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UA9 report for 2019

Executive Summary

This report describes the activity of the UA9 Collaboration during the last 12 months starting from October 2018. Experimental data were collected only in the LHC in November 2018, whilst the analysis of the data collected in the whole 2018 continued. The Memorandum of Understanding of the UA9 Collaboration arrived at its natural end. It has been rewritten for the period 2019/2023 and has been submitted to the Funding Agencies for the final approval. It contains scientific plans dealing with the crystal assisted extraction in the SPS, the upgraded scenario for the double-crystal experiment at the SPS and the characterization and the optimization of the needed crystals. In addition, the telescope and goniometer in H8 are being replaced with better performing ones.

One Doctoral thesis was concluded and discussed in 2019 dedicated to the in-vacuum Cherenkov and Timepix detectors of UA9.

Seventeen publications were issued to illustrate the UA9 results:

1. *R. Rossi et al., Crystal Collimation with Lead Ion Beams at Injection Energy in the LHC,* CERN-ATS-Note-2018-0004-MD**.**
2. *R. Rossi et al. Crystal Collimation During the LHC Energy Ramp,* CERN-ACC-NOTE-2018-0053.
3. *R. Rossi et al., Beam 2 Crystal Characterization Measurements with Proton Beams in the LHC,* CERN-ACC-NOTE-2018-0067.
4. *W. Scandale et al., Dechanneling of high energy particles in a long bent crystal,* NIMB 438 (2019) 38-41
5. *F. Galluccio et al., Physics opportunities for a fixed-target programme in the ALICE experiment,* European Particle Physics Strategy Update 2018-2020 .
6. *W. Scandale et al., Focusing of 180 GeV/c pions from a point-like source into a parallel beam by a bent silicon crystal ,* NIMB 446 (2019) 15-18
7. *B. Balhan et al., Improvements to the SPS Slow Extraction for High Intensity Operation,* CERN-ACC-NOTE-2019-0010.
8. *F. Velotti et al., Septum shadowing by means of a bent crystal to reduce slow extraction beam loss, submitted to PRAB (2019).*
9. *F. Velotti et al., Demonstration of Loss Reduction Using a Thin Bent Crystal to Shadow*

an Electrostatic Septum During Resonant Slow Extraction, [Proc. of IPAC'19, Melbourne, Australia, p. 3399](#).

10. *G.Claps et al. Diamondpix: A CVD Diamond Detector With Timepix3 Chip Interface. IEEE Transactions on Nuclear Science 65, ISSUE:10 p. 2743-2753*
11. *L. Esposito et al., Crystal for Slow Extraction Loss-Reduction of the SPS Electrostatic Septum, Proc. of IPAC'19, Melbourne, Australia, p. 2379*
12. *F. Addesa et al., Commissioning and operation of the Cherenkov detector for proton Flux Measurement of the UA9 Experiment, NIMA 946 (2019) 162513*
13. *S. Redaelli et al., First channeling observation of ion beams at multi-TeV beam energies, submitted to EPJ-C.*
14. *W. Scandale et al., Angular asymmetry of the nuclear interaction probability of high energy particles in short bent crystals, submitted to EPJ-C.*
15. *W. Scandale et al., Channeling efficiency reduction in high dose neutron irradiated silicon crystals, submitted to EPJ-C.*
16. *W. Scandale et al., Beam steering performance of bent silicon crystals irradiated with high-intensity and high-energy protons submitted to EPJ-C.*
17. *A. Natochii et al., Use of a hybrid semiconductor pixel detector as a precision beam monitor at CERN accelerator facilities JINST, Volume 14, March 2019*

1. Upgrade of the UA9 device in the H8 beam line of the SPS North Area

The UA9 collaboration is using its installation in the H8 beam line for more than a decade using a two-arm telescope and a goniometer to test and characterise crystals for the CERN accelerator complex. The devices in H8 are obsolete and are being replaced with more modern and better performing ones.

