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EXPLOITATION OF CRYSTAL SHADOWING VIA MULTI-CRYSTAL ARRAY, OPTIMISERS AND REINFORCEMENT LEARNING

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Abstract

The CERN Super Proton Synchrotron (SPS) routinely delivers proton and heavy ion beams to the North experimental Area (NA) in the form of 4.8 s spills. To produce such a long flux of particles, resonant third integer slow extraction is used, which, by design, foresees primary beam lost on the electrostatic septum wires to separate circulating from extracted beam. Shadowing with thin bent crystal has been proposed and successfully tested in the SPS, as detailed in [1]. In 2021, a thin crystal was used for physics production showing results compatible with what measured during early testing. In this paper, the results from the 2021 physics run are presented also comparing particle losses at extraction with previous operational years. The setting up of the crystal using numerical optimisers is detailed, with possible implementation of reinforcement learning (RL) agents to improve the setting up time. Finally, the full exploitation of crystal shadowing via multi-array crystals is discussed, together with the performance reach in the SPS.

INTRODUCTION

The CERN-SPS delivers approximately 3.5×10^{13} p every 15 s to serve a large number of fixed target experiments in the NA. Particles are extracted via resonant third-integer slow extraction. For most of these experiments, the integrated protons delivered along the year is a fundamental figure of merit. As documented in [1], the main limiting factor to the number of particles that can be extracted from the SPS Long Straight Section (LSS) 2 is limited by the electrostatic septum (ZS) activation. The losses are unavoidable for classic third-integer slow extraction as the concept relies on separation between circulating and extracted beam via a thin septum blade which directly sees the primary beam.

To reduce the number of particles impinging on the ZS wires, in [1, 2] was proposed the exploitation of silicon bent crystals [3, 4]. Thanks to this technique, loss reduction up to about 45% was measured in the SPS and up to four times is expected, with better exploitation of machine non-linearities and a thicker crystal (non-local crystal shadowing [1]).

In this paper, the results from a full year of experience with the crystal for septum shadowing and the methodology used to efficiently align it are presented. Also, we propose a manner to further reduce losses during slow extraction using Multiple Volume Reflection Array (MVRA [5]) crystals.

CRYSTAL SHADOWING

IN DAILY OPERATION

The tests carried out in 2018 in the SPS showed that the crystal installed in LSS2 could reduce the beam induced losses on the ZS by about 20% when operating in volume reflection (VR) and up to 45% in channelling.

The main concerns about the channelling regime was the beam stability and the possibility to transport the beam to the NA targets. The first was addressed testing channelling stability during the first part of the physics run. It was possible to maintain this regime for weeks without the need to re-align the crystal. This was possible only for extracted intensities lower than 1×10^{13} p, due to the losses arising from losing the channelled beamlet along the transfer line to the targets. Attempts to adjust the transfer line optics and steer the beamlet together with the main beam were made, as proposed in [6], but measured losses remained unacceptable for daily operation. The impossibility of transporting the channelled beamlet through the transfer line is believed to be related to the inconsistencies observed in the transport line optics, which still remains unsolved.

The transport of VR beamlet is a much simpler task as the deflection angle is only 15 µrad. It was decided to use VR in operation for the full physics year, as the loss reduction was measured to be about 20%. Figure 1 shows the losses as a function of time starting from 2018 (no crystal in the SPS during operation), through 2021 (crystal in VR) to the first month of operation in 2022 (crystal still in VR). The large loss reduction achieved is a combination of the crystal operating in VR and the new ZS, which was exchanged before 2021[1]. The lower loss regime visible between July and August 2021 was thanks to the crystal in channelling.

Crystal Alignment

To align the crystal to the beam separatrix takes in the order of 150 machine cycles as accurate position and angle scans are needed to find channelling or VR and shadowing. For the SPS, this corresponds to a downtime for the physics users of more than 1 h due to unstable beam conditions. In order to speed up the setting up time, numerical optimisers were used. The very accurate tracking model available [1] was used to fit a deep neural network-based surrogate model, Fig. 2. Such a model is a fully connected neural network composed of 3 layers and 256 neurons per layer, with hyperbolic tangent as activation function.

In this manner, numerical optimisers were tested and the most performant chosen for machine operation. The algorithms tested are summarised in Fig. 3. Their performance

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[1] The ZS assembly was exchanged with a new one where the wire support were chosen as the straightest among those available.

