"Overview of crystal performance at SPS-H8 "

HL-LHC Crystal Collimation Day

CERN, Switzerland (19 *October 2018*)

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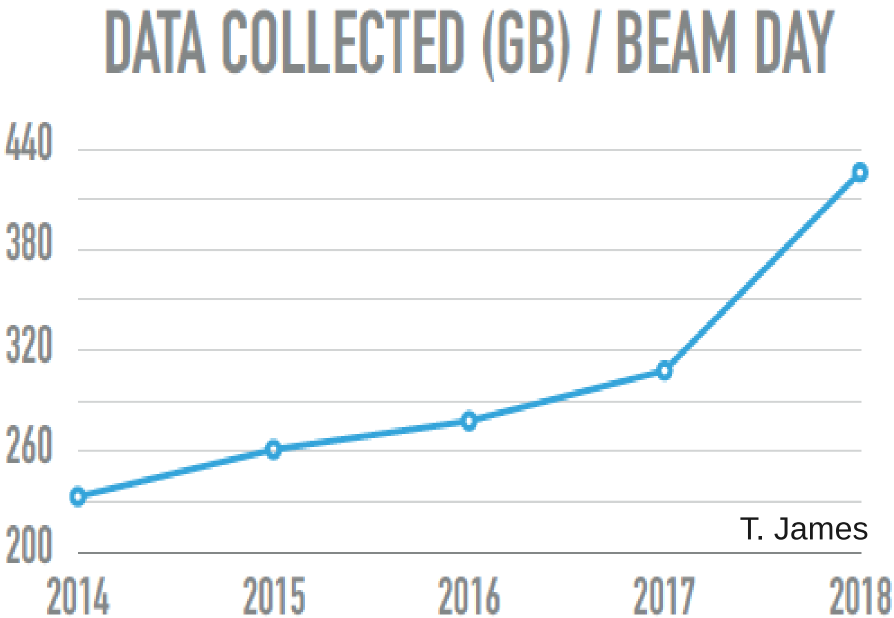
CERN / Imperial College London

UA9 Collaboration

Outline

- General overview since 2012
- UA9 experimental set-up in SPS-H8
- Measurements methods and procedures
- LHC crystals results
- Inelastic Nuclear Interaction studies
- Hi-dose irradiated crystals tests
- Conclusions

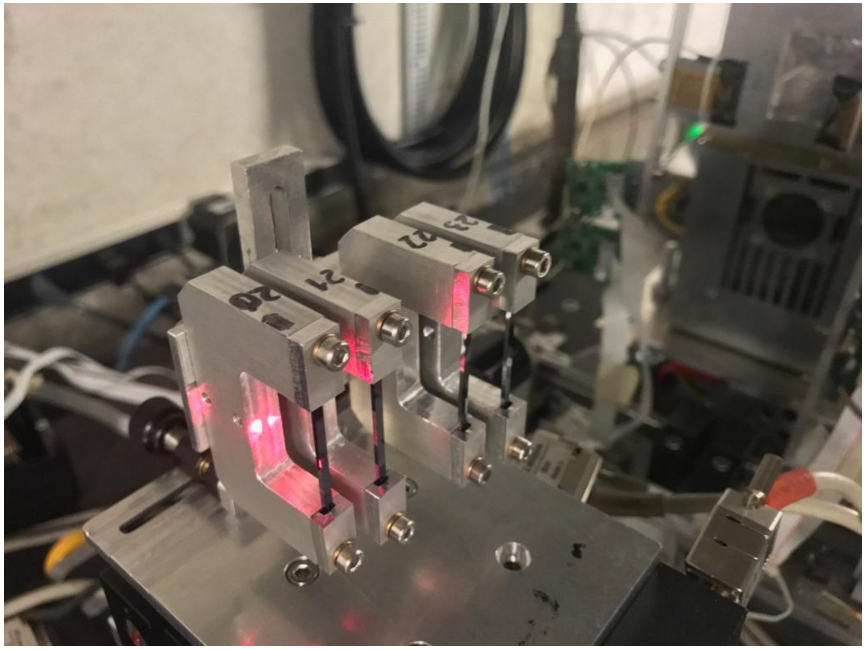
H8 evolution (2012-2018)



In 2012: ~ 2 crystals per day

In 2018: ~ 10 crystals per day !!!

- More than 250 crystal measurements
- More than 190 LHC crystals measurements
- More than 60 single LHC crystals tested
- More than 15 publications
- More than 20 publications pending
- 1 Ph.D thesis
- 4 Master thesis



