UA9 report for 2016

Executive Summary

This report describes the activity of the UA9 Collaboration during the last 12 months starting from October 2015. Experimental data were collected in the North Area of the SPS, in the SPS and in LHC. Preliminary tests to investigate slow extraction assisted by bent crystals in the SPS using the UA9 devices were organized with the CERN-TE-ABT group. The intensive irradiation of LHC-type crystals was delayed to 2017, because high intensity beams were not available in the HiRadMat facility due to the vacuum leak in the SPS beam dump.

The investigations in the North Area were devoted to the characterization of new crystals and detectors. Five crystals of LHC-type, one strip and four quasimosaic, were characterized and approved for future applications. The silicon tracker was upgraded for an optimal performance with lead-ions whilst a new configuration was proposed to measure crystals with large bending angles. Focusing crystals were improved to provide focusing (or defocusing) of the incoming beam together with highly efficient particle deflection. Multi-strip crystals of a new design were able to provide large particle deflection based on high efficiency multi-volume reflection mechanism. Long crystals for large beam deflection with anticlastic bending were proposed. Variants with self-sustained bending were also produced and tested. A considerable effort was dedicated to calibrate and operate Cherenkov based monitors to measure the flux of deflected particle in the vacuum pipe both in the SPS and in the extraction line TT20 also in view of applications to LHC.

The study in the SPS were devoted to the commissioning the Cherenkov detector for proton flux measurement. Promising applications were identified consisting in the detection of the deflected beam size and in the determination of the diffusion coefficient by which the halo density is sustained during storage operation. A configuration of UA9 simulating the one used in LHC was also studied, aiming at evaluating the effect of amorphous primary collimators set in the vicinity of the bent crystals. Crystals with very different polishing quality of the face intercepting the halo particles were compared. The possibility to detect the diffusion coefficient in the SPS was investigated using a method based on orbit deformation with the closed orbit dipoles.
A run was devoted to investigate the configuration for slow extraction assisted by bent crystals in the SPS.

Runs in LHC could demonstrate the high reproducibility of the crystal collimation devices. The data collected were showing a considerable reduction of the loss rate in channeling mode both in the vicinity of the crystal and in the full LHC ring.

A Master thesis was concluded and discussed in 2016 devote to the investigation of various inelastic interaction regimes in bent crystals.

Four publications were issued to illustrate the UA9 results:


"High-efficiency deflection of high energy protons due to channeling along the \(\langle 110 \rangle\) axis of a bent silicon crystal”, Scandale et al., Physics Letters B, 760 (2016) 826-831

“A crystal routine for collimation studies in circular proton accelerators”, D. Mirarchi et al


“Measurements of coherent interactions of 400 GeV protons in silicon bent crystals”, R. Rossi et al,


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

Data taking in H8 lasted 30 days split over 4 runs. During this period of time, UA9 was main user for 22 days and secondary user for 8 days. The overall efficiency of the runs was 65% of the assignment. The list of the activities and of the main results includes six main items.

1. **Upgrade of the Tracker.** During the run with 30 A GeV lead ions in November 2015 a long commissioning of H8 beam line and of the Tracker were performed. The goal was to achieve the performances necessary for properly testing crystals with lead ions at full energy during the November 2016 run. Moreover, starting from July 2015, a
new DAQ configuration to test crystals with large deflection angle (> 2 mrad) was completed and made operational.

2. **Test of crystals for future use in LHC.** Dedicated tests were performed in each run in order to study LHC-type crystal performance. The main goal was to identify crystals (strip or quasimosaic) with a bending angle in the range of 50 to 55 µrad, with a bending efficiency of the order of 60% or more and to test their stability before and after the thermal cycle required for degassing. Some crystals were tested several times and submitted to more than one thermal cycle (up to three in one case) to test the long-term stability. Four quasimosaic crystals were confirmed as fully satisfactory. The bending angles, ranging from 50 to 52 µrad, were well inside the specification, with no measurable change during thermal cycles. All of them were accepted as fully adequate to assist crystal collimation in LHC. Three new strip assemblies were also produced, with a titanium frame submitted to a more severe thermal annealing cycle in view of improving the mechanical stability. Two of them are stable in time and after the heating process for degassing, but only one has the angle of 50 µrad useful for LHC. The other has an angle of 40 µrad, too small to assist LHC crystal collimation. The third one has an angle of 55 µrad and is stable in time, but it has not yet been tested after the thermal cycle. In conclusion, five new crystals are ready for installation in LHC.