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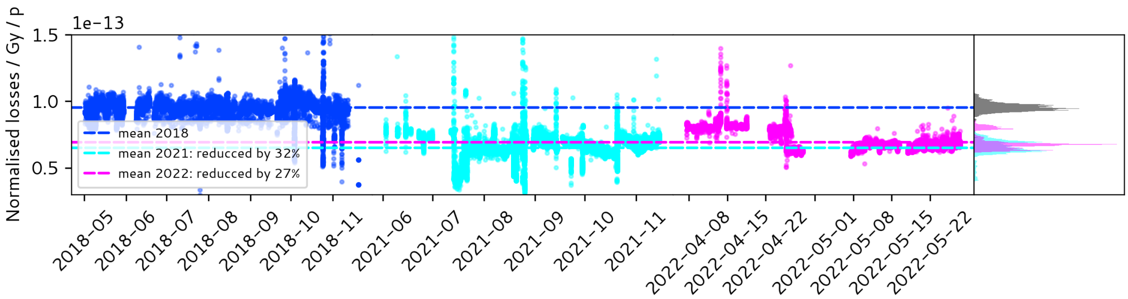

Figure 1: Normalised losses evolution in the LSS2 extraction channel as a function of time. The three colours represent the different operational years. The dashed lines are the mean over the different years.

is compared using the so-called *performance profile* ρ_s, as proposed in [7]. A set of 500 different initial conditions were randomly picked in the surrogate model validity domain and, for each of them, a full optimisation with a maximum of 100 neural network calls was performed. It is clear that the best performance was obtained for the Bayesian optimiser. This is due to the complexity of the objective function landscape (Fig. 2), as all the other algorithms have strong performance bias on convex functions. All other algorithms have a success rate to find channelling lower than 50%. Such an algorithm was tested in daily operation and convergence obtained as expected. An example of this optimisation procedure is shown in Fig. 4, showing convergence to channelling in 60 iterations. Due to the operation in VR, BOBYQA is now used as default algorithm to set up the crystal in VR, in case the machine orbits drifts. Thanks to these algorithms, the setting up time of the crystal for physics operation was decreased to about 30 machine cycles.

The results presented in the previous subsection open the way to evaluate different methodologies, as Reinforcement Learning (RL). A possible state description for the RL agent is identified as the SPS closed orbit together with the absolute settings for the crystal position and angle. The obvious reward would be the extraction efficiency, defined as: $r = -\epsilon_{loss}$, where ϵ_{loss} is the sum of the losses recorded in the LSS2 extraction channel. The minus sign is to force the agent to favour settings to quickly find channelling, as every iteration with the environment will reduce the cumulative reward over the episode. Work is ongoing to assess the feasibility of this proposal both in simulations and with the operational crystal in the SPS.

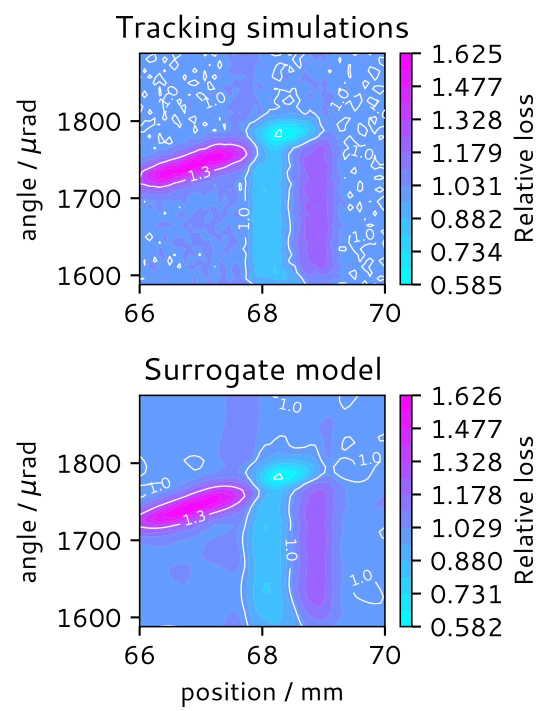

Figure 2: Simulated relative losses as a function of position and angle of the crystal installed in LSS2. (Top) Tracking simulations. (Bottom) Neural network based surrogate model.

FURTHER LOSS REDUCTION

Local shadowing is limited to a maximum of factor two loss reduction, regardless the thickness of the crystal [1]. In order to achieve a better loss reduction, the concept of non-local shadowing was proposed in [2], where the maximum loss reduction achievable using a more favourable location in the SPS could be increased to a factor of four. So far this has been only observed in simulations and machine tests to start benchmarking the simulations are foreseen for this year. Building on the results obtained with local shadowing and the encouraging simulations of non-local shadowing, further loss reduction can be obtained exploiting the efficiency of VR. As proposed in [5], it is possible to stack together a series of thin bent crystals and align them either in channelling or VR. For the latter, the disadvantage is the low deflection angle achievable, but the key benefit is the high efficiency of the process. In a very first approximation, the array efficiency will scale with number of crystals used: $\epsilon_{MVRA} \sim \epsilon_{VR}^N$, where N is the number of crystals and ϵ_{VR} is the efficiency of a single crystal. In case of the crystal used for the SPS tests, a VR efficiency of about 98% was estimated [8]. Under these very simple assumptions, the expected loss reduction would be in the order of a factor ten, assuming that the

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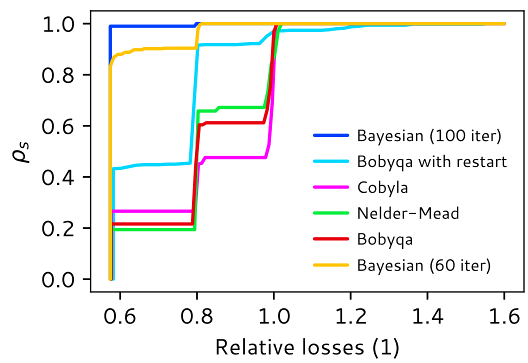

Figure 3: Success rate (expressed as performance profile) as a function of relative losses obtained for six different algorithms.