UA9 Experimental apparatus at the H8 SPS extraction line

High rate and high angular resolution beam telescope based on CMS Tracker HW&SW

M. Pesaresi, T. James, J. Borg

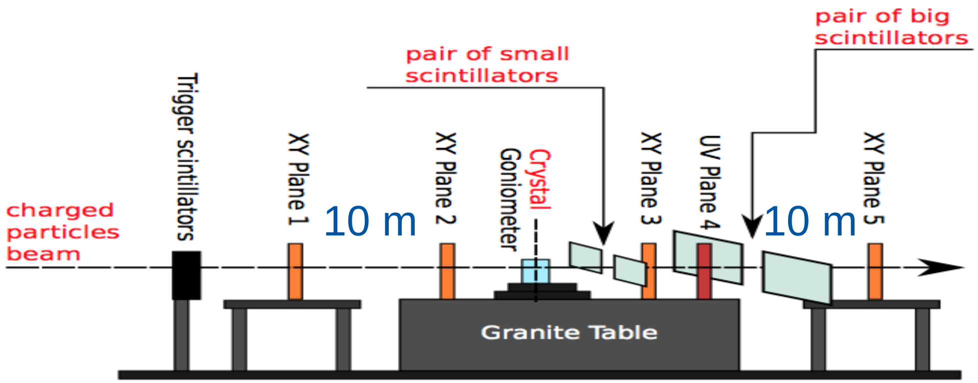
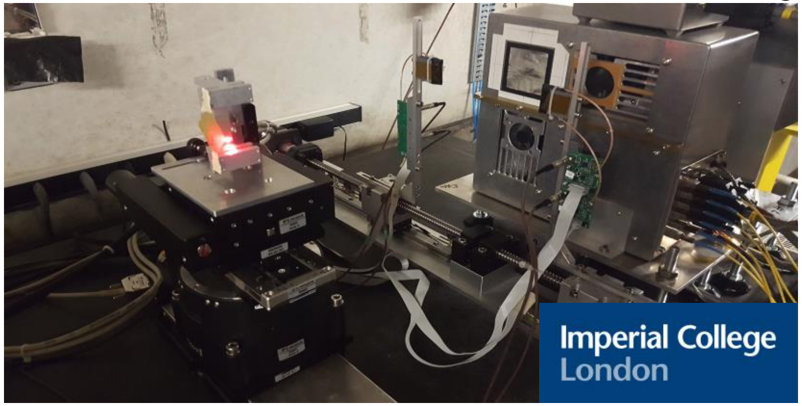


FIG. 1: Experimental layout in the H8 beam line.



- Systematic error < 1μrad
- Statistical error negligible

Main steps in the characterization of bent crystals:

1. **Alignment run:** only the tracking stations are in the beam line
2. **Linear scan:** the crystal is placed on the beam line
3. **Angular scan:** ~10^5 events/step are acquired around the channeling orientation looking for CH
4. **High statistics runs:**
   - the crystal is left in the optimal channeling position for hi-stat. of ~16 M events
   - the crystal is left in the AM orientation for hi-stat of ~16 M events

Beam/Tracker performances

400 AGeV protons → Best experimental conditions

- Micro beam: ~10 µrad of divergence, ~1 mm of dimension (1 sigma)
- Tracker resolution (single track): 5.4 µrad (due to multiple scattering)
- Faster and more accurate measurements

180 AGeV pions → Medium experimental conditions

- Normal beam: ~ 30 µrad of divergence, ~ 2 mm of dimension (1 sigma)
- Tracker resolution (single track): 12.3 µrad (due to multiple scattering)
- Slower and less accurate measurements

150 AGeV Xe & Ar ions → Medium experimental conditions

- Wide beam: ~ 18 µrad of divergence, ~ 2 mm of dimension (not gaussian)
- Tracker resolution (single track): 7.8 µrad (due to multiple scattering)
- Contaminated beam
- Slower and less accurate measurements

30 AGeV Pb ions & 40 AGeV Xe ions → Extreme conditions

- Very wide beam: ~ 50 µrad of divergence, ~ 6 mm of dimension (not gaussian)
- Tracker resolution (single track): 29.6 µrad (due to multiple scattering)
- Very contaminated beam and hurtful for the sensors
- Very slow and very inaccurate measurements → too low energy !!!

Off-line analysis procedure (1/2)

1. The raw data are reconstructed off-line and converted directly in Root format (~ 12 h per 1 standard LHC crystal measurement)

2. The events with incoming and outgoing single tracks with the a common vertex in the crystal are analyzed

   Main information in the data:
   - Particle impact position (X & Y) on the crystal
   - Particle incoming angles (Θ_{X_in} & Θ_{Y_in}) on the crystal
   - Particle outgoing angles (Θ_{X_out} & Θ_{Y_out}) from the crystal
   - Goniometer angles: Θ_{X_gonio}, Θ_{y_gonio}

3. The data quality check and a first preliminary analysis is performed by UA9@CERN

4. The data are shared with the whole UA9 Collaboration

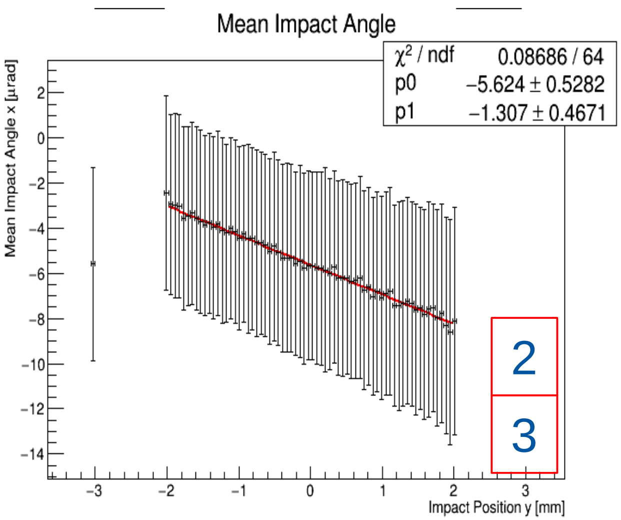
5. The crystal suppliers perform a cross-check analysis

