ROBUSTNESS TEST OF A SILICON STRIP CRYSTAL FOR CRYSTAL-ASSISTED COLLIMATION STUDIES IN THE LHC

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Abstract

Over the past years, the UA9 experiment has successfully demonstrated the viability of enhancing the collimation efficiency of proton and ion beams in the SPS by means of bent crystals. An extension of UA9 to the LHC has been recently approved. The conditions imposed by the LHC operational environment, in particular the tremendous energy density of the beam, require a reliable understanding of the crystal integrity in view of potential accident scenarios such as an asynchronous beam dump. For this purpose, single pulse irradiation tests have been performed at the CERN-HiRadMat facility to examine the mechanical strength of a silicon strip crystal in case of direct beam impact. The tests were carried out using a 440 GeV proton beam of σ=0.5 mm transverse size. Individual pulse intensities reached up to 3×10^{13} protons, where a significant fraction is assumed to have impacted on the crystal. First visual inspections revealed no macroscopic damage to the crystal. Complementary post-irradiation tests are foreseen to assess microscopic lattice damage as well as the degradation of the channeling efficiency.

INTRODUCTION

The concept behind crystal-assisted beam collimation is to exploit channeling or volume reflection in bent crystals to selectively deflect beam halo particles such that they have a large impact parameter when being intercepted by an absorber [1]. Such a concerted halo deflection exhibits certain advantages over conventional multi-stage cleaning systems at hadron colliders which instead rely on the stochastic occurrence of scattering processes in an amorphous deflector to steadily increase the betatron amplitude of halo particles over several turns. The prospect of a crystal-based system lies particularly in the reduction of detrimental leakage from the collimation region into other areas of the accelerator – a critical concern for today's superconducting colliders like the LHC.

Over the past years, the UA9 experiment has successfully demonstrated the operational feasibility and reproducibility of crystal collimation for highly relativistic proton and lead ion beams in the SPS [2, 3]. A loss reduction could be observed both locally as well as in a high-dispersive area, the latter indicating a considerable decrease of the off-momentum halo population [5]. An extension of UA9 to the LHC (designated as LUA9) has been recently recommended by the LHC Committee (LHCC) [6], with a possible installation during the first LHC long shutdown (2013–2015). In order to employ a crystal deflector in high-intensity studies, and eventually under real operational conditions at top energy (7 TeV for protons), one requires a reliable knowledge of thermal and radiation effects which could potentially compromise the crystal functionality (e.g. degradation of channeling efficiency) and, in the worst case, its mechanical stability. In particular, one concern to be addressed is the crystal integrity in case of an accident scenario (e.g. an asynchronous beam dump) where full bunches could be deflected onto the crystal.

Table 1: Properties of the silicon strip crystal [4] used in the HiRadMat irradiation tests

Length/width/height	3/1/55 mm
Bending angle	50 μrad
Channeling planes	(110)
Torsion	$\sim$1 μrad/mm
Amorphous layer thickness	absent
Mis-cut angle	$\sim$100μrad

A first indication of possible effects to crystal deflectors can be inferred from previous irradiation tests with high-energy proton beams performed at different facilities [7, 8], where no macroscopic damage but some degradation of the channeling efficiency (for 2.4×10^{20} protons/cm^2) was observed. However, to realistically probe the mechanical strength of a crystal under beam impact conditions imposed by the LHC operational environment, dedicated irradiation tests have been carried out at the CERN HiRadMat [9] facility. The tests were performed with a 440 GeV high-intensity proton beam of $\sigma\approx$0.5 mm transverse size. The crystal under study was a silicon strip crystal produced at INFN-Ferrara [4], with properties as detailed in Table 1. A comparable crystal is foreseen to be used in future collimation experiments in the LHC. The irradiation tests were carried out with the crystal out of any angular alignment which could excite a coherent interaction with the beam. In this paper, we present the experimental setup, measurement procedures as well as a preliminary analysis.

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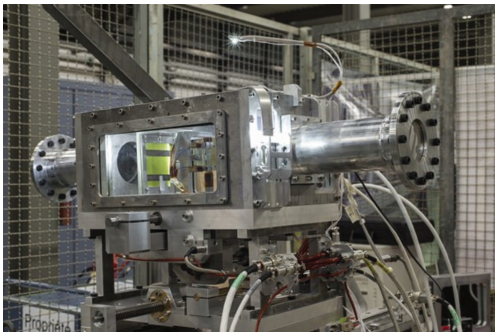

Figure 1: Photo showing the aluminium box containing the crystal. Photo by courtesy of Maximilien Brice.

