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Crystal collimation for Pb ion beam operation in Run3

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on behalf of WP5
With inputs from BE-ABP and SY-STI

11th HL-LHC Collaboration Meeting, 20.10.2021

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Introduction

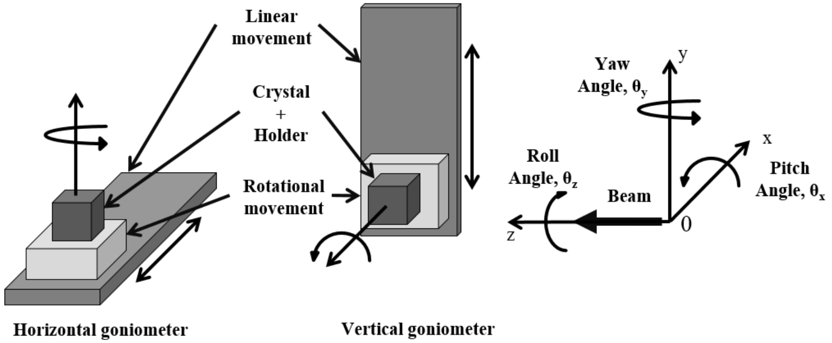
- For Pb operation in HL-LHC and Run 3: expect higher power loads from beam losses on superconducting magnets
  - ✓ Pb stored beam energy will increase from 12.9 MJ (2018) to 20.5 MJ (Run 3 and HL-LHC), beam energy goes up, and quench limit goes down
  - ✓ Needed upgrade of collimation system for Pb ion operation
- Initial upgrade baseline: TCLD collimators + 11T dipoles
  - ✓ Not achieved in LS2 due to 11T performance degradation
  - ✓ Falling back to previous backup solution: crystal collimation
- Present strategy: crystal collimation to be used operationally as main collimation strategy for Pb throughout Run 3
  - ✓ Crystals are considered a mature technology to be used in routine operation *
  - ✓ Need one crystal as primary collimator per beam and plane
- Crash program put in place to build two new goniometers at CERN for installation already in LS2
  - ✓ Goal: replace two out of presently installed four devices

* http://cdsweb.cern.ch/record/2778809/files/document.pdf
https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.14.064066

Courtesy of Roderik Bruce

Goniometers for Crystal Collimation– A technological challenge

- High-precision angular positioning system

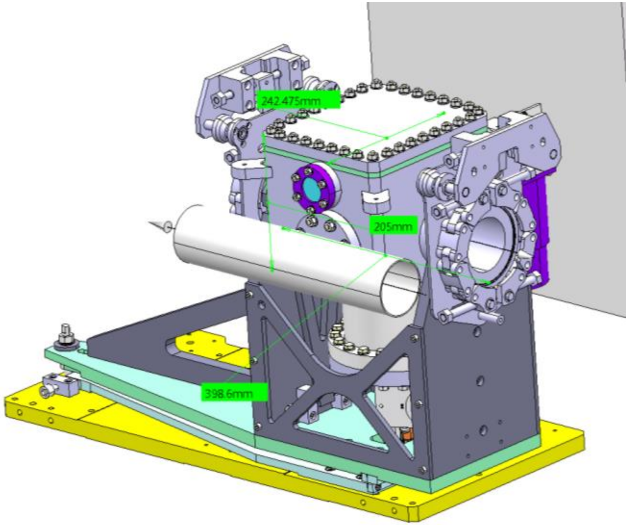


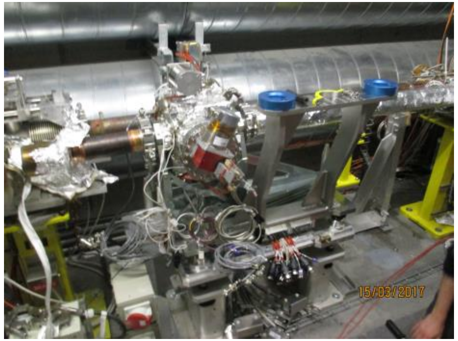
Orientation independent angle nomenclature	Angle w.r.t. beam	
	Horizontal goniometer	Vertical goniometer
Rotation	Yaw	Pitch
Tilt	Pitch	Yaw
Roll	Roll	Roll

Property	Specification
Linear stroke	> 50mm
Linear resolution	5 um
Linear accuracy	+/- 20 um
Total angular range	+/- 10 mrad
Yaw angular resolution	0.1 urad
Yaw angular accuracy over the entire linear range	+/- 1 urad
Yaw angular overshoot	10%
Yaw angular settling time	20 ms
Yaw angle max speed in scan mode	50 urad/s
Pitch angular accuracy over last 10 mm travel	Few urad
Roll angular accuracy over last 10 mm travel	Few tens of urad

Piezo goniometer design concept

- Linear movement: Stepper motor actuated lead screw drive axis
- Rotational movement: Piezo actuated rotational stage

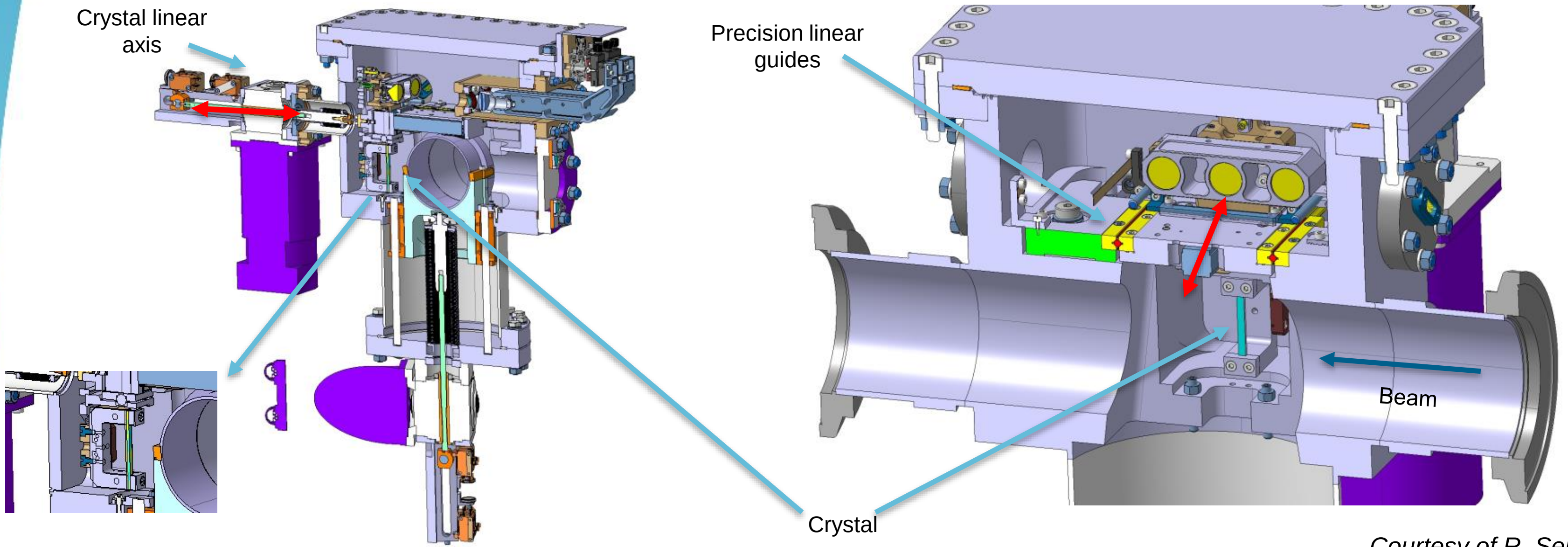




TCPCV.A6R7 B2 Vertical

Linear movement

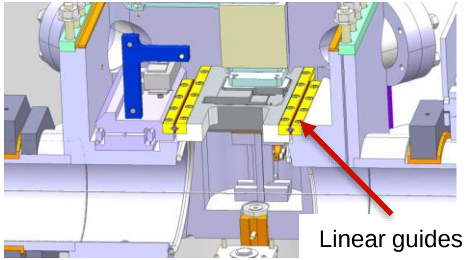
- Stepper motor actuated linear axis to insert/move-out the crystal from beam path
  - ✓ Beam pipe segment inserted when goniometer not in operation to make device ‘transparent’ to the high-intensity circulating proton beam
- Precise bearings to minimize the crystal parasitic angles during the linear movement

