Executive Summary

This report describes the activity of the UA9 Collaboration during the last 12 months starting from October 2017. Experimental data were collected in the North Area of the SPS, in the SPS itself and in the LHC.

North Area. Several new crystals and detectors were tested in the H8 line. Eighteen LHC-type crystals were measured. Eleven of them were fully characterized for crystal assisted collimation, three are in stand-by waiting for data analysis and further tests. One bending crystal was tested for the double-crystal experiment in SPS. Some crystals, with an increasingly large bending angle, were produced to demonstrate if bending angles exceeding 10 mrad can be made available for a possible extension of the double-crystal experiment to LHC. One focusing crystals was improved to provide focusing (or defocusing) of the incoming beam together with highly efficient particle deflection. R&D on self-standing crystals, for which a bending device is not needed, has been pursued. The silicon tracker was upgraded for an optimal performance also with bending angles larger than ten mrad. Cherenkov-based and Timepix-based monitors to measure the flux and the induced background of deflected particle in the vacuum pipe both in the SPS and in the extraction line TT20 were intensively tested for an upgrade of their performances and calibration.

SPS. A new absorber, a third Timepix station, and new wide cross-section crystals were timely added to the UA9 layout for the double crystal channeling experiment. The first evidence of the double crystal channeling process was recorded in October 2017. During 2 runs in 2018, procedures were established to orient the two crystals to maximise the channeling efficiency, which revealed the fundamental importance of having performant local diagnostics. Systematic data were acquired for the evaluation of the relative background. The layout was further upgraded by the insertion of a target in front of the second crystal to evaluate efficiency and backgrounds in a configuration similar to that proposed by Physics Beyond Colliders experiments. An extra run of 10 hours has been requested, but not allocated yet.

Slow Extraction in SPS. An additional short goniometer UA9-like equipped with one crystal only has been installed about 5 m upstream the first electrostatic septum of the extraction beam line towards TT20 and the North Area. After a short dry-run test of the new devices, one run (4 Oct 2018) was devoted to investigate the local septum shadowing assisted by a bent crystal in collaboration with CERN TE/ABT and EN/STI groups. A reduction of the overall
losses, up to 40%, was observed along the extraction line when the crystal, properly aligned to the septum wires, was in channeling orientation. Another set of measurements is foreseen before the end of October.

Eight crystals were irradiated with neutrons in a nuclear reactor for an equivalent dose of $10^{19}$ particles per cm². Tests performed before and after the irradiation should clarify the potential radiation damage. The results will be shortly available.

**LHC.** A continuous support was offered to the LHC Collimation Team to test crystal-assisted collimation in the two LHC rings. Performance of crystals now conforms to the expectation, showing a substantial improvement at least at low current of the collimation efficiency all along the LHC magnetic cycle (at injection, during the ramp of the magnetic field and during the collision flat top). During the October runs, crystal collimation was put in operation during data taking of TOTEM with high-β optics, demonstrating, for the first time ever, the usefulness of bent crystals in a hadron collider.

**Two Doctoral thesis** were concluded and discussed in 2018
- one dedicated to the in-vacuum Cherenkov detector of UA9
- the other to the performance of crystal assisted collimation in LHC.

**One more Doctoral thesis** is due in 2019, devoted to characterization of the double channeling process in the SPS.

**Three publications** were issued to illustrate the UA9 results:
- “*Focusing of a particle beam by a crystal device with a short focal length,*”, W. Scandale et al., NIMB 414 (2018) 104-106;
One contribution was presented at the IPAC2018 conference in Copenhagen:

“Testing the Double-Crystal setup for physics beyond colliders experiments in the UA9-SPS experiment”, S. Montesano on behalf of the UA9 collaboration.

Three contributions were presented at the Channeling 2018 conference in Ischia to be published in Physical Review Accelerators and Beams:

- “Dechanneling Population at Extreme Crystal Bending with 6.5 TeV Proton Beam”, R. Rossi et al.;
- “Crystal-Assisted Beam Manipulation at CERN SPS”, F. Galluccio on behalf of the UA9 Collaboration;

1. UA9 tests in the H8 beam line in the SPS North Area

The UA9 operation in H8 lasted 47 days split over 7 runs. UA9 was the main user for 15 days and the secondary user for 32 days. The overall efficiency of the runs was 45%, mainly due to machine problems. The list of the achievements includes the following items.

