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DEMONSTRATION OF LOSS REDUCTION USING A THIN BENT CRYSTAL TO SHADOW AN ELECTROSTATIC SEPTUM DURING RESONANT SLOW EXTRACTION

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Abstract

A proof-of-principle experiment demonstrating the feasibility of using a thin, bent crystal aligned upstream of an extraction septum (ES) to increase the efficiency of the third-integer resonant slow extraction process has been carried out at the CERN Super Proton Synchrotron (SPS). With the primary aim of reducing the beam loss and induced radioactivation of the SPS, the crystal was aligned to both the beam and the septum to reduce by up to 40% the beam intensity impinging the ES and increase the intensity entering the external transfer line. In this contribution, we introduce the concept and the prototype system that was installed in 2018 before reporting in detail on the dedicated program of machine development studies carried out to characterise its performance and demonstrate operational feasibility. The performance reach and compatibility with other loss reduction techniques proposed to further increase the extraction efficiency, such as phase space folding with octupoles, is discussed in view of future high intensity operation.

INTRODUCTION

The main physics program at the SPS comprises the delivery of high intensity hadron beams to the North Area (NA) experimental facility. A constant flux of particles, in a time scale of a few seconds, is extracted from the SPS and steered on different primary targets. In order to guarantee the requested time scale of the extraction, resonant slow extraction is used, which results in a few per cent of beam loss. For high intensity hadrons this induces highly problematic radioactivation of the extraction equipment. The extraction element most exposed and activated is the electrostatic septum (ES), which is used to make the initial separation between the extracted and circulating beam. The focus of recent R&D efforts has been on tackling the source of the problem and improving the extraction efficiency [1, 2]. Presently at the SPS, the measured inefficiency of the slow extraction process is limited by the tolerances and relative misalignment of the long wire-arrays delimiting the low and high field regions inside the ES [3].

In literature, past examples and discussions of concepts where a crystal is aligned to a non-resonantly extracted beam upstream of a magnetic extraction septum are described using volume reflection [4, 5]. At CERN the authors took on the challenge of aligning a thin crystal to both the ES and the separatrix arm of a resonantly slow extracted beam, testing both the channelling and volume reflection schemes. We refer to this scheme as the ‘shadowing’ of the septum by the thin, bent crystal, which forms one of the cornerstones of the recent R&D effort on SPS slow extraction [6]. A more complete description of the recent results described in this paper can be found in [7].

SPS TEST CONFIGURATION

A suitable location for the crystal in Long Straight Section (LSS) 2 was identified ~5 m upstream of the ES separated by a wide-aperture focusing quadrupole with 4° of betatron phase advance from the crystal to the ES. This small phase advance was still adequate to demonstrate the shadowing concept. The prototype crystal and goniometer was specially developed by the UA9 collaboration for this application and installed in the location previously used for a prototype passive (wire-array) diffuser [8], which was swapped out during the second Injectors Technical Stop in September 2018. More details about the prototype crystal and goniometer can be found elsewhere in these proceedings [9].

Constant Optics Slow Extraction

At the SPS, a different way to drive the third integer slow extraction has been developed. The so-called Constant Optics Slow Extraction (COSE) [10] has been operational at the SPS for the second half of 2018. As discussed in [10], the im-

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plementation of COSE represents a significant improvement for the SPS slow extraction operation. In order to keep the optics constant for the portion of the beam instantaneously extracted, all machine power supplies are ramped together. This is done programming the beam rigidity variation as a function of time to follow the momentum distribution [10]. This permits to have achieve a flat spill, as previously done just ramping the main quadrupole current, and keep the optics constant in time. As a result, the separatrix presentation at the electrostatic septum is reduced in area. The separatrix is now kept stationary during the whole spill duration. This is a key advantage to fully exploit the crystal shadowing concept potential, as the channelling efficiency is strictly dependent on the angular distribution of the particle impinging on the crystal. As shown in the following sections, evidence of the gain of using COSE have been also experimentally observed during the crystal shadowing tests reported. More details regarding COSE can be found in [10].

TEST RESULTS WITH BEAM

In October 2018, the prototype shadowing system was tested with 400 GeV/c protons at an intensity of approximately 5×10^{12} protons per cycle, parasitically to the dedicated SPS Beam Dump Facility [11] prototype target tests which totalled about 20 hours of beamtime and ~ 6000 extractions. The shortened cycle with COSE and a 1.2 s flat-top was used for the test. The beam tests were characterised by the following observables using the available instrumentation: (i) beam loss signals (including time resolved data at 100 Hz) recorded at two LHC-type Beam Loss Monitors (BLM) installed next to the crystal and the ES, (ii) sum of the 5 beam loss signals recorded at SPS-type BLMs installed along the ES, (iii) encoder readings of the motors driving the goniometer position and angle, and (iv) beam profile monitors, most notably the wire grid located immediately upstream of the ES. The data was normalised to the measured extracted intensity in order to remove the cycle-to-cycle intensity fluctuations in the SPS.