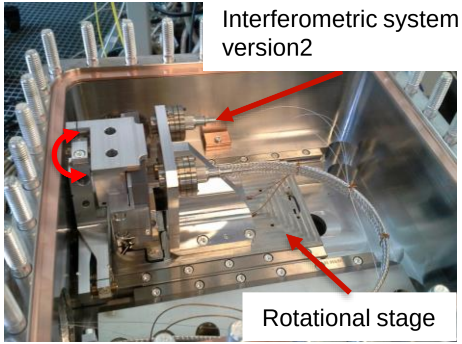


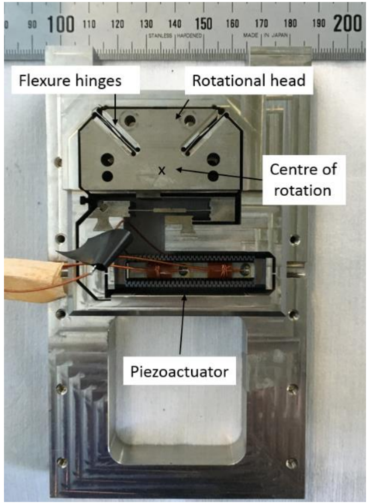
Courtesy of R. Seidenbinder

Rotational movement

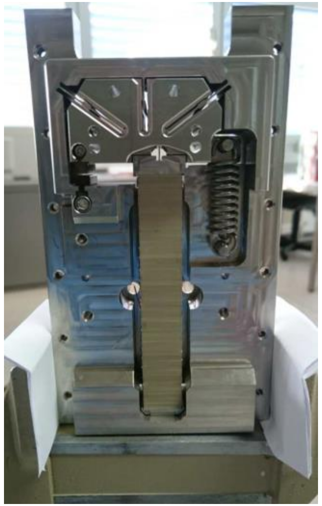
- Piezo actuated high-precision rotational stage mounted on linear axis
  - ✓ Controlled in closed-loop
- Interferometric system to monitor the crystal rotation w.r.t. beam axis



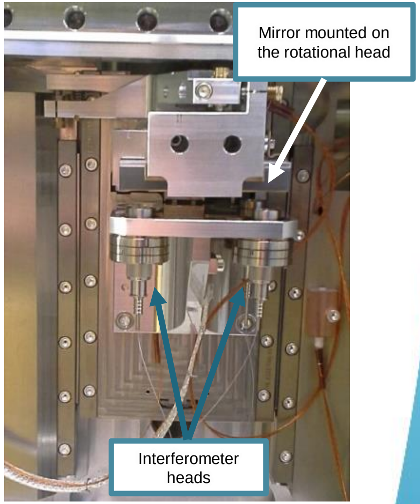




Rotational stage (V1) used in Beam 1 goniometers.



High stiffness rotational stage (V2) used in Beam 2 goniometers.



Interferometric system common in all goniometers.

Goniometers for Crystal Collimation

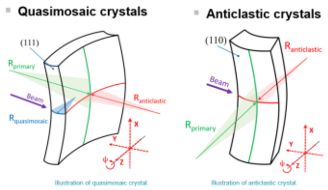
- **4 Goniometers installed for RUN2-MDs. They were not designed/conceived to be operational devices for RUN3 without any upgrade during LS2**

Functional Type	Position	Crystal Type	Installation Year	Version
TCPCH	A4L7.B1	SD (INFN)	2013 (LS1)	1
TCPCV	A6L7.B1	QM (PINP)	2013 (LS1)	1
TCPCH	A5R7.B2	SD (PINP)	2018	2
TCPCV	A6R7.B2	QM (PINP)	2017	2

- ✓ **Version 1 used for beam 1 (2015)**
- ✓ **Improved hardware V2 installed on B2 (2016-2017)**

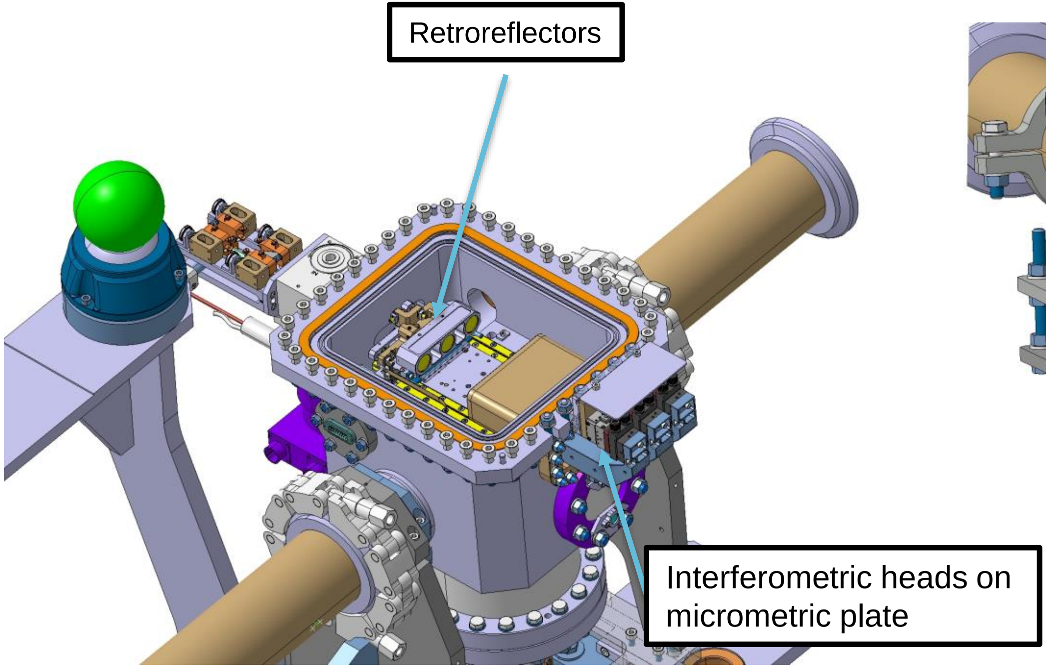
Table from from slides by M. Calviani, HL-LHC Crystal collimation Day, 19.10.2018

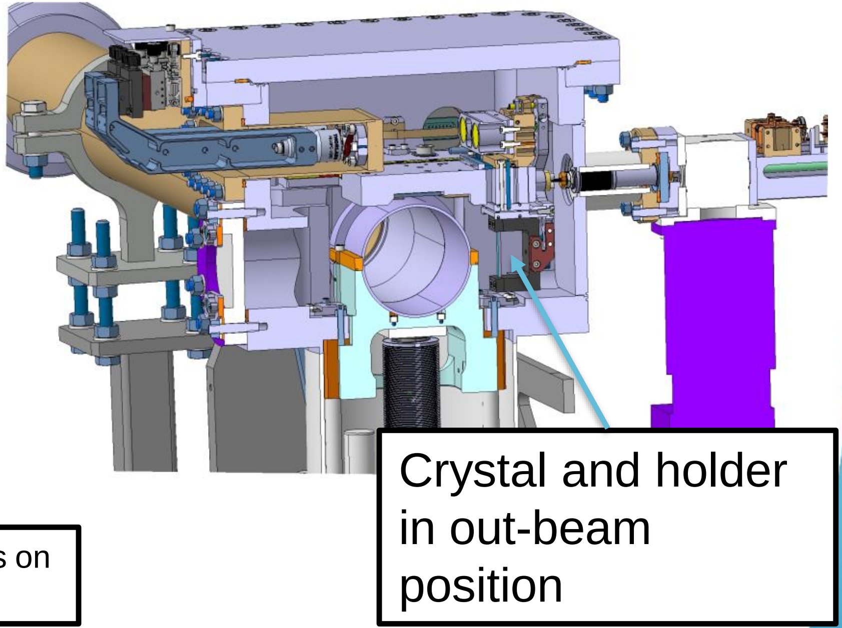
- **Different type of crystals**
  - ✓ **2 Strip (SD) and 2 Quasi-mosaic (QM, less performance with ions)**
  - ✓ **Same specifications for all crystals (~50 μrad bending angle)**



