Bent crystals for the SPS crystal-assisted slow extraction at CERN

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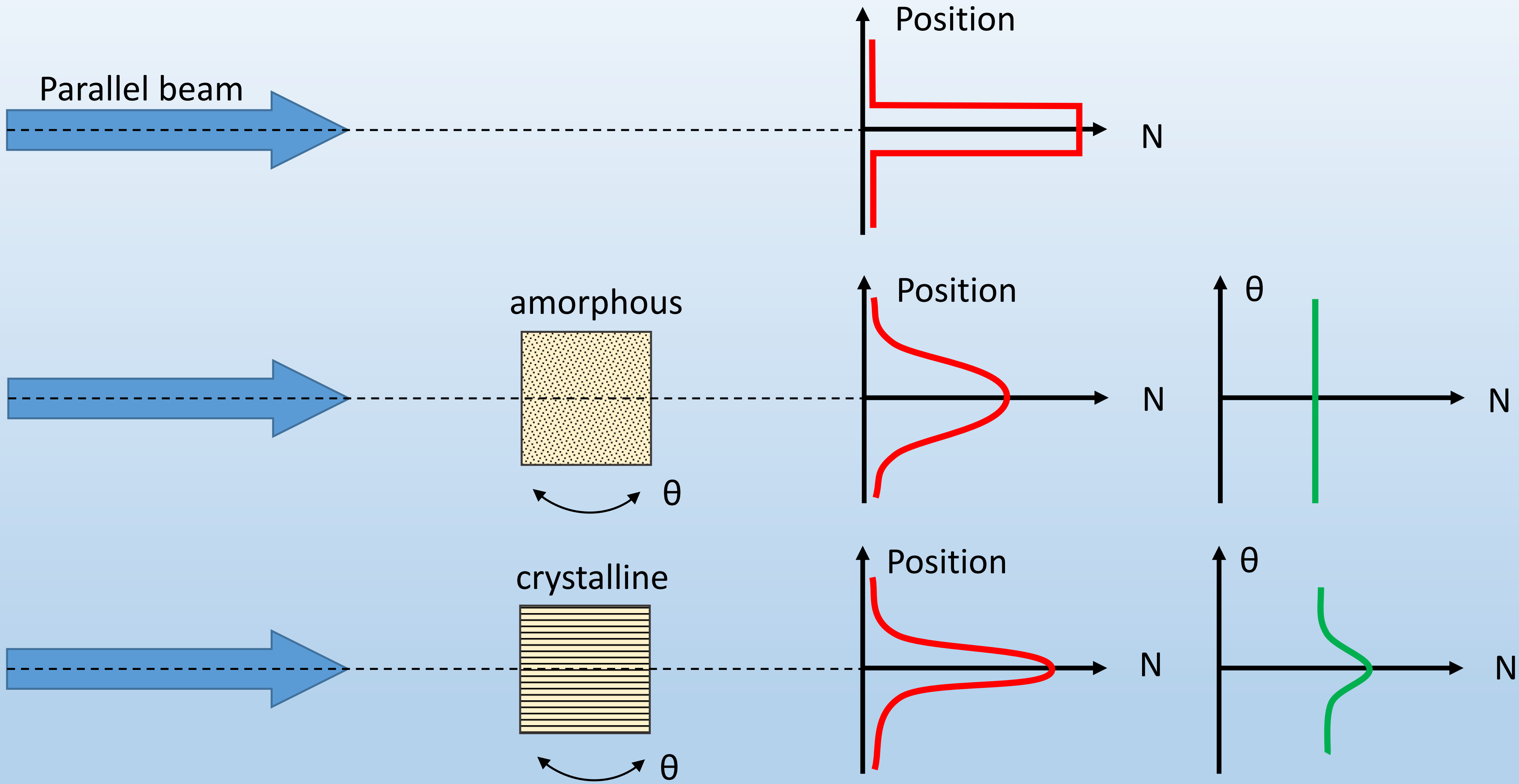
Slow Extraction Workshop, 24-28 (JST) Jan, 2022, J-PARC/KEK

Channeling


Parallel beam
Position
N
amorphous
θ
Position
N
θ
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crystalline
θ
Position
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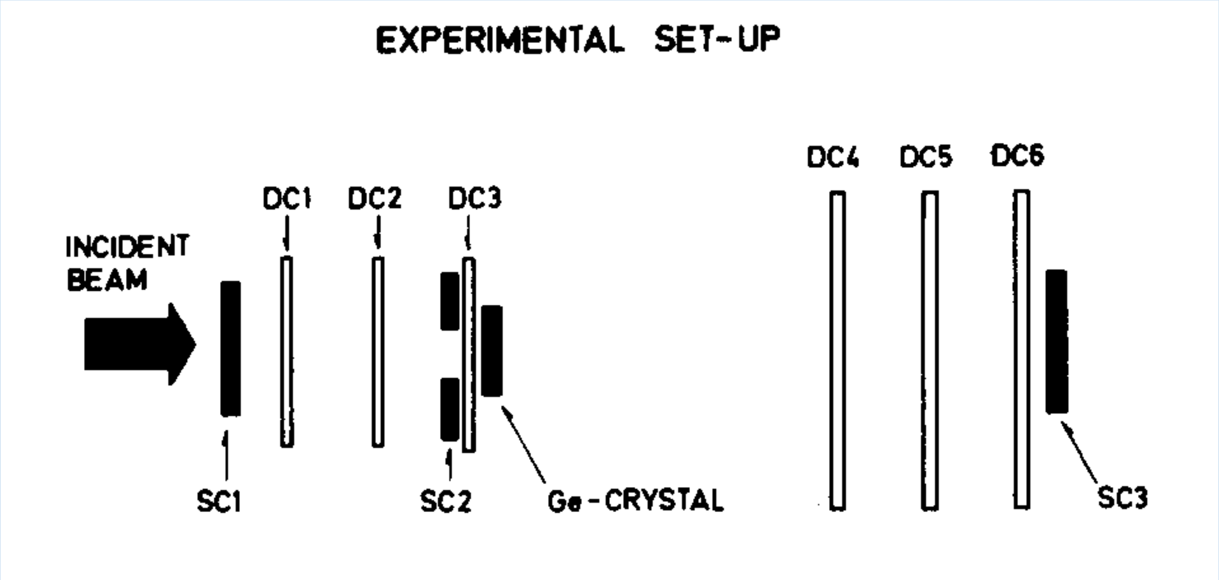
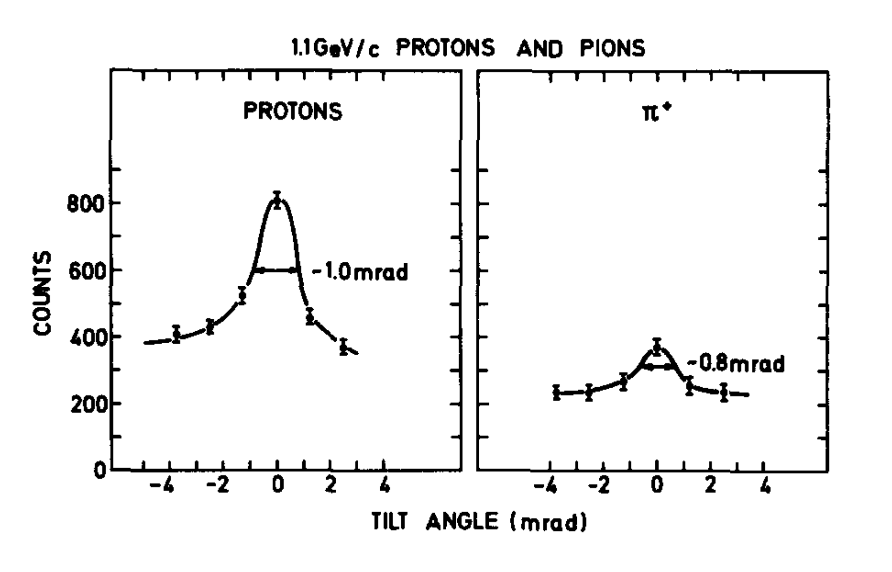
θ
N

High energy channeling in a flat crystal, CERN

O. Fich, J.A. Golovchenko, K.O. Nielsen, E. Uggerhoj, G. Charpak and F. Sauli, Channeling of 1.1 GeV/c protons and pions, Physics Letters 57B(1975)90

"… we have observed the channeling of positive particles in a thick crystal as an increase in forward-scattering probability under channeling conditions…"





High energy channeling in a bent crystal, JINR

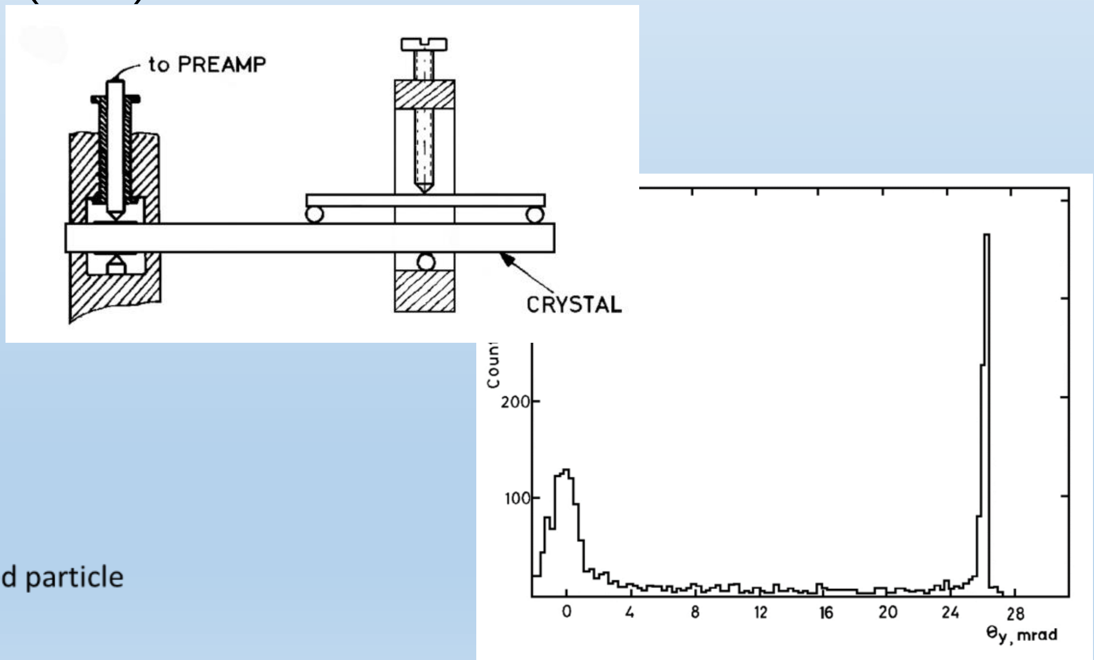
- Idea – E.N.Tsyganov, 1976

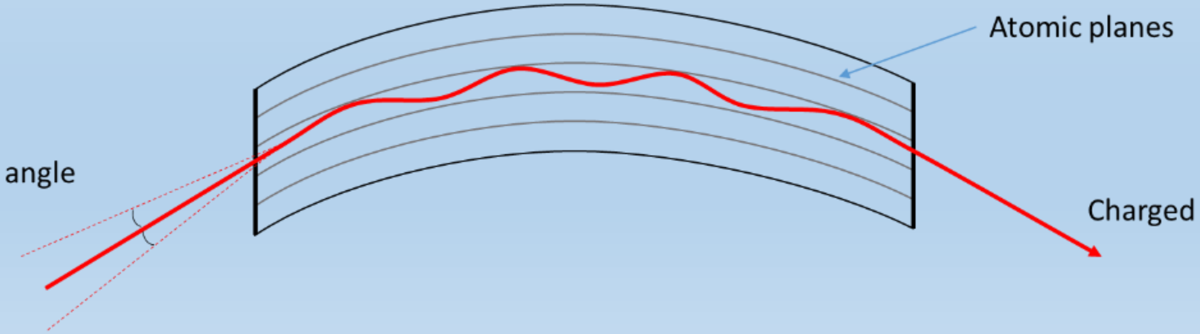
E.N.Tsyganov, Some aspects of the mechanism of a charge particle penetration through a monocrystal, Fermilab TM-682, 1976

"Up to some critical value of the bending radius a particle trajectory will repeat the shape of a bent crystal."