As the goniometer tank was pre-aligned with the SPS axis the crystal could be well-positioned in front of the ES. With the crystal inserted into the edge of the extracted separatrix, a first angular scan of the crystal's orientation was performed and the beam loss observed on an LHC-type Beam Loss Monitor (BLM) installed immediately downstream of the goniometer.

The large dynamic range, sensitivity and fast-readout of the LHC BLM allowed a clear signal of channelling to be identified with a significant reduction in the beam loss on the crystal. Once the channelling angle was found, the transverse position was varied and successive angular scans performed. The position was changed with the aim of finding the correct transverse location to achieve shadowing of the downstream ES. The range of the angular scans were adapted as the transverse position changed using the theoretical linear projection of the separatrix in trace space.

The shadowing phenomenon was optimised by carrying out angular scans at different crystal positions in front of the ES. The result of an angular scan in the optimum position of the goniometer is shown in Fig. 1, demonstrating clearly the two regimes that provide loss reduction at the ES: (i) channelling, with a loss reduction recorded of 44 % and (ii) volume reflection, with a loss reduction in the order of 20 % across a much wider angular acceptance of ~170 μrad. The maximum loss reduction recorded when the crystal was channelling is in good agreement with predictions from tracking simulations that assume an effective ES thickness of 500 μm. The tracking simulations can be found detail elsewhere in these proceedings.

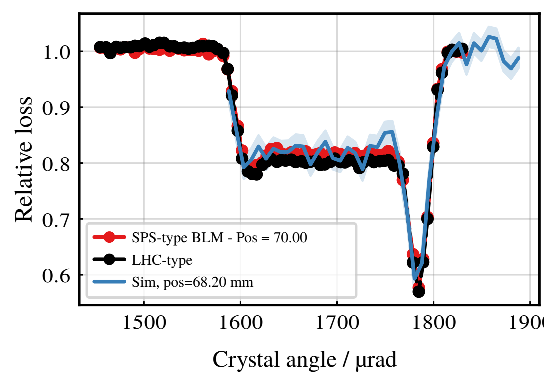

Figure 1: Relative beam loss measured on the BLMs next to the ES during an angular scan of the crystal with it aligned at the optimum position to shadow. The best loss reduction was obtained when the crystal was placed at 70 mm in the goniometer reference system, at which this scan refers to.

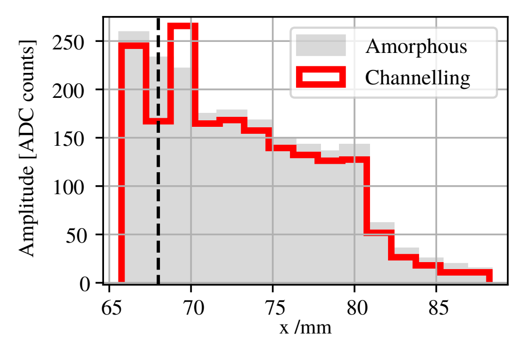

Figure 2: Horizontal beam intensity distribution measured on a wire-grid beam profiler located immediately upstream of the ES.

The channelled beamlet could be observed jumping the ES wires, along with a depleted region of density, on the wire-grid profiler located immediately upstream of the ES, as shown in Fig. 2.

The repeated angular and linear scans performed in order to find the global optimum of the loss reduction are summarised in Figs. 3 and 4, with the crystal aligned in channelling and volume reflection (VR), respectively.

Channelled Beamlet Trajectory in TT20

The new BLMs installed in the extraction transfer line were crucial in helping to identify where the channelled

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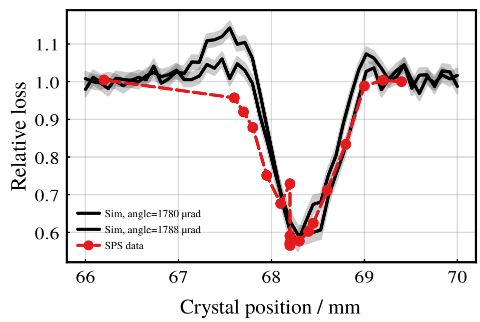

Figure 3: Relative beam loss measured on the BLMs next to the ES as a function of the crystal position when aligned to the beam in channelling.