1.1 Telescope. The present telescope installed in 2010 is able to collect 60 k events per SPS-spill of primary protons. It has also been operational with pions, pb-ions and xe-ions beams interacting with bent crystals. With such a setup the Collaboration was able to measure up to 10 crystals per day. It is however inappropriate to provide:

- increased downstream angular acceptance for nuclear interaction studies
- very large angle channeling
- multiple hits in outgoing arm
- heavy ion signals (signal size = Z^2.MIP => 2916 MIP [Xe] - 6724 MIP [Pb])
- operation by novices
- transfer to another site

The new telescope will be based on the new CMS tracker pads shown in Fig. 1. The expected improvement will mostly rely on the increased speed of event collections, thanks to the data links and module interfaces, the DAQ back-end, the rebuild modules for a larger speed and the new module types for a possible online data processing, or triggering.

1.2 Goniometer. The new goniometer is made of the industrial components, shown in Fig 2. There will be two linear and two angular actuators. It should allow positioning the crystal in the horizontal and the vertical directions to bring the crystal into the beam line with a repeatability 0.1 μm over a range of 50 mm. It should also be able to orient the crystal along the horizontal and the vertical axes with a repeatability of 1.4 μ, over a full range of up to 360 degrees.

2. Upgrade of the UA9 device in the SPS

The modified double-crystal layout is illustrated in Fig. 3. The blue lines encircle the horizontal circulating beam envelope at 4 σ in the region of the experiment, for a beam momentum of p = 270 GeV/c, a tune of Q_h = 20.13 and a physical emittance at 1σ of ε_h = $5\times10_9$ meter×radians, expected in operational conditions. Several beam intercepting devices are also shown: the Crystal1 and Crystal2 are represented by red boxes, the Collimator by a black box, the original UA9 Absorber by a grey box, and the Timepix sensor in its Roman pot by a pink box. The BLMs, indicated by light blue boxes, are installed about 1 m downstream each crystal and absorber to allow detecting interactions with the beam.

Protons channeled by Crystal1 are deflected into the green area (single-channeling beam envelope). If they are also channeled by Crystal2, they are further deflected into the darker green area (double-channeling beam envelope). The Collimator, a LHC-style prototype 1 m long made of graphite, and the Roman pot containing a Timepix detector should probe the transverse particle distribution and the size of the channeled beams.

2.1 Lattice modifications. The Crystal1, originally close to Crystal2, has been shifted backwards by one SPS cell in order to obtain the appropriate shift of the horizontal phase advance between the two crystals and guarantee that the halo particles deflected by the Crystal1 are sufficiently far from the beam core at the azimuthal position of Crystal2. A new 60 cm long tungsten absorber, not shown in Fig3, has been added just upstream of Crystal2 to intercept the halo particles deflected by Crystal1, whenever required. The old 60 cm long absorber made in tungsten has been left in the original position. Moreover, during the double-channeling operation, the integer part of the horizontal tune should be reduced by six units from 26 to 20. The consequent change of the phase advance is such that both the single- and/or the double-channeled beams could be safely stopped just by the original UA9 absorber. Early investigations, relying on two crystals that were built and optimised for collimation tests, provided a useful insight to the double-crystal arrangement. However, no quantitative evaluations could be made of the double-channeling process efficiency, because of the inappropriate width of Crystal2 0.5 mm, too small to match the single-channeled beam size, that at this position was 2 mm. Two new crystals with larger width and increased bending angle were prepared. They are shown in Fig. 5, and have the characteristics summarised in Table 1. They have installed in the double-crystal setup to eliminate the geometrical mismatch of Crystal2 and to increase the clearance of the deflected particle trajectories from the circulating beam for a more comfortable operation of the movable devices.

TABLE 1 Characteristics of the crystal for double-channeling tests		
	Crystal1	Crystal2
Crystal name	TCP78	TCP75
Deflection [μrad]	301	197
Length [mm]	4.0	6.0
Width [mm]	1.5	4.0

A further upgrade consisted in inserting a short tungsten target in front of Crystal2, as schematically shown in Fig.5. The target (drawn in pink color), 3 mm long and 5 mm wide, attached to crystal support (in blue) through an intermediate support (drawn in green) is well aligned to the Crystal2 (drawn in yellow).