- **2 new generation goniometers (Version 3) will be installed during YETS2021-2022 to increase reliability, availability, maintainability and safety**

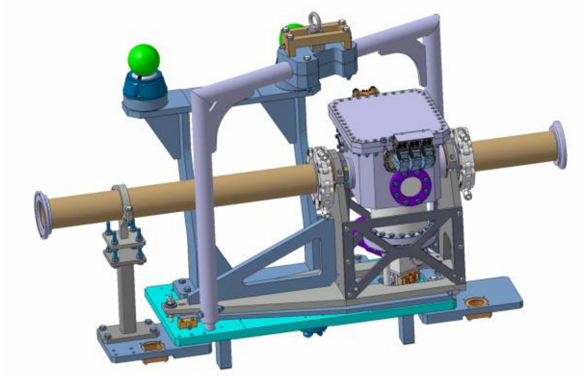
New Design -> Version 3 – Quick Overview

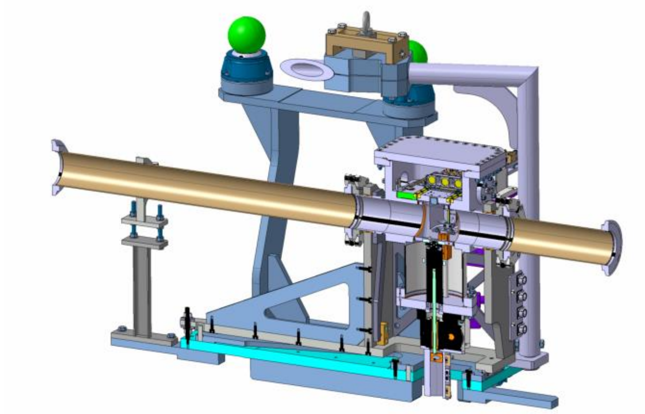


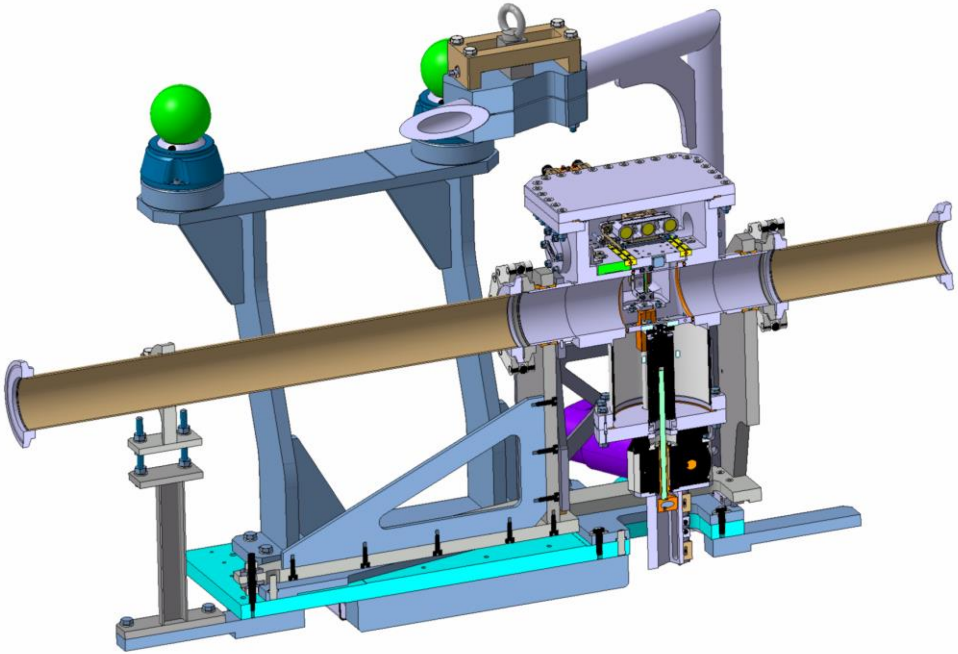


Courtesy of R. Seidenbinder

New Design -> Version 3 – Quick Overview







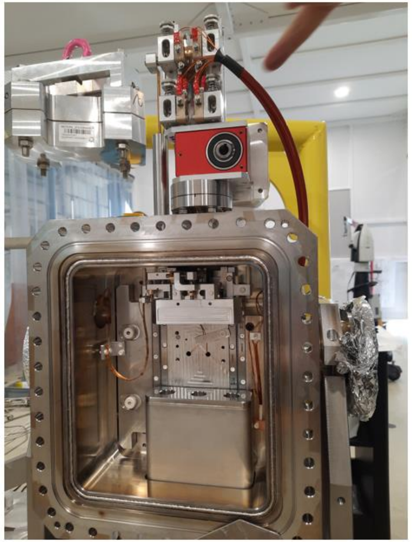
Courtesy of R. Seidenbinder

New Design -> Version 3 – Main Improvements

- Replacement chamber for high-intensity proton operation (coupling impedance reduction)
- Added redundancy in angle measurements
- Retroreflectors substitute mirrors in the interferometric system to increase angular acceptance ranges
- Interferometer heads moved to the outside of the vacuum chamber allowing:
  - ✓ Maintenance/replacement of fibres without opening the tank
- 2 x new generation Goniometers to be installed for RUN3 during YETS 2021-2022, which will replace two existing goniometers (vertical ones)
  - ✓ ECR (EDMS Nr. 1973224)