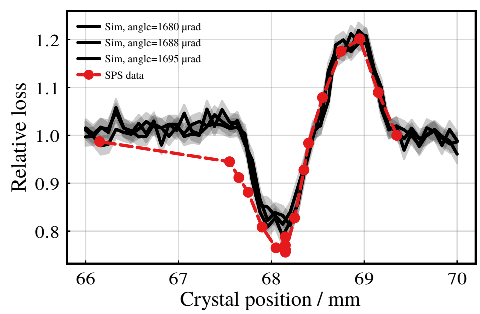

Figure 4: Relative beam loss measured on the BLMs next to the ES as a function of the crystal position when aligned to the beam in VR.

beamlet grazed the aperture and to help re-steer the trajectory of the beam in the transfer line towards the SHiP prototype target. The location of the observed beam loss matched the locations identified in simulation (Fig. 5). Re-steering the line to optimise the acceptance removed the beam loss and allowed the beam tests to progress without perturbation to the SHiP prototype target test. For the operational system, the channelled beamlet will need to be properly handled in the transfer line, to avoid local activation or even damage, given the high intensity in the relatively small spot size and the need to split the beam to the different NA production targets. Different solutions are under investigation.

For example, a collimator in TT20 could be foreseen to absorb the channelled beam and avoid uncontrolled losses. Also, a transport optics which accounts for the channelled beamlet is under deployment and this could represent the fastest and easiest solution to deploy crystal shadowing on the operational cycle. The non-local scenario, as briefly mentioned before, could lead to the possibility to reduce the phase-space area occupied by the extracted beam and simplify the optics requirements for TT20.

Stability and Reproducibility

One of the main concerns for the feasibility of the shadowing concept with a resonantly extracted beam was the machine stability required to hold the separatrix angle at the crystal within the very limited channelling angular acceptance. It was apparent from the first tests that channelling and loss reduction could be achieved consistently with re-

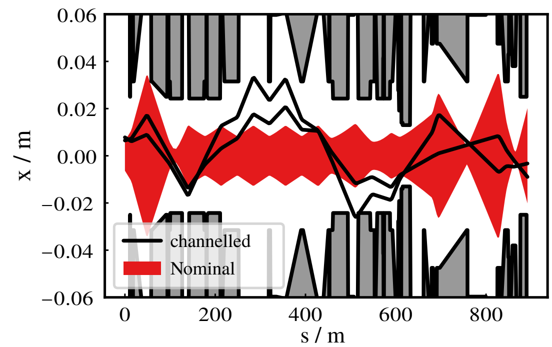

Figure 5: Envelope of the extracted beam and channelled beamlet transported to the target and the envelope of the channelled beamlet.

markable stability. The stability was tested by holding the crystal fixed for a large number of cycles in channelling and volume reflection, with an RMS stability of 1.1 % and 0.4 %, respectively, as shown in Fig. 6. The results are fully acceptable for operation in all three regimes tested.

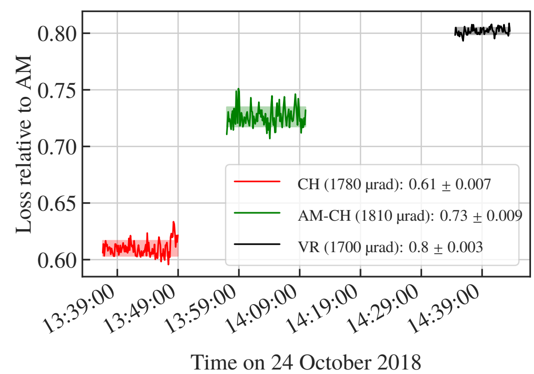

Figure 6: Beam loss measured at the ES relative to a misaligned crystal in the amorphous (AM) scattering regime during the stability checks. The crystal orientation was fixed in channelling (CH), in the channelling-amorphous (CH-AM) and volume reflection (VR) regimes. The average loss reduction factor is indicated in the legend.

Slow drifts over longer timescales are not excluded, but a simple automatic algorithm to optimise the crystal angle could be implemented, triggered either on demand or when the normalised losses become too high. Changes in the magnetic history of the SPS as its super-cycle is changed might represent a more difficult problem to tackle, although efforts to try to solve the problem at its source are ongoing [12, 13].

More problematic are the changes in loss reduction when the SPS cycle composition changes. Efforts are underway to understand and improve the stability of the SPS as it's magnetic cycle is changed in order to mitigate such issues at the source [12].

