

## **Apparatus and Experimental Procedures to Test Crystal Collimation**

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UA9 is an experimental setup operated in the CERN-SPS in view of investigating the feasibility of halo collimation assisted by bent crystals. The test collimation system is composed of one crystal acting as primary halo deflector in the horizontal plane and an absorber. Different crystals are tested in turn using two-arm goniometers with an angular reproducibility of better than 10 microrad. The performance of the system is assessed through the study of the secondary and tertiary halo in critical areas, by using standard machine instrumentation and few customized equipments. The alignment of the crystal is verified by measuring the loss rate close to the crystal position. The collimation efficiency is computed by intercepting the deflected halo with a massive collimator or with an imaging device installed into a Roman Pot. The leakage of the system is evaluated in the dispersion suppressor by means of movable aperture restrictions. In this contribution the setup and the experimental methods in use are revisited in a critical way and thoroughly discussed. Particular emphasis is given on feasibility, reproducibility and effectiveness of the operational procedures.

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# APPARATUS AND EXPERIMENTAL PROCEDURES TO TEST CRYSTAL COLLIMATION\*

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## Abstract

UA9 is an experimental setup operated in the CERN-SPS in view of investigating the feasibility of halo collimation assisted by bent crystals. The test collimation system is composed of one crystal acting as primary halo deflector in the horizontal plane and an absorber. Different crystals are tested in turn using two-arm goniometers with an angular reproducibility of better than 10 microrad. The performance of the system is assessed through the study of the secondary and tertiary halo in critical areas, by using standard machine instrumentation and few customized equipments. The alignment of the crystal is verified by measuring the loss rate close to the crystal position. The collimation efficiency is computed by intercepting the deflected halo with a massive collimator or with an imaging device installed into a Roman Pot. The leakage of the system is evaluated in the dispersion suppressor by means of movable aperture restrictions. In this contribution the setup and the experimental methods in use are revisited in a critical way and thoroughly discussed. Particular emphasis is given on feasibility, reproducibility and effectiveness of the operational procedures.

## INTRODUCTION

In 2009 the UA9 Collaboration started investigating crystal assisted collimation at the CERN Super Proton Synchrotron (SPS). Crystal collimation may provide advantages with respect to standard systems: reduced activation of primary collimators, reduction of scattering from the absorber into the beam pipe, relaxed tolerances for secondary collimators and reduction of off-momentum particles produced by single diffractive collisions.

The initial layout of the experiment in SPS was presented in [1] and a detailed description of the instrumentation upgrade in 2010 was published [2]. Since 2009 the experiment has benefited from 5 days of data taking each year: single or multiple bunches of 120 GeV/c and 270 GeV/c stored protons or lead ions have been used for the tests.

The reduction of the particle loss rate in positions near to the crystal has been demonstrated when the crystal is aligned to the beam with the correct orientation, both for proton [3] and for ion [4] beams. The efficiency of the channeling process for particles impinging on the crystal has been measured. The off-momentum halo population leaking from the collimation system has been estimated,

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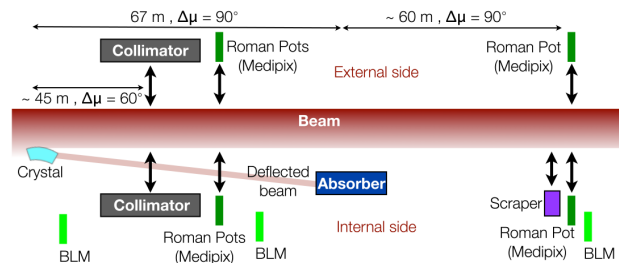


Figure 1: Conceptual layout of the UA9 experiment.

being considerably smaller in crystal channeling conditions than for amorphous orientation [4].

During the past year, upgrades to the instrumentation and new procedures have been put in place in view of a future installation of the experiment in the LHC. This paper reports a description of these upgrades and procedures, while the most recent results are described in [5].

## EXPERIMENTAL EQUIPMENT IN 2011

The conceptual layout of the experiment is shown in Figure 1. The crystal collimation prototype system is composed by the crystal itself and by the absorber. All the remaining equipment is used to test the system.

### Collimation System

The crystals tested in 2011 are mounted on two supports that allow horizontal linear movements. When one of the two crystals is placed at a fixed distance from the beam, it can be rotated in an angular range of tens of mrad by applying a linear movement (1 mm range) to the second one. This rotational movement is designed to have a resolution of 1  $\mu$ rad and an accuracy close to 10  $\mu$ rad. Accurate calibration by means of a laser autocollimator were done in laboratory and directly in situ through optical windows. Average deviations from linearity were found compatible with the design value.

The first crystal (C4) is a silicon strip ( $0.5 \times 70 \text{ mm}^2 \times 2 \text{ mm}$ ), with the 2 mm side in the beam direction. The holder compensates for the strip torsion down to 0.6  $\mu$ rad/mm. Torsion, bending angle (176  $\mu$ rad) and residual miscut ( $200 \pm 20 \mu$ rad) of the crystal have been measured both at the SPS-H8 beam line and with optical methods.