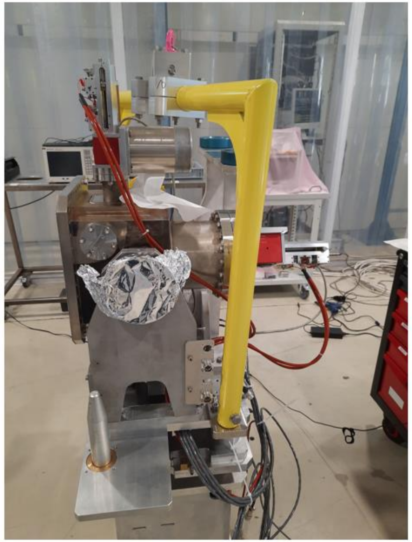
2 new TCPC

- Currently the new 2 TCPC devices are under bake-out test

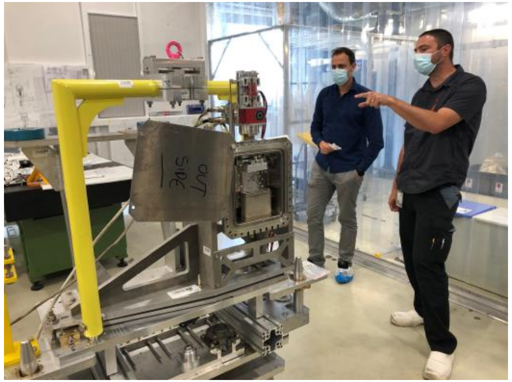


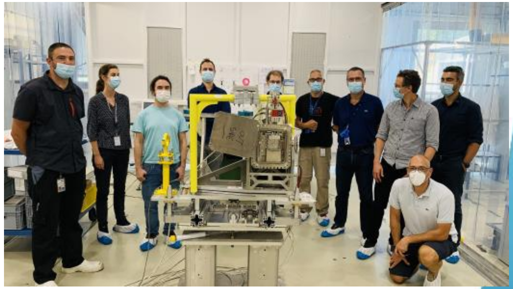
Rotational stage

Alignment mirrors on Device 1



Device 2





Courtesy of M. Calviani

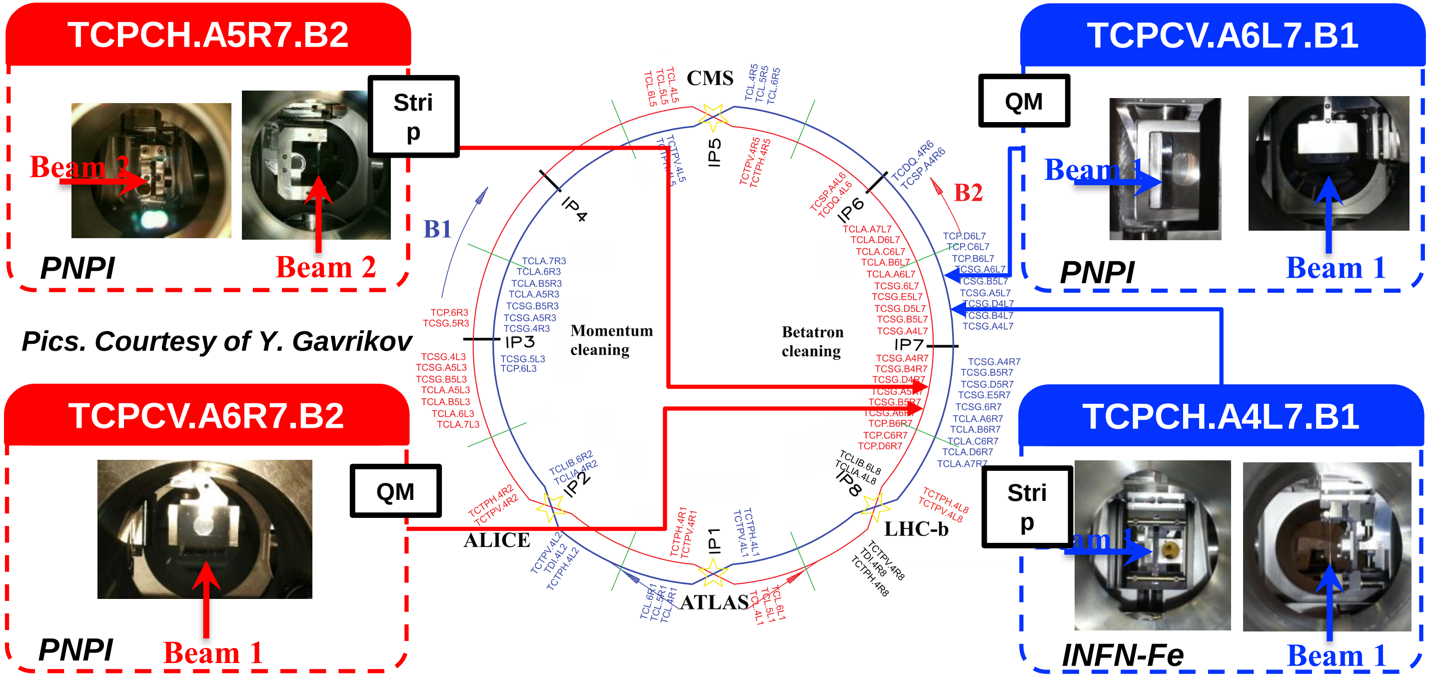
Operational Considerations for RUN3

- Crystal validation tests
  - ✓ Test using X-Ray have been made
  - ✓ Tests with beam in H8 have been made to measure crystals efficiency

- Functions for crystals positioning control will be prepared for RUN3 operation
  - ✓ The interlocking strategy and the requirements for the operational sequence were discussed
  - ✓ Time-dependent interlock limit functions will be added for the crystal linear stage to allow changes in dynamic machine phases, for example in the energy ramp (discussed at the LHC Collimation Working Group #252 - Joint MPP)
  - ✓ Insertion in the proton sequence of crystal checks

- Crystal Goniometers will be “treated” like any other operational Collimators

Present LHC crystal collimation layout



Courtesy of M. D'andrea, ColUSM #138

Crystals performance

- Extensive campaign of tests to evaluate crystal performance during Run 2
  - ✓ Low-intensity proton beams: initial channeling assessment, cleaning measurements, ramp functions
  - ✓ Low-intensity ion beams (Pb, Xe): cleaning measurements in different configurations
- 2018: cleaning measurements with high-intensity Pb ion beams
  - ✓ Potentially operational settings: adiabatic insertion of crystals in present collimation system

	Crystal	Maximum normalized BLM signal [a.u.]		Global leakage ratio
		Standard	Crystal	
Anticlastic	B1H	$(5.81 \pm 1.03) \cdot 10^{-13}$ Q8-9	$(7.30 \pm 0.15) \cdot 10^{-14}$ Q8-9	8.0 ± 1.4
Quasimosaic	B1V	$(1.95 \pm 0.07) \cdot 10^{-13}$ Q8-9	$(6.39 \pm 0.05) \cdot 10^{-14}$ Q12-13	3.1 ± 0.1
Anticlastic	B2H	$(2.76 \pm 0.39) \cdot 10^{-13}$ Q12-13	$(7.89 \pm 0.78) \cdot 10^{-14}$ Q8-9	3.5 ± 0.6
Quasimosaic	B2V	$(2.25 \pm 0.01) \cdot 10^{-13}$ Q8-9	$(1.46 \pm 0.36) \cdot 10^{-13}$ Q8-9	1.5 ± 0.4

Courtesy of M. D'Andrea, ColUSM #138

Prioritized for installation of new devices

- Angular range of B2V goniometer reduced over time

New Crystals Procurement

- Contracts stipulated for:
  - ✓ 6 Crystals from INFN
    - ❑ 4 received and validated
    - ❑ Additional 2 to be received in the next months
  - ✓ 12 Crystals from PNPI
    - ❑ 6 received and validated
    - ❑ Additional 6 to be received in the next months

INFN crystal

PNPI crystals

Crystals Validation Process

Acceptance Criteria Description: EDMS 2593152

Test	Description	Duration
X-ray Characterization & Visual Inspection	Measurements of miscut, torsion and bending angles Visual check under microscope	1 day setup, 1 day per crystal
Thermal Cycle Tests	3 x Ramp up/down at 50 degrees C/hour, up to a maximum of 250 degrees	1 working week per 3 crystals
X-ray Characterization & Visual Inspection	Measurements of miscut, torsion and bending angles Visual check under microscope	1 day setup, 1 day per crystal
Bake out & RCG	As per LHC installation (EDMS 1831197)	2 working weeks per 3 crystals
H8 Beam Test	Measurements of channeling efficiency and bending angles of the crystals	2 weeks (10 crystals)

X-Ray Diffractometry for crystal characterisation

- **X-rays** - wavelength **λ** is typically the same order of magnitude (1–100 angstroms) as the spacing ***d*** between planes in the crystal.
- **Crystalline diffraction -** the interaction of the X-ray beam with the crystalline structure causes the diffraction of the beam into many specific directions.
- **Bragg's Law:** $2\,d\sin(\theta) = n\,\lambda$