EXPERIMENTAL SETUP

The experimental setup was accommodated in an aluminium tank equipped with glass windows permitting a visual inspection of the internal equipment (see Fig. 1). Tube extremities with $\sim$250 μm-thick beam windows made of beryllium were installed at the up- and downstream face of the tank, ensuring the containment of any projected material debris in case of a crystal break-up. The crystal, mounted vertically on an aluminium holder, was deliberatly rotated by 1° about its vertical axis to rule out channeling or volume reflection. The holder itself was fixed on a sliding support, which permitted a linear horizontal movement with a resolution of 5 μm. LVDTs were used for monitoring its absolute position.

As the width of the crystal was smaller than the beam FWHM, one of the most challenging aspects to be mastered during the experiment was an accurate alignment. Owing to its short size compared to the inelastic nuclear scattering length of silicon ($\sim$44 cm), losses induced by the crystal in a beam-based alignment with low-intensity pulses were estimated to be not clearly distinctive from the background. Hence, to enhance the beam losses, a stainless steel strip (AISI 316LN), with a width of 1 mm, was installed on the sliding support at a fixed and calibrated lateral distance from the crystal. Being 15 mm long in beam direction and having an inelastic scattering length nearly 3 times shorter than silicon, such a steel obstacle allowed to increase induced losses by more than one order of magnitude compared to the crystal. Two diamond detectors (CIVIDEC Instrumentation), serving as beam loss monitors, were installed on the downstream face of the tank. The detectors were connected to an oscilloscope in the HiRadMat control room. No absolute calibration of the detector signals was performed prior to the experiment as this was not required for the alignment procedure. Detectors of the same type have demonstrated previously to deliver a reliable signal in high-radiation fields of HiRadMat experiments and during LHC operation [10].

To allow for a visual verification of the alignment, a screen with a self-developing film (GAFCHROMIC® EBT3) and a ruler were installed upstream of the crystal. The screen, together with the stainless steel strip and the crystal, could be monitored online through a commercial webcam (see Fig. 2). The webcam could be reset remotely to reestablish its functionality after (expected) soft errors due to Single Event Upsets (SEUs).

The tank was installed on a support which itself was mounted on a standard HiRadMat table. The table was placed on the second of three test stands available in the HiRadMat experimental area.

MEASUREMENTS

An initial steering of the beam was performed by the SPS operation crew. The typical SPS beam instrumentation was available in order to measure the beam characteristics. The position and the dimension of the beam were surveyed using a BTV screen monitor in the HiRadMat primary beam line (TT66) and were found compatible with the requirements of the experiment.

After the beam setup, a series of alignment measurements was carried out. Low-intensity bunches ($\sim 10^{10}$ protons) were repeatedly extracted from the SPS while the stainless steel strip was moved in small steps between the pulses. For each extraction, the peak signal measured by the diamond detectors was recorded. Normalized to the pulse intensity, the signals were assumed to be proportional to the number of inelastic nuclear encounters of protons in the strip and hence to the intercepted fraction of the beam. Scans were performed with an initial step size of 500 μm, which was then refined to 200 μm and further to 100 μm. The measurements were iterated a few times until the alignment of the target was considered satisfactory and the beam position could be defined (scans were also repeated with the silicon crystal, however no loss signal distinguishable from the background could be observed, which was compatible with expectations). For illustration, Fig. 3 shows the normalized peak voltage versus strip position recorded during two of the initial scans.

The crystal was then placed at the derived beam position and high-intensity pulses were extracted from the SPS.

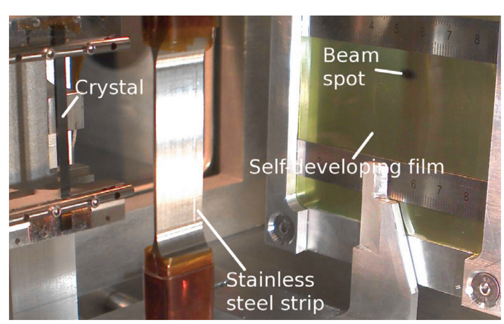

Figure 2: Snapshot captured with the webcam during the measurements, showing the crystal mounted on the aluminum holder (left), the stainless steel strip used during the alignment (center) and the self-developing film (right) with the beam spot being visible as black area.

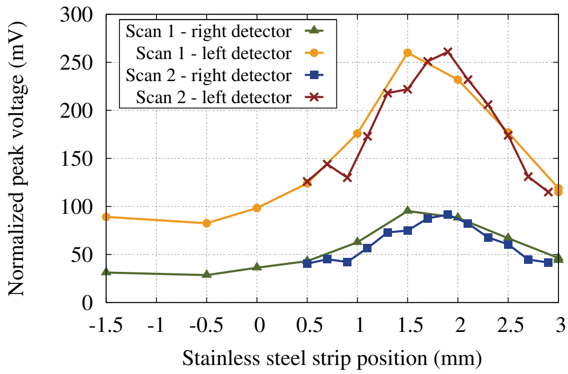

Figure 3: Examples of position scans aiming to align the target with respect to the beam.

