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DEMONSTRATION OF NON-LOCAL CRYSTAL SHADOWING AT THE CERN SPS

F. M. Velotti, * M. Fraser, P. A. Arrutia Sota, M. Calviani, M. Di Castro, S. Cettour Cave, M. Donze, L. S. Esposito, B. Goddard, V. Kain, E. Matheson, S. A. Solis Paiva, R. Seidenbinder
CERN, Geneva, Switzerland

Abstract

The main SPS users are the experiments installed in North experimental Area (NA) which are served with a continuous 4.8 s long spill of protons and heavy ions. A third-integer resonant slow extraction is used to provide a uniform, long spill. Such a technique comes at the cost of particles directly hitting the electrostatic septum wires and activating the surrounding of the extraction channel. In recent years, silicon bent crystals have been exploited to shadow the wires of the septum blade and reduce the beam induced activation. It was then demonstrated the experimental success of local shadowing in the SPS and a way to further reduce losses with a non-local installation of the crystal. After the last yearly stop, a new Si bent crystal was installed in LSS4 of the SPS. In this paper, the first results from measurements with beam are reported together with limitations and possible upgrades of the present installation.

INTRODUCTION

A large number of fixed target experiments in the North Area (NA) of CERN are served by the Super Proton Synchrotron (SPS), which delivers about 3.5×10^{13} p every 15 s. The extraction scheme is based on resonant third-integer slow extraction. The main figure of merit for most of these experiments is the integrated proton intensity over the year. However, the intensity that can be extracted from the Long Straight Section (LSS) 2 of the SPS is constrained by the activation of the electrostatic septum (ZS), which separates the circulating and extracted beams with a thin blade exposed to the primary beam. This is an intrinsic limitation of the conventional third-integer slow extraction method. A possible way to mitigate the losses on the ZS wires is to use silicon bent crystals [1, 2], which can deflect the beam away from the septum by exploiting channelling and volume reflection phenomena [3, 4]. Previous studies [3] have shown that this technique can reduce the losses by about 45% in the SPS, and even more if non-linearities in the SPS ring and a thicker crystal are properly exploited - we refer to this as non-local crystal shadowing [3].

During the yearly stop of the CERN accelerators at the end of 2021, a thin crystal, identical to the one previously installed in LSS2 (TECS) and described in [3], was installed in LSS4 (TECA [5]). The crystal installed is 0.8 mm thick, as already available in LSS2. In a second stage, a thicker crystal will be installed to fully exploit the non-local shadowing concept.

* francesco.maria.velotti@cern.ch

In this paper, we present the results of a measurement campaign to demonstrate non-local shadowing of the ZS septum blade. We discuss the performance of using a single crystal in non-local shadowing, the results of combining two crystals, one in LSS4 and one in LSS2 to achieve a clear factor of 2 loss reduction in the slow extraction region.

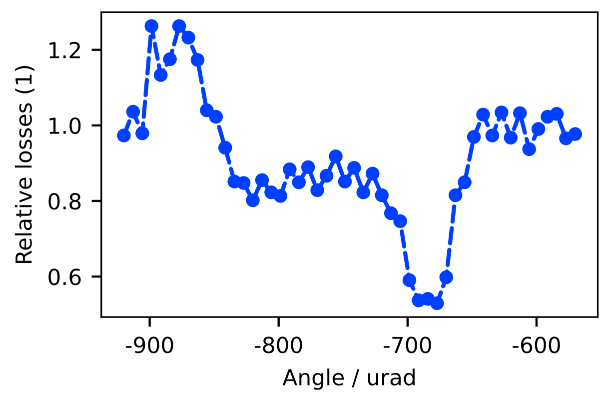

Figure 1: Simulated angular scan of the TECA showed as slow extraction losses, normalised by nominal losses without crystal, as a function of the TECA relative angle with respect to the separatrix. Assumed ZS width of 0.4 mm