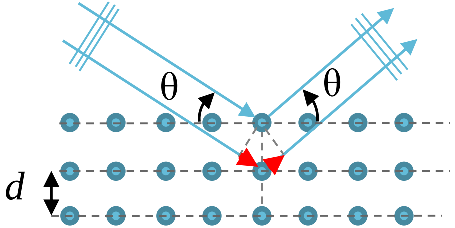
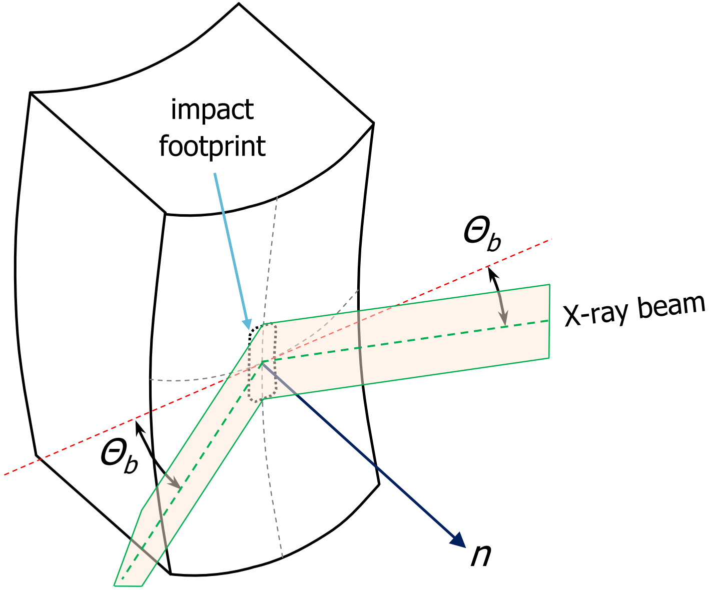


Illustration of crystalline diffraction.



Determination of normal n to crystal area labelled "impact footprint" where X-ray diffraction occurs at Bragg angle Θ_b.

Bent Crystals Parameters Measured

- **Miscut angle**

  (~ 1 - 2000 μrad)

- **Bending angle**

  (~ 20 - 300 μrad)

- **Torsion**

  (~ 1 - 50 μrad/mm)

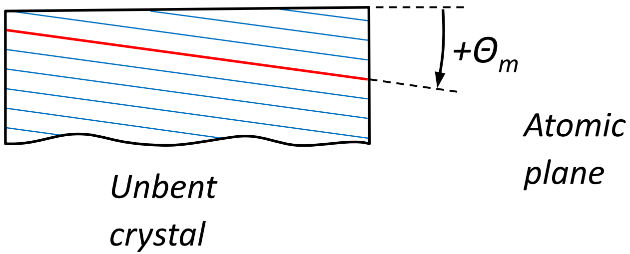


Illustration of unbent crystal with miscut angle..

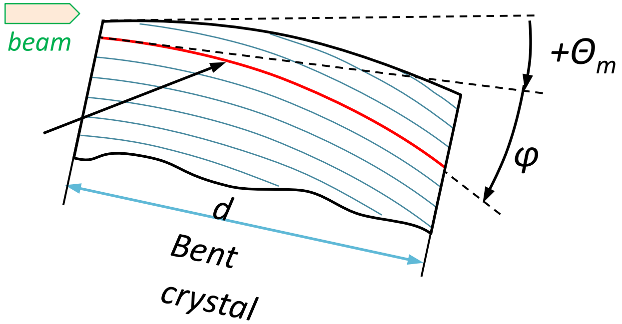
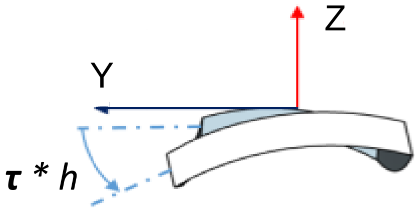
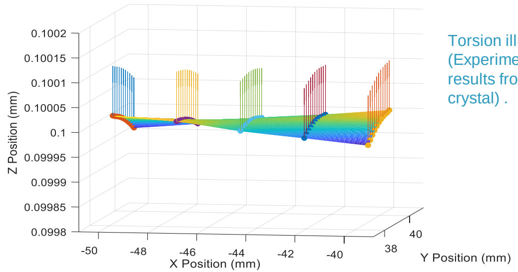


Illustration of bent crystal with miscut and bending angles.



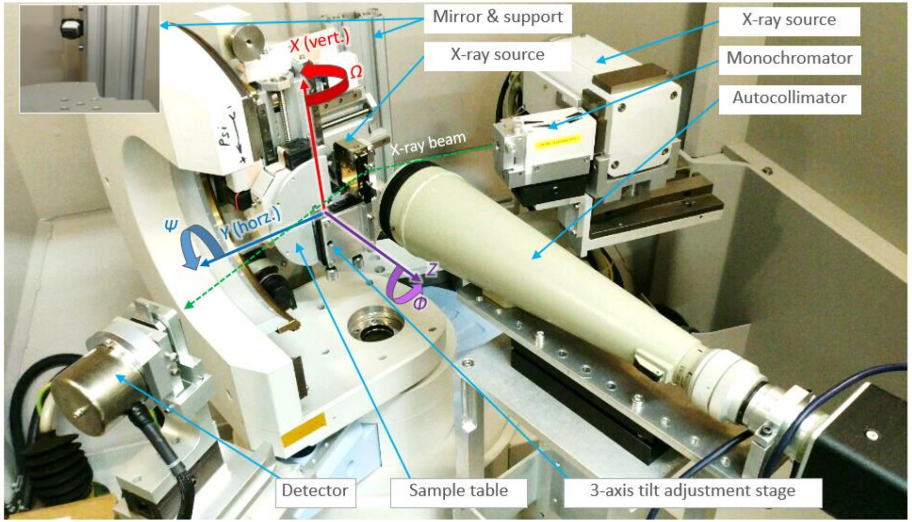
Torsion illustration with top view of the crystal.



Torsion illustration (Experimental results from bent crystal) .

Crystals validation using X-RAY diffractometry

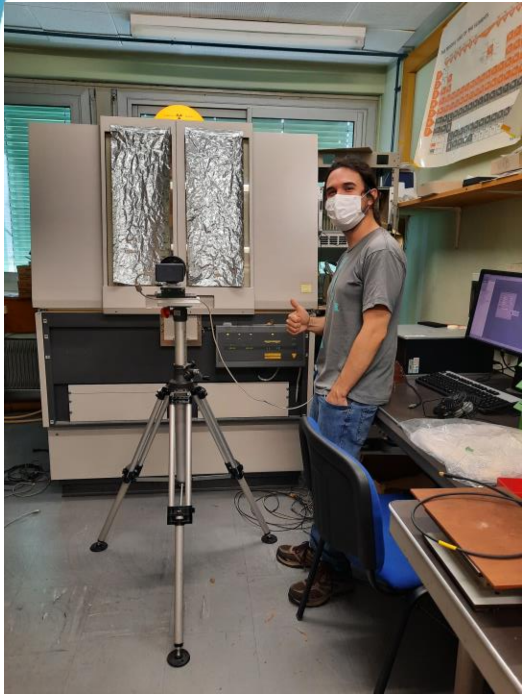
- 1x X-RAY based diffractometer at CERN to measure miscut angle, bending angle and torsion
  - ✓ More than 40 crystals measured and validated during the last 2 years
  - ✓ Uncertainty on bending and miscut angles → ± 2 µrad, on torsion → ± 1 µrad
- Crystal efficiency needs beam to be measured
  - Rossi, Roberto, et al. "Measurements of coherent interactions of 400 GeV protons in silicon bent crystals." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 355 (2015)

