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

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On behalf of the Mu2e collaboration

Talk Outline

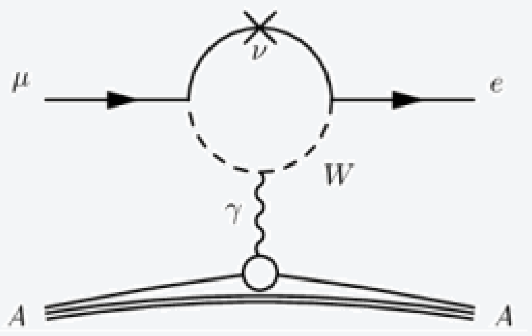
- The Mu2e Experiment
- Channelling in bent crystals
- Bent crystal parameters
- Crystal production and characterization

The Mu2e Experiment

- Charged Lepton Flavour Violation (CLFV) has never been observed and in the muon sector the Standard Model (SM) Branching Ratio (BR) is predicted to be:

$$BR(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu i} - m^2_{\nu 1}}{M^2_W} \right|^2 < 10^{-54}$$

- CLFV@Mu2e: Neutrino-less conversion of a muon to an electron in the field of an Al nucleus **observed as single monoenergetic 105MeV electron (C.E.)**



The measured quantity is:

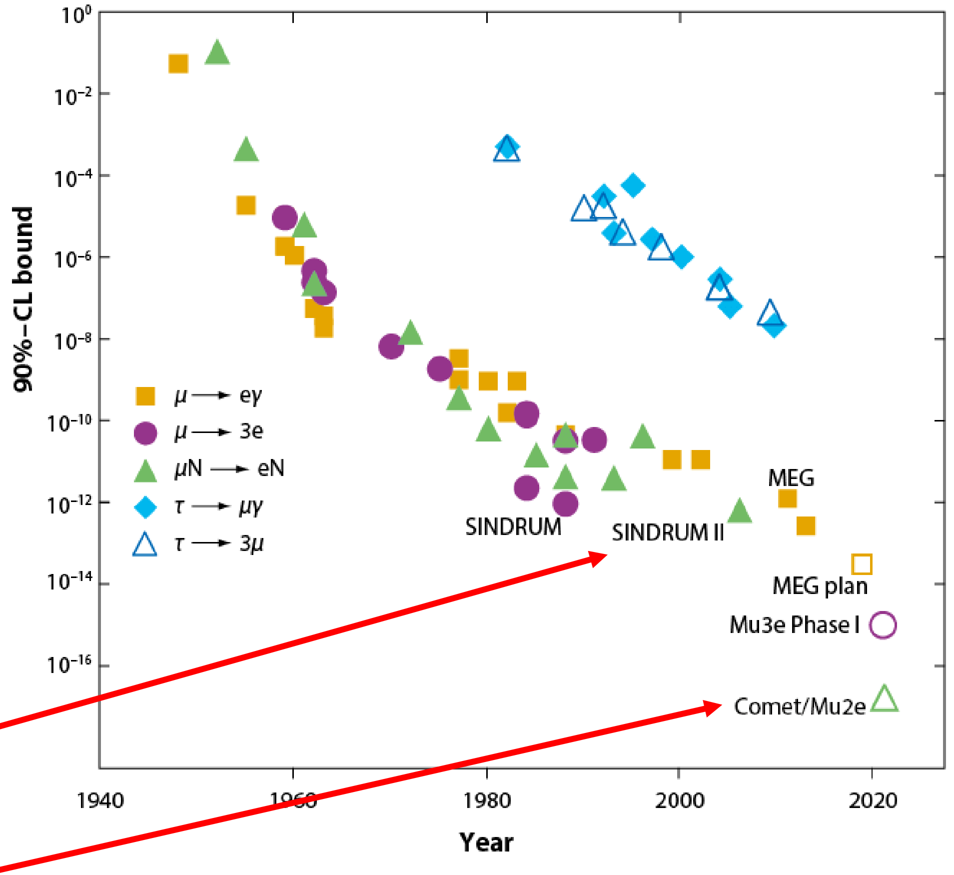
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow All\ captures)}$$

