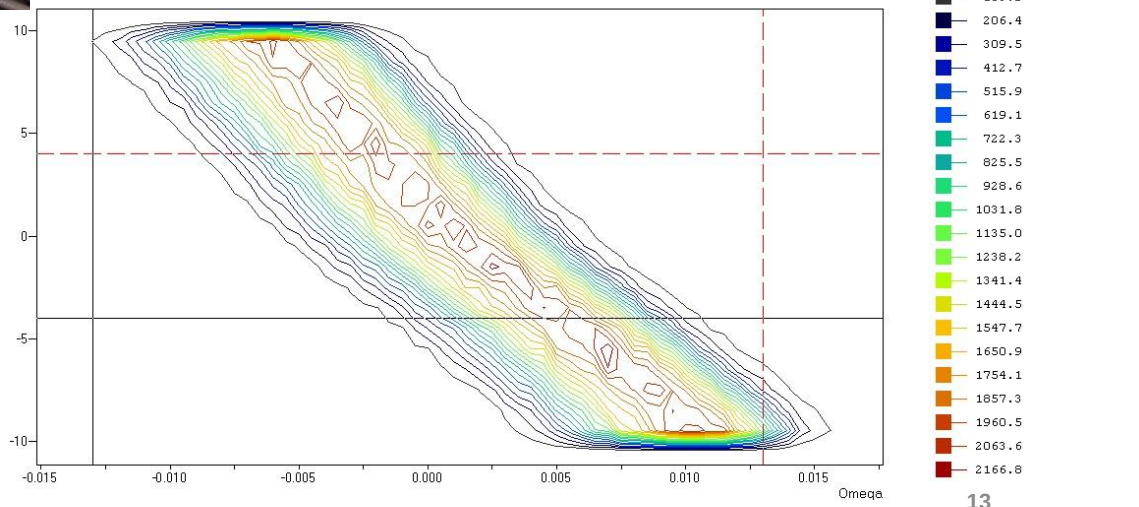
Crystalline planes characterization





Panalytical X'pert Pro x-rays:

- **Miscut**
- **Principal bending**
- **Anticlastic bending**
- **Torsion**



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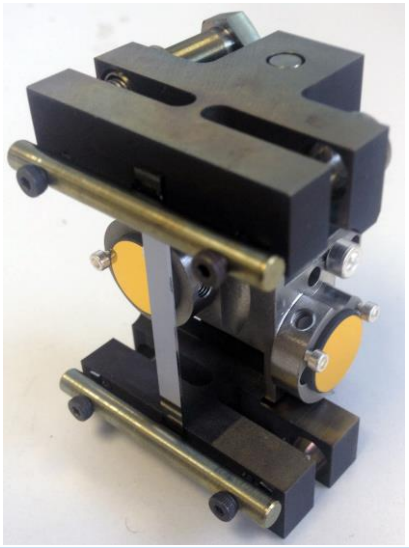
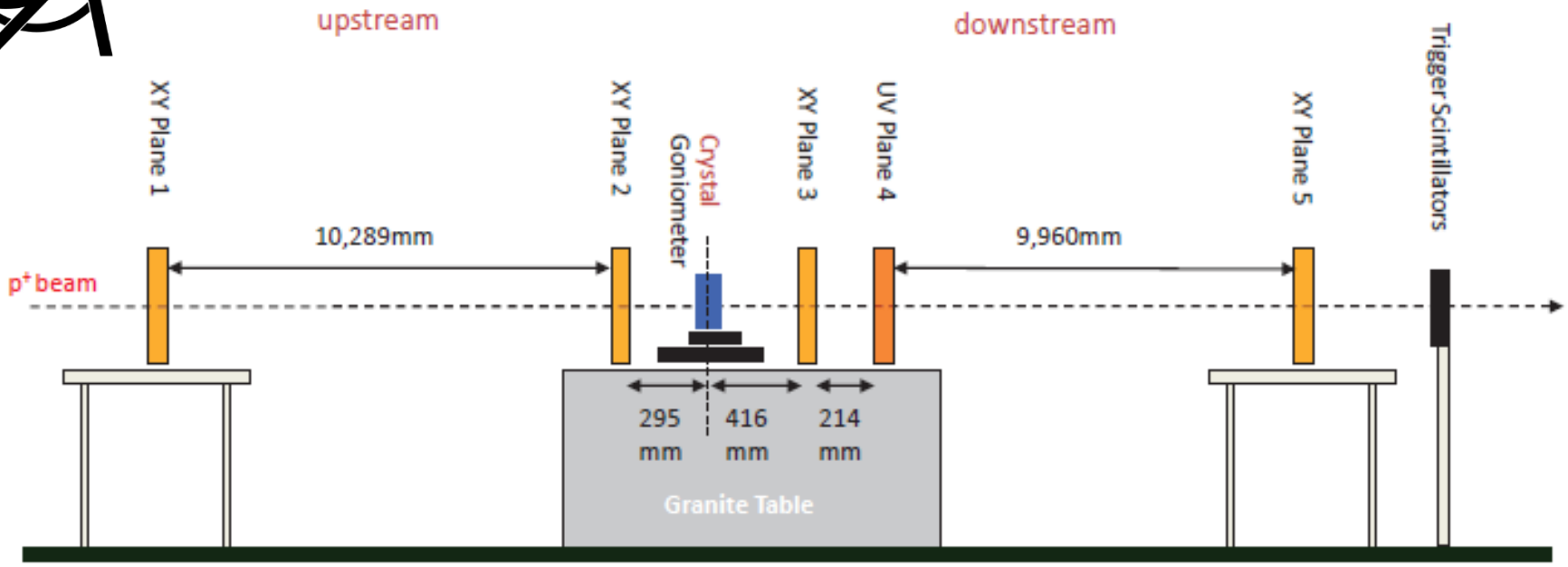
Strip crystal for the collimation in the LHC (UA9 experiment)



