DOI: 10.1016/j.nima.2023.168892
FERMILAB-CONF-23-473-AD
(accepted)

Feasibility of using crystal channeling for the beam loss mitigation in Slow Extraction at 8GeV

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Abstract

In the accelerator applications of slow extraction for High Energy Physics (HEP), one of the prime challenges is the mitigation of beam losses, which is becoming increasingly critical with the continuous rise in beam power. A significant breakthrough was achieved earlier at CERN through the successful deployment of proton beam channeling in a crystal at 400GeV, effectively diverting the beam away from extraction septa and offering new avenues for improving slow extraction efficiency. However, a crucial question remains whether this approach is still effective at lower and medium proton beam energies. In this paper, we present the promising results of the computer simulation studies of the septum shadowing at 8GeV for the Mu2e project slow extraction at Fermilab. Across the wide range of beam parameters, the beam loss reduction is shown to range between 40% and factor of three.

Introduction

The Mu2e experiment [1] is under the final stages of construction at Fermilab. The 8GeV, 8kW proton beam will be delivered to the experiment using the Slow Extraction (SX) from the Fermilab Delivery Ring (DR). The experiment applies stringent requirements on beam quality and especially on the beam losses, as the elevated radiation levels may result in reduction of the available beam intensity and therefore, number of available protons on the target. The latter is critical for the first experiment run, given its limited duration.

While the radiation protection plan [2] is designed to provide sufficient shielding against the expected beam losses of 1.5% at the nominal beam power, any variations in losses or their locations pose a notable risk to the experiment. In an effort to mitigate this risk, we are exploring ways to further improve extraction efficiency.

The use of bent oriented crystals to deflect a portion of the beam away from the Electrostatic Septum (ESS) plane, a technique known as shadowing, holds significant potential for reducing beam losses in SX. This method has previously demonstrated success at 400GeV [3]. However, its application at lower energies presents well-known challenges, primarily due to increased beam emittance.

In the case of the DR, the typical angular beam spread exceeds the crystal's critical angle by more than an order of magnitude. Fortunately, the DR's extraction scheme possesses the capability to produce an extracted beam with significantly reduced angular dispersion.

Shadowing septum using crystal channeling in Slow Extraction

In the conventional SX, intentional destabilization of the beam is employed through the excitation of betatron resonance in the circular machine. The process of 3rd integer resonance extraction can be illustrated using a normalized horizontal phase space diagram, shown in Figure 1. When far from the resonance, the beam's phase space occupies a circular region (shown in blue). When in proximity to the resonance, the phase space splits into stable and unstable regions, delineated by a triangular shape (the separatrix). The size of this separatrix is directly proportional to the tune's distance from the resonance (either 1/3 or 2/3).

Particles located outside of the separatrix drift away following three distinct separatrix branches until they reach the Electrostatic Septum (ESS), as shown in Figure 2. The portion of the beam falling to the left

* This work has been supported by US Department of Energy, Contract number DE-AC02-07CH11359
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the Xsep (highlighted in green in Figure 1) undergoes deflection in the E-field of the ESS, leading to its extraction.

There are different ways to push the beam out of the separatrix. In the DR, the scheme is optimized to minimize the angular width of the extracted beam. The separatrix squeeze is performed by ramping the tune to the resonance. The machine horizontal chromaticity is minimized, so that only the very narrow edge of the separatrix is removed at each turn. And finally, a dynamic orbit bump is being ramped during the spill to maintain the main extraction branch of the separatrix at a constant angular position. As a result, the rms dispersion of the extracted beam angle remains below 40 μRad. This characteristic renders the SX beam at the DR exceptionally suitable for the application of crystal channeling at 8 GeV.