Better upper limit is from Syndrum II @ PSI

$R_{\mu e} \sim 7 \times 10^{-13}$ @ 90% CL

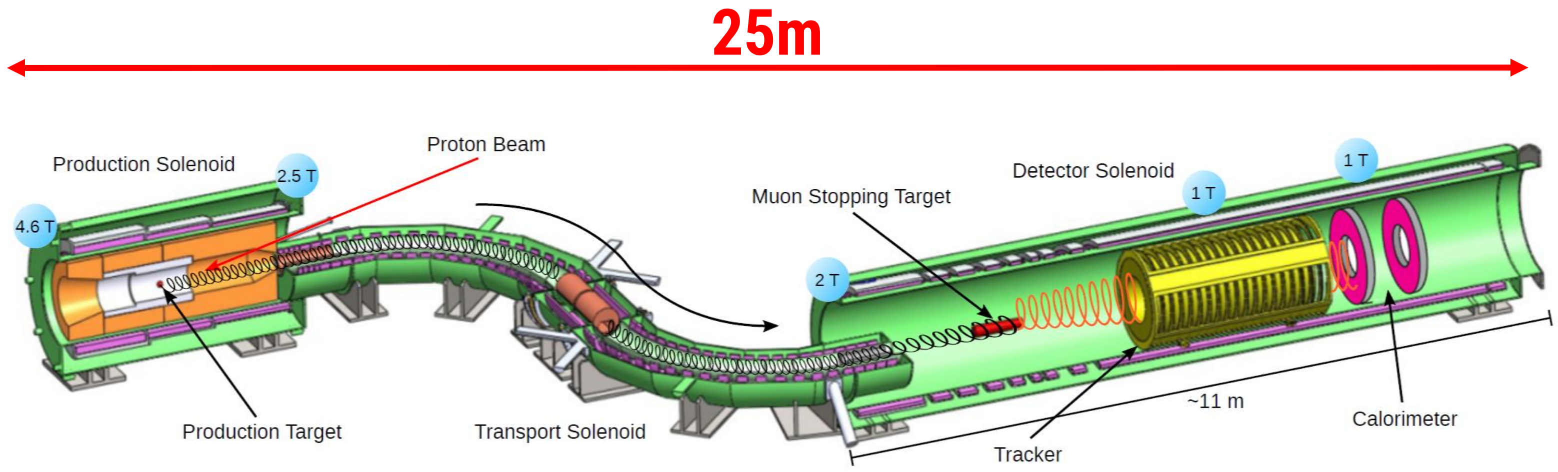
Mu2e aim to improve this upper limit by 10^4

$R_{\mu e} < 8 \times 10^{-17}$ @ 90% CL



The Mu2e Experiment

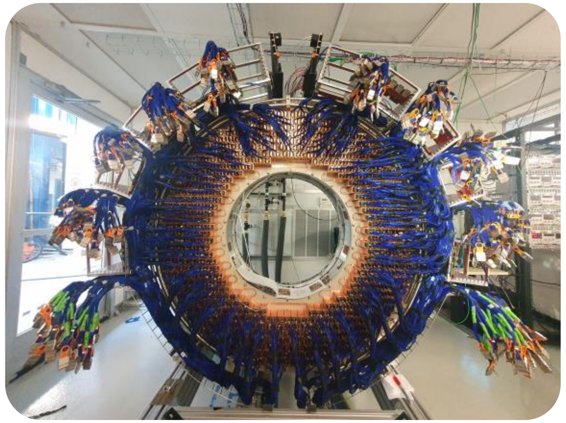
To achieve its goal Mu2e requires:
- **High precision detectors**
- **High Statistics**
- High Background rejections



Cosmic ray veto (CRV)
Covers entire DS and half TS
Efficiency ≥ 99.99%

Tracker
18 stations of ~20,000 low mass straw drift tubes filled with 80:20 Ar-CO2
Core momentum resolution 159 KeV/c

Calorimeter
2 Disks of 1348 CsI crystals coupled to 2 custom UV-extended SiPM with
$\frac{\sigma_E}{E[100MeV]} = \mathcal{O}(10\%)$ and $\sigma_t < 0.5$ ns