2.3 Roman pots and Timepix. The Roman pots and the Timepix are no longer supported by the Collaboration because of their fragile and non-standard design. The new Roman pot design is shown in Figs 6, and 7. The detector to be installed is the so-called Timepix3 version of the Timepix detector family. The Timepix3 readout will be developed in collaboration with the CERN-BI group. The new devices are being designed and built to allow :

- identical mechanical structure in all the UA9 positions in the SPS,
- fast insertion of the Timepix detector to reduce the installation time and the probability of damages,
- more reliability and reproducibility of the alignment of the Timepix detector
- the active area could be tailored on the specific beam size expected : three alternatives are possible 14x14 mm^2, 14x54 mm^2 and 28x28 mm^2
- very good time resolution (1 ns) and dE/dX measurements for the fragment studies.

With this installation, the double-crystal setup proposed for studies of short-lived baryon should be completely implemented. However, it is worth mentioning that in the upgraded lattice there is the space to insert a possible detector system for particle identification downstream of the second crystals and for evaluating the induced background.

3. UA9 experiments in the SPS: data analysis

3.1 Long Crystals. Further investigations were devoted to analyse the performance of the long crystals producing large channeling angles (more than a few mrad) for future applications. Three of these crystals have been tested. One with 3.5 mrad of deflection angle has ~20% efficiency, as shown in Fig. 8. For the other two crystals with a deflection angle of 12 mrad the analysis is ongoing. A new method to analyse the tracks with such large bending was needed given the reduced angular acceptance of the standard telescopic tracker. Also, given the crystal length along the beam, of about 8 cm, a dedicated reconstruction was required. The tracker was used in 4-planes configuration, with the outgoing arm composed of only 2 planes (instead of three). To increase the angular acceptance of the of the outgoing arm of the tracker only the two closest planes were used. As a consequence, the length of the outgoing arm was reduced to ~ 50 cm. The reconstruction was performed excluding the fixed interaction point constraint; this was done in order to take into account the large depth of the crystal (8 cm) in which the interaction can happen. Preliminary results, shown in Fig. 9, have been presented in PBC-FT (Physics Beyond Collider programme, Fixed-Target working group) meeting and are being submitted for publication.

3.2 High-dose irradiated crystals. The characterization of two LHC crystals irradiated at the HiRadMat CERN facility with 288 bunches of 450 GeV protons has been performed, with the goal of studying possible changes of their beam steering performances. High-intensity and high-energy particles could produce thermo-mechanical stresses on the crystal system, inducing deformations, evaporations, vetrification, cracks, etc... The HiRadMat test at CERN was used to study the consequences of unwanted fast irradiations during injection or dump procedures. A high particle fluxes produce crystal lattice damages that affects the channeling performance (i.e. the channeling efficiency). Thus, efficiency measurements before and after irradiation is measured to validate their robustness. A preliminary comparison of the data collected before and after the irradiation does not show any relevant change in performance, when the crystal is exposed to several proton bunch trains similar to those injected in LHC. The same test has been performed also on eight crystals irradiated with 10^{20} fast neutrons (E > 1 MeV). Exposure to neutrons from a nuclear reactor is the fastest way to irradiate a crystal with a dose comparable to the crystal usage in operation. Test with protons or heavy ions would imply irradiation time comparable to the operational ones for several years. In addition, neutrons produce similar damages, but with a reduced activation of the sample. Height crystal samples were tested (bent) before and after the irradiation in the same conditions. A ninth crystal was not irradiated to check its stability for the duration of the whole test. The channeling efficiency was measured to assess the robustness of the crystals to radiation damages. On average, a channeling efficiency reduction of ~ 8 % was observed after the irradiation, see Fig. 10.

3.3 FLUKA Crystal Simulation Routine. The FLUKA crystal routine developed by P. Schoppfs in 2011/’14 was used to be benchmarked with data collected during the Run II. This standalone routine uses FLUKA library, thus, it is able to simulate the interaction of all particles listed in FLUKA, included heavy ions with bent crystals. Benchmarks were done with H8 data collected with 180 GeV pion, 150·A GeV Pb and Xe ions, and 75°A GeV Ar ions beam. The results were in sufficient agreement (see Fig.11), considered that no special modification was made to include heavy ion simulation. This new set of benchmarks allowed to point out the main differences between data and simulations, and the possible improvements are under investigation. The simulation tests will be soon extended to the SPS data.