6. The final results are discussed inside the UA9 Collaboration

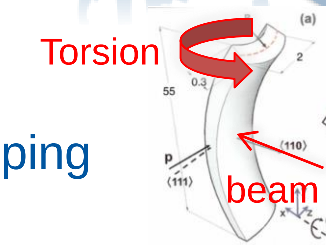
7. The final results are reported to CERN

~ 1 month

Off-line analysis procedure (2/2)

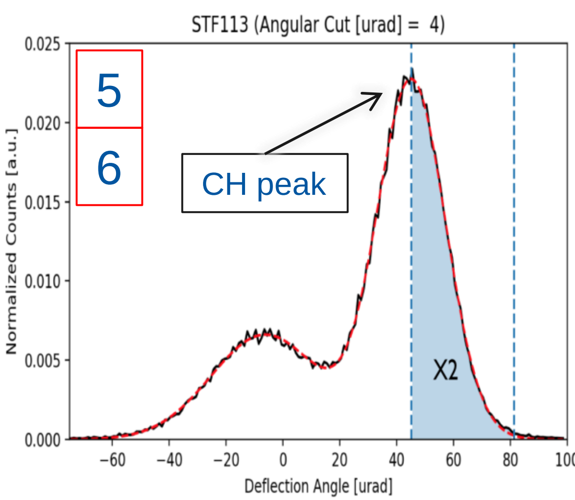


Strip (ST) crystals analysis



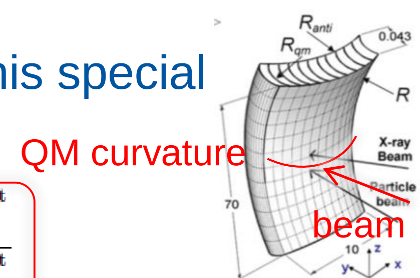
1. Geometrical cuts: beam/crystal overlapping
2. Torsion analysis: torsion estimation
3. Torsion masking: before angle and efficiency analysis
4. Angular cuts: Θ_c & $\Theta_c/2$
5. Gaussian fit of the channeling peak: to estimate the angle central value
6. Efficiency: events in the CH peak (+/- 3 σ) divided by total events

Mask the torsion effect $$\theta_x^{corr} = \theta_x^{in} - (t(y) \cdot d_{0y} + \Theta_x^{off})$$



Quasi-mosaic (QM) crystals analysis

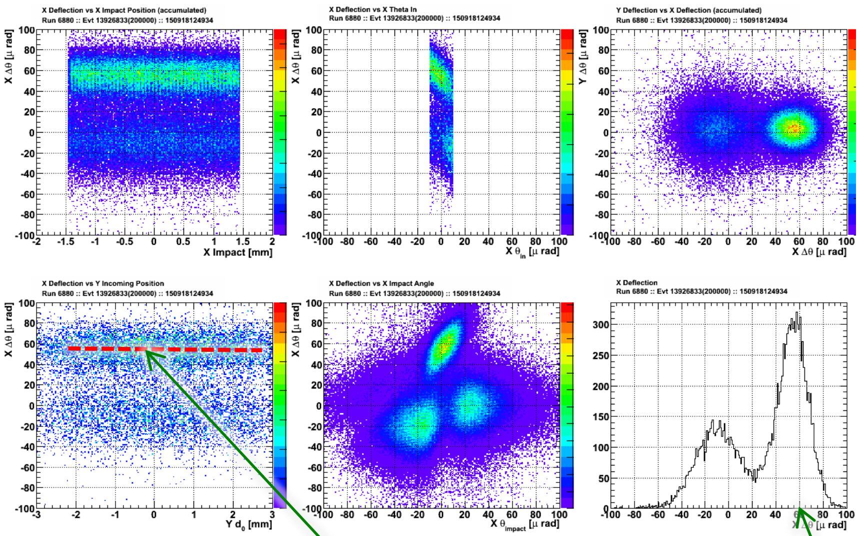
- The procedure is similar, except for the fact that QM crystals do not have torsion, but are affected by quasi-mosaic curvature horizontally.
- So the points 2 & 3 are replaced by this special masking before points 5 & 6