- Experiment – JINR (Dubna), 1979

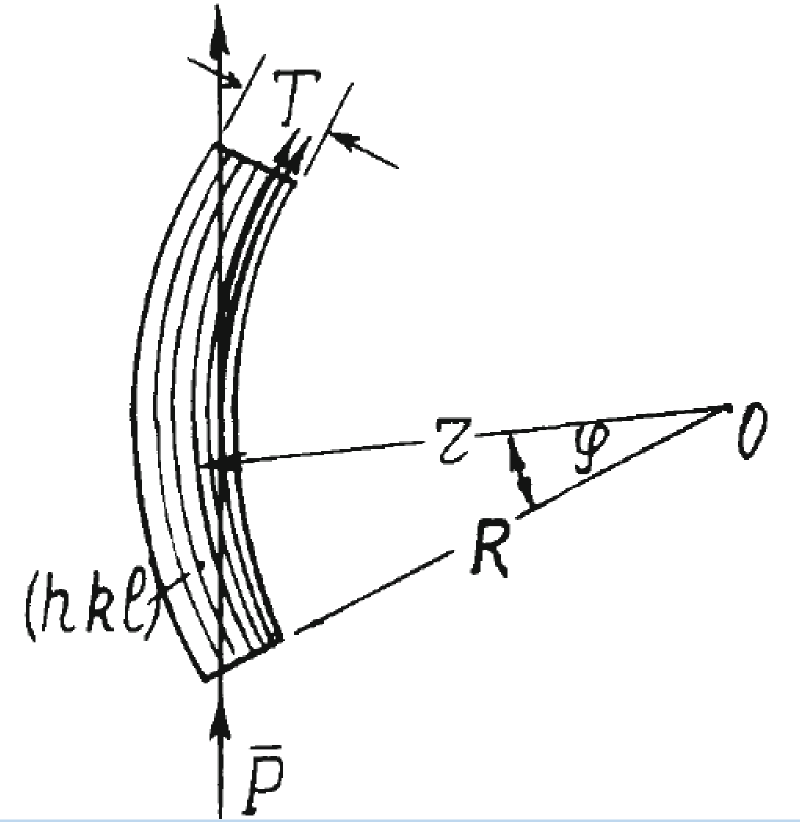
A.F.Elishev et al., Steering of charged particle trajectories by a bent crystal, Physics Letters 88B (1979) 387





High energy volume capture in a bent crystal, PNPI

- Idea – O.I.Sumbaev, 1980



- Experiment – PNPI (Gatchina), 1982

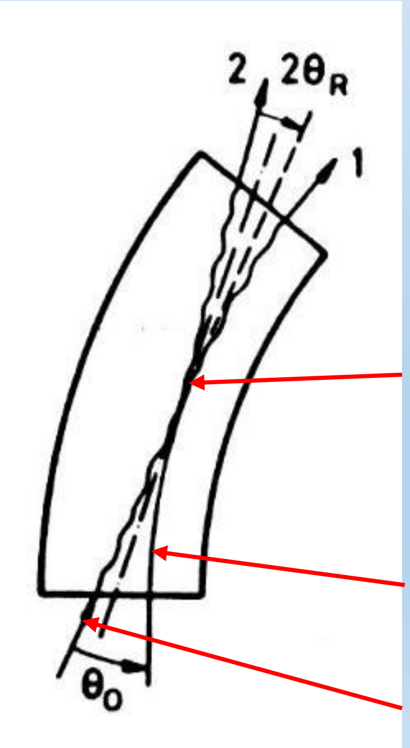
V.A.Andreev et al., Experimental observation of volume capture by a curved single crystal in the channeling regime, JETP Letters 36 (1982) 415

"It is shown for the first time that a curved single crystal can capture particles in the channeling regime for angles exceeding the Lindhard angle. 1-GeV protons were captured during channeling by (111) and (110) planes and by <110> axis along the entire length of 1-cm silicon single crystal curved along a radius of 46 cm in the entire angular range up to 20 mrad."

High energy volume reflection in a bent crystal

- Idea – A.M.Taratin and S.A.Vorobiev, 1987

A.M.Taratin and S.A.Vorobiev, “Volume reflection” of high energy particles in quasi-channeling states in bent crystals, Physics Letters A 119 (1987) 425



1 – Volume Captured particles

2 – Volume Reflected particles

VR/VC effect area - here the particle trajectory is tangent to the atomic plane

Bent channeling plane

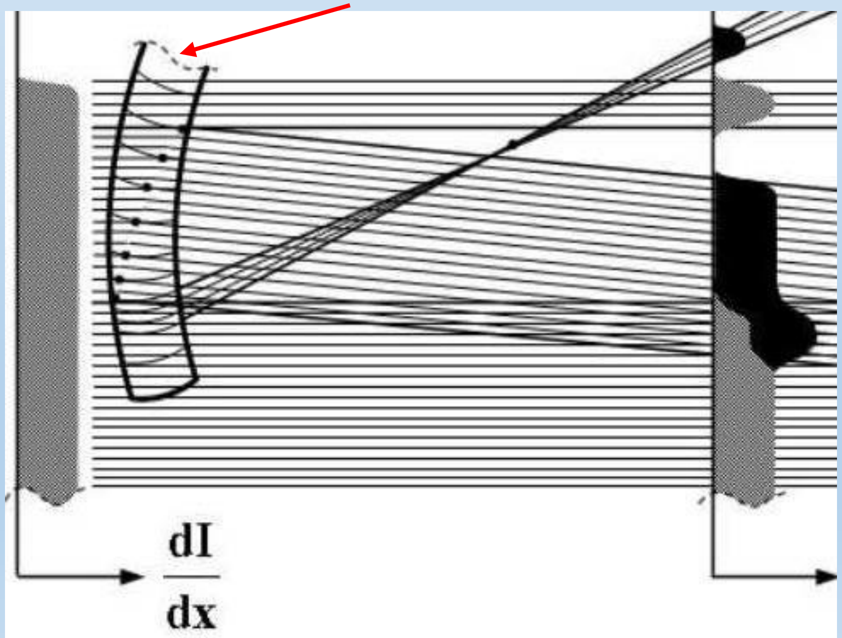
Incident particle

- Experiment – PNPI-IHEP, 2006

Yu.M.Ivanov et al., Volume reflection of a proton beam in a bent crystal, Phys. Rev. Letters 97, 144801 (2006)

Beam Thin bent crystal Emulsion

Bent channeling planes



Channeled beam

Beam

Area without beam

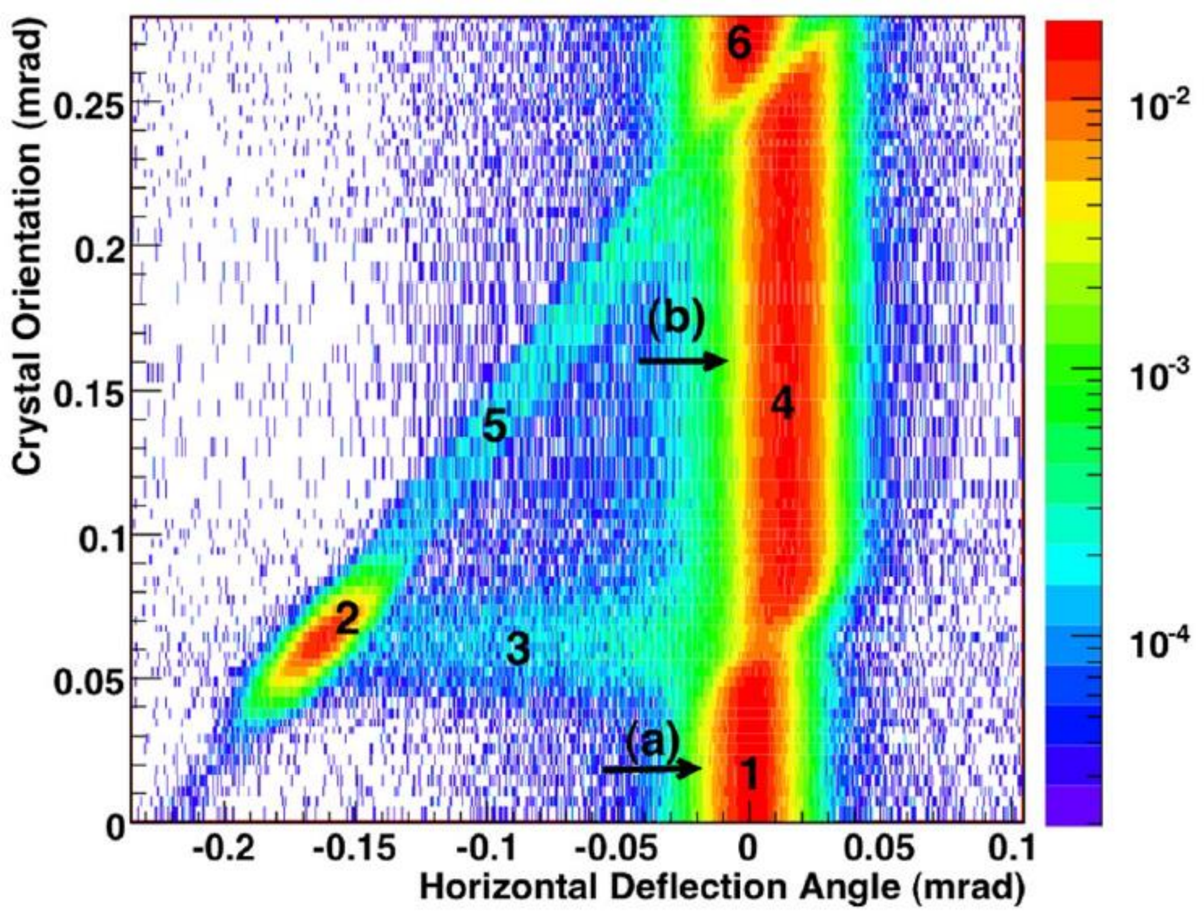
Volume reflected beam

Superposition of volume reflected and unchanneled beams

Beam

Channeling, volume capture and volume reflection with 400 GeV/c protons (H8-RD22, CERN)

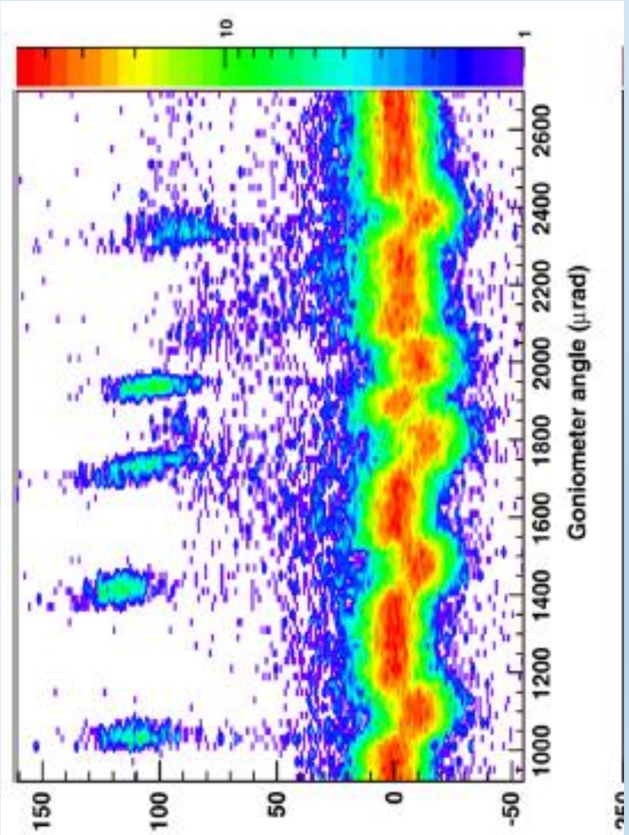
W.Scandale et al., High-efficiency volume reflection of an ultrarelativistic proton beam with a bent silicon crystal, Phys. Rev. Letters 98, 154801 (2007)