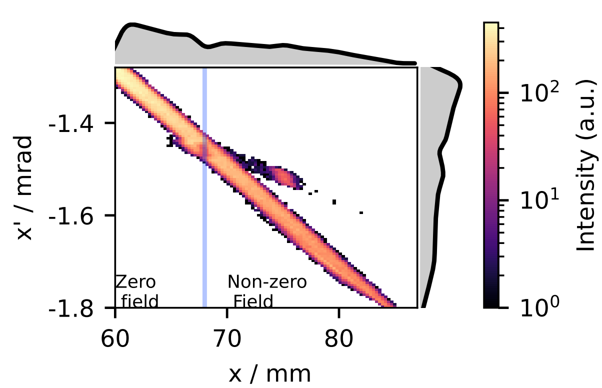

Figure 2: Trace-space representation at the extraction septum, ZS, with the perturbation induced by the interaction of the TECA with the beam. In grey, the density of the coordinates are also shown, indicating a clear density deep at the coordinate of the ZS wires (blue vertical line).

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NON-LOCAL SHADOWING SIMULATIONS

The report [3] explains the concept of local and non-local shadowing and how it can be applied to reduce losses in the extraction channel region using thin crystals. Non-local shadowing involves placing a crystal in a different accelerator sector than the ZS, which allows for better use of the machine space, lower losses and improved emittance of the extracted beam.

The advantages of non-local shadowing over local shadowing are due to two factors: i) the phase-advance dependence on amplitude induced by the extraction sextupoles between the crystal and the ZS, ii) the large angle between the separatrix and the crystal, which enables particles to interact with the crystal under different regimes (channelling, volume reflection and amorphous). The amplitude-dependent motion also affects the emittance of the extracted beam, which can be significantly lower than in the local shadowing case. This facilitates the transport of the extracted beam to the targets and prevents losses in the transfer line. Moreover, the amplitude-dependent motion influences the width of the low density well in the separatrix, which is responsible for the loss reduction. The size of this low density well depends on the crystal width and the angle of the separatrix at the crystal location. Previous measurements indicated a ZS effective width of 400 µm, after it was replaced during the Long Shutdown 2 of the CERN accelerators.

Under these conditions, Fig. 1 shows an example of angular scan performed in simulations. A clear loss reduction of about 45 % can be observed. The resulting phase-space at the ZS, when placing the crystal at the angle for the maximum loss reduction, is depicted in Fig. 2. The proximity of the channelled beamlet to the extracted portion of the separatrix ensures that the beam envelope of the whole extracted beam can easily be transported through the transfer line to the targets.

MEASUREMENTS IN THE SPS

The concept of non-local shadowing was experimentally validated in 2022 through a series of dedicated measurements session in the SPS. Before the measurements, a debugging stage was required to ensure the proper functioning of the goniometer hardware, controls and software tools. Moreover, the compatibility with high intensity LHC beams had to be verified experimentally.

Due to a mechanical issue with the crystal actuation system, the closed-orbit bump needed to align the crystal with the beam had to be reduced from 35 mm to 25 mm in order to achieve the channelling angle. This issue will be addressed in future versions of the goniometer.

The goniometer and its location were conceived considering parallel operation with LHC beams, as the crystal is installed on the opposite side of the magnetic septum used for the LHC beam extraction. The aperture was demonstrated to be adequate to accommodate both the SFTPRO and LHC beams at injection, thus no losses at injection or during the acceleration cycle were observed when the TECA was in beam position.

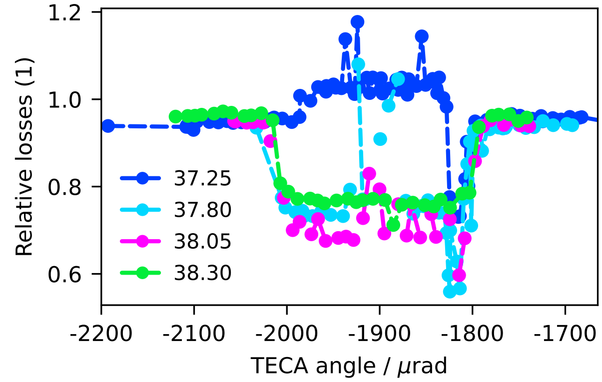

Figure 3: Measured angular scans of the TECA for different positions (different colours and position quoted in the legend in mm). The y-axis represents the measured losses at the ZS normalised by the nominal losses without crystal. The x-axis is the measured angle of the TECA.