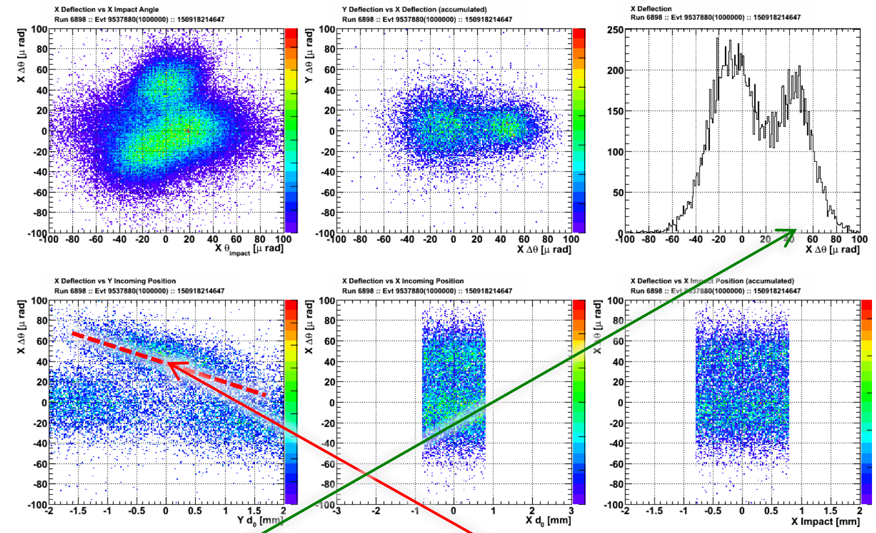
Evaluate the channeling efficiency $$\eta_{ch}^{\theta_x^{cut}} = \frac{N_{ch}^{-\theta_x^{cut}<\theta_x^{in}<\theta_x^{cut}}}{N^{-\theta_x^{cut}<\theta_x^{in}<\theta_x^{cut}}}$$

On-line analysis

Crystal without torsion



Crystal with torsion



Torsion ~ 0 μrad/mm torsion

Torsion ~ 10 μrad/mm

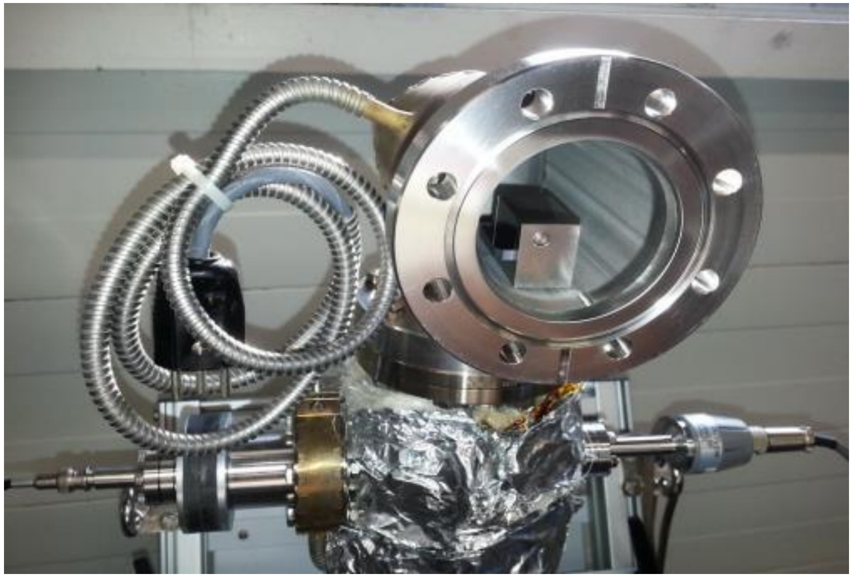
CH angle ~ 50 μrad

In only 2 h of data taking is already possible on-line to have a preliminary information about the quality of the crystal, in terms of CH angle and torsion

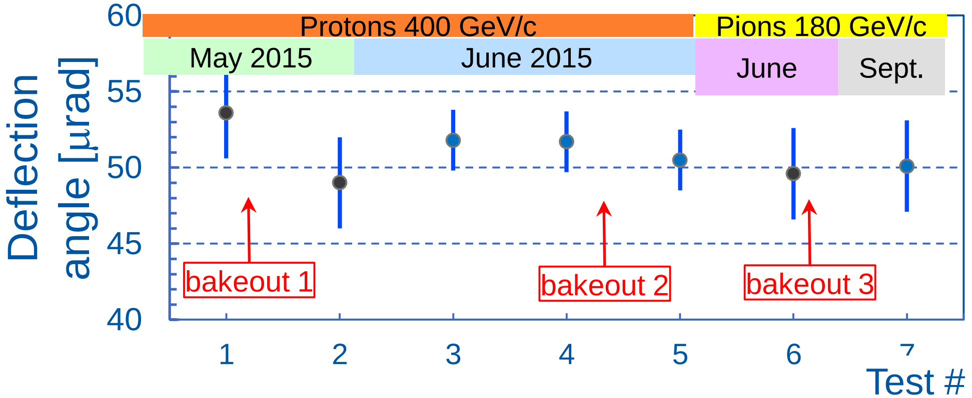
Performance stability

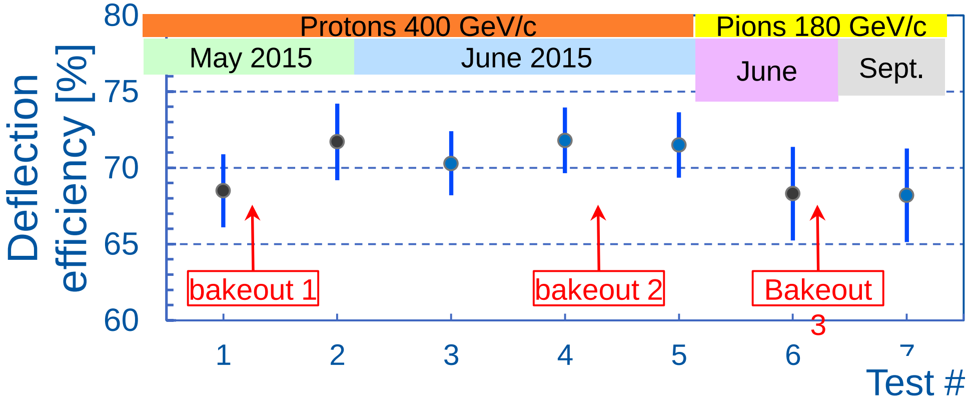
Bake out of crystals

- Heating is performed at CERN by vacuum team
- Typical LHC bake out procedure is implemented
- Ramp up, ramp down is 50 °C/hour
- 24 hours at T_{max} = 250 °C



Example of stability plots





Crystal I.D.

