REDUCTION OF RESONANT SLOW EXTRACTION LOSSES WITH SHADOWING OF SEPTUM WIRES BY A BENT CRYSTAL

F. M. Velotti, M. A. Fraser, B. Goddard, V. Kain, W. Scandale, L. S. Stoel
CERN, Geneva, Switzerland

Abstract

A new experiment, Search for Hidden Particles (SHiP), is being studied at CERN to investigate the existence of three Heavy Neutral Leptons in order to give experimental proof to the proposed neutrino minimal Standard Model. High-intensity slow-extraction of protons from the Super Proton Synchrotron (SPS) is a pre-requisite for SHiP. The experiment requires a resonant extraction with in a 7.2 s cycle, and about 4×10^{13} protons extracted at 400 GeV in a 1 s flat-top, to achieve the needed 2×10^{20} Protons On Target (POT) in five years. Although the SPS has delivered this in the past to the CNGS experiment with fast extraction, for SHiP beam losses and activation of the SPS electrostatic extraction septum (ZS) could be a serious performance limitation, since the target number of protons to resonantly extract per year is a factor of two higher than ever achieved before and a factor of four than ever reached with the third-integer slow extraction. In this paper, a novel extraction technique to significantly reduce the losses at the ZS is proposed, based on the use of a bent crystal to shadow the septum wires. Theoretical concepts are developed, the performance gain quantified and a possible layout proposed.

INTRODUCTION

The resonant slow extraction is an intrinsically lossy process. The electrostatic septum physically cuts the beam when, due to the crossing of the third order resonance, the transverse size of the beam is blown up and particles are forced over the wires of the ZS. In the SPS, the Long Straight Section (LSS) that hosts the slow extraction systems, LSS2, is the second most activated area ($> 1 \times 10^3$ μSv/h) of the whole SPS, only the dump system region is higher.

The SHiP experiment, to be housed in the North Area (NA), requests an unprecedented 2×10^{20} POT to be delivered in over 5 years. This means that a record 4×10^{19} POT/year will be required. This is a factor two above the West Area (WA), record and approximatively a factor four above the highest POT/year recorded at the NA. The main challenge to satisfy these specifications is the linear dependence of the activation with the delivered POT (Fig. 1). The activation is expected to be a factor four higher than ever recorded in LSS2. Increased activation levels mean higher doses to personnel in the event of an intervention involving hands-on maintenance of the extraction hardware. In light of the increasingly strict radiation protection regulations, put in place for the safety of CERN's personnel, the cool-down time required before an intervention will become prohibitive for the operation of the NA [1]. A way to mitigate the extraction losses has to be found if the availability of the machine is to be maintained during high intensity operation to the NA.

Different techniques have been developed in the last years to reduce losses at extraction, for instance the Multi Turn Extraction (MTE) [2] in the PS, but none of them permit spills of the order of seconds. Optimisation of the SPS third-integer extraction can clearly bring benefits to the extraction losses, although the optimisation alone cannot permit to reach the required loss reduction factor. A novel concept to significantly reduce the extraction losses has been explored, exploiting the concept of non-local extraction (also comparing it with the corresponding local case) and the recent developments for crystals used in collimation.

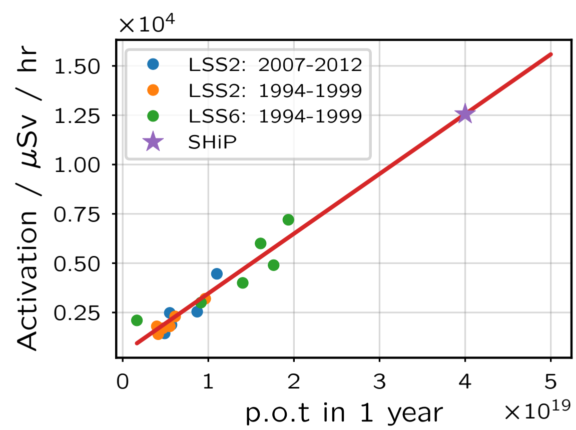

Figure 1: Measurements of the activation 30 hours after end of year operation in LSS2 or LSS6 (next to the ZS) as a function of delivered POT. The star represent the extrapolated scenario for SHiP if no modification to the slow extraction is put in place [3].

SIMULATIONS OF CRYSTAL-ASSISTED SLOW EXTRACTION

Recently, a significant effort has been put in place in the studies of the concept of crystal collimation [4–6]. The phenomenon of high energy particles channelling by means of silicon bent crystals has been experimentally demonstrated both in the SPS and in the LHC [4–6].

A bent crystal deflects the part of the intercepted beam by a certain angle. The different processes that generate different deflection angles of the particles interacting with the crystal lattice can be divided in three regimes [7] and this is extensively described in literature [4–7].

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The probability the different processes occur is a function of the incidence angle. From measurements performed in 2014 on a UA9 silicon bent crystal (SFT45) [8] and available in [7], a map of the relation between output and input angles of particles into the crystal was built [8]. The different deflection regimes are clearly visible and, very important for the following studies, the results refer to single pass effects measured on an experimental transfer line in the NA (H8).