1. Upgrade of the Tracker. The silicon tracker was upgraded and optimized to extend its operational range to large bending crystals of more than ten mrad. This was obtained by reducing from five to four the silicon planes and by reducing by about an order of magnitude the lever arm of the outgoing branch; also, the track reconstruction algorithm has been adapted for this new purpose. The tracker was tuned to detect ion beams, including Pb-beams.

2. Test of crystals for future use in LHC. Dedicated tests were performed to identify crystals adequate for LHC crystal collimation, with bending angles in the range of 50 to 55 µrad, with a bending efficiency exceeding 60% and an angular stability during the thermal cycles required for degassing lower that a few µrad. Eighteen LHC-type crystals were measured. Eleven of them were fully characterized for crystal assisted collimation, three are in stand-by waiting for data analysis and further tests. Four strip crystals in the LHC specifications are shown in Figure 1.
3. **Crystal for SPS studies.** In the context of the double crystal experiment, a new strip crystal was tested with and without a 3 mm thick tungsten target mounted upstream, in view of installing it in the second position of the two-crystal layout. The measured deflecting angle is ~194 µrad, a value required to provide an easier detection of the double deflected beam trajectories. The efficiency changes from ~ 65% with the target to ~ 10% without (Figure 2). Three strip crystals were characterized to assist the slow extraction from the SPS (electrostatic septum shadowing). The results of the best crystal, successfully installed and tested in the SPS, are shown in Figure 3.

4. **Focusing crystals.** One additional trapezoidal crystal was tested, with a different focal length and a better quality with respect to those developed in 2016-17; the data analysis is in progress. A focusing crystal in the first position of the two-crystal layout in the SPS should allow the best irradiation of the second crystal. Moreover, it could be applied for collimation spreading the deflected beam on an absorber thereby reducing the deposited energy density.

5. **Long Crystals.** Further investigations were devoted to long crystals producing large channeling angles (more than 10 mrad) for future applications. Three of these crystals have been tested. One shows 3.5 mrad of deflection angle with ~20% of efficiency (Figure 4). For the other two with a deflection angle of 12 mrad the analysis is ongoing. In addition to the standard method of bending through anticlastic deformation, we tested crystals “self-bent” through thin film deposition (Figure 5). The ultimate goal of these studies is to produce large bending high-efficiency crystals satisfying the specifications for the two-crystal experiment in LHC.

6. **Nuclear interaction rate.** The rate of nuclear interactions in the so-called “quasi channeling orientation” was carefully investigated with pions and ions on LHC crystals. The goal was to detect changes of the nuclear interaction rate when the incoming particles have an angle just outside the channeling acceptance. Figure 6 shows some preliminary results obtained with an ad-hoc detector made of two scintillators surrounding the outgoing arm of the telescope in order to see multiple tracks induced by nuclear cascades downstream of the crystal. Nuclear interactions of 150 GeV/n Xe ions with LHC crystals have been also studied, estimating the reduction factor with respect to the amorphous orientation (Figure 7).

7. **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. The same test has been performed also on eight crystals irradiated with \(10^{20}\) fast neutrons (\(E > 1\) MeV). A preliminary comparison of the data collected before and after the irradiation does not show any relevant change in performance. The final analysis is in progress.

8. **Detectors.** Further tests to optimize the performances and the calibration of the Cherenkov detector for proton Flux Measurements (CpFM) for SPS and LHC were carried out in parasitic mode in almost all the H8 runs. Different kind of quartz radiators, optical filters and photomultipliers were tested. The Timepix based telescope (Figure 8) was fully tested and calibrated. With the new cluster analysis in timing mode the detectors are linear (Figure 9) within 1000 particles per time frame (typically less then 2ms window). In counting mode, the detectors have been calibrated with \(1.7 \pm 0.1\) pixels per impinging particle (Figure 10) with a linearity up to 200 kHz/mm\(^2\), allowing quantitative flux measurements in the SPS. The performances are good and comparable with more sophisticated silicon telescope. The average spatial resolution is less than 20 \(\mu\)m per sensor. The telescope provides very good 70 \(\mu\)rad angular resolution for reconstructed particle tracks with a flight base of 1.2 m and track reconstruction efficiency of about 10%. Increasing the flight base (10-20 m), it is possible to improve the angular resolution of the system up to the physical limitation of 10.5 \(\mu\)rad, which is related to the multiple scattering inside each sensor. The system is portable and can be installed on the different beam lines for crystal measurements and characterization.

9. **Shadowing test.** A set of targets was installed in H8 to investigate issues related to the alignment of distant objects in the SPS. In particular, the studies were used to devise appropriate methods to align the crystal to the wires of the electrostatic septum in the shadowing experiment.