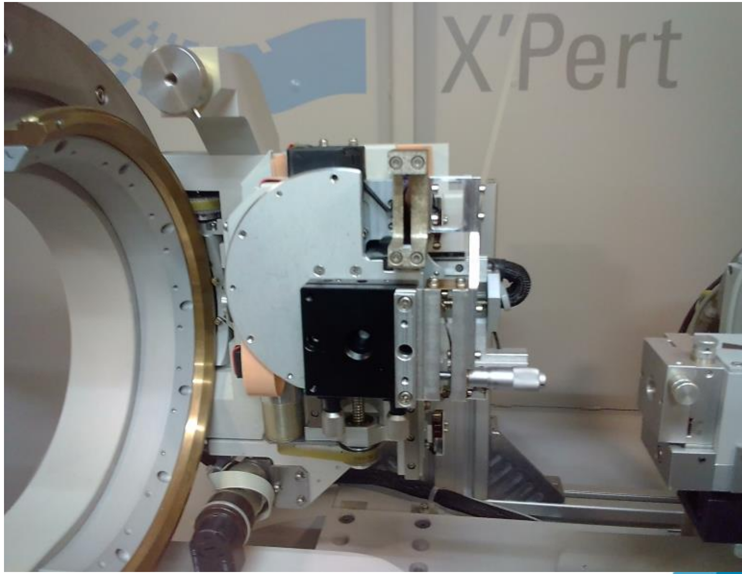


X'Pert Panalytical machine for X-Ray diffractometer (left) "adapted/endorsed" with additional instrumentation for crystals validation (right)
More info @ "Instrumentation and Procedures to Test Bent Silicon Crystals with X-Rays at CERN" (EDMS ID: 2412935)

Crystals validation using X-RAY diffractometry

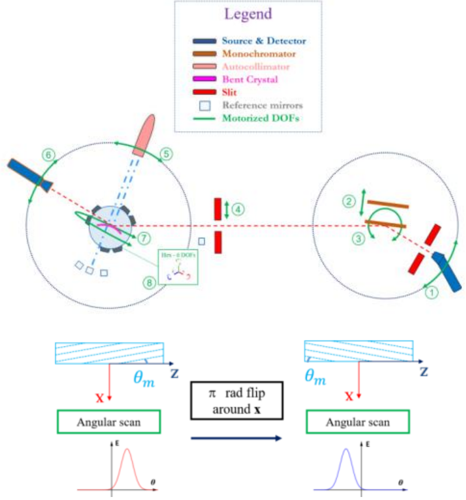
Procedure: EDMS 2412935, EDMS 2466472



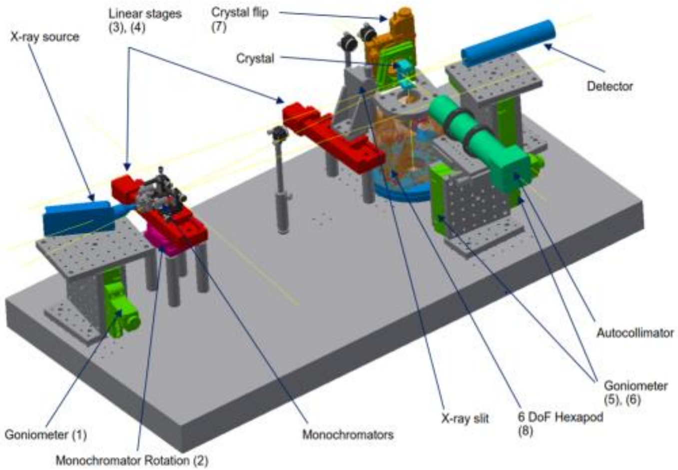


Crystals validation using X-RAY diffractometry

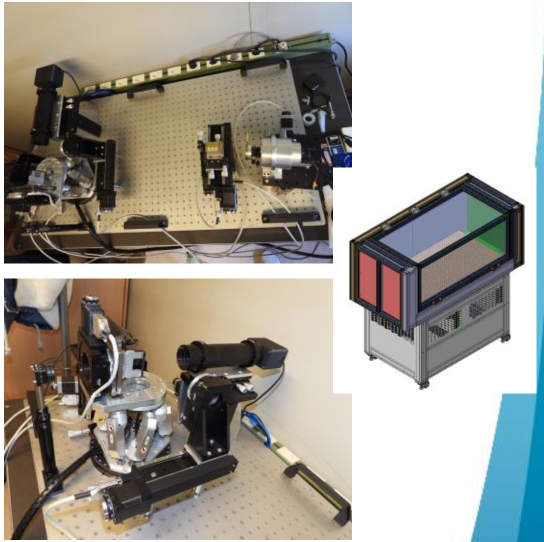
- Novel in-house X-RAY based diffractometer under construction
  - ✓ Possibility of measuring crystal wafers and multi-strip crystals
  - ✓ Possibility of increase efficiency and availability keeping uncertainty levels within ± 1 µrad on the measurements of bending angle, miscut angle and torsion
  - ✓ More info @ S. Gargiulo master thesis – "Modelling for metrological analysis of an X-ray diffractometer for bent crystals characterization in crystal-assisted collimation", CDS doc link: https://cds.cern.ch/record/2764348



Rotational stages and miscut procedure measurements studies



In-house machine layout

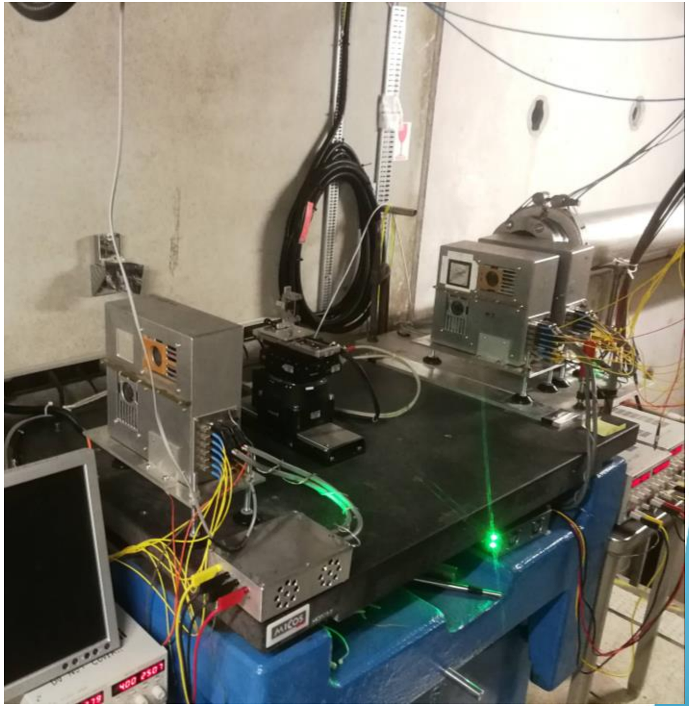


pictures of in-house machine's current status

H8 Beam Test

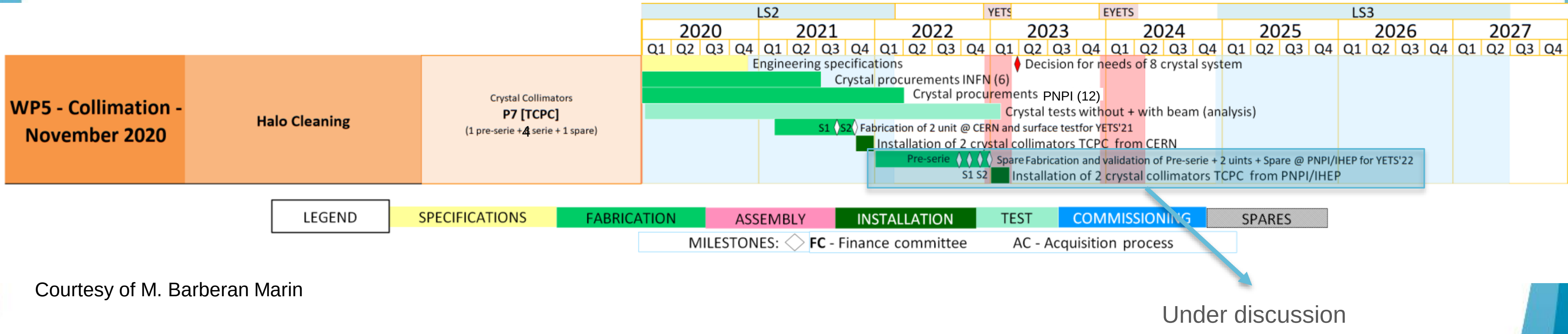
- ✓ The crystal campaign qualification in H8 was successfully completed thanks to UA9 in W37-38
- ✓ 10 LHC crystals measured (all crystals provided by PNPI & INFN).
  - ✓ In total ~20 crystals were measured, including SPS crystal, focusing crystals and long crystals
- ✓ **Reconstruction and analysis of the six top-priority crystals performed during the test to speed up the decision about which crystals to install during the YETS**
- ✓ Decision about the two crystals to install taken on October 1st based on X-RAY and beam measurements

➢ The full reconstruction and analysis is ongoing to provide a thorough characterization of the crystals and a comparison with the X-rays measurements



Courtesy of L. Esposito

Project Timeline



Courtesy of M. Barberan Marin

Conclusions

- 2 new version3 goniometers been produced and validated at CERN, currently under vacuum test and planned to be installed in the LHC during YETS2021-2022.
  - ✓ 2 previously installed devices should be changed during YETS2022-2023

- Production plan/decision for additional 4 goniometers (2 to install, 2 spares) under discussion.

