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CRYSTAL FOR SLOW EXTRACTION LOSS-REDUCTION OF THE SPS ELECTROSTATIC SEPTUM

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Abstract

The use of a bent crystal was investigated in order to reduce the losses at the CERN Super Proton Synchrotron (SPS) electrostatic septum (ZS) during the slow extraction of 400 GeV/c protons toward the North Area. The crystal, installed a few meters upstream of the ZS, bends protons that would otherwise impinge on the ZS wires. Since particle deflection with good efficiency is achieved only when the crystal lattice is aligned within 10 µrad to the trajectory of the incoming particles (at p = 400 GeV/c), a compact goniometer was built to allow the correct angular alignment of the crystal with a precision of a few µrad. In this paper, we report on the crystal features measured during a dedicated beam test by the UA9 experimental installation in the CERN H8 beam line. Details of the goniometer and its installation are also reported. The first results achieved during dedicated Machine Development (MD) sessions are finally presented.

INTRODUCTION

The SPS presently extracts a 400 GeV/c proton beam to the North Area (NA) Fixed Target physics program with spill lengths of several seconds by means of a third integer slow extraction [1]. The extraction system is located in Long Straight Section (LSS) 2 and is composed of an electrostatic septum (ZS) upstream of magnetic septa (MST and MSE). The ZS is divided into 5 separate tanks, 3.15 m in length, each containing an array of 2080 Tungsten-Rhenium (WRe) wires made as thin as possible (ZS1-2: ⌀60 µm, ZS3-5: ⌀100 µm) in order to reduce beam losses. Nevertheless, a few percent of beam is unavoidably scattered on the wires, inducing radioactivity in LSS2 [2].

Methods to reduce the losses per extracted proton are under study in the SPS Losses and Activation Working Group (SLAWG) [3] and are all the more important for the future because of the higher (of approximately a factor four) proton extraction fluxes requested in the framework of the SPS Beam Dump Facility [4]. Increases in the remnant activation would impose longer cool-down times before an intervention or a diagnostic test can be done in the tunnel on the extraction equipment, which has the potential to significantly impact the operational availability of the machine.

A bent crystal installed upstream of the ZS was the second experiment (after a passive wire diffuser [2]) conducted in 2018 to demonstrate the principle of shadowing of the ZS. The bent crystal experiment was prepared within the SPS Crystal-Assisted Slow Extraction Working Group (CASE) [5].

CRYSTAL CHARACTERISATION

Coherent interactions of charged particles in high purity silicon crystals are used for several beam steering applications such as collimation, extraction, focusing and splitting. Planar channelling is a phenomenon that arises when charged particles entering the crystal with a small angle with respect to the crystal planes are canalised between two adjacent planes. Bent crystals can steer charged particles to a large deflection, which is equal to the geometrical bending angle of the crystal, θ_b. The channelling is possible within a critical angle $\theta_c = (2U_0/pv)^{\frac{1}{2}}$ with respect to the plane orientation, where U_0 is the depth of the inter-planar potential, p and v are the particle momentum and velocity. For 400 GeV/c protons, $\theta_c \approx$10 µrad.

In the last decade, the UA9 experiment at CERN developed this technology to exploit the beam manipulation with bent crystals, primarily to improve the collimation system

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in modern hadron colliders such as the LHC [6]. The UA9 Collaboration equipped a test facility in the H8 beam line from the SPS to the North Area with an experimental apparatus to perform the crystal characterisation, in particular to measure the crystal bending angle, the channelling efficiency and the torsion[1]. The experimental apparatus is based on a high-angular resolution telescope composed of five multi-strip detector planes that are able to reconstruct incoming and outgoing single particle trajectories with respect to the crystal position [7, 8].

A novel application is the use of a bent crystal to assist the slow extraction of the beam from the SPS. As an active diffuser, the crystal can shadow the ZS by deviating into the extraction channel the particles that would otherwise impinge on the anode wires and, therefore, effectively reduce losses at the ZS. Ultimately, one can conceive to use a bent crystal to replace partially or in total the ZS [9].