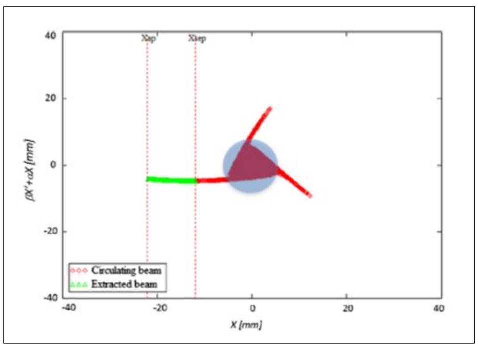

Figure 1. Horizontal phase space of the beam in 3rd integer resonance

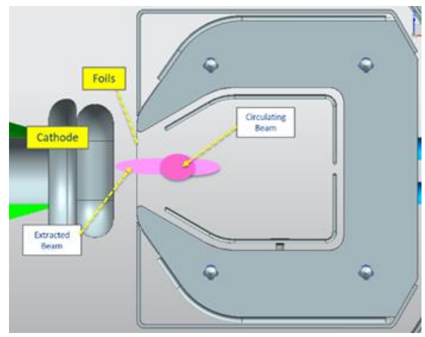

Figure 2. Electrostatic septum

As shown in Figure 2, a portion of the beam traverses the septum foil plane. The DR septum foil plane is made of 25 μm thick tungsten foil strips. All beam losses pertinent to the SX are attributed to scattering within this foil plane. The objective of this study is to assess the feasibility of losses reduction through the utilization of crystal shadowing. The concept of crystal shadowing is visually depicted in Figure 3a and 3b, illustrating how it effectively minimizes beam density at the septum plane.

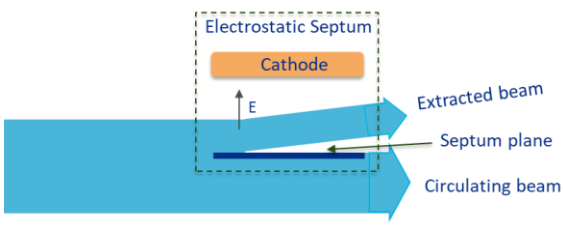

Figure 3a. Beam separation in the ESS in normal SX. Part of the beam passes through the foil plane, causing losses.

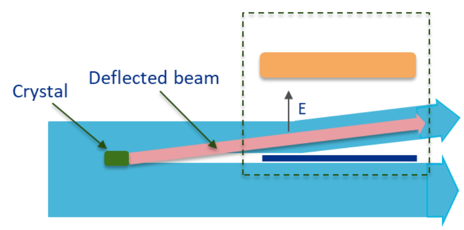

Figure 3b. Using the bent crystal to deflect the beam away from the septum plane and reduce the beam density at its location (Shadowing)

Crystal shadowing acts by allowing only a small fraction of the beam to pass through the thin crystal, thereby minimizing the additional scattering within the crystal while effectively pushing this portion of beam away from the foils.

Tracking simulation framework

The tracking process begins 1.6m upstream of the first ESS and passes through the crystal before entering the septum. For modeling the effect of the crystal, FLUKA model has been deployed to compute the Probability Density Function (PDF) [4]. The FLUKA channeling module describes the coherent effects of positively charged particles in a crystalline lattice [5-7] as the following. When the angle between the particle's direction and the channel's orientation is smaller than the critical angle, particles can be "channeled" inside the Molière potential created by two crystal planes. To reproduce the volume effects in the bent crystals, particles are transported using the electrostatic Molière potential with an additional centrifugal term. Coulomb scattering rate, nuclear interaction rate and electronic stopping power are scaled according to the different impact parameters with the lattice nuclei. The crystal's geometry in this study encompassed a length of 0.4mm (in the direction of the beam), a width of 0.1mm (in the X direction, corresponding to the horizontal direction of the septum kick), and a bending angle of 300 μRad (also in X direction). The resulting computed PDF map can be seen in Figure 4

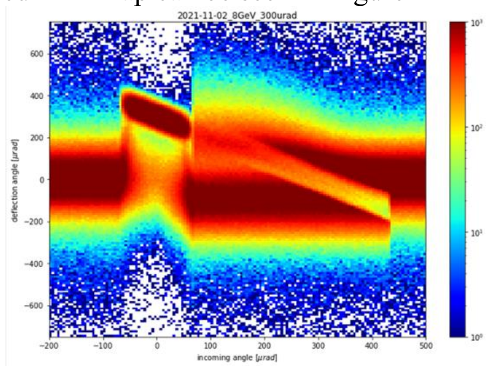

Figure 4. PDF map computed for 8 GeV protons with FLUKA for the (110) crystal length of 0.4mm and 300μRad bending angle.

The further tracking through the DR extraction channel has been performed using the MARS code [8]. The global DR model has been developed for the multi-turn tracking of the SX beam and identifying the main loss locations throughout the ring. It combines the MADX/PTC tracking of the particles in the accelerator lattice with the MARS native tracking in the media for those particles that leave the vacuum pipe and hit the beam line elements [9].