Each characterized crystal has a detailed dossier, updated step by step with the following information:

- Picture and identification code
- Crystal characteristics: dimensions, nominal angle, material, etc…
- Holder characteristics: dimensions, material, weight, etc…
- Production specifications
- X-ray &/or optical measurements: bending radius (angle), torsion
- Beam measurements: angle, efficiency, torsion
- Historical report: locations, treatments, modifications, stability, etc…

Datasheet of crystal ST105

Crystal parameters

Crystal purpose: LHC collimation
Crystal thickness along the beam: 4.07±0.02 mm
Crystal transversal thickness: 0.55±0.02 mm
Crystal height: 55.0±0.1 mm
Channeling plane: (110)
Channeling axis: <111>
Miscut for planar channeling: 40±4 μrad
Miscut for axial channeling: 0±18 mrad
Dislocation density: < 1 cm²
Crystal weight: 0.280±0.002 g
Crystal manufacturing date: 29/04/2015

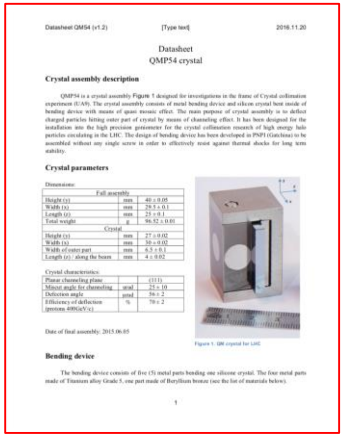
Crystal has been manufactured following with the procedure already described in details in [1].

Holder description and parameters

A bending device (holder) is used to bend the crystal. The holder is composed of a total of 14 parts, i.e.

- 1 "main component", made of Titanium grade V manufactured by "Cinel - Instruments for Research and Industry" in May 2015 by means of milling and and electro-discharge machining operations. Between milling and electro-discharge machining the part was subject to a thermal annealing in order to release the mechanical stress generated in the first operation (see table I for more details). Thermal annealing was conducted on May 4th 2015, while electro-discharge machining was conducted on May 6th 2015. Titanium

Dossier examples



Datasheet QM54 (v1.2) [Type text] 2016.11.20

Datasheet
QMP54 crystal

Crystal assembly description

QMP54 is a crystal assembly Figure 1 designed for investigations in the frame of Crystal collimation experiment (UA9). The crystal assembly consists of metal bending device and silicon crystal bent inside of bending device with means of quasi mosaic effect. The main purpose of crystal assembly is to deflect charged particles hitting outer part of crystal by means of channeling effect. It has been designed for the installation into the high precision goniometer for the crystal collimation research of high energy halo particles circulating in the LHC. The design of bending device has been developed in PNPI (Gatchina) to be assembled without any single screw in order to effectively resist against thermal shocks for long term stability.

Crystal parameters

Dimensions:

Full assembly		
Height (y)	mm	40 ± 0.05
Width (x)	mm	29.5 ± 0.1
Length (z)	mm	25 ± 0.1
Total weight	g	96.52 ± 0.01
Crystal		
Height (y)	mm	27 ± 0.02
Width (x)	mm	30 ± 0.02
Width of outer part	mm	6.5 ± 0.1
Length (z) / along the beam	mm	4 ± 0.02

Crystal characteristics:

Planar channeling plane		(111)
Miscut angle for channeling	μrad	25 ± 10
Deflection angle	μrad	56 ± 2
Efficiency of deflection (protons 400GeV/c)	%	70 ± 2

Date of final assembly: 2015.06.05

Figure 1. QM crystal for LHC

Bending device

The bending device consists of five (5) metal parts bending one silicone crystal. The four metal parts made of Titanium alloy Grade 5, one part made of Beryllium bronze (see the list of materials below).

1

LHC crystal results (1/2)