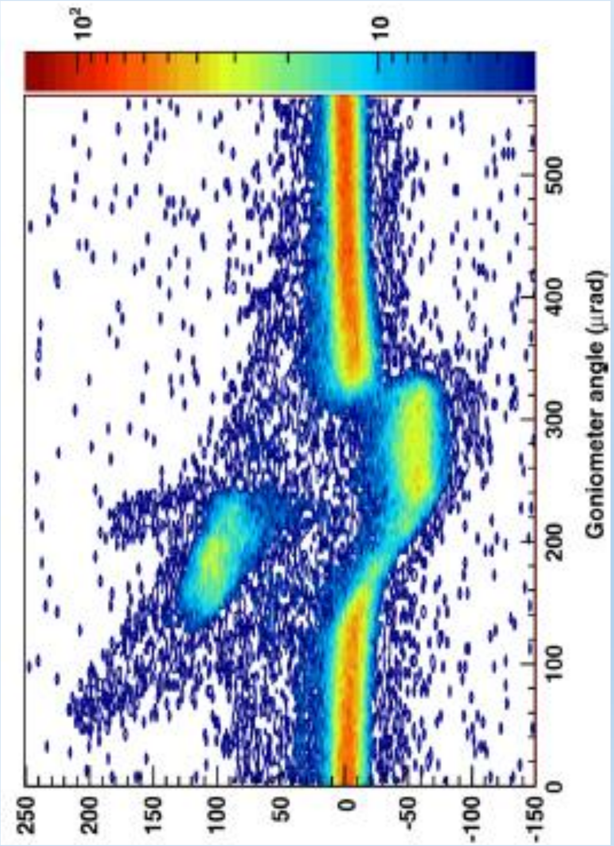
1 – amorphous
2 – channeling
3 – dechanneling
4 – volume reflection
5 – volume capture
6 – amorphous

Multiple volume reflection with 400 GeV/c protons (H8-RD22,CERN)

W.Scandale et al., Observation of multiple volume reflection of ultrarelativistic protons by a sequence of several bent silicon crystals, Phys. Rev. Letters 102, 084801 (2009)



Not aligned 5 bent crystals



Aligned 5 bent crystals

Requirements to single crystal device for SPS nonlocal shadowing

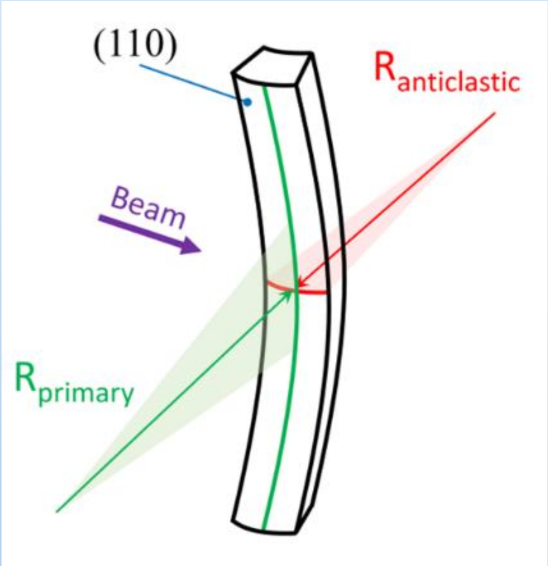
- The crystal should have a thickness of ≈1.8 mm, assuming an effective ZS thickness of 500 μm, and a length of 2.0 mm.

- The crystal should give a deflection angle larger than 150 μrad when aligned in channeling with an efficiency of approximately 50%.

- The crystal should be orientated such that the deflection in channeling is towards the INSIDE of the machine.

Prototype single crystal device for SPS shadowing

- The design of single crystal devices and first prototypes were developed in 2017 for LHC collimation and SPS local shadowing experiments, the both experiments were successfully carried out in 2018.



Anticlastic bending of atomic planes

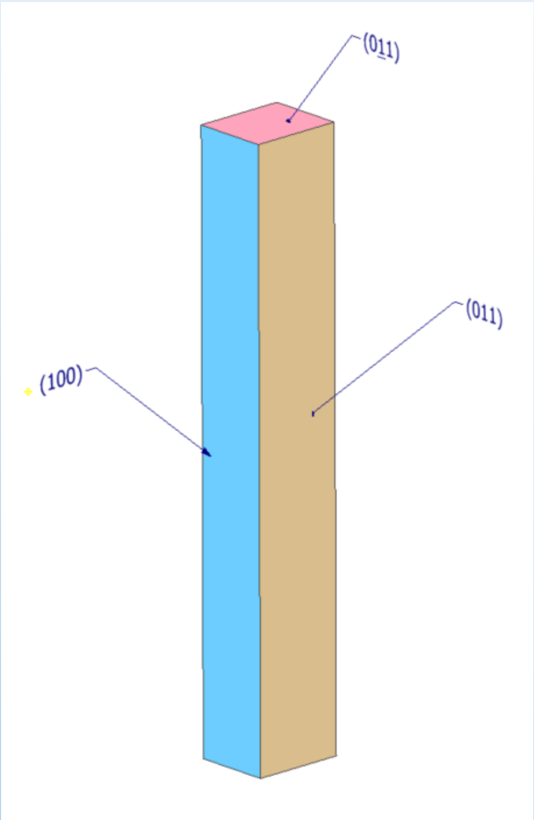
$$R_a \approx \frac{S_{35}^2 - S_{33}S_{55}}{S_{13}S_{55} - S_{15}S_{35}} R_p$$ (V.M. Samsonov, PNPI, 1976)

Firstly used for 70 GeV proton channeling at IHEP, 1998

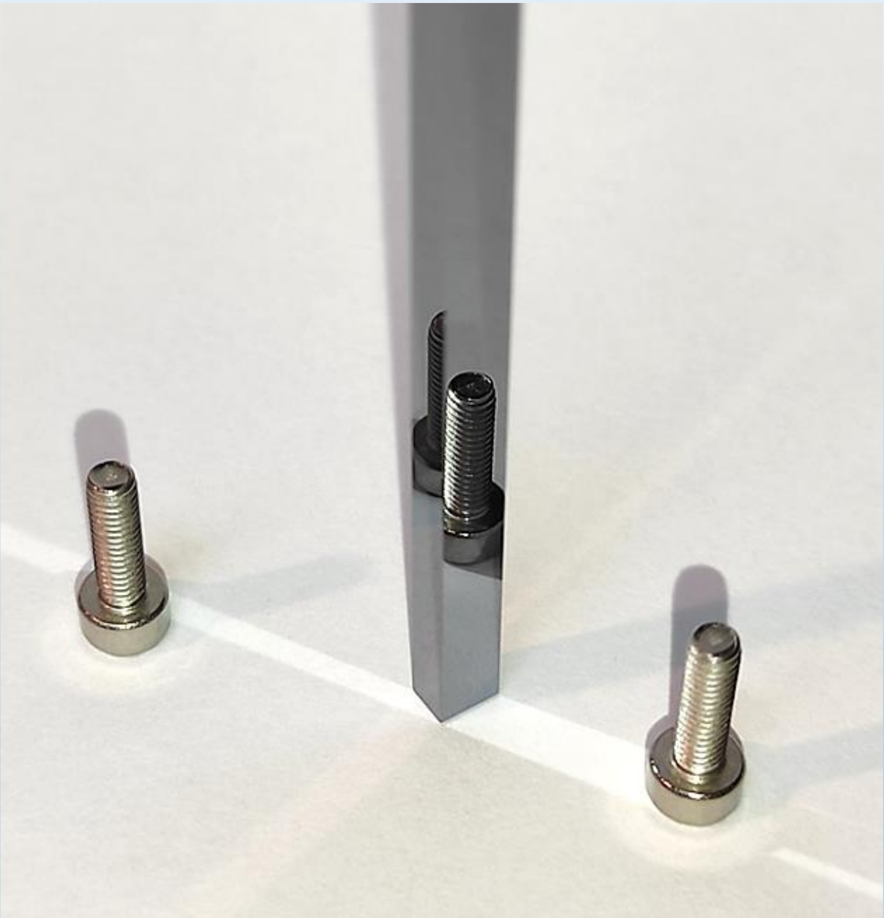
A.G. Afonin et al., First results of experiments on high-efficiency single crystal extraction of protons from the U-70 accelerator, JETP Letters 67 (1998) 781

- We use this design as a base to develop devices for SPS nonlocal shadowing.

Silicon strip design features



- 4 working faces of each crystal strip are deeply polished so each face may be used as a mirror for alignment
- 2 mm (110) faces have flatness ~0.2 μm and miscut ~20 μrad
- 1.8 mm (001) faces have miscut ~20 mrad to prevent axial channeling



Holder manufacturing features

- PNPI in-house CNC manufacturing of all holder parts.
- PNPI in-house sub-micron machining of holder surfaces to provide required bending of the crystal.

Assembly and installation control – digital autocollimators

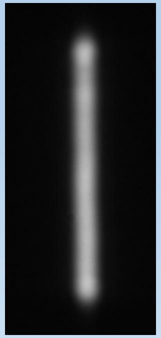
The series of digital autocollimators (AC) developed in-house by PNPI (Yu.A.Gavrikov et al.) since 2006 for crystal applications:

- to measure a surface shape of the flat and bent crystals;
- to control the bending of crystals during assembling;
- to align crystals respect to stations during installations;
- to provide a precise angle measuring with rough and nonlinear goniometers.

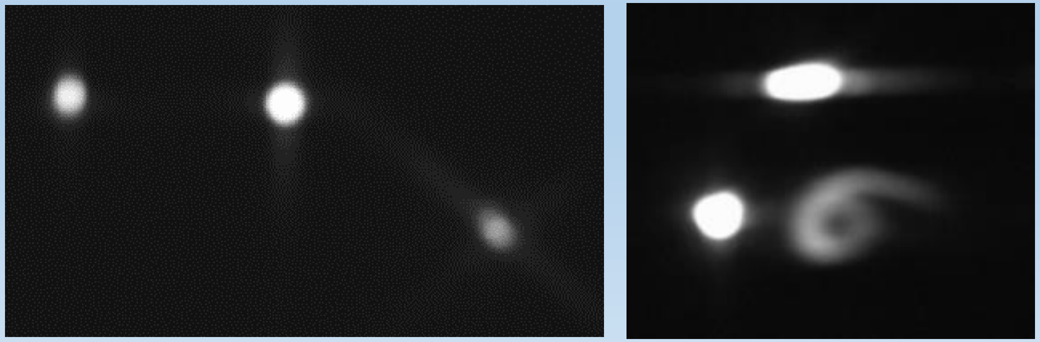
The crucial features:

- high sensitivity to provide precise measurements with silicon surface of area down to 1 mm^2;
- feasibility to measure and analyze multiple reflections from several reflective surfaces;
- angular range from 6000 to 30000 μrad;
- accuracy 1 μrad.