From the data presented in [7] and limiting the impact angles to those expected from the analysed beam, a 1D probability density function (PDF) can be derived (±10 μrad) [7]. The PDF of the expected deflection given from the crystal is shown in Fig. 2 as blue solid line.

Due to the highly non-linear regime of the beam dynamics during the slow extraction process, particle tracking simulations are needed to assess the performance reach of this concept. In order to simulate the effect of the crystal on the beam, the thin tracking module of MADX and *pycollimate* [9] were used. Every turn the particles that interact with the crystal are given a thin kick assigned randomly from the previously described PDF.

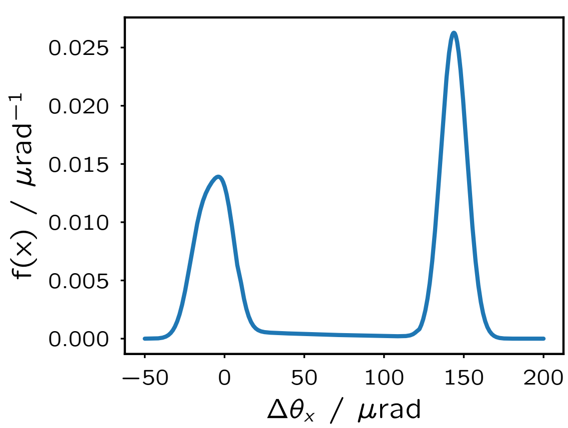

Figure 2: Angular independent probability density function of simulated kick from a thin crystal as implemented in *pycollimate*.

CRYSTAL-ASSISTED RESONANT EXTRACTION VIA SHADOWING

Silicon bent crystals, in principle, could be used to improve the SPS resonant slow extraction in two ways: either to replace completely the ZS or to shadow it. The first solution would offer many advantages with a much more compact device. Studies are currently ongoing to quantify this. The second option may be possible with available and tested technology. In the following, the performance reach and feasibility of crystal shadowing are explored, based on the above described simulation environment.

To avoid restricting the aperture of the synchrotron at injection, a fast actuating crystal, or a series of high energy magnetic bumpers, are needed to move the beam close to the crystal. There are two ways to shadow the ZS wires: locally, by installing a crystal immediately upstream of the ZS or, non-locally, by installing it in a favourable optics location equipped with bumpers. The first option seems the easiest one operationally and the less demanding in terms of optimisation. The drawbacks are the possible integration issues in a high radiation area, small lever arm to the septum and hence larger minimum deflection angle and additional losses coming from un-channelled particles. The second possibility involves the exploitation of a concept discussed in [9], non-local extraction. Here the negatives are increased operational complexity and possible losses elsewhere in the SPS. The advantages of having the crystal elsewhere than in LSS2 are: decoupling of the bumps in LSS2 and in the crystal location, allowing more optimisation parameters, minimum deflection deflection angle and easier installation.

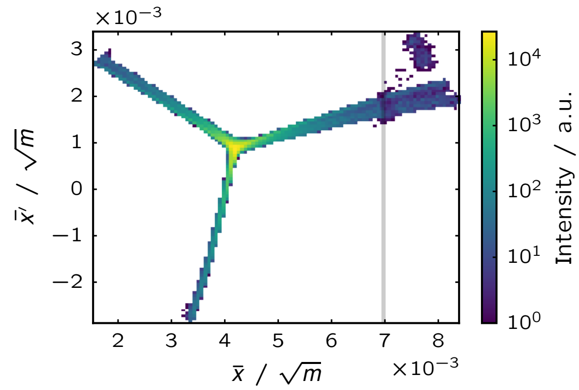

Figure 3: Simulations of the expected normalised phase-space at the ZS for a non-local resonant crystal assisted slow extraction.

A first investigation for a suitable location for the crystal was carried out. The crystal should be installed at $n180° \pm \Delta\mu_{nl}$ from the ZS, with n integer. Here, $\Delta\mu_{nl}$ represents the phase-advance needed to completely move the beamlet intercepted by the crystal away from the ZS wires, for a given crystal deflection angle. Such an angle should be minimised in order to avoid reducing the acceptance of the extracted beam too much. Another requirement for the crystal location in the SPS is the presence of extraction bumpers, as previously discussed. The location should ideally have the same optics functions as the front face of the ZS, although this condition is not strictly necessary and can be compensated with the crystal thickness or with a dynamic bump. Taking all this into account, the best location identified in the SPS is in LSS4, just upstream the extraction septum MSE.

