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Bent Crystal Channeling for Optimized Beam Shadowing in Proton Extraction at Mu2e

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The Mu2e experiment is designed to investigate the CLFV through the observation of a neutrinoless muon-to-electron conversion in the field of an Al nucleus. The observation of such a process would be clear evidence of physics beyond the standard model. Due to the rarity of this process, a cutting-edge, intense muon beam is required to achieve an improvement of the current single-event sensitivity by 4 orders of magnitude. To achieve this goal, a primary proton beam with 8 GeV is extracted from the Fermilab Delivery Ring using the slow resonant extraction technique. Mu2e requires $\sim 3.6 \times 10^{20}$ protons-on-target to meet its goal; hence, it is crucial to minimize the extraction losses. An important source of such losses are the particles impacting on the electrostatic septum blade. A very promising solution to the problem lies in the beam shadowing scheme tested at CERN SPS. In this approach, a bent crystal is strategically placed upstream of the septum, deflecting particles from the blade at a precise angle via the phenomenon of channeling. As a result, a zone with reduced particle flux is created downstream of the crystal, safeguarding the septum anode by minimizing interactions with the beam. This work explores the optimization of beam shadowing design and the process in the manufacturing and characterization of the bent crystal sample. It emphasizes the promising role of channeling in bent crystals, and it underscores the significant potential of channeling in bent crystals to assist the Mu2e experiment.

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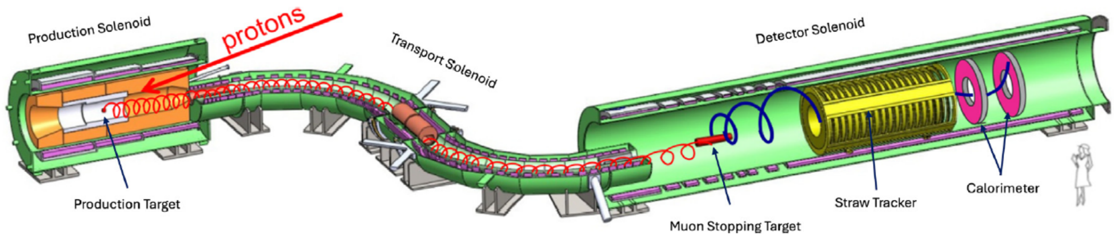

Figure 1: Layout of the Mu2e experiment. Adapted from [5].

1. The Mu2e Experiment

To discover new physics phenomena, several experiments are built to observe processes that are violated or extremely suppressed by the standard model. The observation of quark mixing and neutrino oscillation confirms interaction among Standard Model (SM) fermions non-diagonal in flavour. In SM with massive neutrinos, regardless of their Dirac or Majorana intrinsic nature, a virtual loop with mixing neutrinos can make Charged Lepton Flavor Violation (CLFV) processes happen with a branching ratio to a level below 10^{-50} [1]. The upper bound (90% C.L.) sensitivity of the currents CLFV experiments lies around 10^{-13}; thus, an observation of such processes would be a clear signature of new physics beyond the Standard Model, where several theories predict new particles and interactions that can enhance the branching ratio to levels reproducible at modern experimental sensitivity. At the moment of writing, several international experiments of CLFV search are well established, such as the MEG-II at PSI, which has recently published its latest result on the search for $\mu \to e\gamma$ [2], the proposed Mu3e experiment under construction at PSI [3], and the Mu2e and COMET experiments for the search of $\mu\mathrm{N} \to e\mathrm{N}$. In particular, the Mu2e experiment, under construction at the Fermi National Acceleration Laboratory, aims to observe CLFV as neutrinoless muon-to-electron conversion in the field of an aluminum (Al) nucleus, for which the single event sensitivity is given by:

$$R_{\mu e} = \frac{\Gamma(\mu^- + {}^{13}_{27}\mathrm{Al} \to e^- + {}^{13}_{27}\mathrm{Al})}{\Gamma(\mu^- + {}^{13}_{27}\mathrm{Al} \to \nu_\mu + {}^{12}_{27}\mathrm{Al})} \tag{1}$$

and the experimental signature will be a single monoenergetic conversion electron (CE) of energy $E_{CE} = m_\mu - B - E_R = 104.973$ MeV, where m_μ is the rest mass of the muon, B is the binding energy, and E_R is the recoil energy of the Aluminum nucleus.