Bent crystal/ cylindrical surface

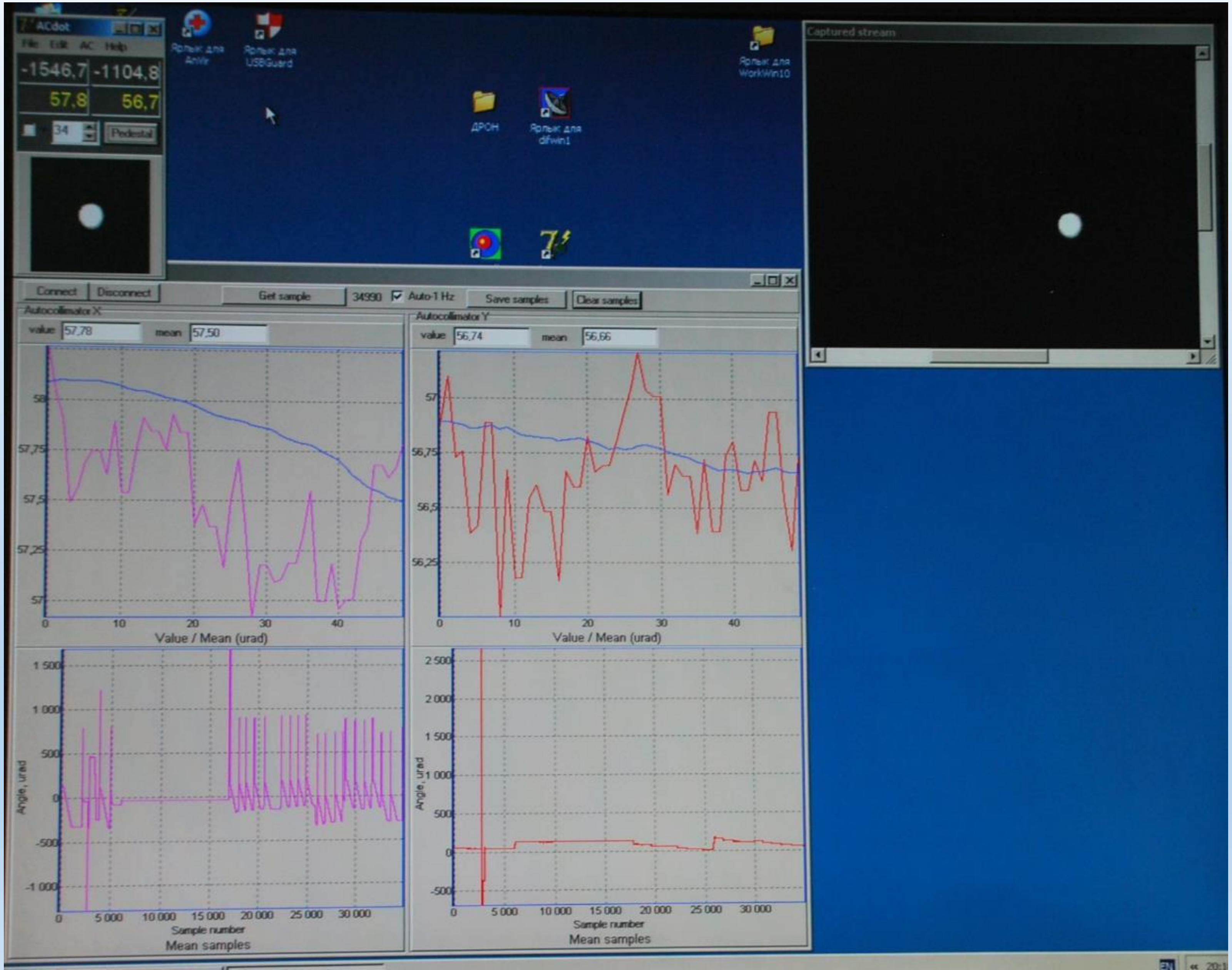


Multiple reflections from flat and non-flat surfaces



Simple and easy interface during measurements with AC

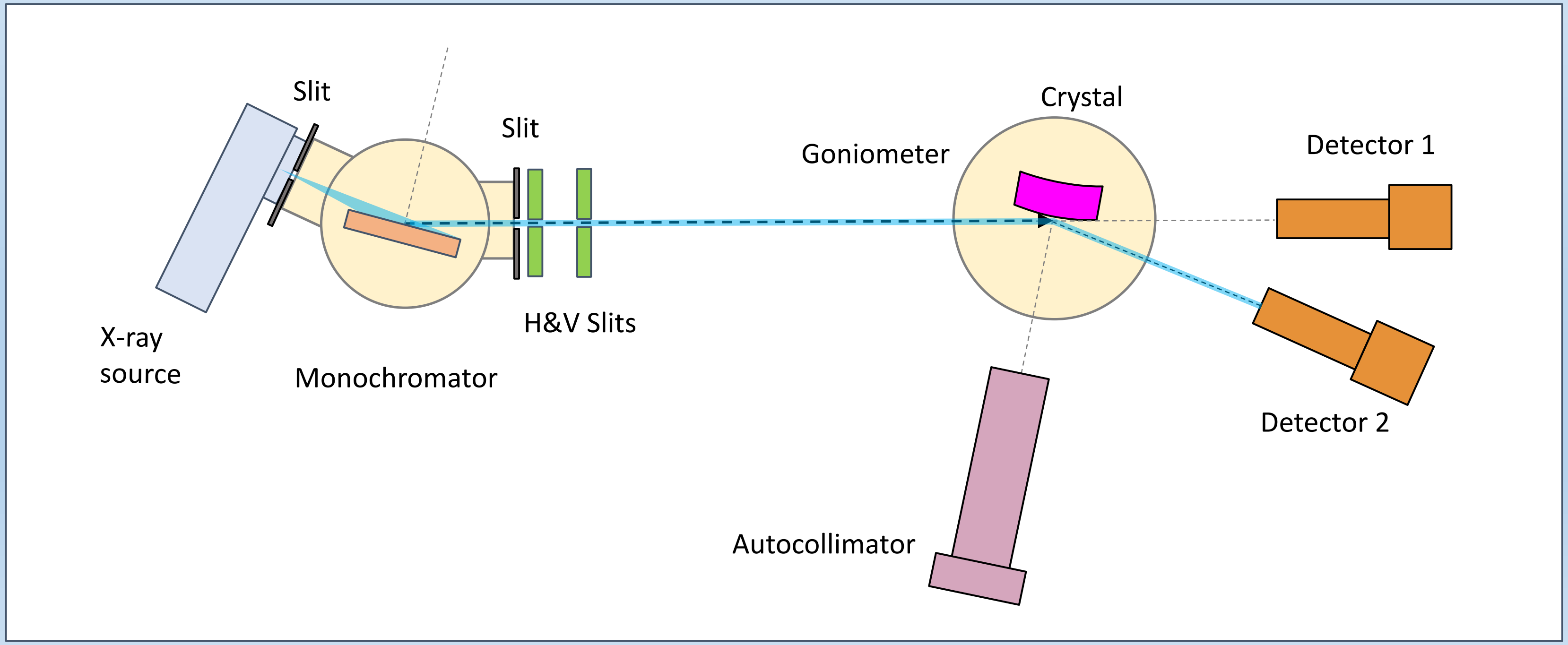
AC window

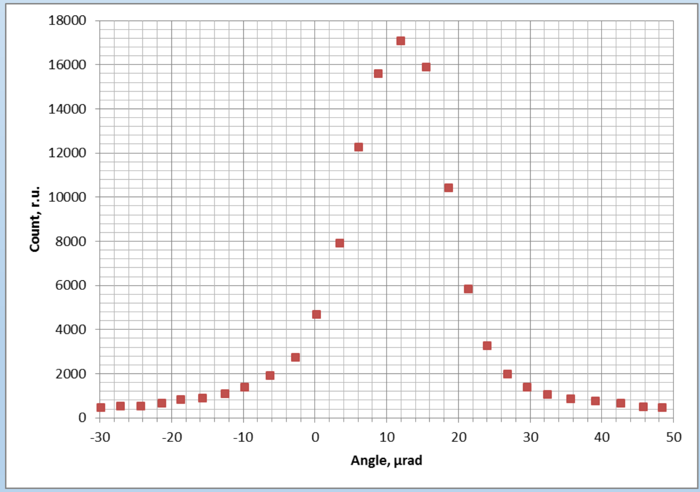


Crystal assembly characterization – X-ray setup

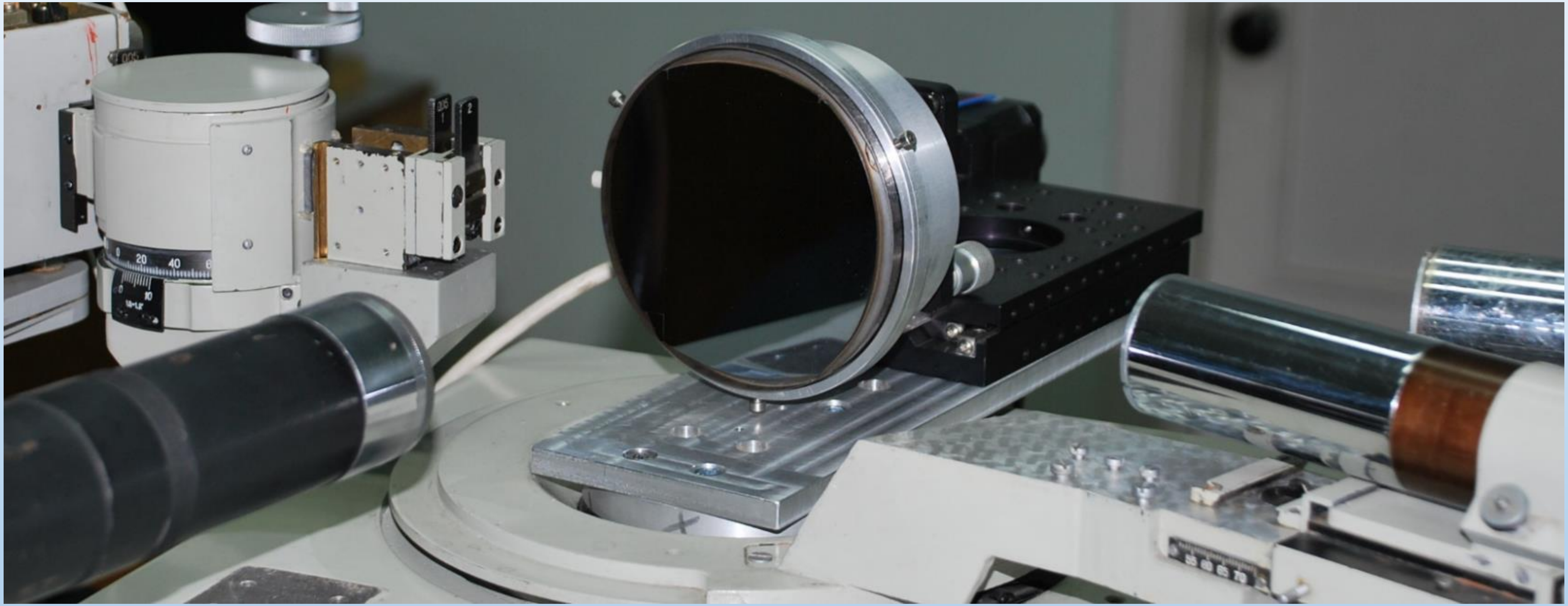
Si(220) Mo Kα1 line from two flat LHC (SPS) crystals:

W ≈ 14.7 μrad (3 arcsec)