Crystals fully tested with 180 GeV pions

Preliminary results

Name	Supplier	Angle [μrad]	Efficiency at $\Theta_c/2$	Torsion [μrad/mm]	Stability * ΔΘ [μrad]	Tests status
QMP46v2	PNPI	56 ± 1	68 ± 2 %	0 ± 1	0 ± 1	Fully tested *
QMP54	PNPI	56 ± 1	68 ± 2 %	0 ± 1	- 1 ± 1	Fully tested
ACP79	PNPI	49 ± 1	69 ± 2 %	0 ± 1	- 1 ± 1	Fully tested
ACP77	PNPI	50 ± 1	70 ± 2 %	5 ± 1	- 2 ± 1	Fully tested
ACP84	PNPI	52 ± 1	68 ± 2 %	0 ± 1	- 2 ± 1	Fully tested
ACP85	PNPI	49 ± 1	68 ± 2 %	0 ± 1	0 ± 1	Fully tested
ACP86	PNPI	56 ± 1	66 ± 2 %	0 ± 1	0 ± 1	Fully tested
STF117	INFN-Fe	50 ± 1	66 ± 2 %	- 5 ± 1	- 1 ± 1	Fully tested
STF118	INFN-Fe	53 ± 1	64 ± 2 %	- 6 ± 1	0 ± 1	Fully tested
STF119	INFN-Fe	52 ± 1	66 ± 2 %	5 ± 1	0 ± 1	Fully tested
STF121	INFN-Fe	48 ± 1	67 ± 2 %	5 ± 1	1 ± 1	Fully tested
STF122	INFN-Fe	46 ± 1	66 ± 2 %	- 14 ± 1	2 ± 1	Fully tested
STF123	INFN-Fe	52 ± 1	62 ± 2 %	- 13 ± 1	0 ± 1	Fully tested

* Fully tested: tested before and after a CERN bake out

* The stability is controlled after the CERN bake-out at 250 °C

LHC crystal results (2/2)

Preliminary results

Crystals partially tested with 180 GeV pions

Name	Supplier	Angle [μrad]	Efficiency at Θ_c	Torsion [μrad/mm]	Stability	Tests status
STF124	INFN-Fe	49 ± 1	67 ± 2 %	0 ± 1	-	Test ongoing *
STF125	INFN-Fe	50 ± 1	65 ± 2 %	3 ± 1	-	Test ongoing
STF126	INFN-Fe	50 ± 1	66 ± 2 %	3 ± 1	-	Test ongoing
ACP80	PNPI	57 ± 1	67 ± 2 %	0 ± 1	-	Test ongoing

* Test ongoing: tested only before the CERN bake out

Crystals installed in LHC

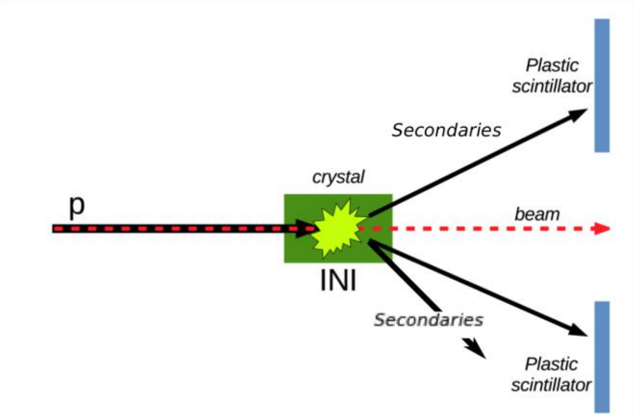
Name	Supplier	Angle [μrad]	Efficiency at Θ_c	Torsion [μrad/mm]	Location	Installation status
STF75	INFN-Fe	63 ± 2	Not meas.	-	B1H	2014-present
QMP34	PNPI	40 ± 2	Not meas.	0 ± 1	B1V	2014-present
QMP52	PNPI	54 ± 1	64% ± 2%	0 ± 1	B2V	2017-present
QMP53	PNPI	56 ± 1	71% ± 2 %	0 ± 1	B2H	2017-2018
TCP76	PNPI	50 ± 2	70% / 55% *	0 ± 1	B2H	2018-present

* Efficiency with 40 AGeV Xenon ions

I.N.I. studies (1/3)
(Inelastic Nuclear Interactions)

H8 Apparatus:

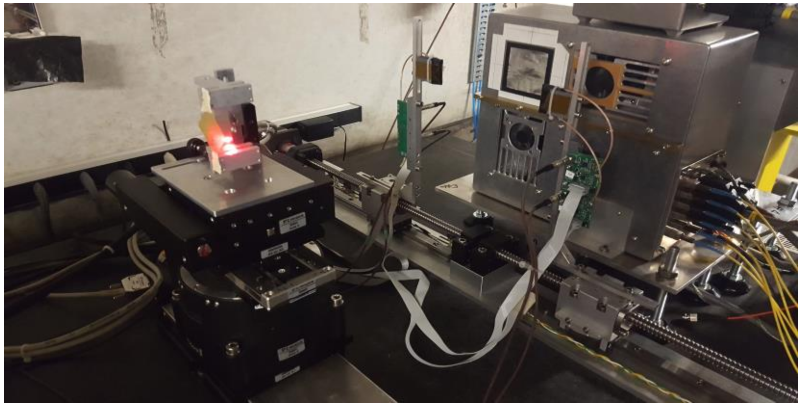
the idea is to perform a coincidence measurement integrated in the Tracker DAQ