The second crystal (C3) is bent through the quasi-mosaic elastic effect. The part of the crystal exposed to the beam is  $20 \times 40 \text{ mm}^2 \times 2.1 \text{ mm}$ . The bending angle is 165  $\mu$ rad, the miscut is 90  $\mu$ rad. The torsion is in the range 2–5  $\mu$ rad/mm.

About 60 m downstream the crystals (phase advance  $\Delta\mu = 90^\circ$ ) the deflected halo is displaced by several mm with respect to the beam core to be collected on a movable tungsten absorber (TAL). The absorber has a section of  $70 \times 60 \text{ mm}^2$  and it is 60 cm long.

### Additional Instrumentation

Between the crystal region and the TAL (42.5 m from the crystal,  $\Delta\mu = 60^\circ$ ), an LHC-type collimator with two horizontal one-meter long graphite jaws is operated. About 1.5 m and 14.5 m downstream the collimator two Roman Pot (RP) devices are installed. They comprise two horizontal motorized axes, each one supporting a secondary vacuum vessel containing a Medipix detector [6]. The pots have 0.2 mm thin aluminium walls and are 3.4 cm wide in the beam direction. The second RP also includes two vertical vessels not yet equipped with detectors.

A high dispersion region is present about 60 m ( $\Delta\mu = 90^\circ$ ) downstream the TAL. A 10 cm duralumin scraper and a Cherenkov detector are installed in this area (TAL2), as well as a third horizontal RP with Medipix detectors. The two 3 cm wide pots have 0.5 mm thick stainless steel walls.

In proximity to each device, outside the vacuum pipe, different types of detectors are installed: polystyrene scintillators, PEP-II-type Beam Loss Monitors (BLM), GEM detectors and LHC-type BLMs [2]. They are sensitive to the production of secondary particles from inelastic interactions in the obstacles within the beam pipe. Each detector is optimized to a different range of interaction rates.

Several SPS instruments are also available but, apart from the Wire Scanner and the Beam Current Transformers (BCT), they are generally not sensitive to the relatively low current used in the experiment. During 2011 efforts were made to increase the total intensity of the beam (injecting up to 48 bunches) and to decrease its lifetime (by means of a transversal damper). Also, a new on-line interface was requested to monitor the beam characteristics using BCT, Fast BCT and the Mountain Range Display (MR). These detectors measure the intensity of the beam using electronics with different bandwidth and a comparison among them allows to estimate the fraction of de-bunched beam. Finally, the MR also computes the bunch length.

## EXPERIMENTAL PROCEDURES IN 2011

Typical procedures in use by the experiment consist in the movement of the equipment and in the observation of the induced beam loss rate variation. For example, it is assumed that a moving device *touches the beam* core when a sharp, fast decaying spike is measured in the loss rate downstream the device. In Figure 2 the typical linear movements issued to UA9 devices are drawn for a given data taking period.

### Alignment of Devices

In order to operate the crystal collimation system, its components should be placed at defined distances from the beam center. The crystal orientation with respect to the

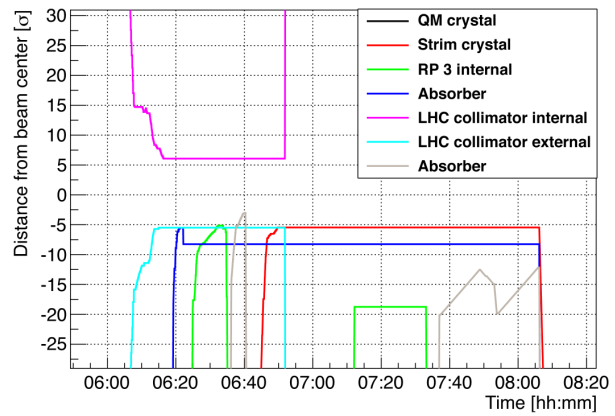


Figure 2: The movement of the UA9 devices during a machine fill.

beam should be defined within the critical angle ( $\sim 13 \mu\text{rad}$  for 270 GeV/c protons) to maximize the probability of channeling interaction and minimize the occurrence of nuclear interaction. The procedure to align the devices (see Figure 2, from 6:10 to 6:50) is the following:

1. The beam horizontal emittance is measured with a Wire Scanner and the desired distance of the devices from the beam center is computed.
2. One collimator jaw is closed to a certain aperture ( $\sim 10\sigma$  from the beam reference position).
3. The second collimator jaw is moved towards the beam in steps. The step size defines the final accuracy of the alignment (usually 50–100  $\mu\text{m}$ ). When the beam is touched, the jaw is stopped.
4. The first jaw is moved in step until it touches the beam.
5. The last two operations are reiterated, until each step of the jaws corresponds to the same loss rate increase. At this point, the jaw positions are symmetric with respect to the center of the beam and they can be closed to the desired aperture ( $\sim 5\sigma$  in Figure 2 at 6:15).
6. The TAL is moved towards the beam in small steps. It is stopped when it touches the beam and it is then retracted by few millimeters (Figure 2, at 6:20).
7. The crystal is moved in small steps, until it touches the beam (Figure 2, at 6:50).
8. The collimator is opened to garage position. The hierarchy of the system is now implemented: the crystal is the primary aperture restriction while the TAL is the secondary one (Figure 2, after 6:50).
9. The crystal is rotated to the channeling orientation, that is found by minimizing the loss rate in the downstream detectors with 1  $\mu\text{rad}$  angular steps.