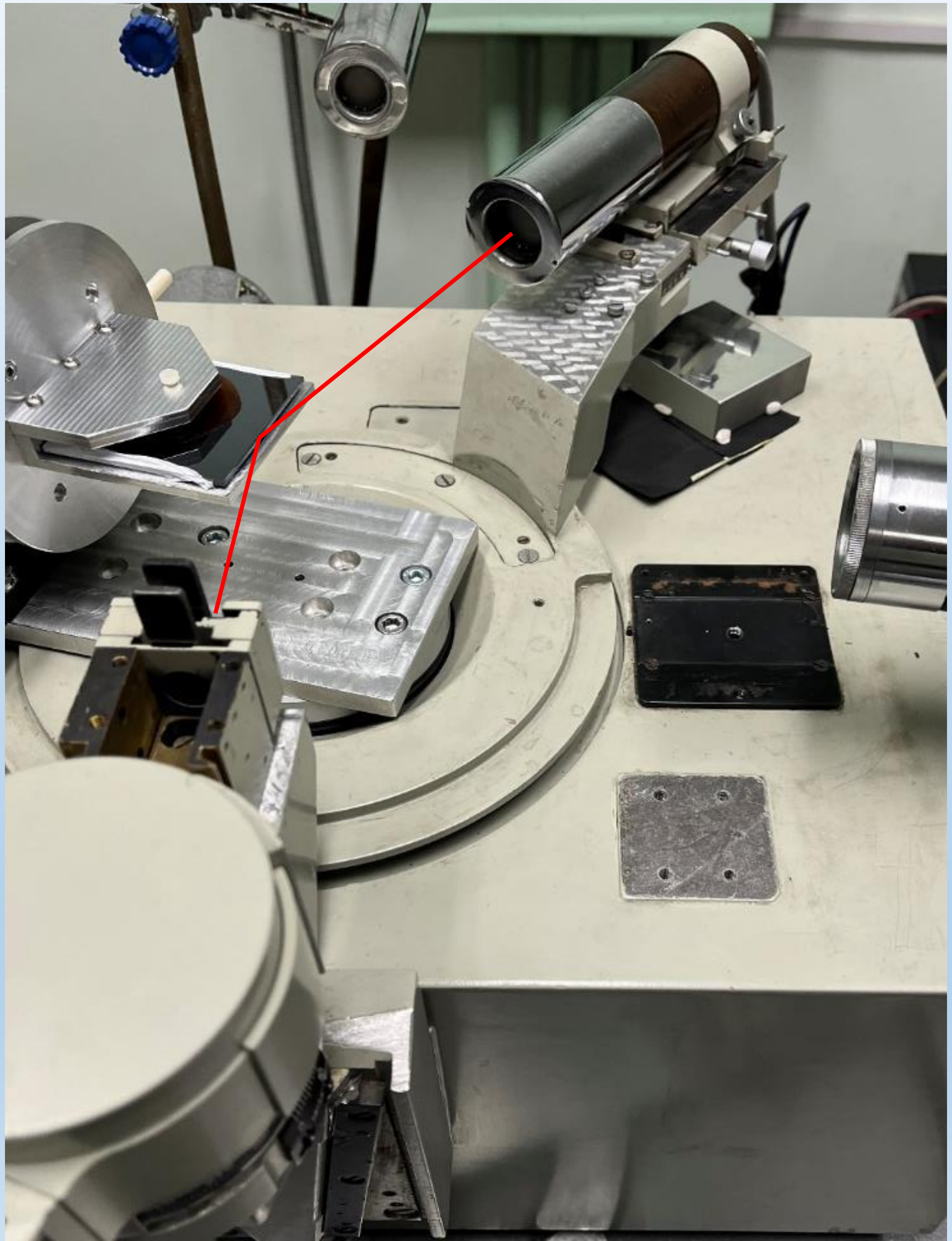


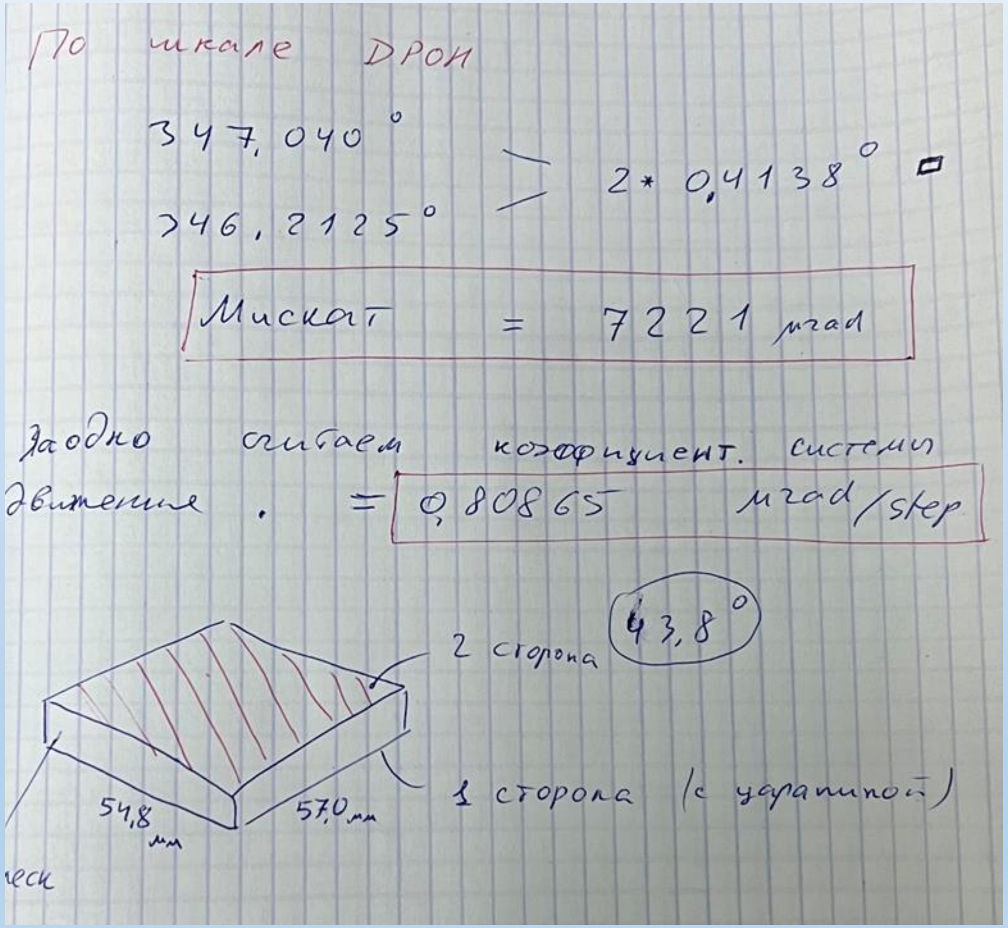


Miscut measurement of polished channeling face



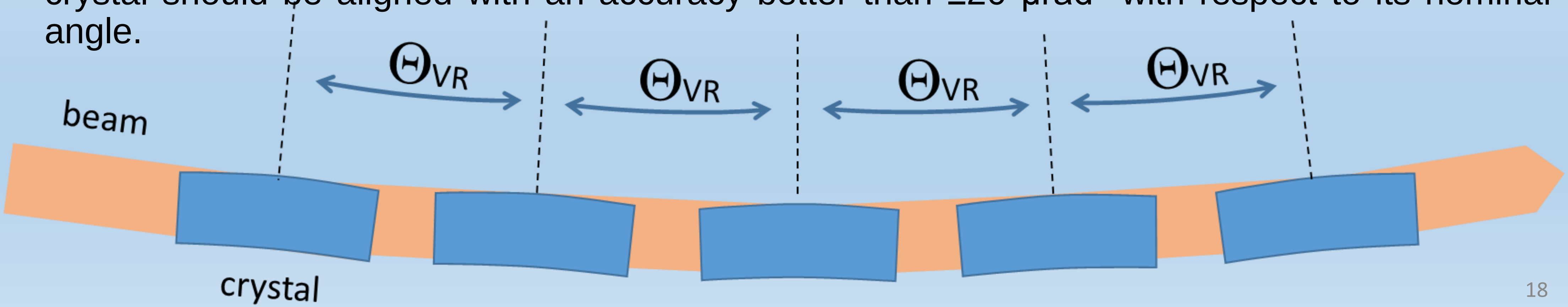
Miscut measurement of entrance/exit face





Requirements to multi-crystal device for SPS shadowing

- The MVR array should have a thickness of ≈1.8 mm assuming an effective ZS thickness of 500 μm.
- The position of the crystals in the array should be aligned with a relative accuracy of ±0.1 mm.
- The MVR crystal should be composed of 5 crystals (which are like the crystal in single variant) each giving a deflection in volume reflection of -13 μrad , giving a total deflection angle of -65 μrad.
- The MVR crystal array should be orientated such that the deflection in volume reflection is towards the INSIDE of the machine.
- To maximize the angular acceptance of the MVR crystal array, each crystal should be aligned on a common support with a relative angle that follows the cumulative deflection in volume reflection from one crystal to the next, i.e. at an angle of -13(n-1) μrad where n = 1 to 5. Each crystal should be aligned with an accuracy better than ±20 μrad with respect to its nominal angle.

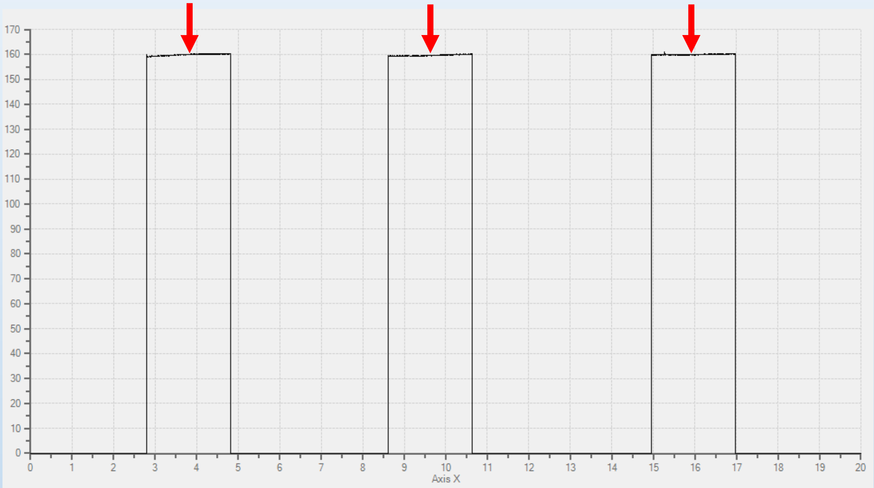


The 3-strip model to prototype multi-crystal device for SPS shadowing

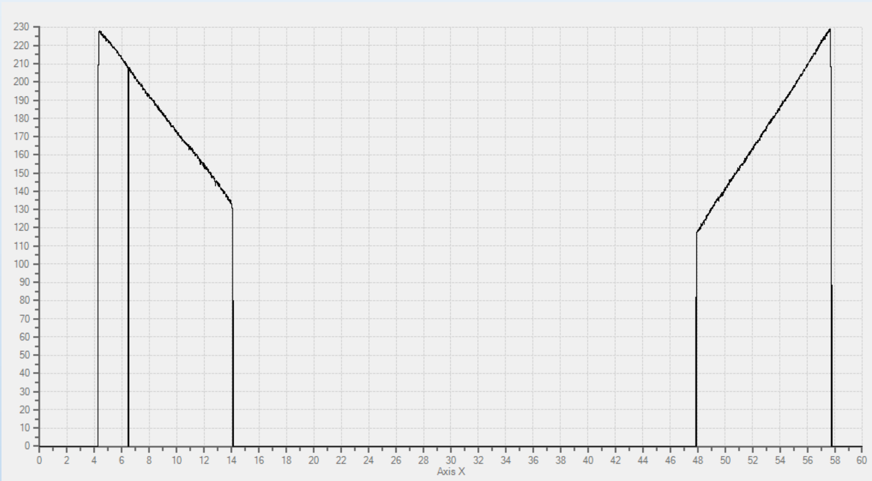
- Three (3) silicon strips of 1mm x 2mm x 54 mm dimensions from commercial (110) silicon wafer 1mm x 100 mm.
- Robust static design without adjustment screws and instability sources.
- Identical bending of crystals in a row.
- Controlled torsion of the crystals during assembly process.
- Contactless optical and X-ray procedures to check multi-crystal array.
- Thermal stability up to 250°C confirmed for single crystals of similar concept developed by PNPI in 2017.