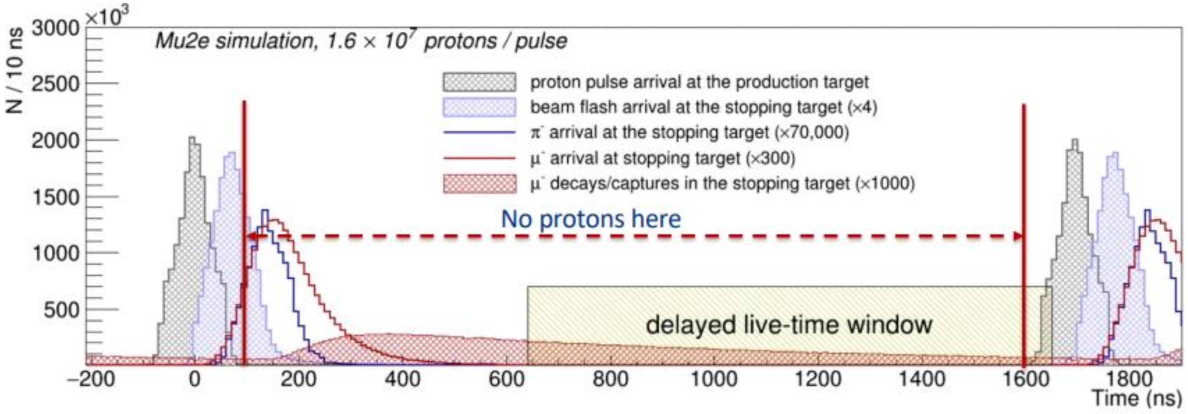


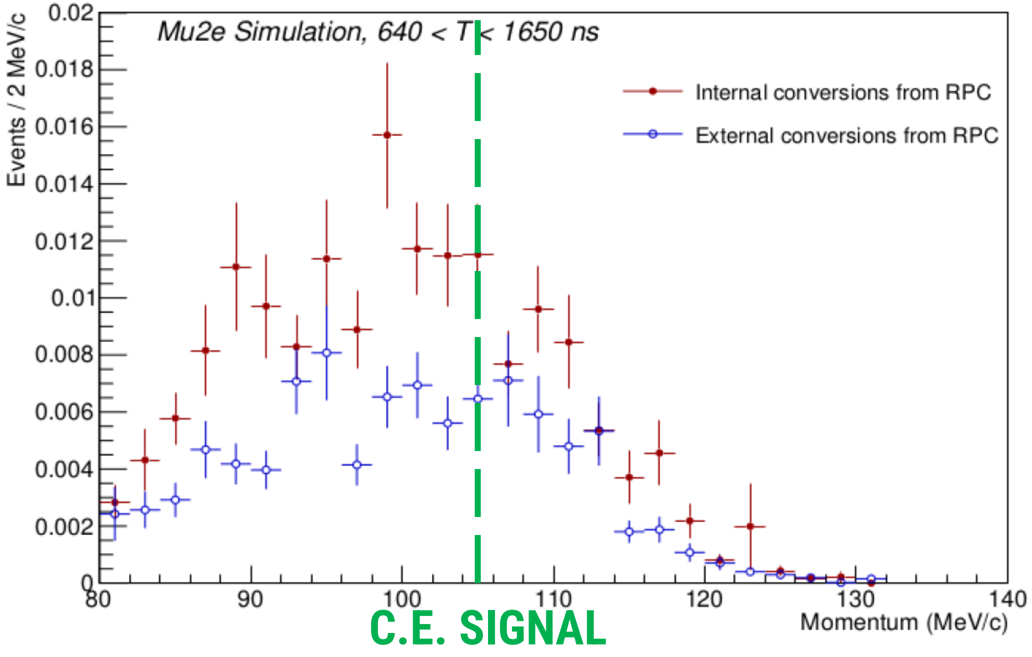
The Mu2e Experiment

To achieve its goal Mu2e requires:
- High precision detectors
- High Statistics
- **High Background rejections**

Background rejection is crucial for the Mu2e analysis. Several type of background:
- Muon Decay in orbit -> High precision tracking
- Cosmic rays -> CRV and Particle Identification
- Antiproton induced background -> Absorbers in the muon beamline
- Radiative Muon capture -> Stopping target monitor
- Radiative Pion capture (RPC) -> Pulsed proton beam