3. **Focusing crystals.** A series of different trapezoidal crystals were investigated using 400 GeV/c proton or 180 GeV/c pion beam. The recent result is really good: an example is shown in Fig. 1. The factor of beam compression and deflection efficiency for protons agrees with expectation. In September 2016, trapezoidal crystals were used in the reversed orientation to defocus the incoming beam. The data analysis is still in progress.

4. **Multistrip crystals.** Tests of multi crystals continued in view of producing an optimal device for crystal-assisted collimation in the SPS. A multistrip crystal of new technology is shown in Fig. 2. The data collected with 400 GeV/c proton beam are very compatible with the data obtained with x-rays. On paper, such a crystal is compatible with the LHC specification at the highest energy due to extremely precise strips alignment. The data analysis of two new multistrip crystals tested in September 2016 is in progress.

5. **Long Crystals.** Part of the beam time was devoted to further investigate long crystals producing large channeling angles, studying new bending technologies for future
applications. In addition to the standard method of bending through anticlastic deformation, we tested crystals “self bent” through: plasticization of the back surface, thin film deposition, innovative crystal growth. These long crystals of the order of the centimeter show deflection angles of several hundreds of µrad and some of them already have also a promising efficiency. The data were taken in the last test beam of September 2016 and the analysis is still in progress. The Fig. 3 shows two preliminary plots reporting the bending angle and the efficiency of two different crystals bent with anticlastic technique.

6. **Detectors.** Further tests to optimize the performances of the new Cherenkov detector for proton Flux Measurements (CpFM) for SPS and LHC were carried out, whenever possible. Different kind of quartz radiators, hardware interfaces with photomultipliers and readout electronics were tested. In particular an efficiency test of the fully assembled Cherenkov detector for slow extraction purposes (SE-CpFM) was completed, before installing it in TT20 SPS extraction line. The results show a single proton efficiency of 89.5 % with a time resolution of ~ 2.3 ns, as shown in Fig. 4.

### 3. UA9 tests in the SPS ring

Data taking in SPS lasted four runs of 24 h with protons (14 Oct 2015, 2 Nov 2015, 6 Jun 2016, 19 Jun 2016) and two runs of 34h and 12h, respectively, with ions (3 Dec 2015, 10 Dec 2015). The efficiency of the data taking was not optimal due to several factors. About 24% of the data taking time the SPS was unavailable due to hardware problems or to users with higher priority (LHC). We spent about 14% of the time optimizing the machine conditions and about 12% did not produce useful data due to machine instabilities (See Figure 5). Four hours (3%) were spent repairing a faulty motor. In the end less than 50% of the granted time produced data that were considered worth to analyze.

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**Beam instabilities:** A sizeable amount of data collected in the proton run at the end of 2015 and in the first run of 2016 showed dramatic beam oscillations impacting on the beam loss rate, which is the main observable of our measurements. To investigate the cause of the problem during data taking the operators spent several hours. At least two different causes were found:

1. An aging dipole was causing non-periodical oscillations at random times during 2015 (see Fig. 5, left). The magnet was found and changed during the winter technical stop at the beginning of 2016.
2. Few times pulsing devices (typically injection or extraction kickers) were left powered during the coasting cycle. The effect on the beam is a periodic perturbation (see Fig. 5, right).