2. **UA9 tests in the SPS ring**

UA9 had already been assigned a 24-hour run with Xenon ions in 2017 (12 Dec 2017). In 2018 UA9 proton runs where only allowed during the radiation cool-down time before the 2 technical stops (18 Jun 2018 and 17 Sep 2018). An extra MD time-slot of 10 hours was allocated on a last-minute basis during the usual Wednesday MD time (15 Aug 2018) to perform LHC related collimation studies.
The overall run efficiency was of about 73%. The inefficiency was mainly due to beam unavailability (5%), beam set-up (12%), critical detector maintenance (2%), beam instability (8%); in particular the June run was dominated by beam orbit instabilities that, when not imposing a beam dump, prevented the usual alignment procedures. The instabilities were caused by an intermittent short circuit on a dipole replaced on the following day.

The run with Xe-ion beam was used to:

- **Study of absorber material:** The 2017 layout allowed studying the effect of different absorber materials on the performance of a crystal collimation system. The TACW, made of tungsten, and one of the TCSM jaws, made of CFC (graphite compound), were used to carry out this study. The results are reported in Figure 11, where the amorphous to channeling loss reduction factors of the layout with a tungsten and a carbon absorber are compared. A factor 2 higher reduction is observed in the dispersive area when the tungsten absorber is used.

Studies made during the proton runs:

- **Study of absorber material:** The upgraded layout of 2018 allowed to use another tungsten obstacle, the TACW0, as absorber. The old TACW (now TACW1) was used for a different measurement. The experimental configuration is presented in Figure 12, where the channelled particles trajectories are highlighted. All the devices are set to their measured horizontal aperture, and is shown how the two collimators where set to cut the same deflection angle, within an accuracy of 10 µrad. As for Xenon measurements one absorber at the time was tested, and the amorphous to channeling loss reduction factor was measured to compare the two systems (Figure 13). Also in this case, the cleaning performances, measured in the dispersive areas, are better with the tungsten absorber. The old TACW1 was used to sample the secondary halo escaping from the crystal collimation absorber. One at the time, tungsten and graphite collimator were used with crystal set in channeling orientation. The TACW1 was at this point inserted in the machine until a clear spike (that indicates the circulating beam position) was observed. As shown in Figure 14, the amount of losses is clearly higher when the graphite collimator is used as absorber.

- **Investigation of double channeling scenario:** the 2017 run with double channeling (Figure 15 and Figure 16) had indicated that the second crystal should have a wider
cross-section to intercept the whole first channeled beam. The UA9 layout was updated during the YETS2017 (Figure 17) with the installation of a 4 mm wide downstream crystal, a large deflecting angle upstream crystal, a new tungsten absorber and a refurbished Roman Pot equipped with 2 Timepix detectors. ATimexpi3 was also installed on the outer side of the SPS vacuum chamber for testing purposes. The June data-taking was spoiled by the already mentioned beam orbit instabilities; nevertheless, it was possible to test all equipment and to establish a procedure to set the optimal double channeling conditions. The UA9 in-vacuum detectors, Timepixes and CpFM, played an essential role in recognising the onset of channeling, being the usual detectors, BLMs and scintillators, almost insensitive to small local variations of the charge. In the September run it was possible to take data more systematically. In Figure 18 the images at the Roman Pots of the beamlet deflected by the first crystal and of the same beamlet split by double channeling are presented. Figure 19 shows the projection of the image at the second Roman Pot on the horizontal axis during a complete angular scan of the second crystal: all the typical deflection regions are visible. In Figure 20 a few snapshots during such an angular scan are displayed. Linear scans of the CpFM (Figure 21) through the channelled beamlets allowed evaluating the extracted proton flux per turn with different beam diffusion rates created by the random electromagnetic noise generator (ADT). In the September Technical stop a tungsten target was mounted in front of the second crystal (Figure 2, left) as requested in PBC experiments. The requested beam time has not been allocated yet.

- **Crystal characterization:** The last two installed crystals were characterized.

**Detector investigations**

- **Timepix detector stress test:** The Timepix detectors were subject to increasing particle fluxes by means of a stochastic excitation of the beam and no saturation effects were observed in counting mode. One Timepix in Roman Pot 3 internal side is not working anymore after three years from the installation.