4. Plans and perspectives

The 2019 (and beyond) plans of the UA9 Collaboration cover the following issues.

GOAL in an experimental area:

- Crystal tests at FNAL and at LNF-BTF facilities
- Build a portable telescope based on Timepix3 sensors
- Continue testing and qualifying crystals for LHC
- Procure and qualify crystals for the SPS test runs during RUN3
- Investigate correlation of crystal parameters measured with beam and with a X-ray source
- New technology crystals in particular
    - large bending angle crystal with a sufficiently large efficiency for FT in LHC
    - multi-crystal for an optimal shadowing of the electrostatic septum for SPS extraction
    - focusing crystals for steering split halo-beam in LHC
    - strip crystals optimised for the multi-injection of muons in a booster ring of a possible muon collider.
- Upgraded detector tests

    - In-vacuum Cherenkov detectors for the double crystal test in SPS and later for characterizing deflected ion beams in LHC
    - Next generation of Timepix for SPS

GOAL in the SPS:

- Complete the upgrade of the UA9 setup during LS2
- Test and performance assessment of a crystal-assisted local/non-local non-resonant slow extraction, in view of reducing loss in the electro-static septum. Consider installing a more local setup or strong bumpers at the crystal to operate in cycled mode and more in-vacuum loss diagnostics.
- Investigate non-resonant extraction scenarios for LHC and beyond to reduce the complexity and cost of the extraction systems.
- Pursue the shadowing test to bring immediate benefits for the daily SPS operation and ensure a safe extraction scenario for the high intensities required by the Beam Dump Facility.
- Pursue investigation of beam splitting scenarios for FT physics in LHC

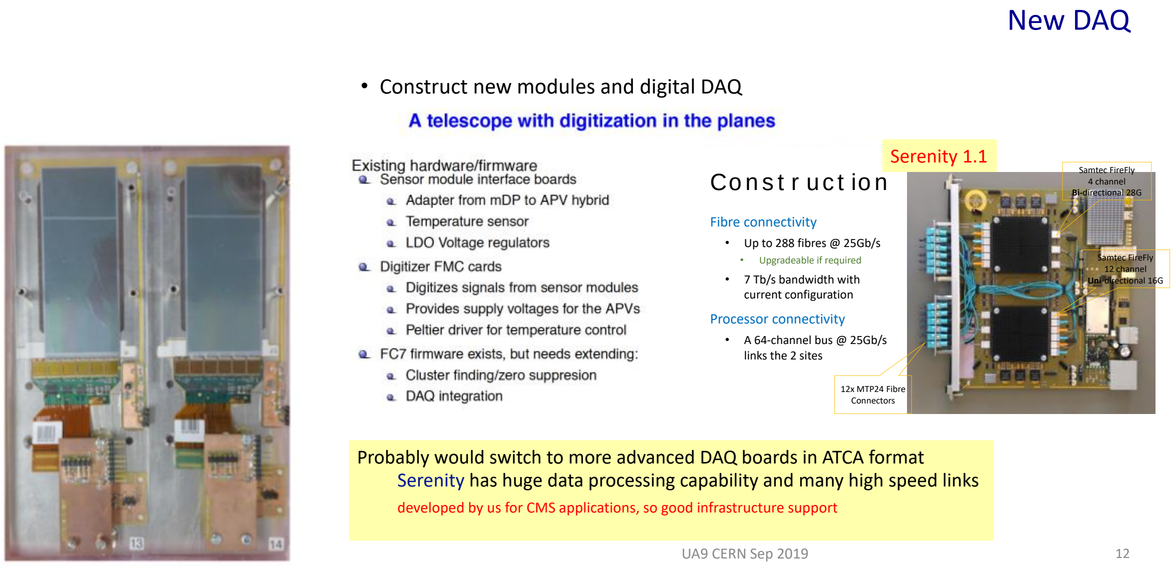

Fig. 1 the new CMS telescope module and DAQ.

Fig. 2 The rotational and translational stages of the new H8 gonioneter for UA9.