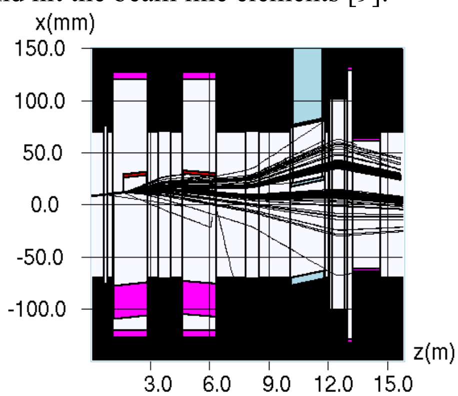

Figure 5a. The horizontal aperture map for Extraction

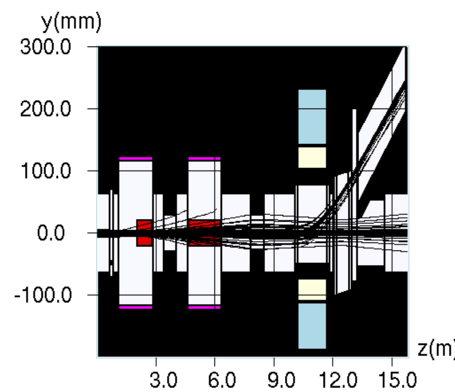

Figure 5b. The vertical aperture map for Extraction channel

In the context of this study, our focus primarily encompassed the extraction channel, with additional details added to the septa geometry and its surroundings. Figure 5a and 5b illustrate the particle tracks within the extraction channel aperture. The extraction channel includes electrostatic septa ESS1 and ESS2, quads Q203-Q205, and magnetic septa ELAM and CMAG.

As depicted in Figure 5, the beam sample used in this analysis represents only a narrow segment of the full beam, spanning approximately ±0.5mm around the septum plane. This significantly reduces computational time since the remainder of the beam outside this region does not contribute to the assessed losses.

The jobs were executed on the Fermigrid multiprocessor facility, with each job typically employing 0.25 million particles. For each run the extraction efficiency was calculated as a fraction of the beam that made it into the acceptance in the ring or the beam line. In a preliminary dry run, conducted without the crystal, we observed an extraction efficiency of 98.5%. This result is consistent with the design specifications and previous simulations [10].

Tracking simulation results, adjustments, final results

Initially, the crystal was positioned 1.3m upstream of the ESS1, with ESS1 plane set up 12mm away from the beam center. The septum plane is aligned with the incoming beam at an angle of 2 mrad. To optimize channeling acceptance, the crystal is also aligned at the same angle. Figure 6 shows the difference between the beam angle distributions at the entrance (red) and at the exit of the crystal (green). There is a distinct channeling peak shifted by 300 μRad in the positive direction. In the remaining, not captured beam,

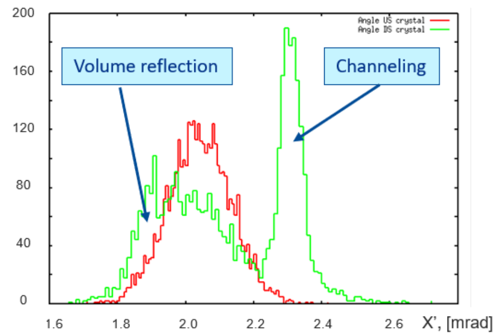

Figure 6. Beam angle distribution before and after the crystal

there is also a slight shift in the opposite direction, accounting for the Volume Reflection. Despite the clear separation and significant shift of the channeling peak, the beam loss reduction appears to be close to 10%. The reason for this modest performance becomes clear in Figure 7, showing the phase space at the ESS entrance. The channeled segment of the beam effectively clears the septum width, indicated by the blue dashed lines. Nonetheless, the depletion of beam density within this region remains relatively weak due to the inherent angular spread of the beam, resulting in notable mixing.