- **CpFM detector upgrade:** After the quartz fiber bundle removal and the detector operation changed to only one readout channel, the light yield per proton increased by a factor 10, as it was assessed during the Xenon ion run in December 2017 (Figure 22). During YETS 2017 the CpFM layout was further upgraded to match the requirements.
of the double-crystal experiments in terms of sensitivity to the single proton. A new Fused Silica radiator of pyramidal shape was mounted. This geometry is the results of an extended R&D campaign carried out both through simulations and on beam tests performed in H8-NA. Featuring the new bar, the light yield/p of the detector further increased by a factor of 10 making the CpFM fully sensitive to the single proton (Figure 23) and suitable for the new UA9 double-crystal experiments as it shown in Figure 21.

**Extraction Tests in SPS**

The crystal assisted slow extraction working group, including members of the UA9 Collaboration and of the BE-ABP, BE-OP, EN-SMM, EN-STI and TE-ABT groups, investigates novel extraction techniques in order to reduce the losses at the electrostatic septa (ZS). A ZS shadowing test was conceived with the objective to deviate the protons that would impinge on ZS by means of a bent crystal installed about 5 meters upstream of the ZS. A new compact vacuum tank with a bent crystal mounted on a goniometer (see Figure 25 and Figure 24) was manufactured in few months and installed during the TS2. The working group operated the crystal parasitically during two machine development times (MDs) dedicated to SHiP T6 test with 400 GeV proton beam.

During the first MD – held on Sep 26th 2018 – most of the time was spent to set-up the beam. Nevertheless, it was demonstrated that the hardware worked properly and the typical loss reduction at the crystal location were observed during an angular scan when the crystal was in channeling orientation.

During the second MD – held on Oct 3rd 2018 – several angular scans were performed with the crystal placed at different positions from the beam axis. At the crystal position with the best observed ZS loss reduction, the losses measured by the SPS BLM’s along the ZS were decreased by about 40% (see Figure 26). Figure 27 shows that when the crystal is closer to the circulating beam, the losses at the ZS increase since the beamlet from the channeling orientation is sent against the ZS. Equivalently, when the crystal is closer to the extracted beam, the losses at the ZS are increased as well, because the beamlet from the Volume Reflection orientation is sent against the ZS. In addition, a linear scan of the crystal in the amorphous orientation confirmed that the position where the maximum loss reduction at the ZS was observed is closer to one where the maximum shadowing effect of the crystal onto the ZS is observed (see Figure 28).
3. Plans and perspectives

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

GOAL in an experimental area:

- Consider continuing the crystal tests at FNAL and at LNF during LS2
- Build a portable telescope Timepix based
- Continue procuring and testing crystals for LHC and 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
  - focusing crystals for steering split halo-beam in LHC
- 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:

- Modify the UA9 setup during LS2 to comply with the installation of a dump in LSS5, required for loss control during the SPS operation
- Test and performance assessment of a crystal-assisted local/non-local non-resonant slow extraction, in view of reducing loss in the ES 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
Figure 1. LHC crystals fully characterized in H8 and available for operations: ACP79, ACP84, ACP85 and ACP86 are stable and in specification, the ACP80 is stable but slightly out of specifications and can be considered as a spare.

<table>
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<td>&lt;1</td>
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Figure 2. On the left, the drawing of the crystal to be installed in the SPS as second crystal in the double-crystal layout, with the 3 mm thick tungsten target mounted in front. On the right, the online plot of the beam deflected by this crystal with and without the target. The channeling angle measured is ~194 µrad in both cases, instead the efficiency changes from ~65 % without the target to ~10 % with the target.
Figure 3. Bending angle (~ 175 µrad) and efficiency (~ 65 %) of the SPS crystal installed with the purpose to assist the slow extraction from the SPS (electrostatic septum shadowing).

Figure 4. Bending angle (~ 3.5 mrad) and efficiency (~ 20 %) of the long crystal for the double crystal experiment in the SPS.
Figure 5. A picture of the self-bending crystal through thin film deposition
Figure 6. Inelastic nuclear interaction probability for a LHC strip silicon crystal as a function of the impinging angle of 180 GeV pions. The probability is normalized to the amorphous value and measurements (red curve) are compared with full analytical simulations (blue curve).

Figure 7. Very first estimation of the inelastic nuclear interaction probability of 150 GeV/n Xe ions in channeling orientation for LHC silicon crystal (quasi-mosaic crystal is in blue and the strip is in violet), normalized to the amorphous orientation rate. The probability is reported as a function of the cutting angle value of the Xe ions impinging the crystal and it is compared with the 400 GeV protons case (quasi-mosaic crystal is in red and the strip is in green).
Figure 8. Experimental layout of the Timepix telescope.