For the shadowing experiment, several crystals were assembled as shown in Fig. 1. The crystal specifications are described in [10]. Each crystal is mounted on a holder with a vertical opening of 35 mm. The clearance from the working crystal surface to its metal support is 35.8 mm (the extracted separatix extends over 20 mm and has an angular spread of ≈ 20 µrad). The holder gives the desired bending angle to the channelling planes (110) thanks to an anticlastic effect.

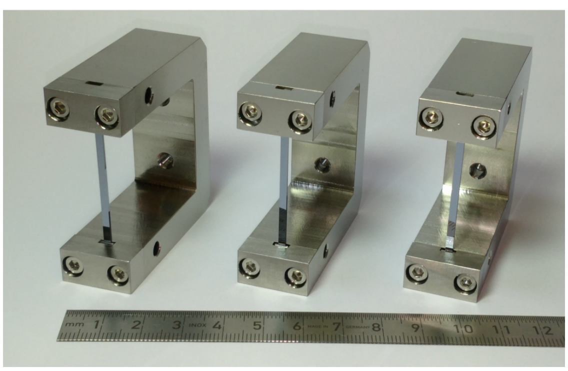

Figure 1: Crystals with holder assembled by PNPI for the ZS shadowing experiment in the SPS.

The crystals were measured using a 180 GeV/c positively charged pion beam produced in a test run in August 2018. The properties of the crystal installed in the SPS for the shadowing experiment are summarised in Table 1. The efficiency is estimated for different angular cuts of the incident track trajectory respect to the crystalline plane orientation: 16 µrad corresponds to $\approx \theta_c$ for 180 GeV/c pions.

Table 1: Crystal Properties Measured in a Test Beam in H8

	Unit	Value
Length	mm	1.999 ± 0.002
Thickness	mm	0.775 ± 0.002
Bending angle (θ_b)	µrad	174 ± 1
Torsion[1]	µrad/mm	1.0 ± 0.5
Efficiency (± 10μrad)	%	61 ± 1
Efficiency (± 16μrad)	%	51 ± 1

CRYSTAL INSTALLATION IN SPS-LSS2

The crystal with its holder is mounted inside a prototype vacuum tank equipped with a goniometer, at ≈0.6 m upstream of the QFA.21610 located in LSS2, with a few degree of betatron phase-advance respect to the upstream end of the ZS.

The goniometer is needed to allow for the correct angular alignment of the crystal with respect to the incoming beam, since particle deflection with good efficiency is achieved only when the crystal lattice is aligned within ≈10 µrad to the trajectory of 400 GeV/c protons. It consists of two linear shift mechanisms: one is used to position the crystal transversely and the second one to rotate the crystal. Due to space limitation in the location available for the installation of the goniometer, the lever arm between the two axes is 100 mm. The minimal incremental motion of each motor is 0.15 µm (half motor step), which corresponds to a minimal angular incremental step of 1.5 µrad.

Each motor is equipped with a Linear Variable Differential Transformer (LVDT) to measure the position, however its signal was found to be coupled to the current of the near magnet during the SPS cycle. In the following, all crystal positions and angles shall be considered as the ones requested by the control system. The control system of the goniometer was synchronised to the beam cycle in order to guaranteed that the goniometer could move only when the beam was not extracted. This way, the crystal was fixed during the beam extraction and the recorded BLM response was unambiguously correlated to the crystal position and angle.

The device was installed in the SPS during a Technical Stop in September 2018 in the same location as the passive diffuser. This allowed to perform a comparison of the two techniques [2]. The channelled particles are deflected towards the outside of the ring and immediately extracted to the North Area.

SPS Beam Loss Monitors (BLM) were used to align the crystal with the beam and to search for the optimal channelling orientation that would shadow the ZS anode as well as possible. In addition, two LHC BLM's located at the position of the crystal and at the third ZS tank were also available.

The data reported in this paper were taken during two Machine Development sessions parasitically to SHiP T6 tests on 3 and 24 October 2018. The intensity of the extracted beam was about 4×10^{12} particles per pulse with a maximum repetition rate of 7.2 s.