**Problem with the normalization of the beam loss rate:** During the data analysis, a still unresolved issue was spotted trying to normalize the results obtained with protons in 2016. Fig. 6 shows the measurement of the beam loss rate close to one crystal during three angular scans: the loss rate recorded with the crystal in amorphous orientation increases over time, most likely due to an increasing flux of particles on the crystal. This hypothesis can be verified by computing the flux of particles on the crystal and using this value to normalize the loss rate recorded in the different measurements: the three plots must then be identical within the uncertainties of the measurement. Indeed, this procedure was routinely applied and validated in the past years and the normalization factor was computed for each measurement using the derivative of a polynomial fit of the recorded beam intensity. When applying the same procedure to the most recent data, results similar to the one in Fig. 7 are obtained. In this case, we considered the intensity measured by two different detectors: the BCTDC that

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measures the total beam current in the machine and a BCTFR (Fast BCT) that measures the current due to each bunch in the machine. Ideally the result should be the same with both detectors and the plots should be superimposed within the uncertainty of the measurement. This is not the case, meaning that our usual assumptions are not valid. Our first hypothesis is that the flux of particles on the crystal is not correctly estimated. Fig. 8 shows the beam intensity measured by the BCTDC and by a BCTFR: after some time, the slopes of the decreasing intensity starts to diverge; which could be an indication that part of the beam is not bunched anymore and could be lost in the machine far from the crystal. For this reason, we started investigating how to estimate the flux from the measurements of the BCTFR.

Unfortunately, from the discussion with the beam instrumentation experts we found out that the SPS has two Fast BCT detectors: a prototype one (BCTFR5) which is working but is not correctly estimating the intensity and a production one (BCTFR3) which is not working due to a broken cable. At the moment we are investigating further possibilities to normalize existing data and we have asked to repair the broken detector before our next run. Most of the plots presented in this report are normalized imposing artificially that the loss rate registered when the crystals are in amorphous orientation is constant.

1. **Complete the test of the LHC type goniometer:** This activity started in 2015 and could not be completed. A further test is pending to assess the possibility to move the crystal linearly towards the beam while varying its angular position in order to maintain the channelling orientation. This functionality is required in the LHC operations, during which the collimators are moved to follow the shrinking of the beam during the “ramp up” of the energy. An upgrade of the software that controls the motion of the goniometer has been prepared to address this issue and will be tested in the upcoming SPS run.

2. **Complete the commissioning of CpFM and use it to characterize different crystals and different collimation setups:** After the installation and the initial commissioning already presented last year, the CpFM has been routinely used during the data taking runs. While some measurement could be performed (see for example Fig. 9, described in the following), some characteristics of the detector could not be initially explained: one of the bars showed larger signals then the other, cross talk larger than expected was estimated as well as low efficiency. In order to investigate these issues, two interventions were organized during the Technical Stops of the SPS. During a short access, all the cable connections, the PMTs, and one end of the fiber bundle were inspected and no significant
issue was found. It was therefore supposed that the problem was inside the optical fiber bundle and a new one was produced. During a longer Technical Stop in September the bundle was replaced under the supervision of the Vacuum Team, since the connection of the bundle to the vacuum optical window is considered a risky intervention. It was found that the existing connection of the bundle to the window was loose and could have caused cross talk between the channels and loss of light. Tests with the beam will be performed during the upcoming run to verify if the issues are solved.

The plot reported in Fig. 9 shows a preliminary result that could be obtained during the proton runs, despite the problems described. Here the amplitude of the signal registered in the two channels of the CpFM is studied as a function of the distance of the longer bar from the center of the beam. The detector is moved with a constant speed (0.01 mm/s) to cross the channeled beam. As the detector starts intercepting the beam (at $x > -15$ mm for CpFM1 and $x > -10$ mm for CpFM2) the amplitude increases proportionally to the number of intercepted protons. A further increase is seen (at $x > -3$ mm for CpFM1) when the bar starts approaching the circulating beam. The events in the plot are selected to be within 10 ns from the UA9 trigger (which is synchronized with the circulating bunch). The two distributions are fit with a special function that takes into account the contributions to the proton flux just described, as well as the cross talk between the channels. The spread of the channeled beam is estimated ($22+/-5 \mu$rad, in agreement with the critical angle at 270 GeV) as well as the deflection angle of the crystal ($152+/-12 \mu$rad, to be compared with nominal value of $176+/-10 \mu$rad). The distance between the edges of the bars results $5.5+/-0.2$ mm, where the design value is $5.0$ mm. Due to the problems described, the number of extracted protons could not be reliably estimated.