Figure 9. Comparison between two types of the Cluster Analysis (CA) for the H8 beam in ToA mode operation. The reference number of the incoming particles was taken with a plastic scintillator installed on the beam.
Figure 10. Distribution of the fired pixels number per particle. The fit was done with Landau function (red dashed line). MPV is the most probable value.
Figure 11. Run with Xe beam. The TACW, made of tungsten, and one of the TCSM jaws, made of CFC (graphite compound), were used to carry out this study. The amorphous to channeling losses reduction factors are shown for the layout with a tungsten and a carbon absorber. A higher reduction is observed in the dispersive area when the tungsten absorber is used (about a factor of 2).
Figure 12. The experimental configuration during the proton run is presented. The channelled particles trajectories are highlighted. All the devices are set to their measured horizontal aperture, and it is shown how the two collimators where set to cut the same deflection angle, within an accuracy of 10 µrad.
Figure 13. Run with proton beam. The amorphous to channeling loss reduction factor was measured to compare the two systems (Figure 12), in different machine locations. As for the Xde beam, the cleaning performances, measured in the dispersive areas, are better with the tungsten absorber.
Figure 14. TACW1 linear position as a function of local losses. The absorber was used to sample the secondary halo escaping from the crystal collimation absorber. One at the time, tungsten and graphite collimator were used with crystal set in channeling orientation. The TACW1 was at this point inserted in the machine until a clear spike (that indicates the circulating beam position) was observed. The amount of losses is clearly higher when the graphite collimator is used as absorber.
Figure 15. Horizontal beam envelope and position of the main devices in the UA9 Experiment installation of 2017.

Figure 16. Image of the single-channeled (top) and double-channeled (middle) beams on the Timepix detector. The image should be rotated by 90° counter-clockwise in order to reproduce the real spatial position of the beams. The color scale represents the average number of counts per second per pixel. Only a small fraction of the first channeled beam is channeled a second time because of the small thickness of the 2nd crystal (0.5 mm).
Figure 17. UA9 Layout Update 2018

Figure 18. Left: Channeled beamlet at the first Roman Pot (RP0), before the downstream crystal. Right: Channeled plus double channeled beamlets at the second Roman Pot (RP1).

Figure 19. While the upstream crystal is kept in channeling orientation, the downstream crystal performs an angular scan, and the beam is deflected towards amorphous (AM), volume reflection (VR), volume capture (VC), dechanneling (DCH) and channeling (CH) amplitudes.
Figure 20. Upstream crystal in Channeling orientation. Snapshots of the downstream crystal angular scan: A, amorphous orientation; B, volume reflection; C, volume reflection plus volume capture; D, Channeling.
Figure 21. CpFM integrated beam profile obtained using two different values of the transversal damper (ADT), proton UA9 MD, September 2018. As the detector is moved to smaller apertures, it intercepts first the beam channeled by the second crystal (first plateau region in both the profiles) and then the beam channeled by the primary crystal (higher plateau region in both the profiles.)
Figure 22. CpFM amplitude distribution, Xenon ions UA9 MD, December 2017. Ion beams offer the opportunity to in-situ calibrate the detector due to the excellent light yield per ion. Beside the Xenon ion peak are also visible two peaks associated to ion fragments with charge $Z = 53$ and $Z = 52$.

Figure 23. CpFM amplitude distribution for a single proton (fitted peak), UA9 MD, June 2018. After the installation of the new pyramidal bar (right), the in-situ calibration of the detector is feasible also with proton beams.
Figure 24. Model of the compact vacuum tank containing the goniometer installed in SPS LSS2.

Figure 25. Picture of the PNPI crystal candidates for the ZS shadowing test in SPS. They have all the same characteristics: 175 urad bending angle, 2 mm long and 0.8 mm thick across the beam. The crystal installed in the SPS is the ACP82.

Figure 26. Observation of the loss profile as function of the crystal angle with respect to the channeling orientation at the crystal location (left) and along the ZS (right) at the crystal position with the best reduction factor. The BLM signals are normalized to the value when the crystal is in amorphous orientation.
Figure 27. Observation of the loss profile as function of the crystal angle with respect to the channeling orientation at the crystal position (left) and along the ZS (right) at the crystal position at different positions of the crystal. The positions are referred to the beam axis. The BLM signals are normalized to the value when the crystal is in amorphous orientation at 70 mm.

Figure 28. Observation of the loss profile as function of the crystal position in amorphous orientation measured with the SPS BLM’s along the ZS (right) at the crystal position at different positions of the crystal. The position where the best loss reduction at ZS was observed is also shown.