Loss Reduction via Non-Local Crystal Shadowing

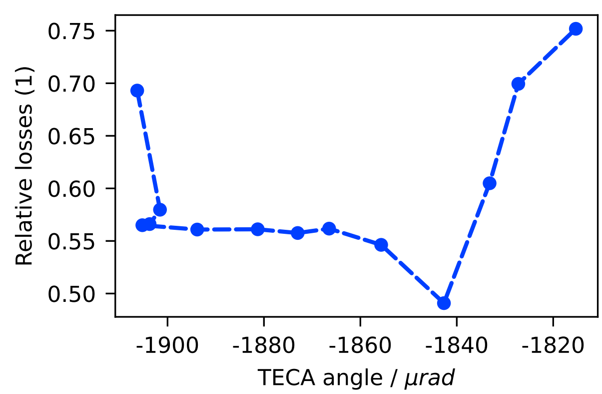

Figure 4: Measured angular scan of the TECA while the TECS is oriented in volume reflection.

The crystal's shadowing position was determined by scanning its position when the TECA was aligned in amorphous. A loss dip of about 4% was detected when the TECA completely shadowed the ZS. Near the shadowing position, several angular scans were performed, as depicted in Fig. 3. A significant loss dip of about 45% was recorded, as expected from simulations. The different angular responses of the crystal at different positions are shown in different colours. The maximum loss reduction observed during the data collection campaign is consistent with the simulation predictions.

The data also reveal a maximum of 30% loss reduction for a pure volume reflection interaction of the crystal with the

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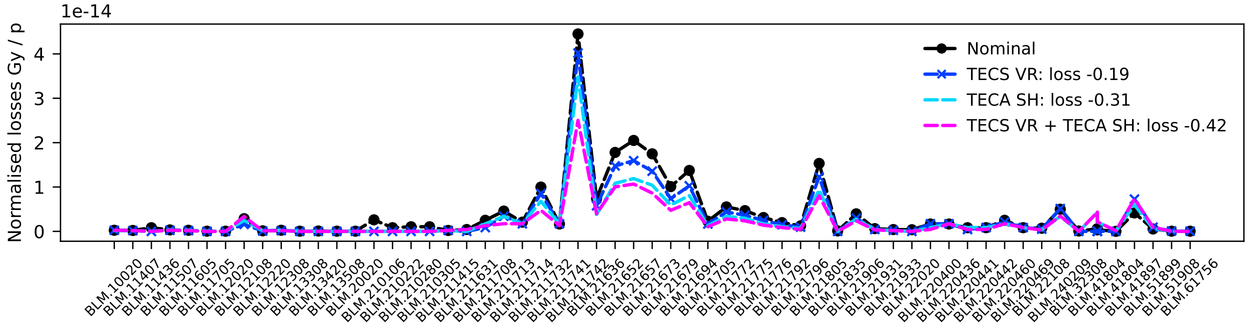

Figure 5: BLM reading along the SPS circumference that have readings above noise level for slow extraction without crystal (black), with TECS in volume reflection (VR - blue), with TECA in shadowing (SH - cyan) and with both TECS and TECA aligned in VR and SH (magenta), respectively. In the legend is also quoted to relative loss reduction for the sum of all BLMs along the ring.

beam, and clearly depending on the position of the crystal with respect to the ZS.

Loss Reduction via Non-Local and Local Crystal Shadowing Combined

During the last available data collection period, it was also possible to measure the loss reduction achievable using both LSS4 and LSS2 crystals. Also, direct comparison of the overall loss reduction is possible with the available data.