- **Channeling plane: (110)**
- **Titanium holder**
- **Mirrors installed for laser alignment**
- **STF75 installed in LHC in February 2014**
- **Spare crystal STF76 and twin crystals STF105 and STF106 (fabricated in 2015) were then characterized at the extracted lines of CERN-SPS**

Parameter	Expected	STF75	STF76	STF105	STF106
Thickness along the beam (mm)	≈ 4	4.10 ± 0.02	4.10 ± 0.02	4.07 ± 0.02	4.08 ± 0.02
Bending angle (interferometer, µrad)	≈ 50	52 ± 2	52 ± 2	51 ± 5	46 ± 5
Bending angle (X-rays, µrad)	≈ 50	51 ± 1	53 ± 1	49 ± 3	41.5 ± 1.5
Miscut (X-rays + autocollimator, µrad)	< 10	6 ± 1	6 ± 1	40 ± 4	40 ± 4
Torsion (interferometer, µrad/mm)	< 1	6 ± 1	6 ± 1	<2	<2
Torsion (X-rays, µrad/mm)	< 1	6 ± 1	6 ± 1	<2	<2
Heating compatibility	Yes	Yes	Yes	Yes	Yes

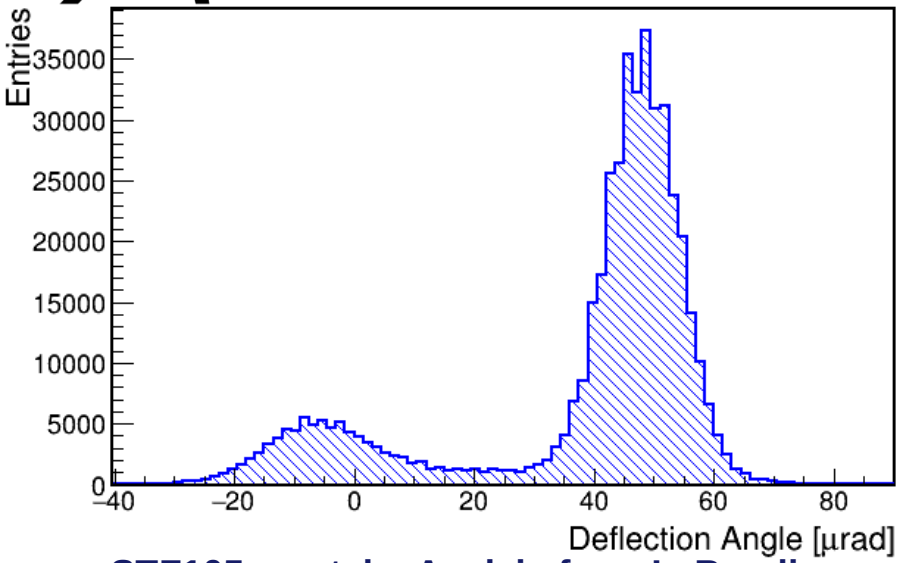
Setup for characterization at H8-SPS



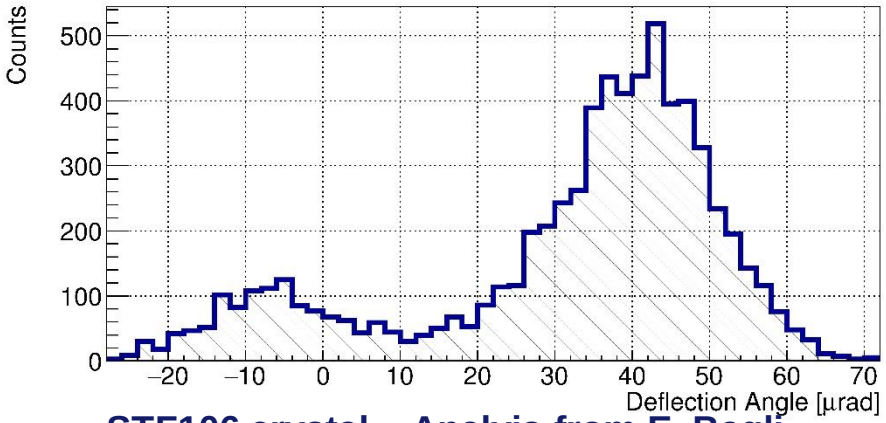
M. Pesaresi et al., Journal of Instrumentation (2011)