Data were taken also during the ion run, where multiple bunches were present in the machine: the analysis of the acquired waveform showed that the detector is able to resolve the single bunches. A different configuration of the DAQ software is in preparation to allow on-line measurements while multiple bunches are circulating in the machine.

3. **Assess the effect of a “protective” upstream collimator on the collimation efficiency of the crystal:** The minimal setup for a crystal-assisted collimation system consists of a crystal deflecting the halo and an absorber stopping the deflected particles. While this setup can provide good cleaning performance, it cannot ensure the absorption of a full beam incorrectly steered, as the present LHC collimation system would do (although suffering
substantial damage). For this reason, the first tests with the crystals in the LHC where performed with the primary collimators still close to the beam, while leaving the crystal as primary aperture restriction. In order to evaluate the possible effect of this “protective” collimator on the performance of the system a measurement campaign was put in place in the SPS. Data were collected with both proton and ion beams; the loss rate was registered while performing angular scans with the crystal and a two-sides tungsten collimator (10 cm long) about 45 m upstream the crystal (-60 degrees phase advance) was used as “protective” collimator. The aperture of the collimator (measured in $\sigma = 1/\sqrt{\beta \varepsilon}$ where $\varepsilon$ is the measured beam emittance) was varied in steps to identify the onset of the possible effect. A preliminary analysis of the data is reported in Fig. 10 for protons (left) and ions (right). Notice that proton data have been normalized to the loss rate in amorphous orientation, while ion data have been normalized using the derivative of the beam intensity, as discussed in a previous paragraph. A clear deformation of the shape of the angular scan is visible when the aperture of the collimator approaches the one of the crystal. For the proton beam, this effect is visible already when the difference in aperture between the crystal and the collimator is $1 \sigma$, while for ions it starts when the collimator has almost the same aperture of the crystal. A detailed simulation study is needed to fully understand these results, taking into account the multi-turn effect and the fact that a non-negligible number of particles are expected to traverse the collimator (nuclear interaction length for W is $\sim$ 10 cm). This behavior is also expected in LHC data, where the “protective” collimator has 60 cm long Carbon Fiber Composite jaws (nuclear interaction length for graphite is $\sim$ 40 cm).

4. Compare crystals with different polishing quality: Over the years, new techniques to polish the surface of the crystals have been investigated. In particular, one of the strip crystals installed in SPS (“Crystal 1”) has been polished using Magnetoreoeological Finishing, a technique that employs special fluids whose shape and stiffness can be magnetically manipulated in real time to remove material from a selected area on a surface with nm accuracy. This treatment has reduced the angle between the surface of the crystal and the direction of the lattice planes (mis-cut angle) to less than 10 $\mu$rad (6+/−1 $\mu$rad according to measurements performed with X-ray diffractometry). It was therefore decided to systematically compare the performance of this crystal with the one of “Crystal
4”, which is the reference strip crystal installed in the SPS. The main characteristics of the two crystals are reported in the table.

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<th>Bending angle</th>
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<th>Width</th>
<th>Mis-cut angle</th>
<th>Torsion</th>
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<td>1.87 mm</td>
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<td>6 µrad</td>
<td>&lt; 1 µrad/mm</td>
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<tr>
<td>Crystal 4</td>
<td>176 µrad</td>
<td>2 mm</td>
<td>0.5 mm</td>
<td>200 µrad</td>
<td>&lt; 1 µrad/mm</td>
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The two crystals are installed in SPS in two different mechanical goniometers, separated by a 2-meter distance. Angular scans were performed after aligning the two crystals at the same distance from the beam center and loss rates in different regions of the machine were measured. Fig. 11 shows the comparison of the beam loss profile as a function of the crystal orientation obtained with the two crystals during a proton run. Data have been normalized using a linear fit of the loss rate in amorphous orientation and imposing that, in this orientation, the loss rate must be the same for all measurements. The reduction of the loss rate due to channeling (angle = 0 µrad) is remarkably similar in the two cases, while for Crystal 1 the volume reflection region (0 µrad < angle < 200 µrad) has steeper walls and features a hump followed by a dip which are not visible in the profile registered for Crystal 4. Further investigations of these differences are ongoing.