Simple idea

↓

Good results

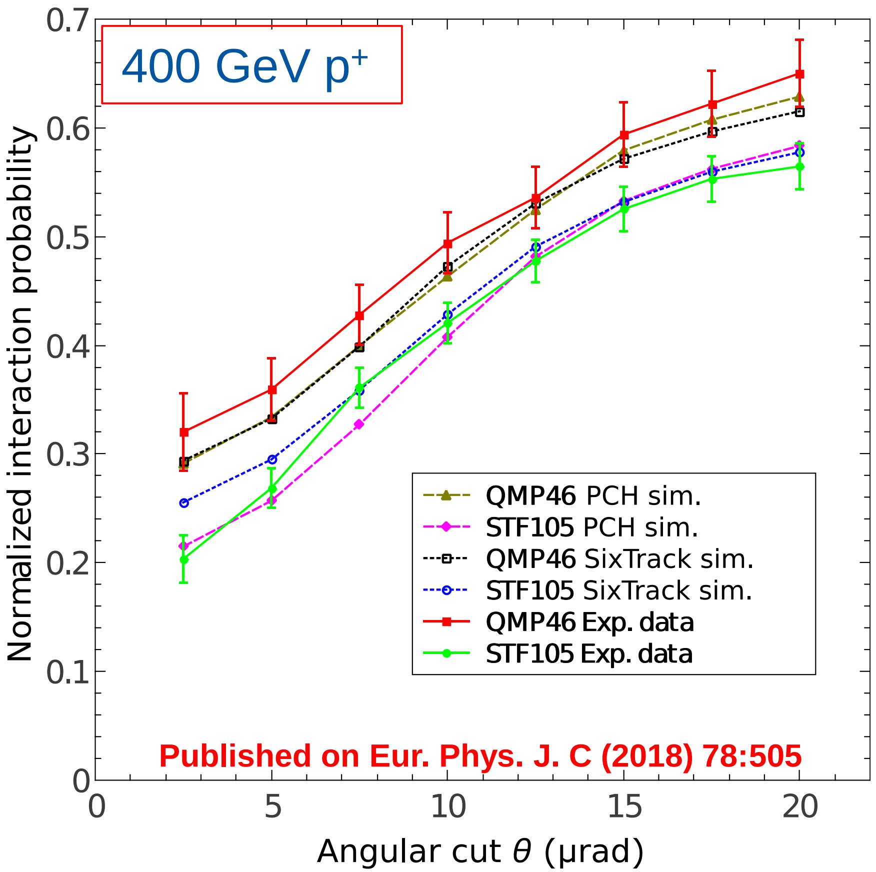


- Two mini scintillators (5x10x25 mm^3): to cut the background stream along the line
- Fast coincidence (gate ~ 2 ns): to register “only” I.N.I. correlated with a single track
- Scintillators acquisition is linked to the Tracker acquisition:
  - Selection of events only with single incoming tracks and multiple outgoing tracks
  - Very precise and simple off-line analysis: it is possible to apply geometrical and angular cuts, filtering only the interesting events
- Systematic measurements on any kind of crystal: in parallel with crystal bending angle and efficiency measurements

I.N.I. studies (2/3)

I.N.I. studies for LHC collimation purposes:

comparison between the two kinds of crystals successfully tested in LHC: for CH strip crystals use (110) planes, instead quasi-mosaic uses (111) ones



I.N.I. reduction factor in CH w.r.t. AM orientation (within $\Theta_c/2 = 5$ μrad):