Initially, the alignment procedure was followed for each fill of the machine, taking often more than half an hour. It was then verified that, given the good reproducibility of the orbit from fill to fill, the position of the devices could be computed from previous alignment results with an accuracy of 50–100  $\mu\text{m}$  (i.e compatible with the accuracy of the alignment itself). The correct orientation of the crystal was

always found in the same 100  $\mu\text{rad}$  interval, with expected variations due to different device positioning and changed machine conditions. For this reason the alignment procedure has recently been applied only once per data taking session. During subsequent fills, only the position of the center of the beam and the emittance were measured thus reducing the setting up procedure to about 10–15 minutes.

Other devices used during the measurements (RP or scrapers) are aligned with similar procedures, before setting up the system hierarchy. The alignment of each additional device takes few minutes, if done from scratch.

### *Estimation of Collimation Efficiency*

The efficiency of the system is defined as the ratio between the number of particles deflected to the absorber and the total number of particles impinging on the crystal. Two methods were used by the UA9 experiment to estimate it.

The first method consists in moving the collimator internal jaw towards the beam and assuming that the provoked loss rate is proportional to the number of particles impinging on it. During the movement the deflected beam is intercepted, increasing the local loss rate to a value  $R_{ch}$ . When the jaw finally touches the beam core a loss rate  $R_{tot}$  is measured. Assuming that the number of particles impinging on the primary aperture restriction is constant, the efficiency is estimated from the ratio  $R_{ch}/R_{tot}$  [7].

To apply the second method, one of the RP should be inserted between the crystal and the TAL to have the deflected beam traversing the Medipix. Careful positioning is necessary, in order to avoid touching the beam core with the RP vessel. The distance of the deflected beam from the beam core and its width can be fit from the spatial distribution measured by the Medipix. From comparison with simulated data, the exact orientation of the crystal and the efficiency of the channeling process can be estimated.

### *Leakage from the Collimation System*

The TAL2 scraper and the RP installed in the high dispersion area are used to estimate the fraction of halo particles escaping from the collimation system (tertiary halo). In particular, particles that have lost energy experience a large lateral displacement in this region.

A linear scan performed with the scraper towards the beam (see Figure 2, from 7:35 to 7:50) allows to intercept the tertiary halo, increasing the loss rate proportionally to the number of impinging particles. The movement should be stopped before reaching the aperture defined by the TAL in order to maintain the hierarchy of collimation system. An optimal speed of 10  $\mu\text{m/s}$  (faster than halo diffusion speed) is normally used and few minutes are spent between consecutive scans to allow the halo to repopulate.

The RP allows to place the Medipix detector in the tertiary halo to measure the flux of incoming particles. As for the scraper, special attention and careful initial alignment are necessary to maintain the correct hierarchy of the collimation system. By using the two sides of the RP, comparison can be made between the population of the tertiary

halo on both sides of the beam.

## HARDWARE UPGRADE IN 2012

Following the experience gained in 2011, a major upgrade of equipment took place in early 2012.

In the area where crystal are installed, a big tank was replaced by four small tanks, that allow the installation of new devices and minimize the time needed to restore the vacuum after interventions. A movable Cherenkov detector (0.3 mm thin quartz radiator) is installed in one of the tanks. Another one hosts a 14 cm long graphite jaw, whose performance as primary deflector will be compared with the one of the crystal. The goniometer used in 2011 was moved by few meters and an updated version was added to the experiment: its design accuracy is about 1  $\mu\text{rad}$ , thanks to optimized motors and mechanical transmission.

In the high dispersion area new tungsten scrapers on both sides of the beam have replaced the old one.

New detectors are under construction. An optimized ring-shaped GEM detector will be fixed to the beam pipe, close to the crystals. A scintillator made of plastic fibers will be tested into one of the RP. Finally, pixel detectors more robust than the Medipix are under consideration.

## CONCLUSION

The UA9 experiment is installed in the SPS since 2009. Several procedures have been tested and many aspects of a crystal collimation system have been investigated. The performance of crystal collimation have been evaluated with encouraging results, using a stored beam of 120 GeV/c and 270 GeV/c protons and lead ions. Therefore, a similar prototype system will be installed into the LHC to continue the studies at higher energy and with tighter requirements.

For this reason, the apparatus in the SPS has been renovated, to allow more exhaustive studies. The newly installed devices will be tested as prototypes for the future installation into the LHC.

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