The current upper limit on this measurement is set by the SINDRUM II experiment, which has a value $R_{\mu e} < 7 \times 10^{-13}$ (90% C.L.). The full data-taking program of the Mu2e experiment aims to enhance this limit by four orders of magnitude [4], and to reach such a challenging achievement, the experiment needs very high statistics, collecting at least 10^{18} stopped muons on target, very high detector precision, and high control of the background events. The design of Mu2e [5], which is based on these concepts, is illustrated in figure 1: $\sim 3.6 \times 10^{20}$ 8 GeV/c protons coming from the Fermilab Delivery Ring strike on a $1.6\mathrm{X}_0$ tungsten Production Target (PT), generating pions and, from their decay, muons. A Production Solenoid with a gradient magnetic field from 4.6T to 2.5T increasing in the beam direction acts as a magnetic lens selecting low-energy particles and transporting them to the S-shape Transport Solenoid (TS), which also has a graded magnetic field, from 2.5T at the TS entrance to 2.1T. The TS efficiently transports charged particles to the detector area and discards any possible contamination from neutral particles, selecting the beam sign thanks to a rotatable collimator placed in its center. The Detector Solenoid (DS) has two different regions of graded magnetic field: from 2T to 1T in the upstream region, where the muon stopping target resides, and a uniform 1T magnetic field in the detector system, which comprises a high precision straw-tube tracker and two calorimeter disks made of undoped CsI. The whole DS region and parts of the TS are covered by an ultra-efficient cosmic ray veto (CRV). Detailed information can be found in the references [5–11]. Together with high statistics and high detector precision, background control is another crucial element for the success of the Mu2e experiment. The CLFV process $\mu\mathrm{N} \to e\mathrm{N}$ suffers from different background processes:

- **Intrinsic backgrounds**: Represents all the processes which are produced by the muonic atoms formed after the muon capture. Among them, the Muon Decay in Orbits (DIO) ($\mu^- \to e^-\bar{\nu}_e\nu_\mu$) represents the primary intrinsic background of the Mu2e CLFV process. Indeed, unlike the standard muon decay spectrum, which has an endpoint at 52.8 MeV [12], the DIO spectrum is altered due to the possible recoil of the final electron with the nucleus of the muonic atom, mimicking the signal of the CE.

- **Cosmic Rays**: A through-going cosmic ray that interacts with the Mu2e stopping target can knock out an electron with the conversion energy; such an event will be indistinguishable from a real conversion process. From simulations [4], the Mu2e experiment expects a Cosmic Ray background event per day, making it necessary to implement a hermetic CRV with the highest efficiency possible.

- **Beam Induced Background**: Represents all the processes related to the contamination of the muon beam, the most important of which is the Radiative Pion Capture (RPC) ($\pi^-\mathrm{N} \to \gamma\mathrm{N}'$) where N′ is an excited nuclear state. The RPC photon spectrum exhibits a peak around 110–120 MeV, and an asymmetric conversion may produce an electron at the conversion energy. The RPC background processes constrain the Mu2e experiment to the use of a pulsed proton beam.

To drastically reduce the RPC due to the contamination of charged pions in the muon beamline, the Mu2e experiment exploits a complex structure of a pulsed primary proton beam: an 8 GeV (8kW) proton beam coming from the Booster is bunched in 8 large batches in the Recycler Ring and subsequently stored in the Delivery Ring. Finally, the proton batch is delivered to the experiment using the Slow Extraction (SX) every 1695ns ($\sim 2\tau_\mu^{\mathrm{Al}}$) with 250 ns-wide pulses. This beam delivery configuration ensures that the charged pions decay before the signal window opening, 700 ns after the proton pulse. SX is a well-established method to extract the proton beam efficiently. In the conventional scheme, the SX implements a destabilization of the proton beam through the excitation of betatron resonance, which is driven by sextupoles. In proximity to the 3rd integer resonance, the phase space splits into stable and unstable regions with a triangular shape (separatrix). Particles that are outside of the separatrix deflect thanks to the interaction with the electric field of an Electrostatic Septum (ESS), leading to its extraction [13]. Although the radiation protection plan is designed to provide adequate shielding for the expected 1.5% beam losses at nominal power, deviations in either the magnitude or the location of these losses represent a significant risk to the experiment, forcing the reduction of the beam intensity and consequently loss of statistics.

2. Slow extraction assisted by Bent Crystal channeling

Charged particles traveling in a crystal aligned with crystal atomic planes perceive the continuous interaction with the potential well of the atomic plane (U_0). If the particle incidence angle is within the Lindhard angle $\theta_L = \sqrt{(2U_0)/(pv)}$, a charged particle with momentum p and velocity v can enter the channeling regime, with its transverse motion bound in the planar potential well [21]. Positively charged particles are repelled by nuclei and oscillate between adjacent planes, whereas negatively charged particles are attracted toward the planes and oscillate closer to the atomic rows. As a result, the inelastic nuclear scattering is strongly suppressed for positive particles and comparatively enhanced for negative particles [22]. If a crystal is also bent, the channeled particles are forced to follow the curvature of the lattice plane, which acts as a sort of waveguide, steering them at an angle depending on its geometry with an equivalent steering power of hundreds of Tesla magnetic dipole [14]. Different applications of bent crystals in accelerators comprise:

- **Beam collimation:** precise interception of beam halo and separation from beam transport [23–26].
- **Beam extraction:** controlled deflection of a well-defined beam fraction to a target location in the machine or to an external line[27, 28].
- **Beam focusing:** reduction of the beam spot size at a designated location using graded-curvature or crystal-lens configurations[29, 30].
- **Radiation sources:** for channeled electrons and positrons ($e^{\pm}$), photon emission is strongly enhanced (channeling radiation)[31, 32].
- **Spin precession:** the large effective fields in bent crystals yield much faster spin precession than in dipole magnets, enabling Electric dipole Moment and Magnetic Dipole Moment studies of short-lived particles[33, 34].