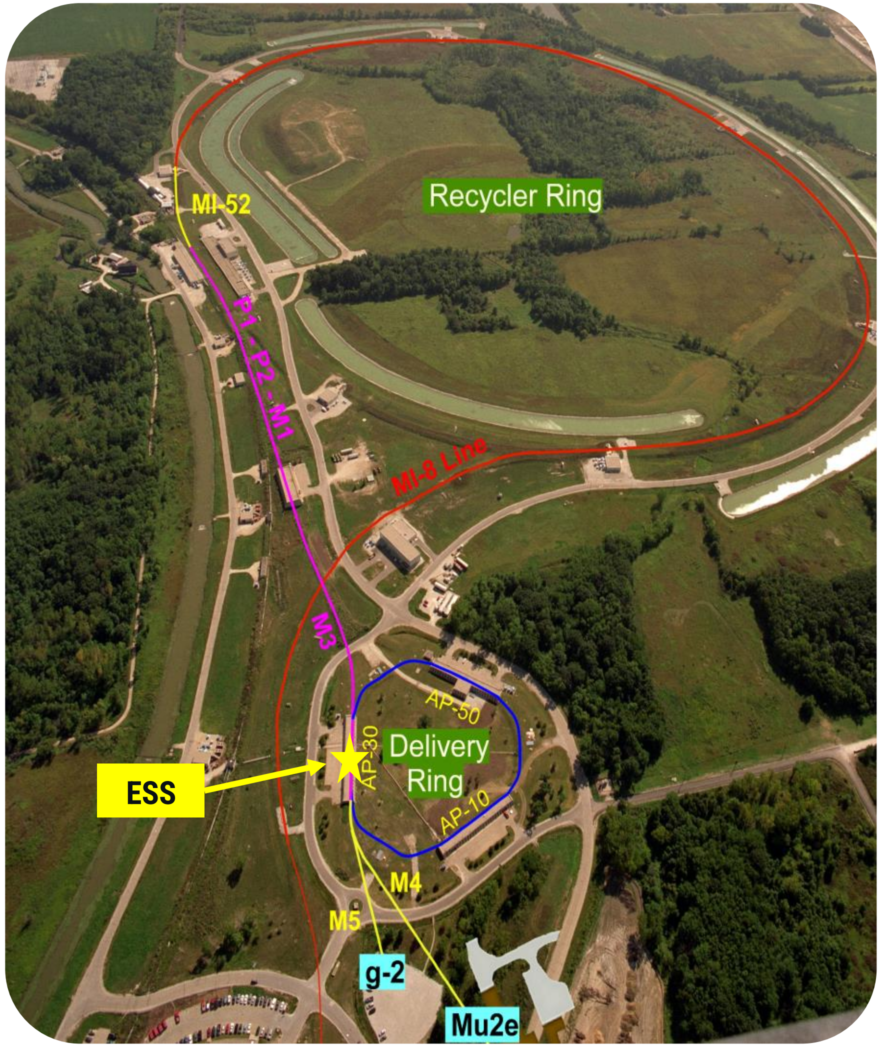
Mu2e Collaboration, Universe 2023, 9(1), 54.