- **5 pairs of Si microstrip sensors, with an active area of $3.8 \times 3.8\ cm^2$ each**
- **Long baseline (~ 10 m for each arm)**
- **Angular resolution: 2.8 μrad for the incoming arm, 5.2 μrad for the difference of the two arms (< critical angle for channeling ~10 μrad for 400 GeV/c protons)**
- **Planes 1 and 2 used for measure incoming tracks, while 3, 4 and 5 planes for outgoing tracks**
- **Events triggered on the signal coincidence with a plastic scintillator placed downstream**

Strip crystal for the collimation in the LHC (UA9 experiment)



STF105 crystal - Analyis from L. Bandiera



STF106 crystal - Analyis from E. Bagli

- **STF105 and STF106 crystals tested with 400 GeV/c protons**
- **Crystals mounted on a high resolution goniometer, and aligned to find channeling**
- **Protons trajectories tracked with the silicon telescope**
- **Results are in agreement to characterization performed at SSL Ferrara**

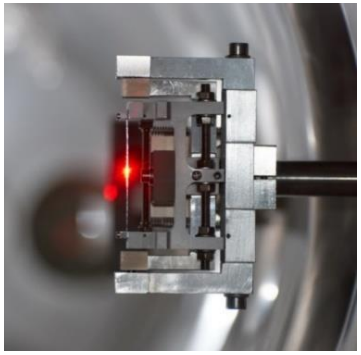
Parameter	STF105	STF106
Bending angle (µrad, 400 GeV/c channeled protons)	49 ± 1	41.5 ± 1.5
Deflection efficiency (400 GeV/c channeled protons)	(80±1)%	(81±2)%
Torsion (µrad/mm, 400 GeV/c channeled protons)	<2	<2

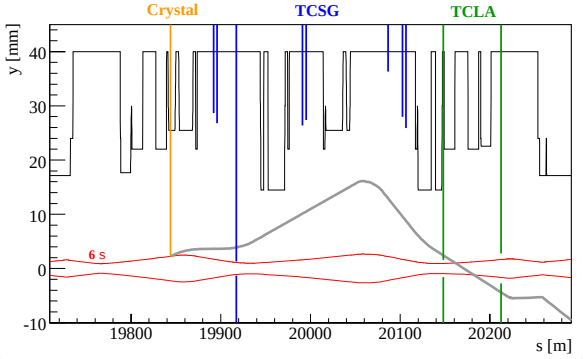
Summary and conclusions

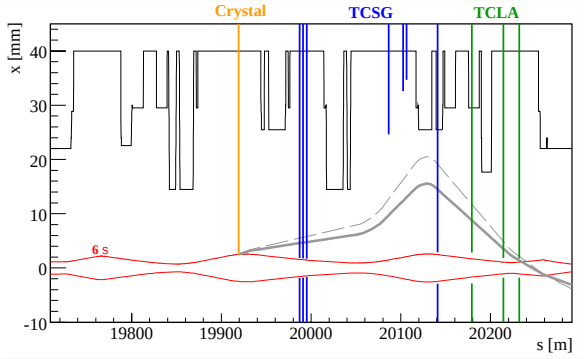
- Methods for crystal manufacturing presented
- Crystal-assisted beam collimation:
  - Several prototypes were fabricated and characterized
  - Strip tested with 6,5 TeV protons at CERN-LHC


Thank you for your attention!!!

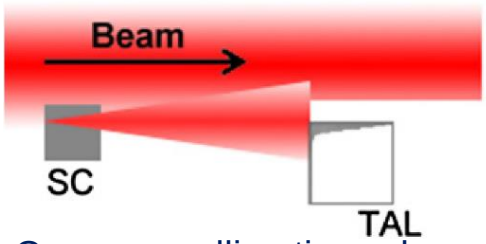
First crystal-assisted collimation tests in the LHC