Another concern was whether the channelling efficiency could be maintained throughout the 1 s spill as the tune is swept. This was the motivation behind the development and operational implementation of COSE to hold the separatrix angle steady during the spill. In Fig. 7, the time evolution of

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the loss reduction at the ES is plotted for the optimum case presented in Fig. 1, which demonstrates that the separatrix angle is indeed maintained throughout the spill.

In Fig. 8, the comparison between the quadrupole sweep (referred as standard) methodology and COSE is compared. It is clear how the loss reduction with COSE is constant in time, as result of maintaining the separatrix fixed in time. The dynamics of the beam loss during the spill with and without COSE optics is discussed in detail in [10].

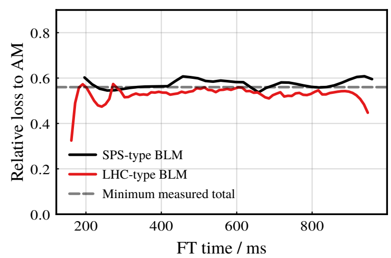

Figure 7: Time evolution of the loss reduction for the optimised case in channelling presented in Fig. 1.

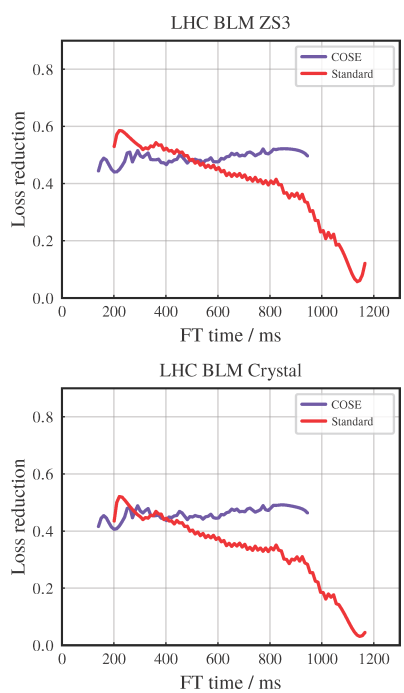

Figure 8: Loss reduction with a bent crystal in LSS2 as function of time during slow extraction reconstructed from LHC type beam loss monitors at the peak loss location electrostatic septum ZS3 and crystal: The crystal was aligned to shadow the ES wires. As with tune sweep the separatix angle at the ES changes, the loss reduction is not constant over time and drops rapidly when reaching the edges of the crystal's angular acceptance. With COSE on the other hand the loss reduction is constant within the noise level during slow extraction.

Deployment of the System in Operation

The crystal was also deployed for a 13 h period on the operational beam to the NA experiments, with a high intensity of 2.8×10^{13} protons per spill. A total of $\sim 6 \times 10^{16}$ protons were extracted during this time with approximately 5 % of the intensity estimated to have directly impinged the crystal. For simplicity, it was decided to test the shadowing concept in volume reflection to avoid the complications and possible downtime to operation from losing the channelled beamlet on an aperture restriction in TT20 (the transfer line optics were different to that used during the during the SHiP prototype target tests). The absolute prompt dose level observed at the location of the crystal was a factor two lower than for the passive diffuser [8], with only 1 % of the total dose saved around the SPS ring being increased locally at this location. No issues were experienced during the test and a 20 % loss reduction was observed throughout, as expected.

CONCLUSION & NEXT STEPS

The concept of ES shadowing using thin bent crystals as a mean to reduce the SPS slow extraction losses has been subject of extensive R&D at CERN. Using a prototype crystal diffuser tank, developed by the UA9 collaboration a loss reduction of up to 44 % was demonstrated, when the crystal was aligned and placed in channelling. The stability of the loss reduction was tested in different, including channelling and VR, and satisfactory results were demonstrated, opening the way to operational deployment during normal machine operation. The operational test during the NA physics run was carried out by aligning the crystal in VR. A constant loss reduction of about 20 % was recorded throughout the entire time the crystal was in shadowing.

The experimental results have identified clear directions for further optimisation of the system in the SPS. To further reduce losses at the ES in local mode, a series of crystals, placed in VR to optimise and increase the single-pass efficiency could be envisaged. In this configuration, the sensitivity to separatrix variation would also be reduced due to the larger angular acceptance.

A non-local case [6], where a single crystal aligned in channelling crystal is installed at a more suitable location in the SPS could represent a solution to further reduce the beam loss at the ES by up to a factor of four. Recent simulations summarise elsewhere in these proceedings [14] have shown great potential for such a concept, although the operational complications of tuning two, separate closed-orbit bumps will have to be evaluated with further beam tests.

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