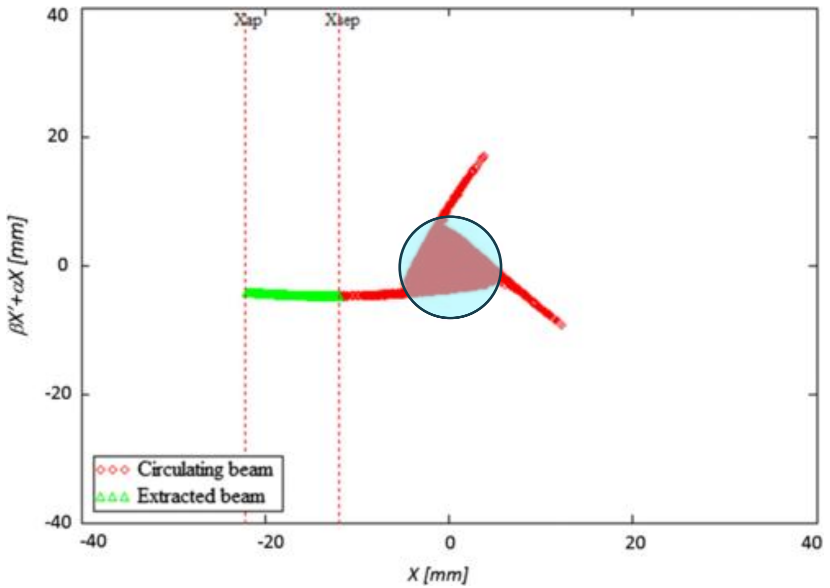
Mu2e beamline

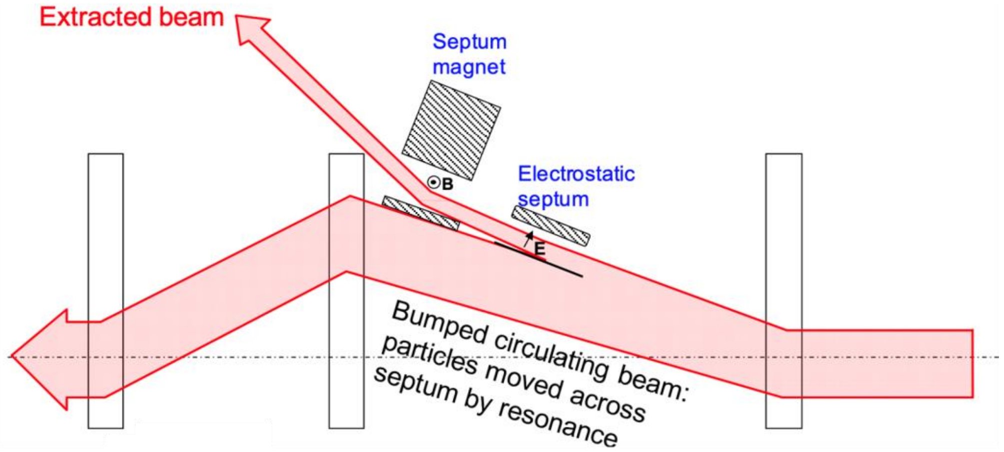
- An 8 GeV pulsed proton beam from the Fermilab Booster is re-bunched in the Recycler Ring
- sent to the Delivery Ring and extracted via resonant (slow) extraction.
- 250 ns-wide pulses every 1695 ns ($\sim 2\tau_{\mu}^{Al}$)
  3.9×10^{7} protons (2 batch), 1.6×10^{7} (1 batch)
- The proton beam interacts with the $\sim 1.6X_0$ tungsten target for muon production
- Directed by the Production Solenoid into the S-shaped Transport Solenoid and then to the Detector Solenoid.
- Mu2e requires $\sim$ **3.6×10^{20} protons-on-target** to meet its goal



Resonant Extraction

- In the conventional SX, destabilization of the beam is employed through the excitation of betatron resonance driven by sextupoles.
- In proximity to the 3rd integer resonance, the phase space splits into stable and unstable regions **triangular shape**.
- Particles outside of the separatrix drift away to the Electrostatic Septum leading to its extraction.
- **Expected beam losses of 1.5%** at the nominal beam power.
- **Any variations in losses or their locations pose a risk to the experiment forcing to reduce the beam intensity.**