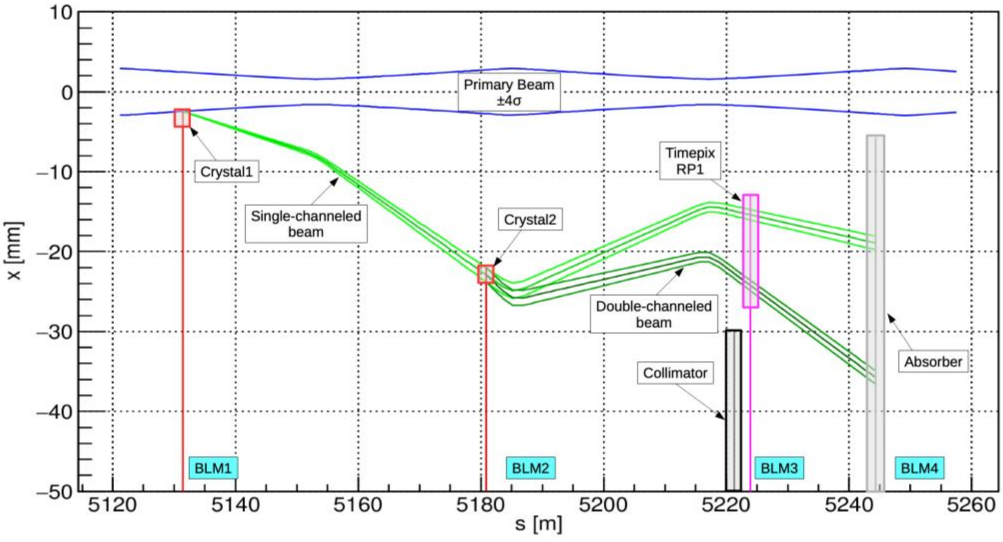

Fig. 3 Layout and horizontal beam envelope for the UA9 double crystal experiment.