FIRST RESULTS

During the two MD sessions, several angular scans were performed at different transverse positions of the crystal in order to characterise the loss reduction and locate the optimal working point.

[1] For a crystal twisted along the orientation of the crystal plane, the torsion represents the variation of the bending angle as a function of the vertical impact point.

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The scans were performed to identify the channelling condition looking at the response of the BLM next to the crystal and, at the same time, observing the response of the BLM's along the ZS, which depends on the relative alignment crystal-ZS and the crystal regimes, as describe below. In order to assess the loss reduction achieved, for each scan it was taken care of acquiring BLM data point when the crystal was also in amorphous orientation. Each point of a scan is normalised to the extracted intensity in that pulse.

The channelling condition at the crystal can be demonstrated as a reduction of the loss rate measured by the BLM next to the crystal: particles in channelling experience a reduced nuclear interaction probability since they travel on average farther from the lattice nuclei than in the amorphous (AM) orientation [11]. Figure 2 shows that a reduction of ≈ 35% relative to the AM orientation. For negative angles, a 5% increase of the losses was observed over the angular range corresponding to the Volume Reflection (VR) orientation, which extends over an angular range equal to the crystal bending angle and has a larger efficiency than channelling [12]. Particles travelling in the direction of the inner side of the crystal can have a trajectory nearly tangential to the bent crystal planes. At this point, a reflection of the trajectory can occur, which changes the sign of the transverse momentum. Therefore, the particle is reflected to the side opposite to the crystal bending direction with a kick of $\approx\ 1.5 \times \theta_c = 15\,\mu$rad. In the vicinity of the reflection point, the atomic density seen by the travelling particles increases since the angle with the crystal bent plane decreases: this can explain the enhancement of the losses in the VR orientation. It is worth to note that the angular scans at different transverse positions exhibit globally the same pattern: this is understandable as the crystal operates in a single-pass mode on the extracted separatrix. The variations between the scans are due to the rather large angular step, which is in the range of 0.5–1 θ_c.

For the same angular scans, the normalised response of the BLM's along the ZS is shown in Fig. 3, which depends on the relative alignment between the crystal and the ZS. For the angular scan at 70 mm (orange curve in Fig. 3), which is the crystal position better aligned with the ZS, the loss reduction in channelling was ≈ 40% normalised to the AM orientation. Despite the larger efficiency and acceptance of VR in comparison to CH, the obtained reduction in this orientation is ≈ 20%. This is due to the smaller deflection kick imparted that is not sufficient to create enough clearance between the volume-reflected beam and the ZS wires. For position closer to the beam core, such as the angular scan at 72 mm (green curve in Fig. 3), the channelled beam is actually directed toward the ZS wires, thus giving an increase of the losses of ≈ 60%. Conversely, for positions further away from the beam core (such as the blue curve in Fig. 3), the loss reduction in CH is lower, since only a part of the beam impinging on the ZS is effectively deviated. In this position, the Volume Reflected beam is sent against the ZS, as indicated by the increase of the losses.

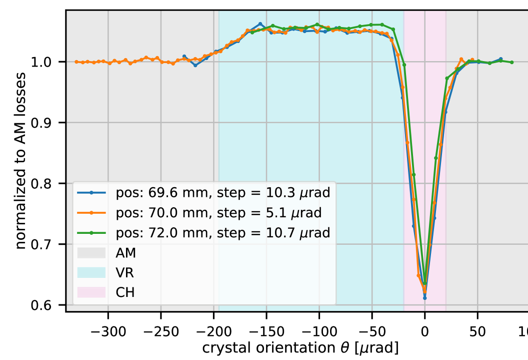

Figure 2: Example of loss profiles as a function of the crystal angle with respect to the channelling orientation for the LHC BLM next to the crystal. The BLM signals are normalised to the value when the crystal is in AM orientation. The vertical bands indicate the different regimes of the crystal: CH ($\pm 2\theta_c$), VR ($\theta_b - 2 \times \theta_c\ <\ \theta\ <\ 2 \times \theta_c$) and AM (elsewhere).