Contactless optical measurements with the 3-strip model

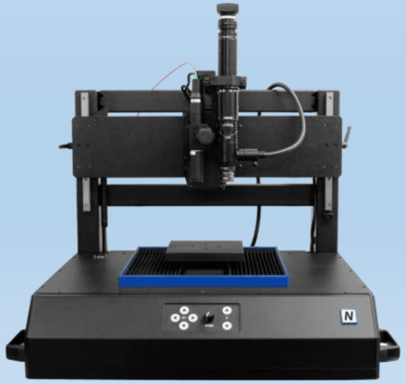
3 strip crystals are in line within 2 µm

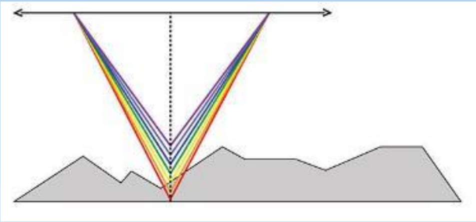


Shape of holder surfaces defining the primary bending of crystals

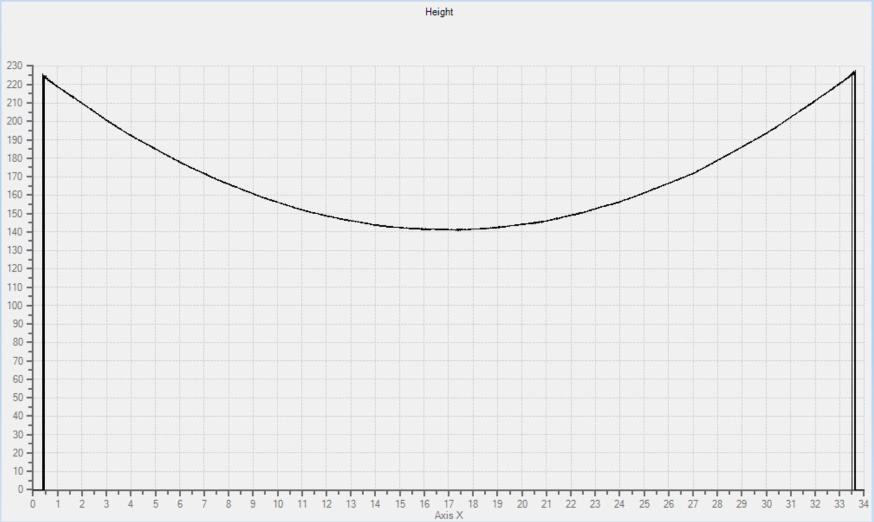


Optical profilometer NANOVEA ST400 to measure polished and unpolished surfaces



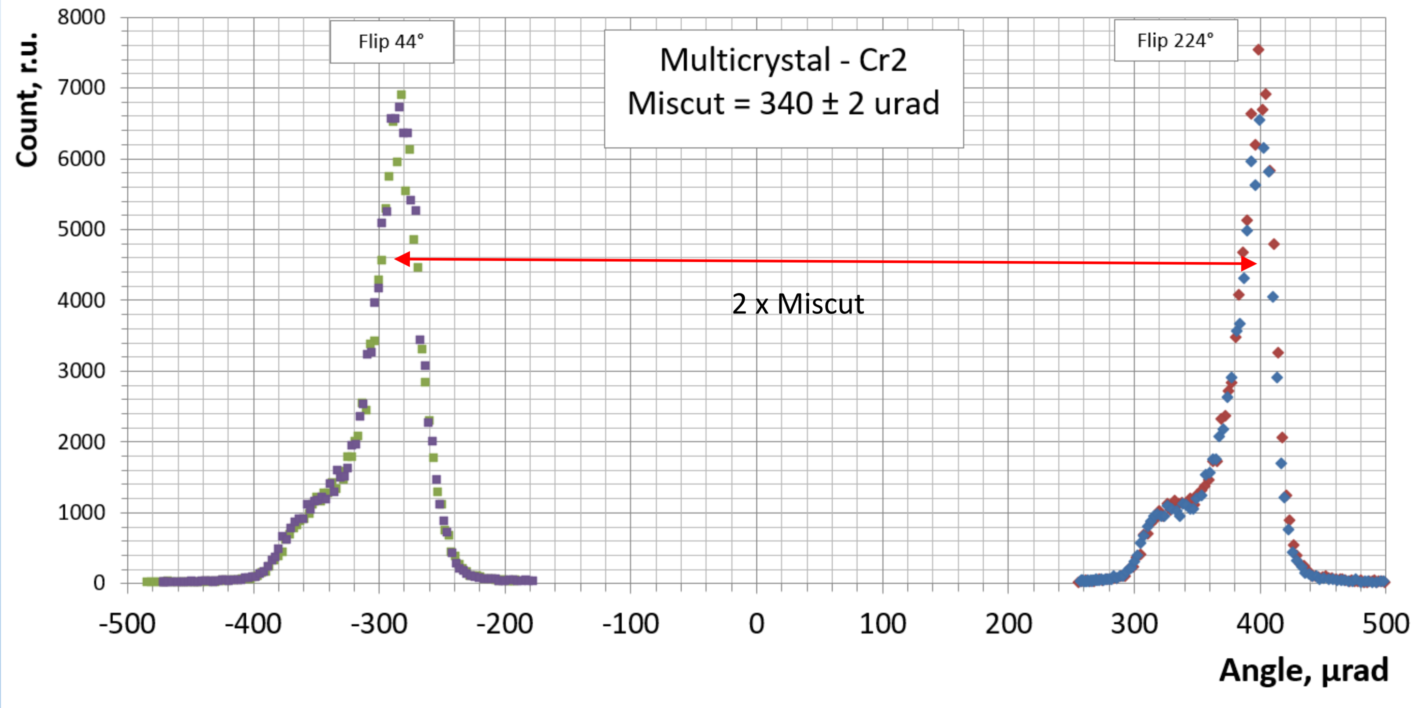


Shape of bent silicon strip along height (primary bending)

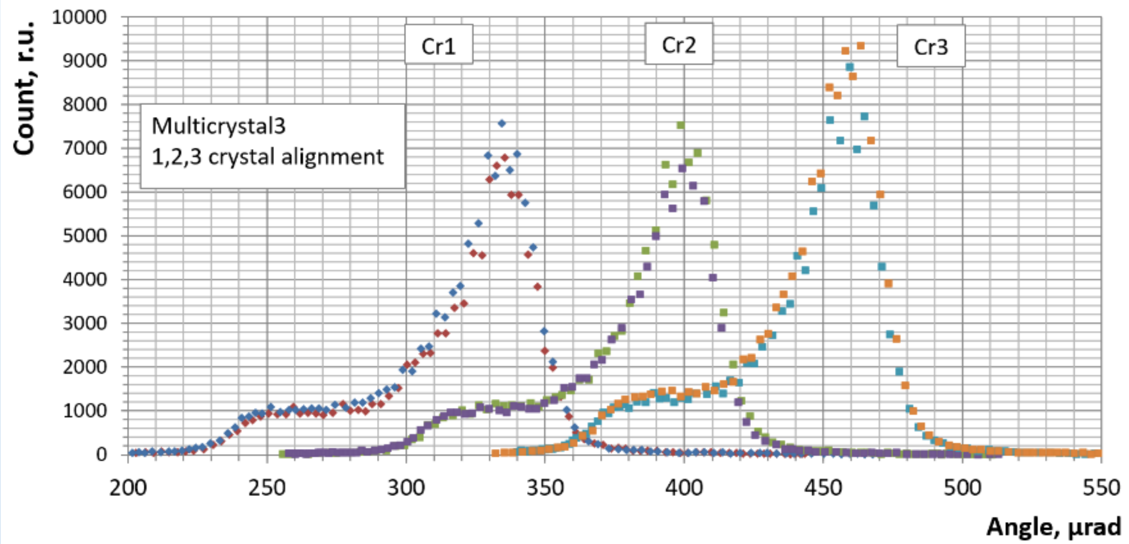


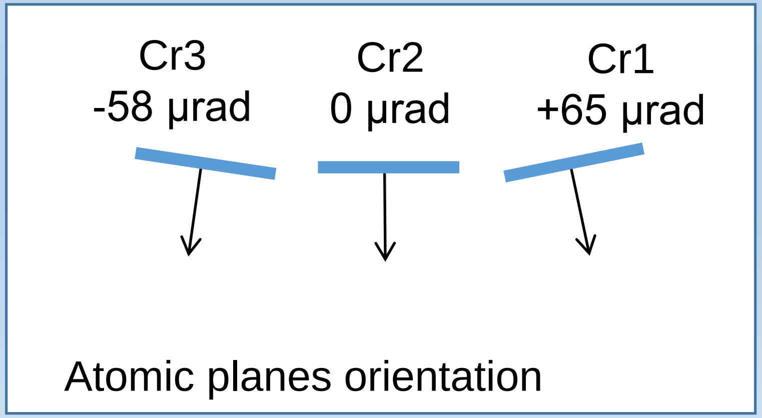
X-ray measurements with 3-strip model

Miscut measurement of each single crystal in 3-strip model



Mutual orientation of crystals in 3-strip model



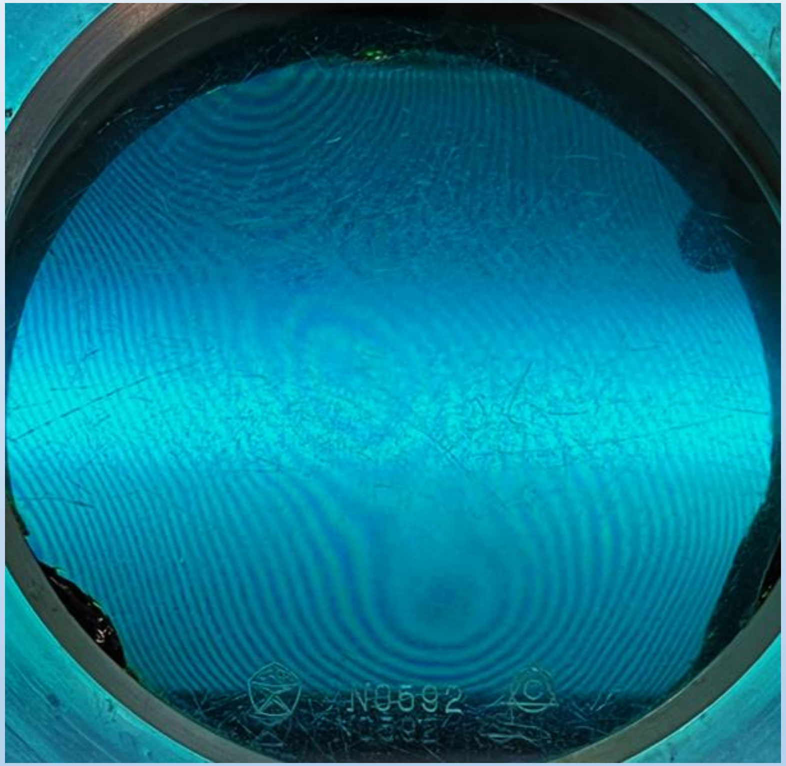


Summary of measurements with 3-strip model

- Bending angle of crystals in array can be defined with accuracy < 10 μrad
- Mutual orientation of crystals in array can be defined with accuracy < 10 μrad
- Miscut angle of crystals in array can be defined with accuracy < 10 μrad
- As a result the method developed to validate the multi-crystal device parameters

The reason of crystals disorientation in 3-strip model

Disorientation of crystals in 3-strip model is due to miscut and shape of typical commercial wafer used to prepare strips for the model