Fig 4 The double-channeling experiment crystals

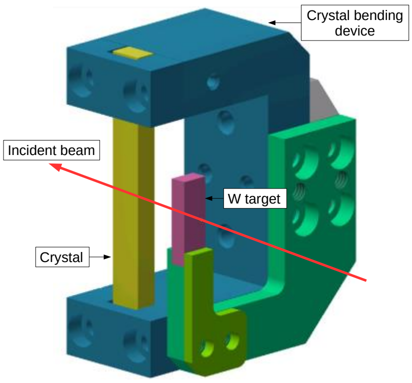

Fig. 5 the Crystal2 with the tungsten target

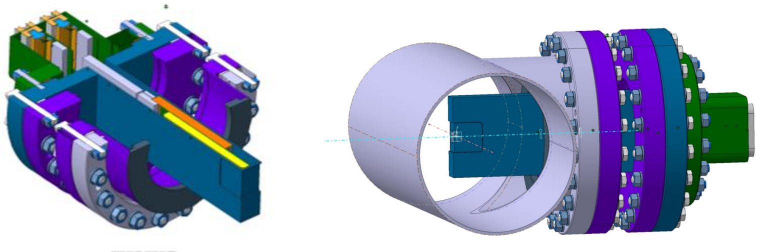

Fig 6 new Roman pot design

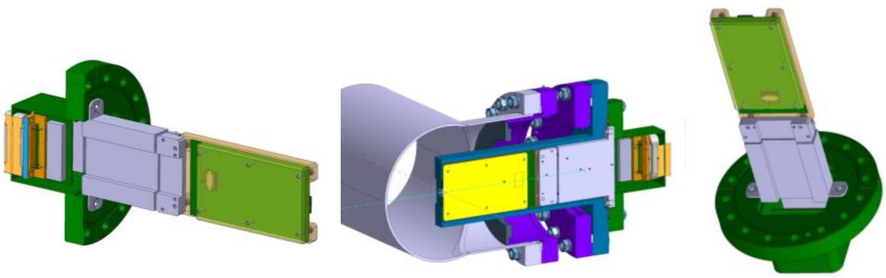

Fig 7 Timepix3 holder

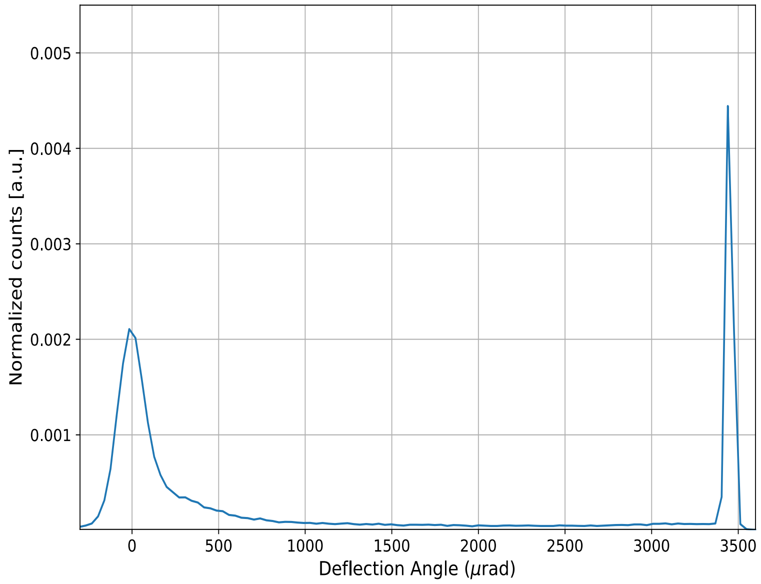

Figure 8. Bending angle (~ 3.5 mrad) and efficiency (~ 20 %) of the long crystal for the double crystal experiment in the SPS.