5. Measurement of the beam halo diffusion speed: In the late 2015 the CpFM was used to perform some preliminary measurements of the diffusion speed of the SPS 270 Z GeV/c lead ion beam with different levels of a controlled electromagnetic random perturbation (ADT = LHC Transverse Damper). The LHC-type collimator installed downstream the crystals was used as obstacle to shape the beam whilst the CpFM was kept at a larger aperture. Opening quickly the collimator to even larger amplitudes allowed the beam halo diffusion until it reached the CpFM aperture. Unfortunately, the motor of the collimator proved not to be fast enough to observe the beam diffusion right after the obstacle removal. It was therefore decided to try the same measurement moving the beam away from the obstacle by means of an orbit bump. The effectiveness of the orbit bump was tested in June 2016, and diffusion measurements are planned for a future data taking run.

Extraction Tests in SPS
Starting from the “Proposal for Investigating Slow Extraction Assisted by Bent Crystals in the SPS”, a working group has been organized, involving members of the UA9 Collaboration, of the BE/ABP, BE/OP, EN/STI and TE/ABP groups.

In this framework the UA9 Collaboration has designed, produced and installed in the TT20 extraction line of the SPS a new version of the CpFM detector. The tank hosting this detector has been redesigned from scratch, which allowed to build a more compact device, easier to install and to align in the beam line. The size of the bellow and of the flanges has been reduced and the optical fiber bundle has been removed, connecting the PMT directly to the optical window. The design is based on a single quartz bar. The clamping system that holds the bar is therefore simplified and has been modified to reduce the risk to damage the bar during installation and transport. The aim of the detector is twofold: 1 – detect a low flux of particles extracted in TT20 during future tests of crystal assisted extraction; 2 – characterize the relative variation in intensity of the beam extracted during normal SPS operation by an analysis in the domain of the frequencies. Investigations are ongoing to prepare electronics systems optimized to perform each of the two tasks. The detector is entering the commissioning phase; the first signals have been acquired and are being analyzed, to verify that the background noise and the possible saturation of the PMTs are not preventing the correct functioning of the device.

Following the proposals of the TE/ABP group, few tests preliminary to the investigation of the crystal-assisted extraction were performed. During a 10h MD in July, the SPS was setup to have a phase advance close to an even multiple of 90 degrees between the crystal and the electrostatic septum used for extraction. This was achieved setting $Q_H = 26.62$, which allows the beam to experience the right phase advance at the septum after one full turn in the machine. Then the septum was retracted (to be protected from a possible beam impact) and the effect of the extraction bump on the channeling orientation of the crystal was investigated: as expected the relative angle between the beam and the crystal is maintained, therefore the channeling orientation is independent of the bump strength. A displacement of the beam by few 100 µm was instead observed with a BPM integrated in the LHC-type collimator downstream the crystal (60 degrees phase advance). During a further test, the absorber normally used to stop the channeled beam few tens meters downstream the crystal was retracted and the channeled beam was left in the machine for an entire turn, stopping it with a tungsten scraper carefully setup for this purpose. In this configuration the second turn of the channeled beam was intercepted with the jaw of the LHC-type collimator and it was found at
the expected distance from the circulating beam. Further tests are being planned before the end of 2016.