The normalized transverse emittance as measured with the SPS beam wire scanner before the high-intensity extractions was approximately 3.5 μm rad in both planes, confirming the desired beam size ($1\sigma^2$) of $\sim 0.5 \times 0.5\,\mathrm{mm}^2$ at the position of the test stand. Starting initially with a single bunch, the number of bunches per pulse was gradually increased to 72, 144 and 288 (with an average bunch intensity of $\sim 1.1 \times 10^{11}$). Figure 4 illustrates the measured intensities during the different extractions. The integrated number of protons extracted during all high-intensity shots was approximately 2×10^{14}.

PRELIMINARY RESULTS AND OUTLOOK

First visual inspections indicated no macroscopic damage to the crystal. A key point is however the accuracy of the adopted beam-based alignment procedure, which is estimated to be 0.5 mm. Given the crystal width of 1 mm and a beam size of 0.5 mm, the fraction of protons intercepted by the crystal could have been at most $\sim$68% ($\pm 1\sigma$) in the ideal case where the crystal would have matched perfectly the position of the beam center. Assuming however a misalignment of 0.5 mm, this fraction would decrease to less than 50% of the incident protons. Besides, beam position monitors in the TT66 line indicated orbit variations of a few hundred μm between high-intensity extractions, yielding an additional uncertainty to which the intercepted beam fraction is known. It is to be fully clarified if a part of the measured orbit fluctuations can be attributed to other effects. Activity measurements performed after the tests however suggest that a considerable fraction of the beam was incident on the crystal.

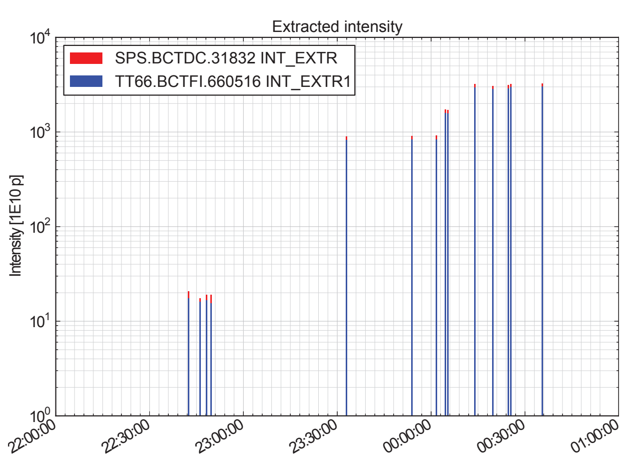

Figure 4: The extracted beam intensity as measured in the SPS and in the HiRadMat beam line.

Possible further irradiation tests will be carried out, adopting an improved alignment procedure. In addition, post-irradiation studies of crystal properties are foreseen, including an assessment of microscopic lattice damage. Measurements of the channeling efficiency are planned at a CERN test beam facility to examine a possible efficiency degradation in comparison with previous experiments.

Despite being carried out at a proton energy of a few hundred GeV, studies like the one presented here allow for conclusions which remain valid at higher beam energies. The small dimensions of crystals typically used in collimation experiments imply that the deposited energy is dominated by the ionising energy loss of impacting protons. On the other hand, the electronic stopping power of protons in silicon exhibits only a variation of roughly 10% between 440 GeV and 7 TeV, which means that the decreasing emittance is one of the key factors driving the induced peak energy density. This is in contrast to present LHC collimators (e.g. primary/secondary collimators made of 0.6/1 m graphite) where also the (beam-energy dependent) development of particle showers within jaws significantly contributes to reachable energy densities and temperatures.

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REFERENCES

[1] W. Scandale, Mod. Phys. Lett. A 27 (2012) 1230007.
[2] W. Scandale *et al.*, Phys. Lett. B 692 (2010) p. 78.
[3] W. Scandale *et al.*, Phys. Lett. B 703 (2011) p. 547.
[4] S. Baricordi *et al.*, J. Phys. D: Appl. Phys. 41 (2008) 245501.
[5] W. Scandale *et al.*, Phys. Lett. B 714 (2012) p. 231.
[6] Minutes of the 107th meeting of the LHC Committee (LHCC), CERN-LHCC-2011-010 LHCC-107.
[7] C. Biino *et al.*, Proceedings of EPAC96, Sitges, Barcelona, Spain, p. 2385 (1996).
[8] V.M. Biryukov *et al.*, Nucl. Inst. Meth. B 234 (2005) p. 23.
[9] I. Efthymiopoulos *et al.*, Proceedings of IPAC2011, San Sebastien, Spain, p. 1665 (2011).
[10] F. Burkart *et al.*, in these proceedings (THPEA047).