Strip: $R_f \sim 3.7$

Quasi-mosaic: $R_f \sim 2.8$

This difference is due to the different average planes distance

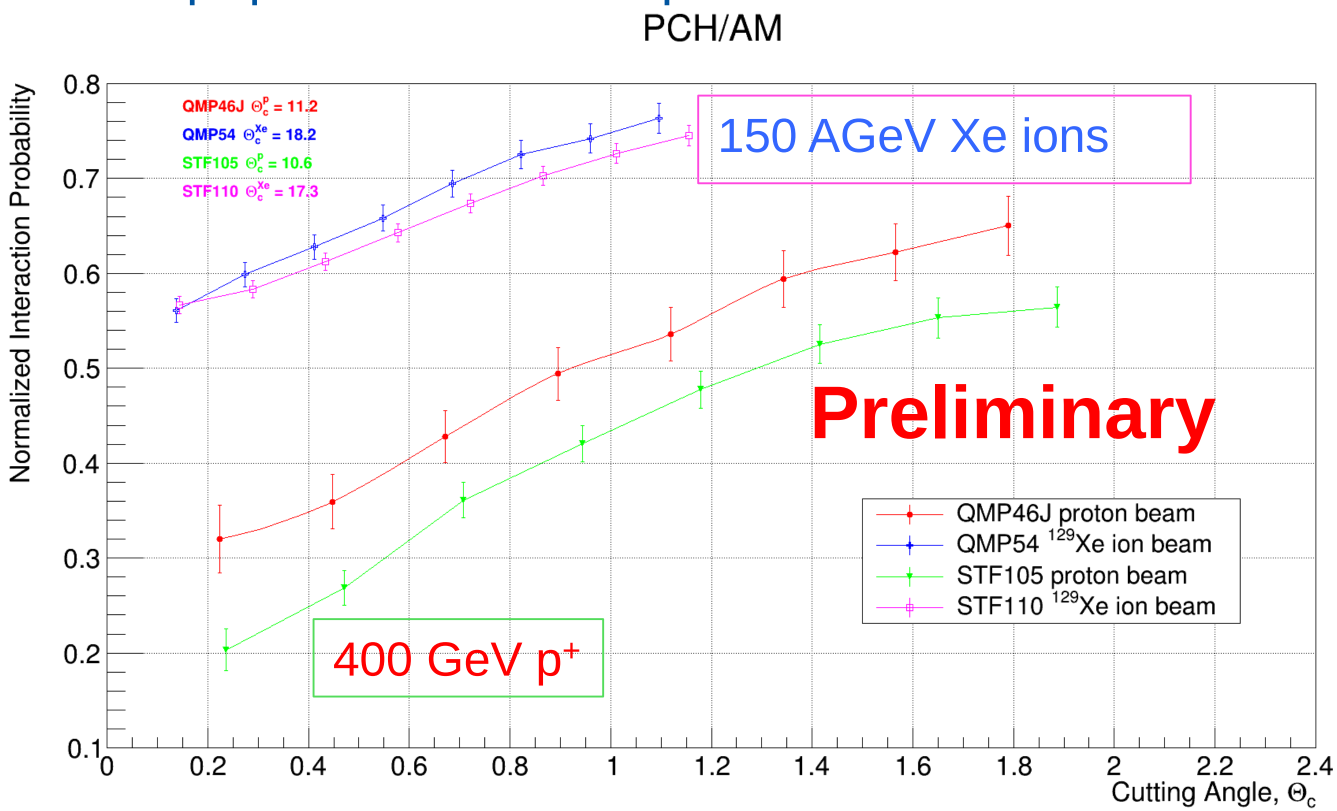
Strip → 1.92 Å
Quasi-mosaic → 1.57 Å

Very good agreement both with Planar Channeling full analytical and SixTrack Monte Carlo simulations

I.N.I. studies (3/3)

I.N.I. studies for LHC collimation purposes:

Strip/quasi-mosaic comparison for Xenon ion beam

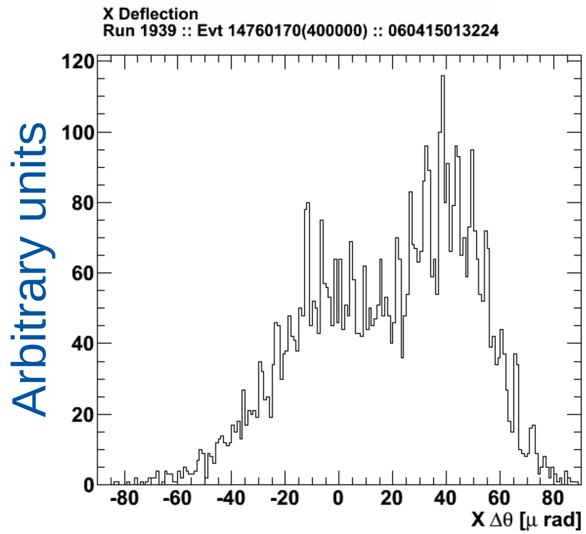


I.N.I. studies are fundamental to estimate the LHC losses at the crystal position and as benchmark for simulations

High-dose irradiated crystals

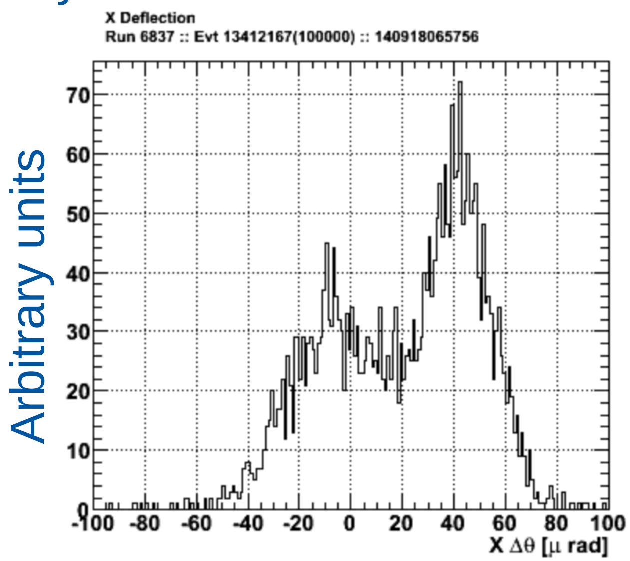
- Test of 2 LHC crystals irradiated in HiRadMat at CERN in 2017 (288 bunches at 450 GeV)

Crystal before HiRadMat irradiation



On-line plots

Crystal after HiRadMat irradiation



- Test of 8 crystal samples irradiated with 5 x 10^{20} fast neutrons (E> 1 MeV)

Comparison with the measurements performed before the irradiation:

- the analysis is ongoing, but in the on-line plots no evidence of relevant changes in efficiency and channeling angle.

Conclusions

- The UA9 setup in H8 has became not only a physics research and R&D laboratory, but also a very efficient crystal characterization facility
- The first “industrial” procedure for LHC crystals beam characterization has been realized: measurements, data analysis, quality check
- It is possible to measure: bending angle, torsion, efficiency and I.N.I. rate
- 11 LHC Strip crystals have been fully characterized and can be exposed to selection criteria
- 4 crystals need further characterizations
- After more than 250 crystal measurements the know how, the method and all the procedures are ready to be “exported” outside CERN during LS2

Thank you for your attention !

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thanks a lot to all the colleagues strongly involved in H8 !!!