The contactless interference pattern between optical glass standard and commercial silicon wafer from mercury lamp (λ ≈ 0.4 μm) which corresponds to sagitta of more than 5 μm

Solution - to improve flatness and miscut of the wafer, or produce a wafer with close to zero flatness and miscut

Steps of manufacturing - 1

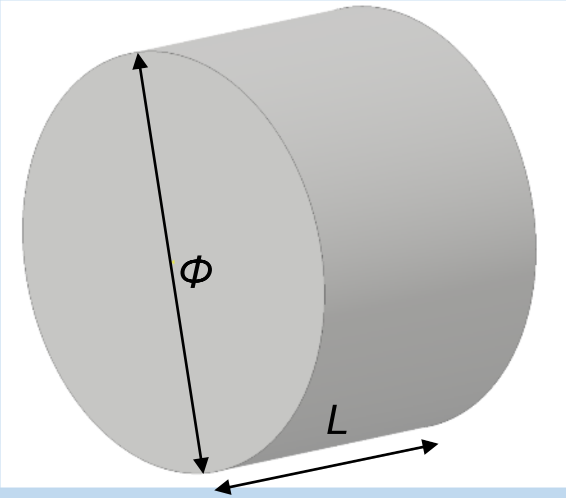
- Float zone dislocation free high purity silicon
- Ingot sizes:

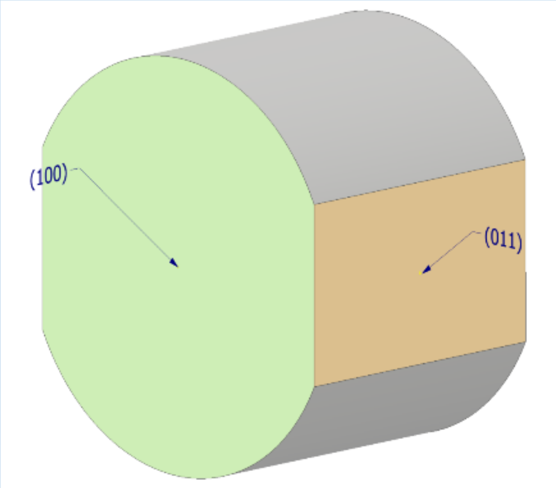
  Φ=80-100 mm

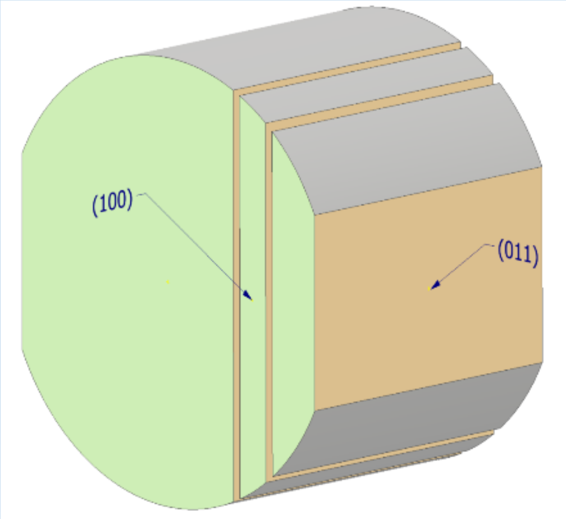
  L=60-120 mm

- Ingot orienting with X-rays
- Grinding of base cuts parallel to required atomic planes providing miscut ~300 μrad

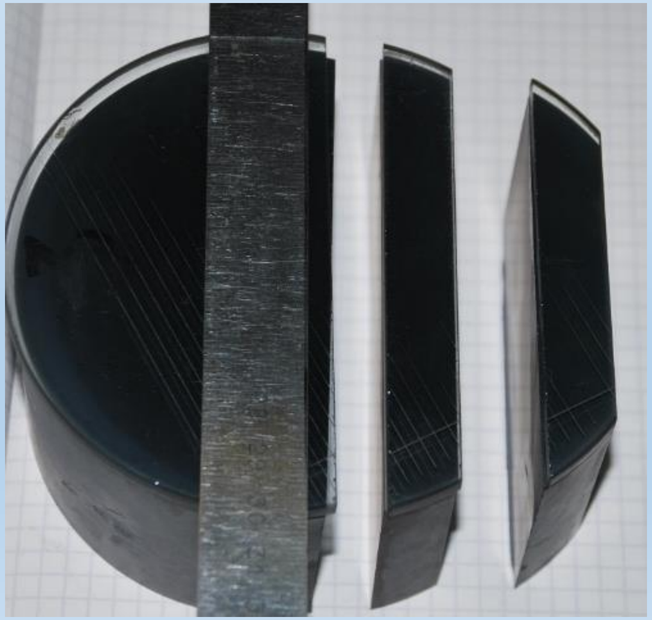
- Thick (15-20 mm) slices cutting from ingot of necessary orientation





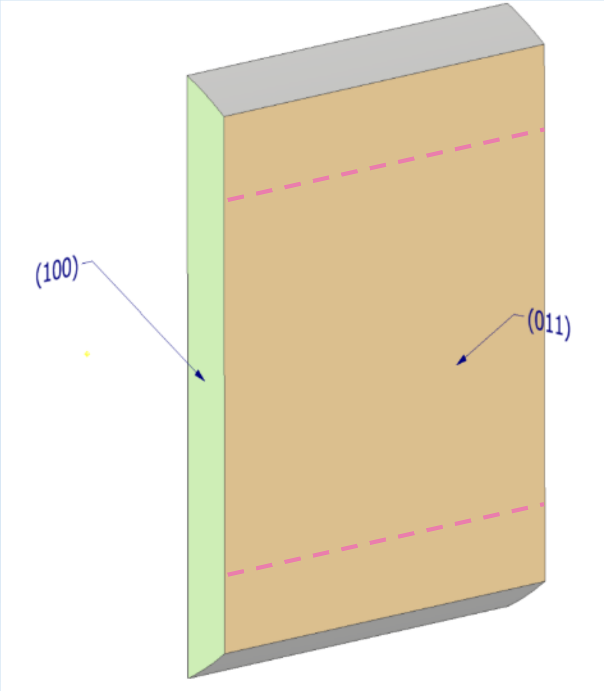


PNPI in-house crystal production – ingot cutting

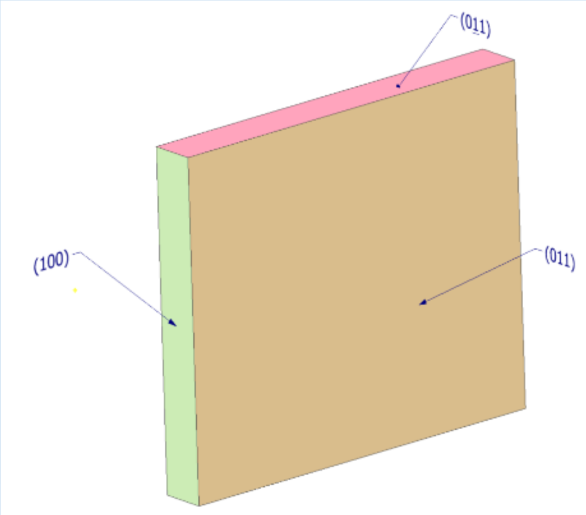


Steps of manufacturing - 2

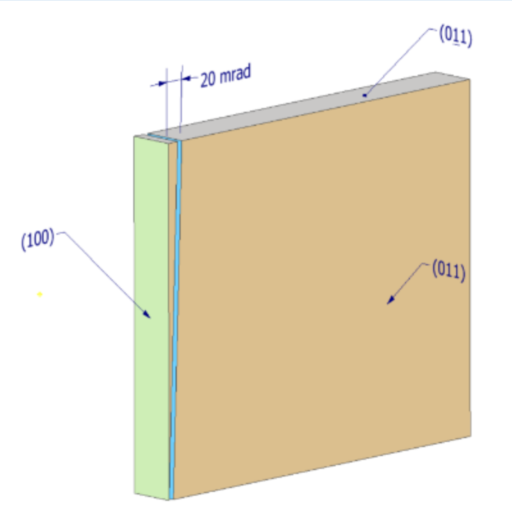
- Cutting thick slice into oriented prismatic plate



- Orienting with X-rays, grinding, deep polishing of faces parallel to atomic planes (011)
- Miscut of faces parallel to (011) planes reduced in series iterations down to ~10-20 µrad
- Provided parallelism between large faces ~10 µrad



- Orienting, grinding, polishing of narrow face to provide miscut angle with (100) plane > 18 mrad

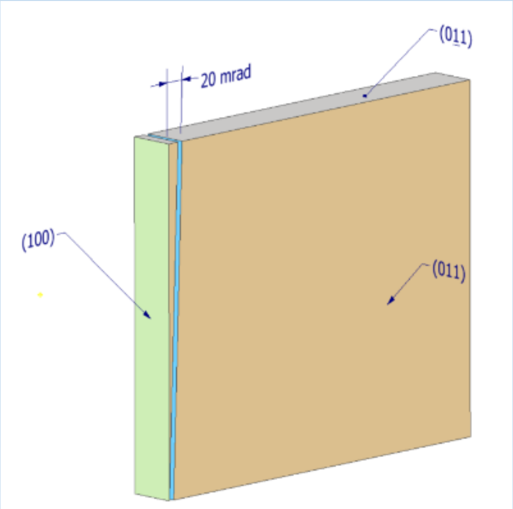


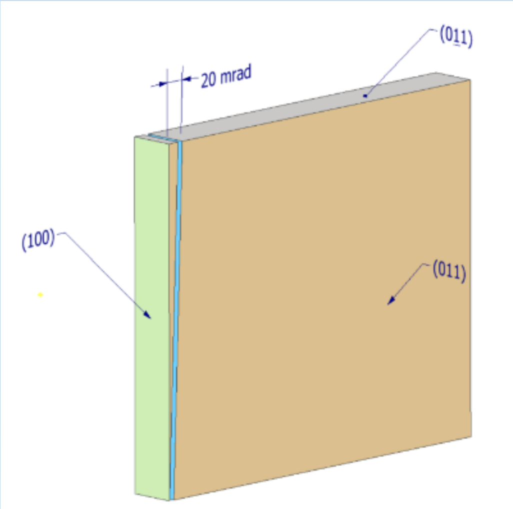
Steps of manufacturing - 3

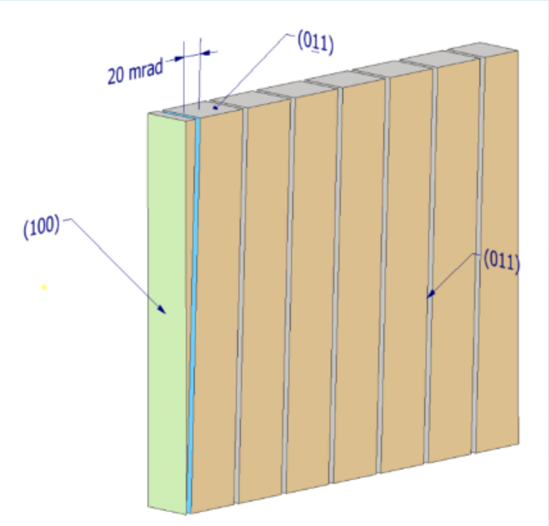
- Cutting from thick (15-20 mm) plate manufactured close to optical standard a thin slice (wafer) of ≈ 3 mm thickness parallel to large face (011)

- Grinding, deep polishing of the thin plate (wafer) face parallel to (011) after dicing
- Contactless flatness check of both large faces of thin plate (wafer)