We first configured the TECS in volume reflection, which resulted in a loss reduction of about 20% in the extraction region [6]. Then, we moved the TECA to a shadowing position and performed several angular scans. Figure 4 shows an example of a single angular scan of the LSS4 crystal - we observed a maximum loss reduction of 51% when both TECS and TECA were aligned to fully shadow the ZS.

We noticed that the optimal angle of the TECA for maximising the loss reduction depended on whether it was used alone or in combination with the TECS. This can be explained by the fact that the ZS shadowing concept is a one-turn process. The beam interaction with the TECA affects the phase-space distribution at the TECS, so a simultaneous adjustment of both devices is required to achieve a constructive interference between them. When both TECA and TECS are properly aligned, the total loss reduction is a linear superposition of their individual contributions.

A key finding from the comprehensive measurement campaign is the absence of enhanced losses in any region around the ring (except for the TECA location) or in the transfer line to the target, as illustrated in Fig. 5. Indeed, one of the main drawbacks of the local shadowing concept via TECS is the impossibility of operating in channelling due to challenges in transporting the channelled beamlet to the targets, as reported in [3, 6].

The main obstacle encountered for a full deployment with high intensity was the beam losses registered at the crystal location. Such an increase is inevitable due to the non-zero interaction length of the crystal. Considering also these losses, the overall loss reduction is 30% using the TECA only and 42% combining it with the TECS in volume reflection.

CONCLUSIONS AND OUTLOOK

We presented in this paper the first experimental demonstration of non-local shadowing with thin crystals for slow extraction at the SPS. The experiment used a crystal that was not fully optimized for this purpose, but still sufficient to test the concept. The crystal had a thickness of 0.8 mm and reduced the losses in the extraction region by 45%, in agreement with tracking simulations. No significant loss increase was observed elsewhere, except at the crystal location. These results confirm the feasibility of the non-local shadowing technique proposed in [4].

We also demonstrated that combining both TECS and TECA results in a reduction of losses in the extraction region of 51% and 42% overall in the SPS. The local loss increase at the crystal is acceptable as it can be confined with dedicated shielding of the device.

The next steps of this research include the fabrication and installation of a thicker crystal of 1.8 mm to achieve a four-fold loss reduction in the ZS region. For such a crystal, the activation of the surrounding material is a critical issue. High-intensity tests with the SPS operational beam are planned for this year and studies of possible shielding solutions are also underway.

REFERENCES

[1] A. Asseev and M. Gorin, “One more possibility of using bent crystals for beam extraction from accelerators,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 372, no. 1, pp. 1–5, 1996. doi:10.1016/0168-9002(95)01277-X

[2] A. G. Afonin *et al.*, “Implementation of multistrip crystals to protect the septum magnets and to generate gamma radiation,” *Phys. Rev. Accel. Beams*, vol. 22, p. 033 001, 3 2019. doi:10.1103/PhysRevAccelBeams.22.033001

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-MOPA098

[3] F. Velotti *et al.*, "Septum shadowing by means of a bent crystal to reduce slow extraction beam loss," *Physical Review Accelerators and Beams*, vol. 22, 9 2019. doi:10.1103/PhysRevAccelBeams.22.093502

[4] F. M. Velotti, "Higher brightness beams from the SPS for the HL-LHC era," Presented 09 Mar 2017, 2017. https://cds.cern.ch/record/2265703

[5] M. Brice, "TECA, a crystal shadowing device in the SPS," 2021, General Photo. https://cds.cern.ch/record/2792521

[6] F. Velotti *et al.*, "Exploitation of crystal shadowing via multi-crystal array, optimisers and reinforcement learning," in *Proc. IPAC'22*, Bangkok, Thailand, 2022, paper WEPOST013, pp. 1707–1710. doi:10.18429/JACoW-IPAC2022-WEPOST013