- 10 new crystals have been validated at CERN. 2 were chosen for the installation in the 2 goniometers to be installed

- The new generation goniometer can ensure an operational device for RUN3, characterized by a proper reliability, availability, maintainability and safety

Thank you!

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Backup Slides

2 Types of Crystals

- **Quasimosaic crystals**
- **Anticlastic crystals**

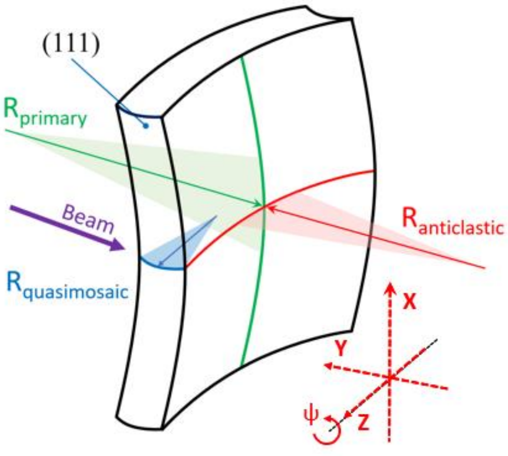


Illustration of quasimosaic crystal.

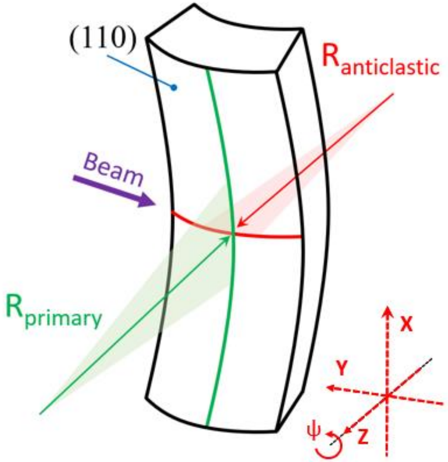
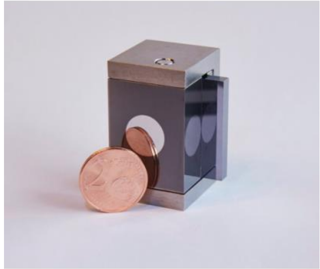


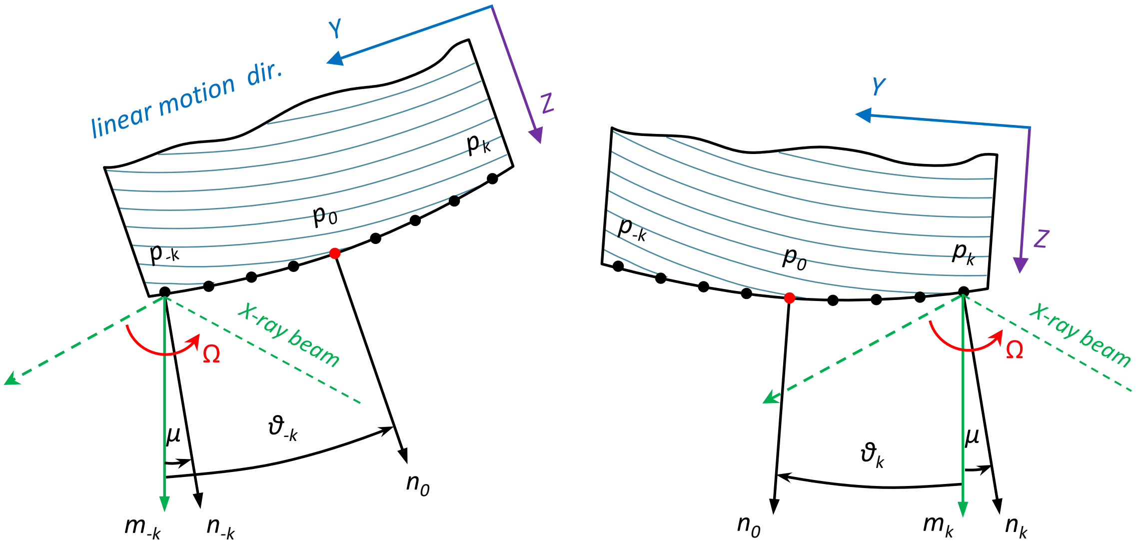
Illustration of anticlastic crystal.



Quasimosaic crystal manufactured by PNPI.

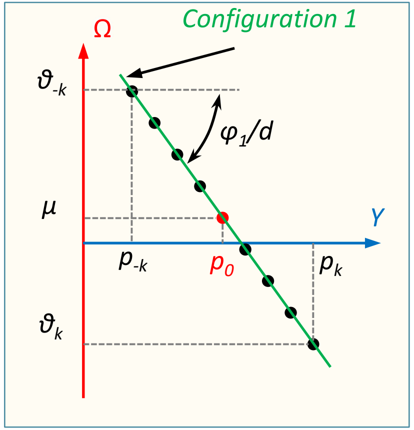
Anticlastic crystal manufactured by PNPI.

Measurement of bending angle



Configuration 1

Fig 1 - Schematic view of the YΩ scan in Configuration 1 along the tested surface from impact point p-k to point pk.