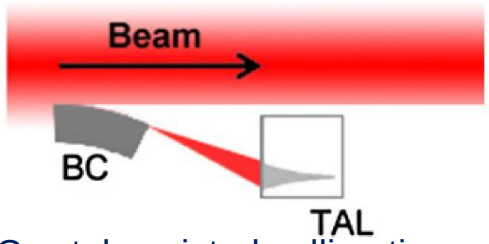




D. Mirarchi et al., IPAC 2014 conference



Common collimation scheme



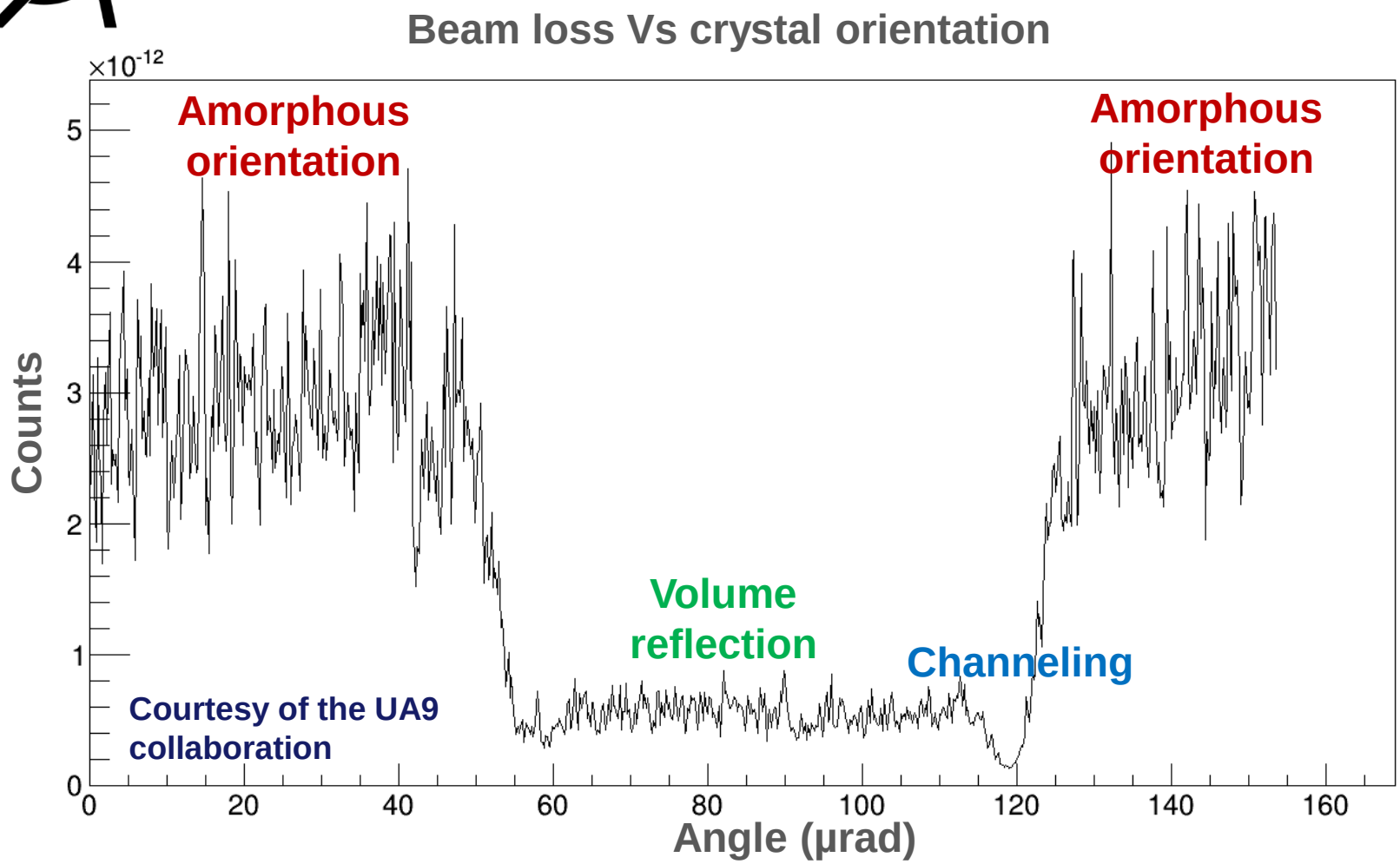
Crystal-assisted collimation

Strip crystal STF75 from Ferrara installed in LHC in the horizontal plane of the betatron collimation insertion (IR7) in February 2014 (quasi mosaic crystal from PNPI installed in the vertical plane)

Collimation tests in channeling mode performed in 2015:

- **30/08: both crystals tested at injection energy (450 GeV) with protons (first time in LHC)**
- **06/11: horizontal crystal tested at flat top (6.5 TeV) with protons (record)**
- **02/12: both crystals tested at injection energy (450 GeV) with Pb ion beam (record for ions)**

First evidence of channeling in the LHC



First strong evidence of channeling at LHC top energy (6,5 TeV) !!!

W. Scandale et al., Physics Letters B 758, 129-133 (2016)