Thanks to the radiation hardness proven by crystals [35], in the Mu2e experiment, a promising approach is to install an optimized silicon bent crystal upstream of the ESS and aligned with the (110) crystallographic plane such that protons are channeled and steered away from the ESS, reducing the scattering with the ESS, and consequently the beam loss. This method, known as Septum shadowing (or Beam shadowing), was already proposed and validated at CERN SPS beamline with 400 GeV protons [17, 36–38]. A scheme of the conventional SX, and SX assisted by a bent crystal, is shown in Figure 2. To define the bent crystal parameters and compute the reduced energy loss, a set of Monte Carlo simulations was performed: the beam sample at the extraction-channel entrance has been defined by performing a full-spill ring tracking using PyORBIT/PTC [20], a specific Geant4 model which describes coherent interactions in oriented crystals [18] was used to determine the beam position distribution after its interaction with the bent crystal, finally, further tracking through the DR extraction channel has been simulated using the MARS15 codes

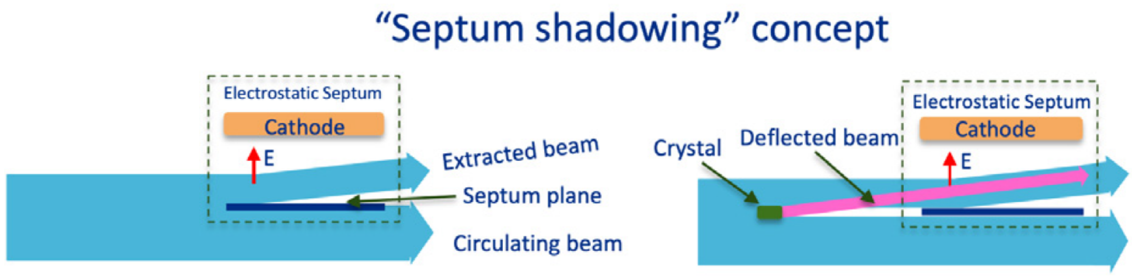

Figure 2: Left: Conventional slow extraction using an electrostatic septum. Right: Scheme of slow extraction assisted by a bent crystal placed upstream of the electrostatic septum, which serves as septum shadowing. Adapted from [13].

Parameter	Estimate
Deflection Angle	300-600 μrad
Thickness along the beam	2-3 mm
Width across the beam	300μm
Torsion	<10 μrad/mm
Distance Crystal-Holder	> 20mm
Holder Material	Stainless steel

Table 1: Range of bent crystal parameters for efficient septum shadowing for the Mu2e experiment.

[19]. The preliminary simulations, implementing a crystal with 600 μm of bending radius and 2mm thickness along the beam, showed an estimate of beam loss reduction of a factor 3 for a proton beam with 40 μrad angular divergence, and a reduction of 41% for a proton beam with 80 μrad angular divergence[13]. Thanks to the full simulations, the crystal parameters were determined and summarized in Table 1.

3. Bent crystal characterization and beam test

In 2025, the production of three crystal samples was carried out at the University of Ferrara following the procedure described in [14–16]. The principal challenges in fabricating a bent crystal are achieving the highest possible channeling efficiency and keeping a uniform curvature, minimizing the torsion. Both parameter optimizations ensure a high probability that a high percentage of protons enter the channeling regime and avoid dechanneling along the crystal path. To this end, several precautions are required. First, the primary crystalline wafer must be verified: although silicon wafers attain high purity thanks to high industrial demand, additional inspection is necessary to ensure crystal quality. We characterized the primary wafer by X-ray tomography at the BM05 beamline at the ESRF facility, enabling the detection of dislocations and other defects. Second, the wafer cutting was performed at the University of Ferrara using micro-diamond–bonded dicing blades. After micrometric-precision cutting, the entrance face was lapped and polished to provide pristine material to the beam. The cut crystal was then housed in a custom holder manufactured by electrical discharge machining (EDM) at the INFN Ferrara mechanical workshop, where the sample was mounted and mechanically forced into an arched configuration. The bending used for

Figure 3: Photograph of one bent crystal from the sample mounted in its custom holder. The proton-beam direction is indicated by the red arrow.

particle deflection exploits the secondary anticlastic curvature that naturally arises in high aspect ratio plates. This choice offers several advantages: (i) narrow crystal width, (ii) the holder can be located at the edges, away from the beam path, and (iii) it enables substantial and more uniform bending. A picture of one of the three crystals from the sample, mounted in its holder, together with the proton-beam direction, is shown in Figure 3.

Finally, characterization of curvature is of utmost importance for control of the channeled particle deflection. A first quality check employs a two-dimensional measure of surface profile that can be achieved with nanometric precision with an interferometric profilometer. From the profilometric analysis of all crystals in the first batch, we expect a curvature in the 300–600 μrad range and a torsion of $\sim 5\mu\text{rad/mm}$ well within the parameters range given in Table 1. For the final characterization of the crystal on beam, we conducted a beam test on the H8 line at CERN's SPS, using 180 GeV protons, which was successful and confirmed the expected performance. The detailed setup, procedures, and results will be published separately.

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