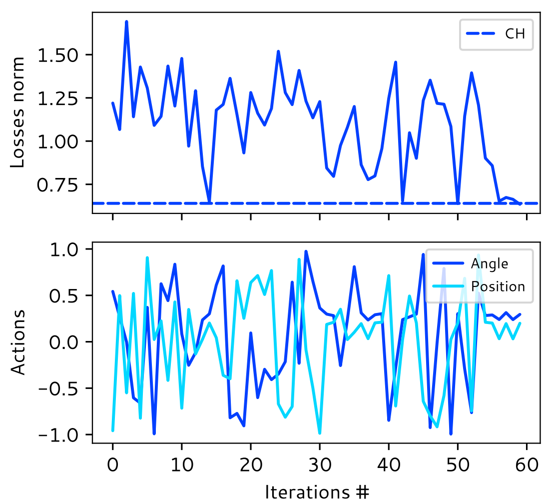

Figure 4: Example of measured successful setting up of the crystal in the SPS in channelling using Bayesian optimiser. The evolutions of angle and position are reported in normalised coordinate between -1 and 1.

deflection angle is sufficient to completely jump the wires. This was tested with tracking simulations using the tools described in [1]. In Fig. 5, the relative loss reduction derived for different combinations of crystals composing the MVRA is shown, for both local and non-local shadowing. In Fig. 5, an artificial continuous deflection is used, which is of course not realistic and shown only for illustrative purposes.

From tracking simulations, a maximum of ten fold loss reduction seems possible, when using MVRA in non-local shadowing. This is achieved with 5 crystals of 1.8 mm thick and 2 mm long, with a VR coherent deflection angle of 15 µrad.

For a MVRA of 5 crystals, the expected horizontal phase space at the electrostatic septum is shown in Fig. 6. Due to the small deflection angle generated by the MVRA, the phase space area occupied by the extracted beam (non-zero field region of the septum) is not increased significantly, making the transport to the targets of such a beam a feasible task.

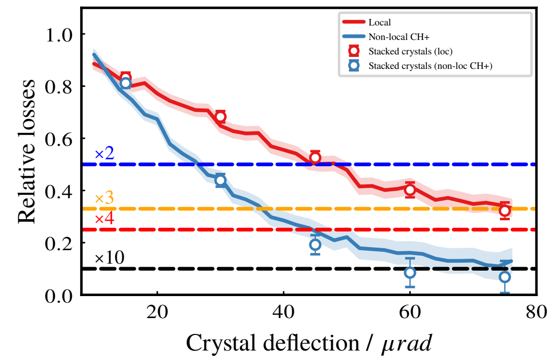

Figure 5: Simulated relative losses evolution as a function of the MVRA deflection for both local (red) and non-local (blue) position of the crystal.

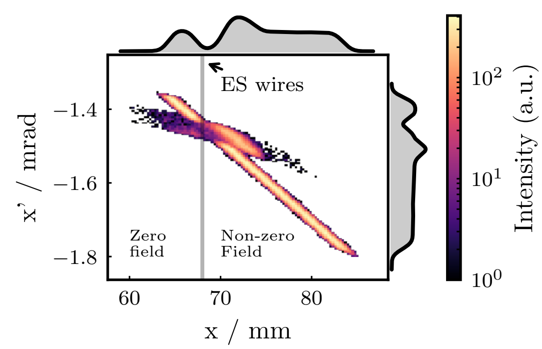

Figure 6: Simulated phase space at the ZS when using 5-crystal MVRA in non-local shadowing configuration.

CONCLUSION AND OUTLOOK

The SPS electrostatic septum shadowing concept was used operationally since the restart in 2021. A consistent loss reduction of about 30% is achieved in the last two operational years and only a few drifts were observed. Operational setting up of the crystal in channelling and VR was addressed with numerical optimisers, showing significant improvement in setting up time. We also laid the foundation for the testing of RL agents to fully automatise the process of alignment.

Finally, to further reduce losses on the extraction septum, MVRA crystals were evaluated in simulations showing a possible factor 10 loss reduction, if used in a non-local configuration. Initial tests of the non-local shadowing concepts are ongoing in the SPS, which will help determine the feasibility and performance reach of such a concept.

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