$$\vartheta_i = \mu - i \cdot \Delta p \, \frac{\varphi_1}{d}$$

Measurement of bending angle

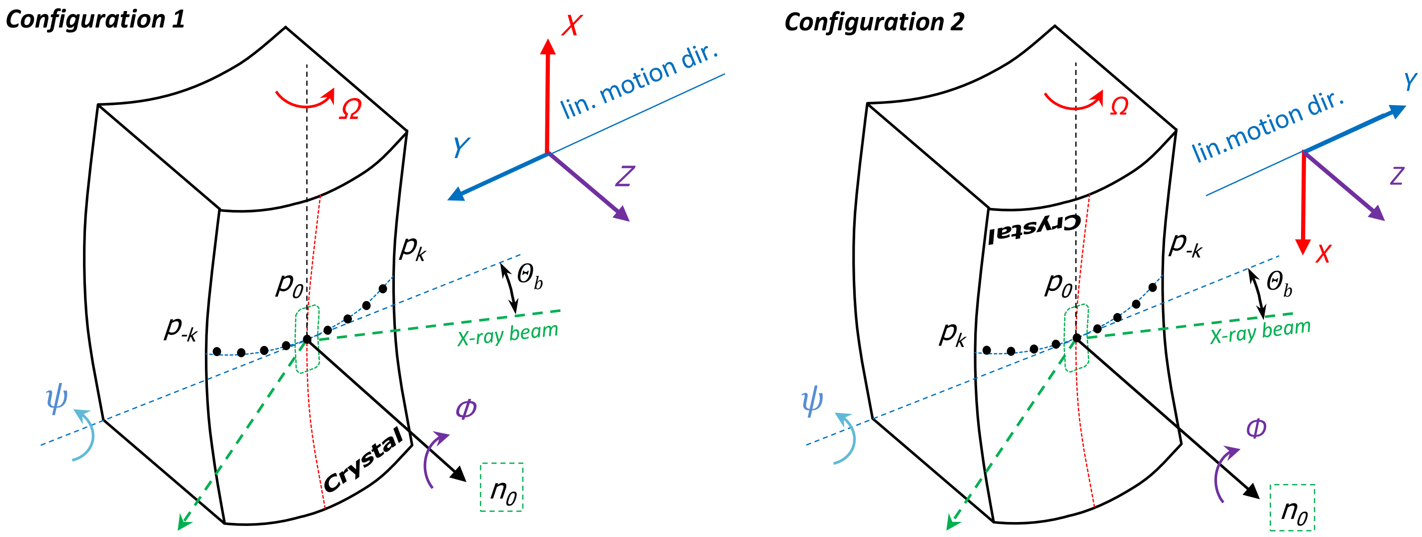
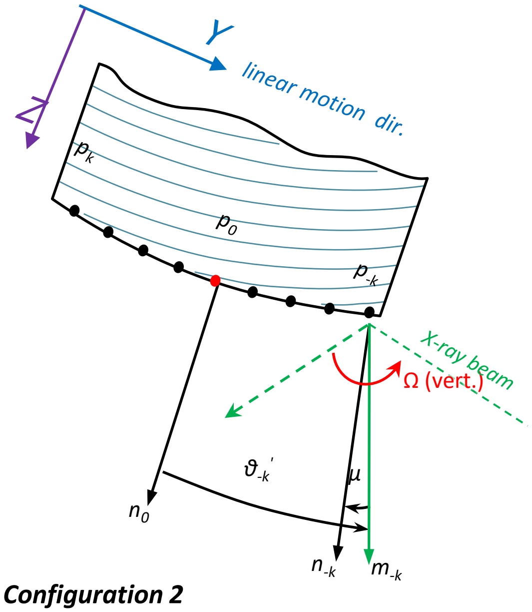


Fig 1 - Schematic layout of the bending angle and the miscut angle measurement orientations.

HiLumi HL-LHC PROJECT

Measurement of bending angle



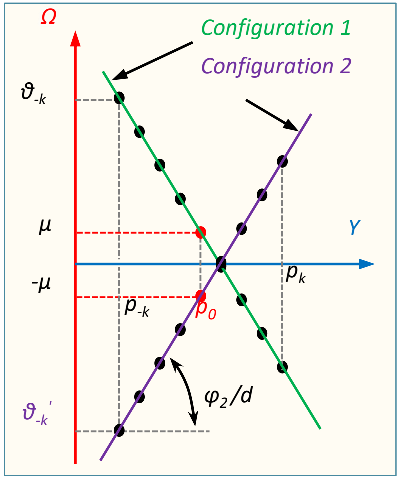


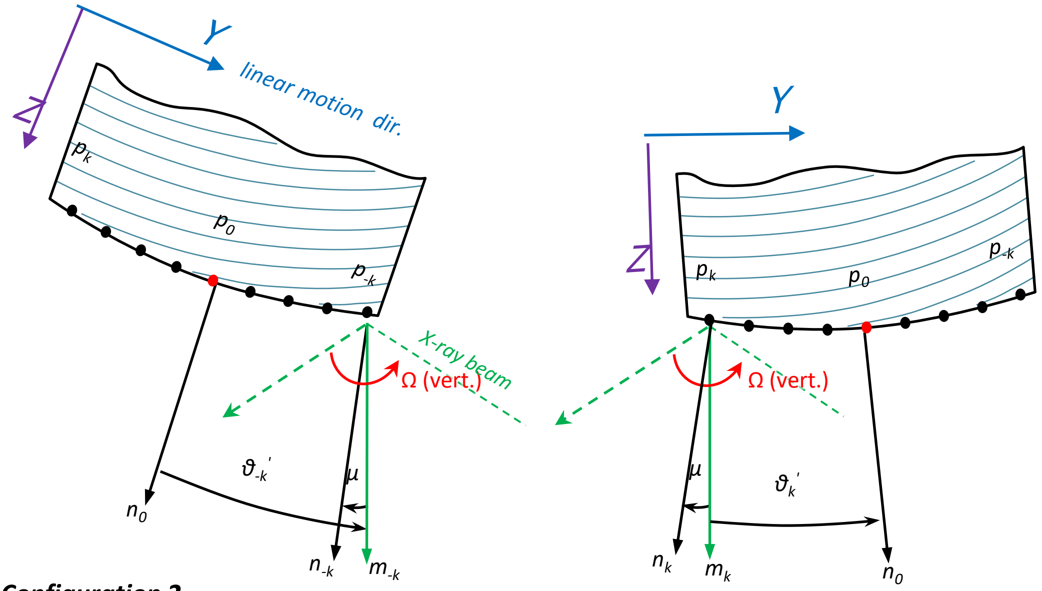
Fig 1 - Schematic view of the YΩ scan in Configuration 2 along the tested surface from impact point p_{-k} to point p_k.

$$\vartheta_i = \mu - i \cdot \Delta p \, \frac{\varphi_1}{d}$$

$$\vartheta_i' = -\mu + i \cdot \Delta p \, \frac{\varphi_2}{d}$$

$$\varphi = \frac{\varphi_1 - \varphi_2}{2}$$

Measurement of miscut angle



Configuration 2

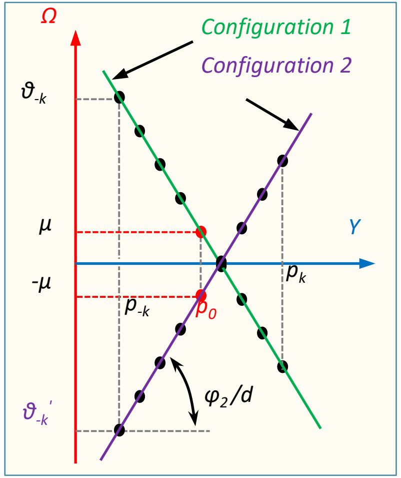


Fig 1 - Schematic view of the YΩ scan in Configuration 2 along the tested surface from impact point p_{-k} to point p_k.

$$\mu = \frac{1}{2} \cdot \frac{1}{2k+1} \cdot \left(\sum_{-k}^{k} (\vartheta_i) - \sum_{-k}^{k} (\vartheta_i') \right)$$

Measurement of torsion

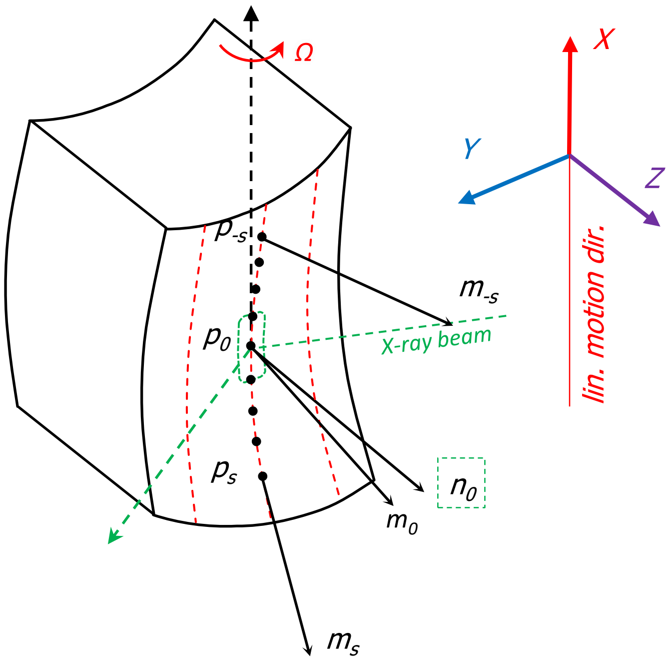


Fig 1 - Schematic layout of the torsion measurement.

Linear fit: a τ +b, where τ is a torsion