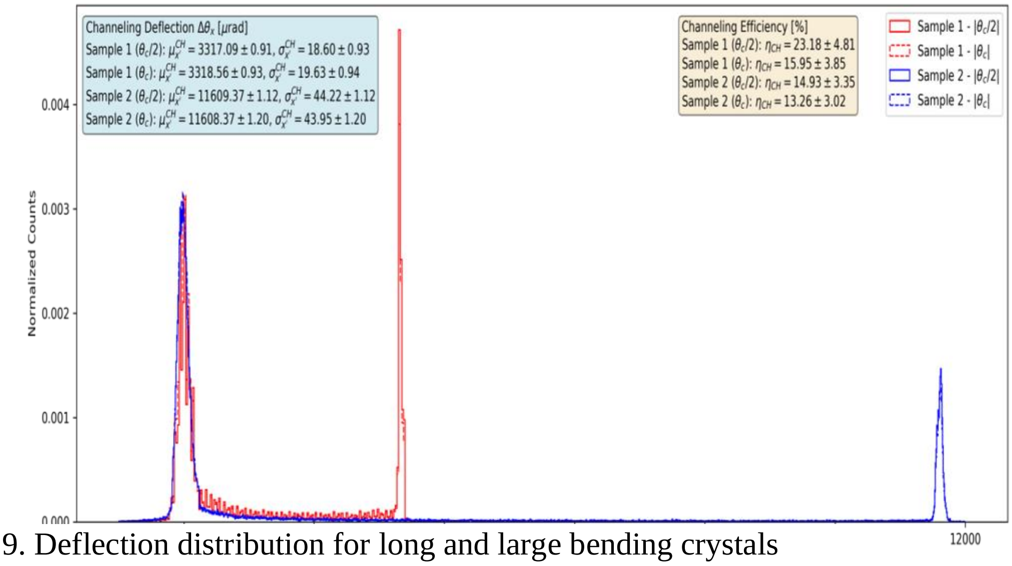

Figure 9. Deflection distribution for long and large bending crystals

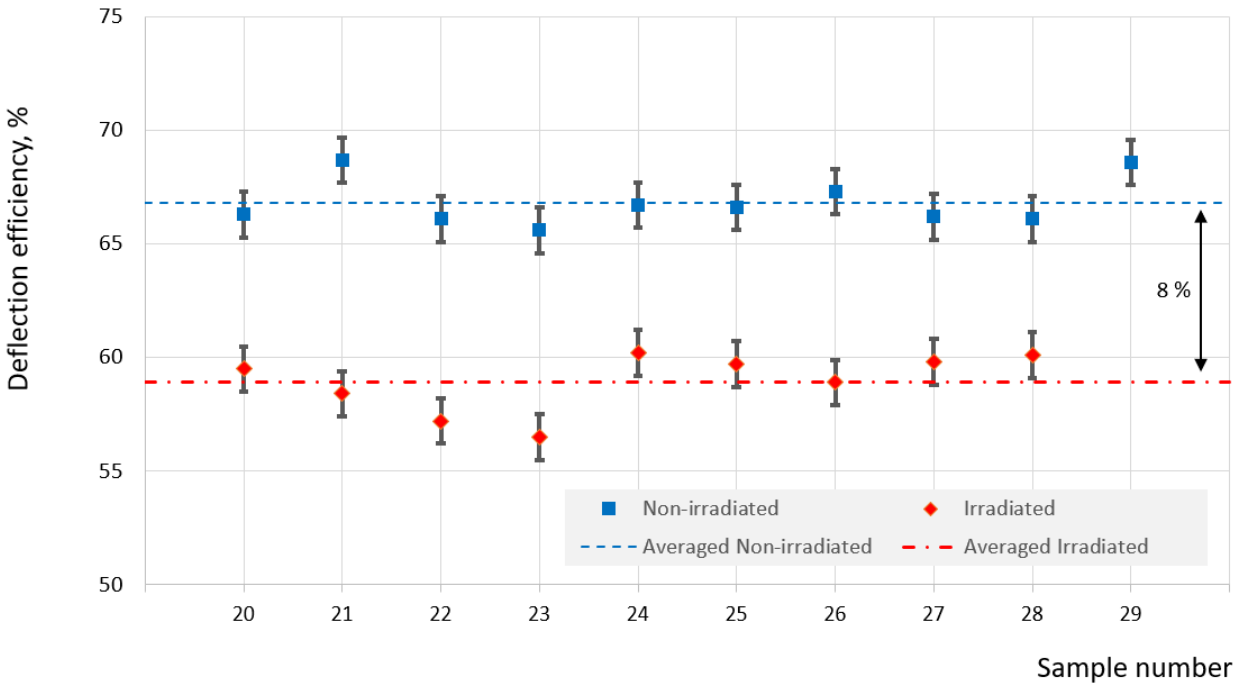

Fig 10. Height crystals were irradiated in a nuclear reactor with 10^{20} neutrons /cm^2.
The channeling efficiency before and after the irradiation is shown.

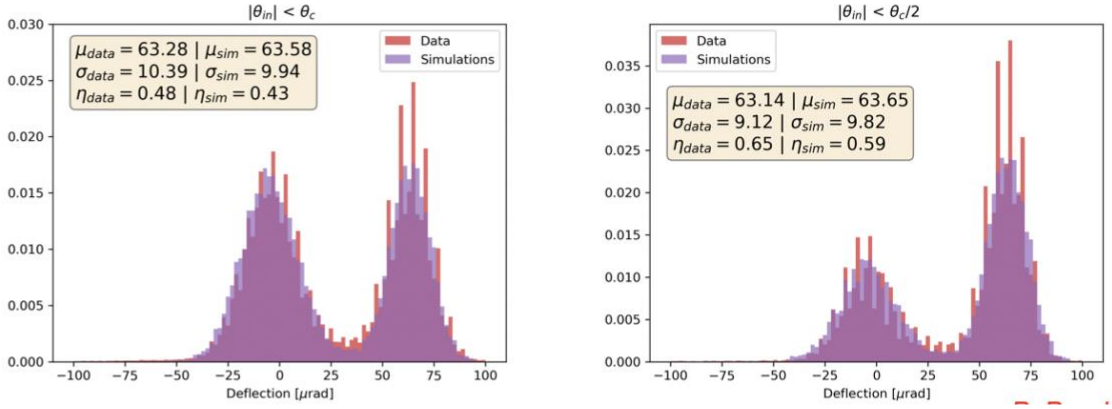

Figure 11. Comparison of experimental data with FLUKA standalone routine simulations. A beam of 150 A GeV Xe ions is considered and interacts with a ~60 urad bending angle crystal. Efficiency and sigma values are in good agreement