To not interfere with the extraction elements and hence to avoid the creation of unwanted aperture bottlenecks, the proposal is to place the crystal on the inside of the SPS (the fast extraction septa are one-sided elements placed on the outside) and profiting from the dual polarity of the extraction bumpers. This translates in the necessity to force n to be an odd integer in order to have the same separatrix intercepting both the crystal and the ZS at the same turn. In this way, the particles intercepted by the crystals are those that, in the same turn, will be intercepted by the ZS wires. The effective thickness of the ZS wires considered here is 300 µm, where conservative misalignment tolerances are taken into account (to be compared with the 60 µm and 100 µm thickness of a single wire). The thickness of the crystal is defined by the total momentum spread of the beam, here assumed as $\delta_p = \pm 1.5 \times 10^{-3}$, due to the non-zero dispersion and its derivative at the ZS location. The ZS effective width has to be accommodated accounting for the total chromatic content of the beam and giving the specified width of 1.8 mm.

In Fig. 3, the results of the tracking simulations are shown. In order to evaluate the loss reduction at the ZS when shadowed by a crystal, the beam momentum spread δ_p is sliced and the particle density of the extraction separatrix is plotted as a function of the horizontal transverse coordinate (Fig. 4). A clear region of intensity depletion can be observed at the ZS location and a consequent increase of extracted particles with spiral step smaller than 10 mm. The observed reduction is a factor 3.4 for a single-pass efficiency of 54 %.

In order to reduce the demands on the efficiency of the crystal and improve the loss reduction the thickness of the crystal can be reduced. In the concept presented, this could be achieved using a dynamic extraction bump, which can be varied together with the horizontal tune to compensate the beam movement at the ZS throughout the spill. Alternatively the momentum spread could be reduced or the positional accuracy of the ZS improved. The crystal thickness specified could comport an increase of the overall losses. This is not the case due to the low probability for a proton interacting with a crystal to perform inelastic scattering and be lost. From [10], the probability of inelastic scattering at 400 GeV for a 2 mm long crystal is about 0.5 %. Hence, the expected losses at the crystal location would be about 0.1 %. This is more than a factor of ten lower than the current situation in LSS2, hence a proper shielding should be sufficient to limit the activation.

Crystal-assisted Local Resonant Extraction

The same concept just described can be adapted using a crystal installed in LSS2, just upstream the ZS (0.6 m upstream the QFA.21610). In this case, a crystal with larger channelling angle is required, as the phase-advance between the crystal and the ZS is only few degrees. Also, the crystal should be installed such that the channelled particles are deflected towards the outside of the ring.

The real phase space presentation at the ZS, in this local configuration, is shown in Fig. 5. Due to the proximity of the crystal and the ZS, the particles that are not channelled will be deflected with small angles and will not produce the same density reduction as for the non-local scenario. The comparison of the local and non-local ZS shadowing by means of bent crystals is shown in Fig. 4. The expected loss reduction using this extraction configuration is about a factor 2.5.

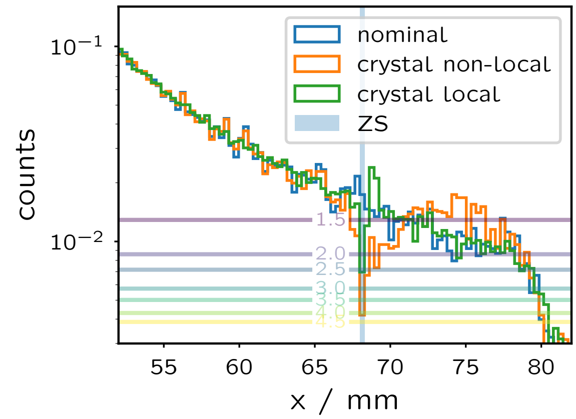

Figure 4: Histogram of the horizontal particle position at the ZS. In blue is shown the case for a nominal SPS FT extraction and in green the case for the non-local resonant crystal assisted slow extraction.

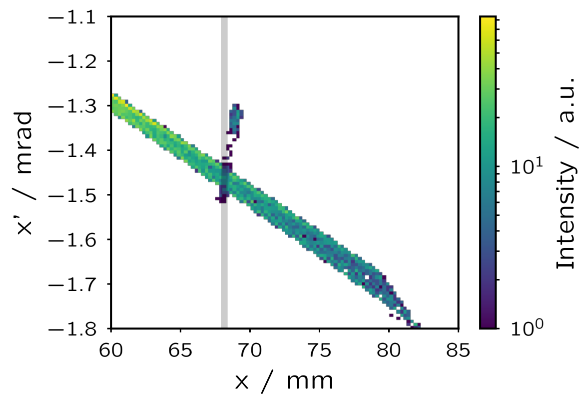

Figure 5: Simulations of the expected real phase-space at the ZS for a local resonant crystal assisted slow extraction.

CONCLUSION

The activation of the area surrounding the electrostatic septum shows a clear linear positive correlation with the POT delivered to the NA per year. For the much higher yearly POT requested (about four times) by new experiments, the subsequent elevation in activation needs to be addressed. The shadowing of the ZS wires with a bent crystal in a non-local extraction fashion should permit a loss reduction close to a factor four at the ZS, according to the simulation results presented. Further simulations are needed using the full crystal interaction PDF, including the angular dependence on the incident particles.

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