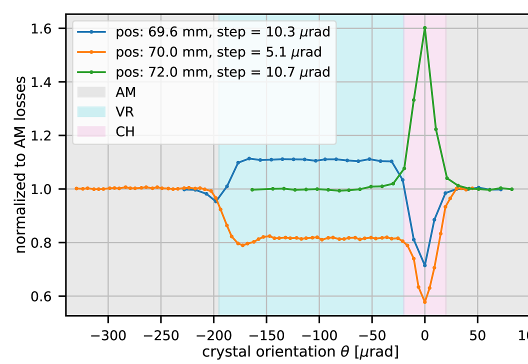

Figure 3: Example of loss profiles as a function of the crystal angle with respect to the channelling orientation for for the sum of the BLM's along the ZS. Refer to Fig 2 for data normalisation and vertical band description.

A bent crystal to shadow the ZS can be used in synergy with other techniques, such as phase space folding with octupoles, to further reduce the losses along the SPS extraction line to the North Area [13].

CONCLUSION

A prototype goniometer equipped with a bent crystal was installed in the SPS to reduce the losses induced on the ZS during the slow extraction of the beam toward the North Area. The device was successfully operated during two MD sessions and it was demonstrated that the crystal can effectively deplete the density region of the particles that would otherwise impact on the ZS wires. The obtained loss reduction was ≈ 40% in CH orientation and ≈ 20% in VR orientation. These results is of high interest in order to reduce the losses and activation of the equipment in the SPS extraction system in view of the future physics program in the framework of the SPS Beam Dump Facility.

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REFERENCES

[1] B. Balhan *et al.*, "Improvements to the SPS Slow Extraction for High Intensity Operation", CERN-ACC-NOTE-2019-0010, CERN, Geneva, Switzerland, Mar 2018.

[2] M.A. Fraser *et al.*, "SPS Slow Extraction Losses and Activation: Update on Recent Improvements", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper WEPMP031, this conference.

[3] SPS Losses and Activation Working Group (SLAWG) meeting series, CERN, Geneva, Switzerland, https://indico.cern.ch/category/7887/

[4] M.A. Fraser *et al.*, "Improvements to the SPS Slow Extraction for High Intensity Operation", CERN-ACC-NOTE-2019-0010", https://cds.cern.ch/record/2668989

[5] SPS Crystal-Assisted Slow Extraction Working Group (CASE) meeting series, CERN, Geneva, Switzerland, https://indico.cern.ch/category/8556/

[6] W. Scandale *et al.*, "Deflection of 400 GeV=c proton beam with bent silicon crystals at the CERN Super Proton Synchrotron", Phys. Rev. ST Accel. Beams 11, 063501, 2008.

[7] M. Pesaresi *et al.*, "Design and performance of a high rate, high angular resolution beam telescope used for crystal channeling studies", Journal of Instrumentation, Vol. 6, P04006, 2011.

[8] G. Hall *et al.*, "A high angular resolution silicon microstrip telescope for crystal channelling studies", *Nucl. Instrum. Methods Phys. Res.*, A 924 (2019) 394–399.

[9] W. Scandale *et al.*, "Possibility of high efficient beam extraction from the CERN SPS with a bent crystal. Simulation results", *Nucl. Instrum. Methods Phys. Res.*, A 848 (2017) 166-169.

[10] B. Goddard *et al.*, "Function specification for bent crystal to test LOCAL shadowing of ZS wires", CERN EDMS document, https://edms.cern.ch/document/1823147

[11] W. Scandale *et al.*, "Study of inelastic nuclear interactions of 400 GeV/c protons in bent silicon crystals for beam steering purposes", *Eur. Phys. J. C* 78, p. 505, 2018.

[12] W. Scandale *et al.*, "High-Efficiency Volume Reflection of an Ultrarelativistic Proton Beam with a Bent Silicon Crystal". *Phys. Rev. Lett.* 98, p. 154801, 2007.

[13] B. Goddard *et al.*, "Demonstration of Loss Reduction Using a Thin Bent Crystal to Shadow an Electrostatic Septum During Resonant Slow Extraction", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, May 2019, paper THXXPLM2, this conference.

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