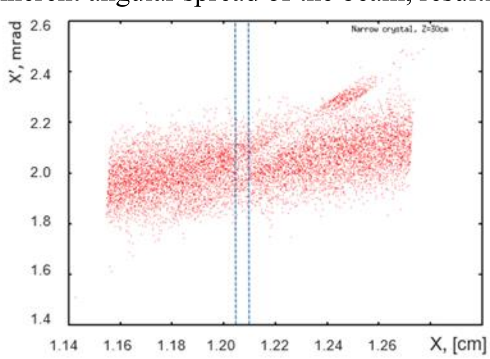

Figure 7. Beam phase space at the septum entrance.

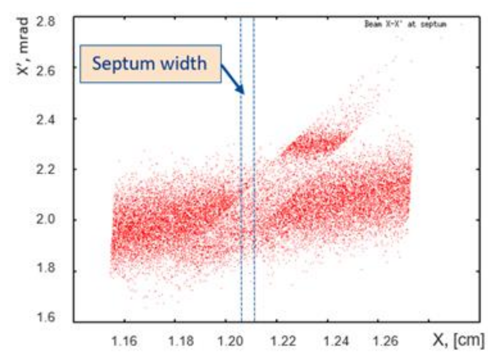

Figure 8. Horizontal phase space at the ESS1 entrance.

This can be addressed by either using a wider crystal or relocating the crystal closer to the septum. We employed both strategies: we increased the crystal width from 0.1mm to 0.2mm, and also moved the crystal 0.4 meters forward, resulting in a new distance of 0.9 meters from the septum. Figure 8 displays the beam phase space with substantially improved density depletion at the septum in the new configuration.

For the best alignment of the crystal with beam, angle and position scans were performed. Figure 9 shows the final horizontal scan made after the angle adjustment has been done. It shows the losses level 3 times lower in the minimum, than that at the far distance, indicated by the green line. The actual ratio is slightly better, as the minimum has to be compared with the configuration with no crystal, as shown further. This result has been obtained for the design beam parameters, with the beam angle rms width set to 40 μRad.

We also want to evaluate how performance may change under more demanding conditions that may arise due to various operational factors, such as potential limitations in beam angle control stability. To achieve this, we increased the beam angle rms span twice, making it equal to 80 μRad.

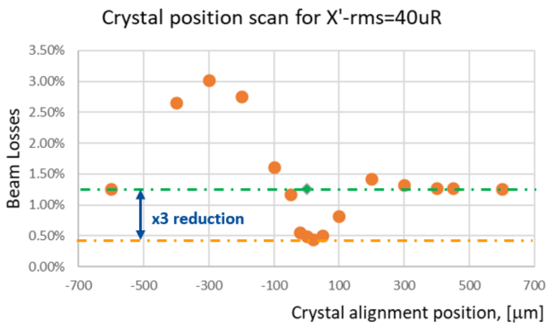

Figure 9. Beam loss vs the crystal X-position. Beam angle rms width=40 μRad.

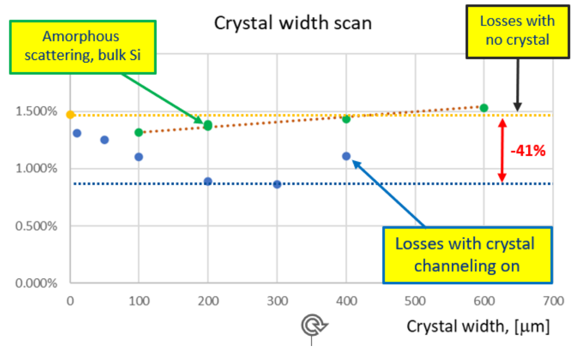

Figure 10. Beam losses vs crystal width. Beam angle rms width=80 μRad.

Figure 10 presents new beam losses vs the crystal width in three cases: crystal channeling is on - blue markers; crystal channeling if off but the amorphous scattering is present – green markers and no crystal is present – yellow line. The optimal crystal width is 0.3mm and maximum beam loss reduction is 40%. Insertion of the crystal itself with no channeling still improves the extraction efficiency due to the diffuser effect of amorphous scattering if the crystal width is below 0.4mm.

Conclusions

We carried out the tracking simulations for the slow extracted beam in the Fermilab Delivery Ring Extraction section, passing through the bent crystal, installed in front of the first septum. We concluded that with the given crystal parameters and the beam line configuration the beam loss reduction by the factor of 3 and more can be achieved for the design beam angle rms dispersion of 40 μRad and 40% improvement is expected for twice wider beam angle spread.

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