4. Tests in LHC

After the first LHC test of crystal channeling held in August 30th 2015, two additional runs were performed one in November 6th with protons and the other in December 2nd with lead ions. The run of November 6th was devoted to crystal channeling in the horizontal plane at 6.5 TeV (record energy) [1]. As in August 2015, when the crystal is inserted in the beam halo as the primary obstacle, oriented in channeling mode, the loss distribution along the collimation area IR7 indicates that the deflected halo is intercepted by a single secondary collimator that acts as an absorber. Channeling orientation was observed looking at loss reduction just downstream the crystal (Fig. 12) and at the loss increase at the so-called TCSG absorber that intercept the channeled beam in the location B4L7. The data in Fig. 12 were collected with the full collimation system in the nominal position for flat top energy. The losses reduction factor between amorphous and channeling orientation was found to be about 27. Comparison with simulations [2] and [3] was also performed. The channeled beam was investigated observing losses downstream the B4L7 during a linear scan, as shown in Fig. 13. With those measurements is possible to characterize the crystal deflection angle. Further analysis is ongoing to check the agreement between nominal and measured data, including the betatron functions in IR7.

During the 2nd of December both the horizontal and the vertical crystals were used to deflect lead ions at injection energy. Unfortunately, an unforeseen dump in LHC and a problem with the ions source caused a loss of 7 hours of MD. Because of this the crystal could not be tested at flat top LHC energy. Using the same procedure as for the proton channeling, we could measure channeling with 450 Z GeV lead ions beam (record energy for ions beam). Reduction factors were found to be ~6 and ~4 for horizontal and vertical crystal, respectively, as shown in Fig 14. Those values are in agreement with previous SPS tests with ions beam at lower energy. Scans of the secondary collimator jaws were also performed in channeling orientation to probe the channeled halo distribution, as shown in Fig. 15. Loss maps were measured at same energy, proving that the leakage of particles on the IR7 dispersion suppressor (DS) was reduced by a factor 2.6 with respect to the standard collimation system, as shown in Fig. 16. This result is very promising for ions beam
operation: the crystal, indeed, was integrated in the LHC collimation system to optimize their performances with ion beams at flat top energy. A run to test again those performances is foreseen during the next ions run in December this year.

In the 29th of July the run was used to complete the program of characterization and measurements of both crystals at LHC top proton energy. Angular and collimator linear scans were performed at both energies. The formers are shown in Fig. 17. The goniometer orientation for channeling was found to be very stable for both crystals at both energies. At injection energy the channeling orientation was found to be $2066.9\,\mu\text{rad}$ (with a standard deviation of $0.85\,\mu\text{rad}$) and $2275.7\,\mu\text{rad}$ ($0.72\,\mu\text{rad}$) for horizontal and vertical crystal respectively. At flat top channeling was found at $2035.3\,\mu\text{rad}$ ($0.14\,\mu\text{rad}$) and $2219\,\mu\text{rad}$ ($0.07\,\mu\text{rad}$) again for horizontal and vertical crystal, respectively. Those values will be used to produce the LHC energy ramp function that will be tested at the end of October this year. Also in this case further analysis on crystals deflection angle and multiturn channeling efficiency are ongoing.

To conclude, loss maps with both the crystals in channeling orientation have been measured with a reduced set of collimators in IR7. Reference loss maps with standard collimation system were performed for comparisons. Multiturn channeling efficiency and loss maps study analysis is still ongoing.

In LHC, the priority is to continue investigating crystal assisted collimation tests in the horizontal and vertical planes.

5. Plans and perspectives

The main goal of the UA9 Collaboration stemmed on the demonstration of the feasibility of Crystal Collimation in LHC. This goal is almost completed. The perspectives of UA9 are slowly moving towards more ample scope. The UA9 devices in the SPS are often used to investigate effects that one should study in LHC, thereby providing a more flexible and extended way of getting invaluable experience for the LHC itself. The H8 installation play the primordial role of characterizing optimal crystals for LHC, whilst new subjects such as the slow extraction is proposed for test. In addition the UA9 detectors had an unforeseen application that consists in measuring beam parameters in particle accelerators.

The perspective of the Collaboration for 2016 includes some ambitious milestones.
In the H8 area, the plan is to test crystals for LHC with ion species. Another goal is to test multi-strip crystals optimized for the multi-reflection mode in the SPS. Studies to evaluate the performance of focusing crystals and of multi-crystal assemblies should be pursued, together with the investigation of large curvature crystals, suited for large angle deflection.