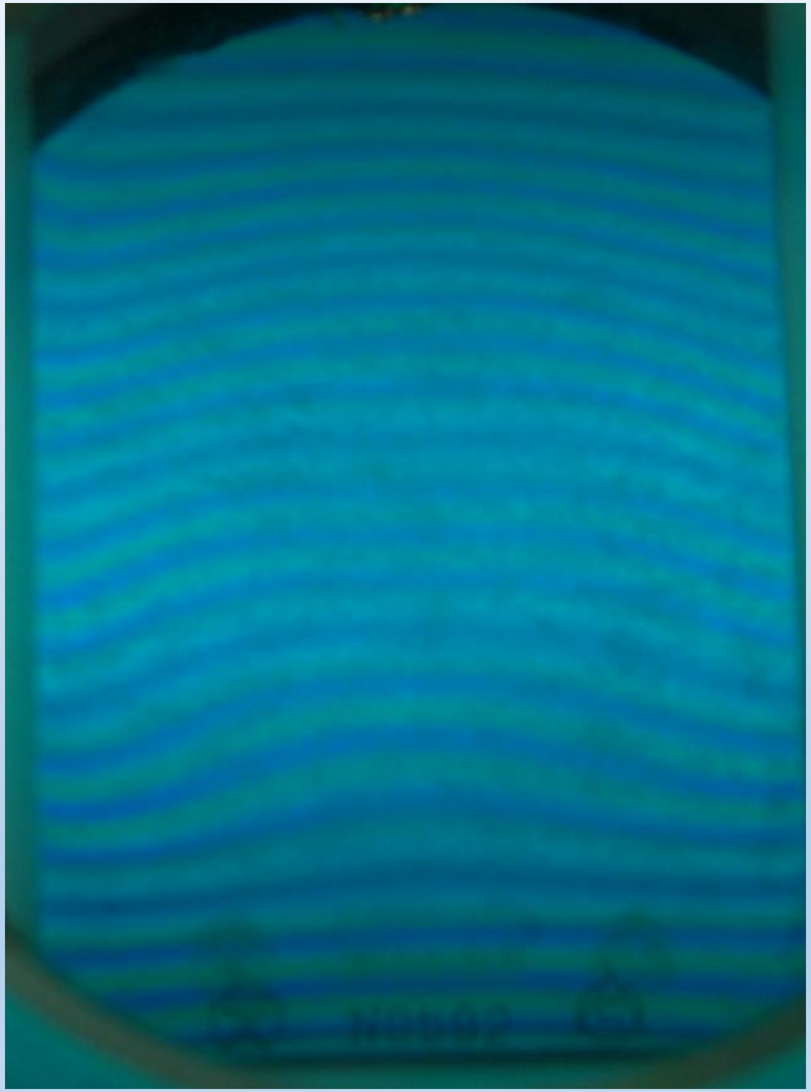
- Dicing thin plate (wafer) into strips

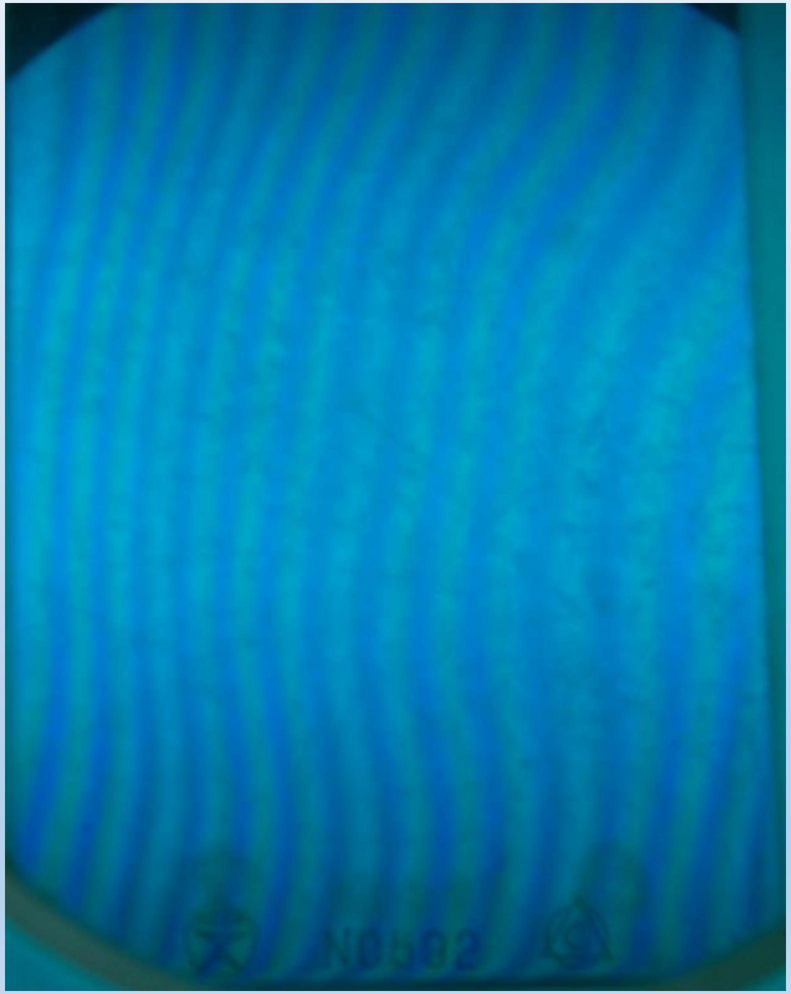


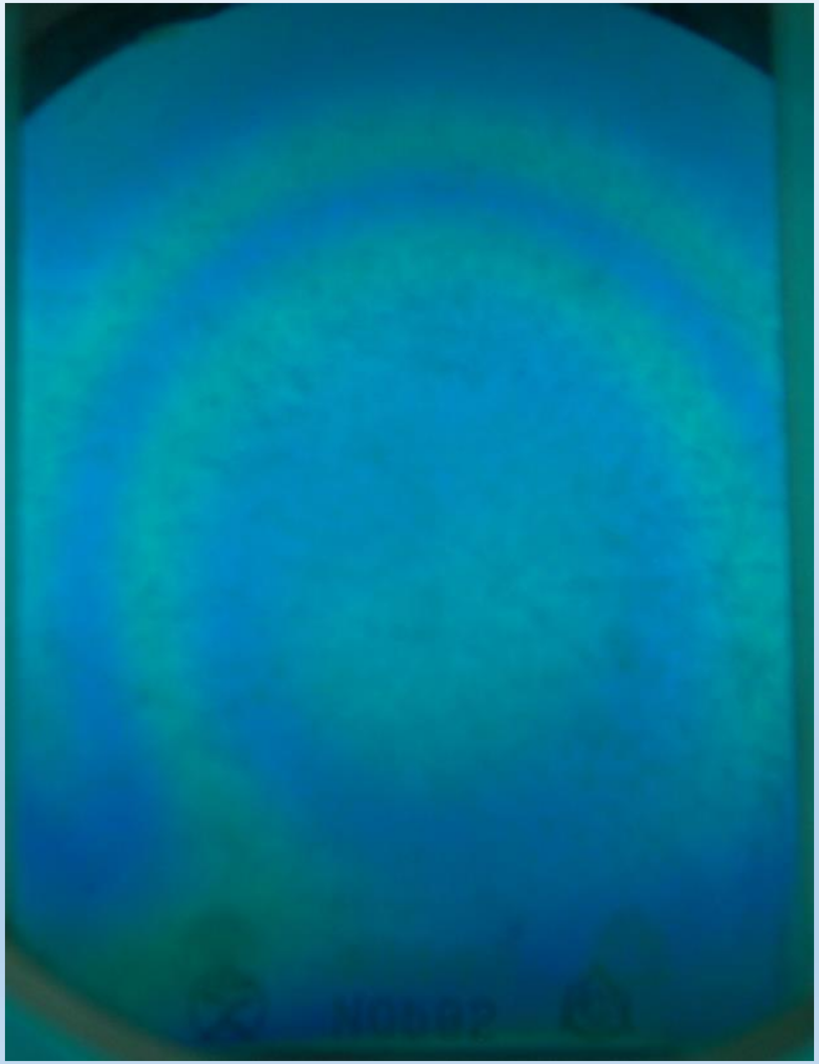




Side 1 after final polishing – concave sphere of about 0.25 micron

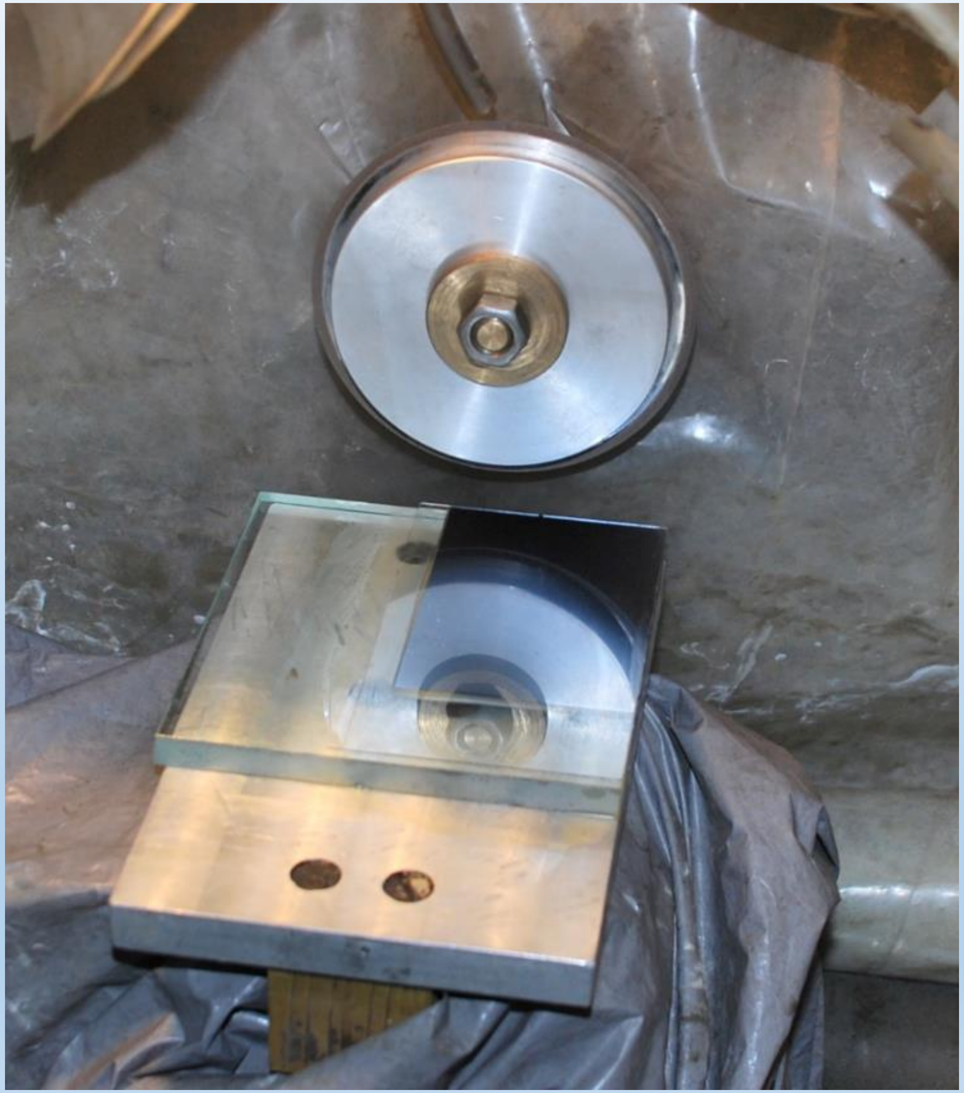






Side 2 after final polishing - concave sphere of about 0.2 micron

PNPI in-house crystal production - cutting strips



Summary

- Production line for SPS strip crystals well established
- We are on final stages of crystal strip production
- A method to control multi-crystal array with X-ray developed
- We are in process of multi-crystal holder production

Thank you for attention !