In LHC, the priority is to continue crystal-assisted collimation tests in both horizontal and vertical planes.

In view of these plans, the Collaboration would like to request in 2016: 20 days in H8 with proton microbeams at 450 GeV, of which 7 days with ion (Ar or Pb) beams and 3 dedicated days (24 h runs in storage mode) in the SPS.

The new investigations suggested this year (slow-extraction based on bent crystals, Selection of the LHC crystals for crystal-collimation operation, measurements of the beam parameters such as deflected beam profile and time-structure and diffusion coefficient) calls for a revision of the goals of the Collaboration and for the enlargement of the participation to more people and Institutions, for an optimal use of the beam time requested. This revision will be started as soon as possible.

References


Fig. 1. TOP: photo of the focusing crystal device – MIDDLE: Plot of the deflection angle as a function of the transversal position – BOTTOM: Plot of the beam envelop.
Fig. 2. TOP: Photo of the multistrip device and scheme of the operating process – BOTTOM: Plots of 400 GeV/c beam deflection.
Fig. 3. Bending angle and efficiency plot for two different kinds of long crystals bent through anticlastic technique.
Fig. 4. SE-CpFM efficiency test: TOP: H8 experimental setup – MIDDLE: Plot of the time distribution: time resolution ~ 2.3 ns – BOTTOM: Plot of the amplitude distribution: single proton efficiency: 89.5 %
Fig. 5 - LEFT: angular scan performed in a period of spikes (x ~ 1350 and x ~ 1580) in the beam loss measurement, due to beam jitters (screenshot from the data taking logbook on November 2015). RIGHT: periodic spikes in the beam loss rate measurement, caused by beam movements provoked by the extraction kicker mistakenly powered during the UA9 cycle (screenshot from the data taking logbook on June 2016).

Fig. 6 - Beam loss rate measured close to a crystal during three angular scans in identical conditions.
Fig. 7 - The measurement of Figure 2, normalized to the derivative of a second order polynomial fit of the beam intensity measured with different detectors (LEFT: DC BCT, RIGHT: Fast BCT 5).

Fig. 8 - Beam intensity measured with different detectors (blue: DC BCT, red: Fast BCT 5).

Fig. 9 - Amplitude of the CpFM signal as a function of the position of the longer bar of the CpFM. The crystal is in channeling orientation and the first rise of the distribution corresponds to the detector intercepting the extracted beam.
Fig. 10 - Normalized beam loss rate close to the crystal as a function of the crystal orientation. Data are collected for different transversal positions of a "protective" collimator. LEFT: proton beam, RIGHT: ion beam.

Fig. 11 - Normalized beam loss rate downstream the crystal as a function of the crystal orientation for two crystals with different surface polishing quality. Data collected with a proton beam.
Fig. 12 – First horizontal crystal angular scan at 6.5 TeV energy in November 2015. Curves 2 (solid blue line) and 3 (dotted red line) show the dependence of the number of inelastic nuclear interactions of protons in the crystal on its orientation angle obtained by simulation according to [2] and [3], respectively.

Horizontal Crystal Scarping @ 6.5 TeV

Fig. 13 – Horizontal crystal absorber scan at flat top energy in November 2015. Crystal is fixed in channeling orientation. TCSG.B4L7 scrape the extracted beam.
Fig. 14 – Horizontal and Vertical crystal angular scan with ions beam in December 2015 MD.

Fig. 15 – Horizontal and Vertical crystals absorber scans with ions beam in December 2015 MD. Crystals are fixed in channeling orientation. TCSG.B4L7 and TCSG.D4L7 scrape the extracted beam for horizontal and vertical crystal, respectively.
Fig. 16 – Horizontal loss maps with 450 Z GeV ions beam for crystal and standard collimation. The leakage of particles in DS area is reduced of a factor 2.6 using crystal in channeling as primary collimator.

Fig. 17 – Horizontal and Vertical crystal angular scan at 6.5 TeV in July 2015 MD.