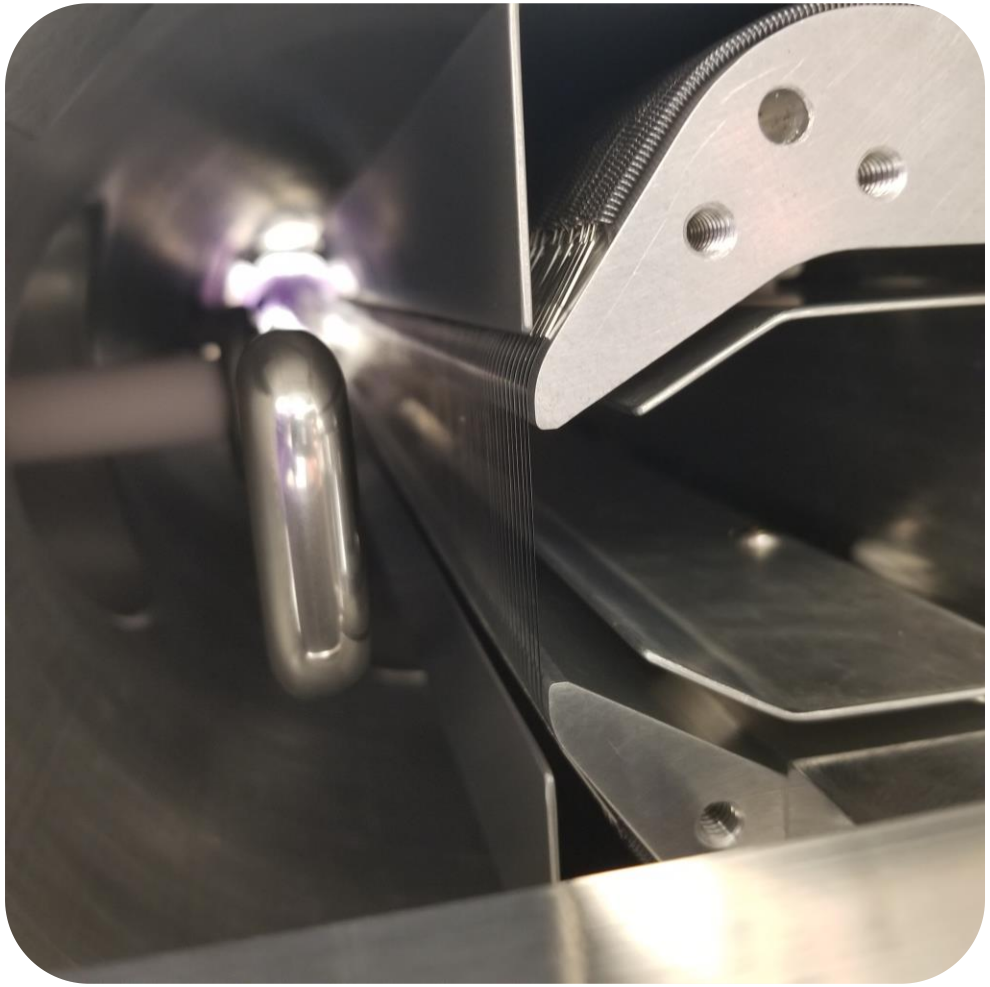


Resonant Extraction

ELECTROSTATIC SEPTUM PARAMETERS

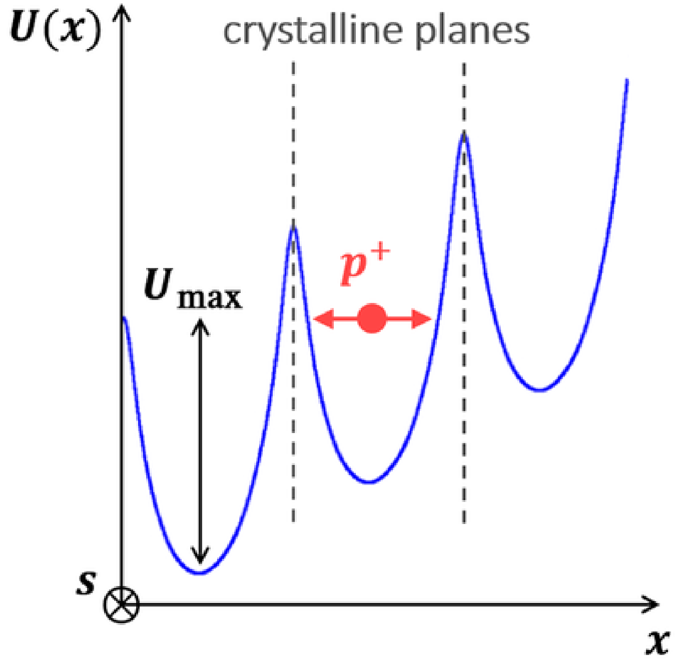
- W/Re FOILS 1mm/25μm
- Effective thickness 50μm
- Beam losses occur due to beam passing through the thin septum plane

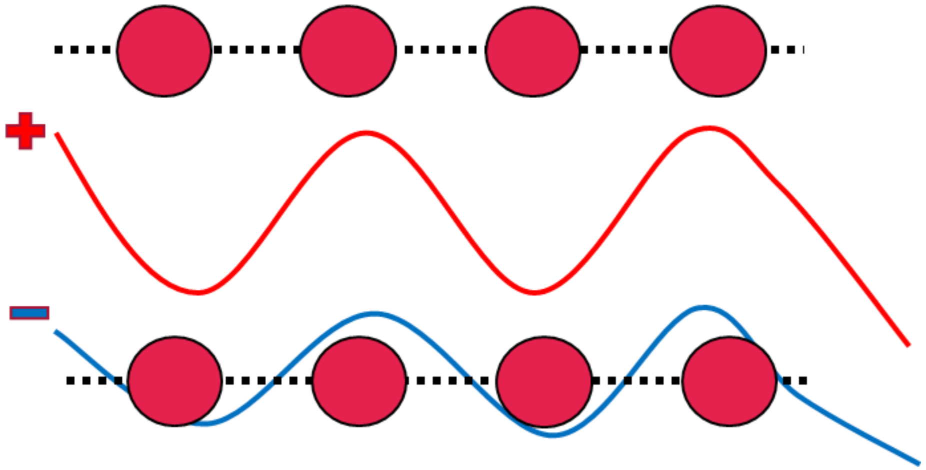
How to steer particles away from it?



Channeling phenomenon

- Particles aligned with atomic planes perceive a continuous potential with wells and barriers
- Particles within a critic angle $\sqrt{(2U_0)/(pv)}$ can be bound to potential:
  - ⊕ Between adjacent planes if positively charged
  - ⊖ Into plane if negatively charged
- Scattering is strongly different in two cases:
  - ⊕ **Reduction of inelastic collision with nuclei**
  - ⊖ Increased inelastic collision with nuclei



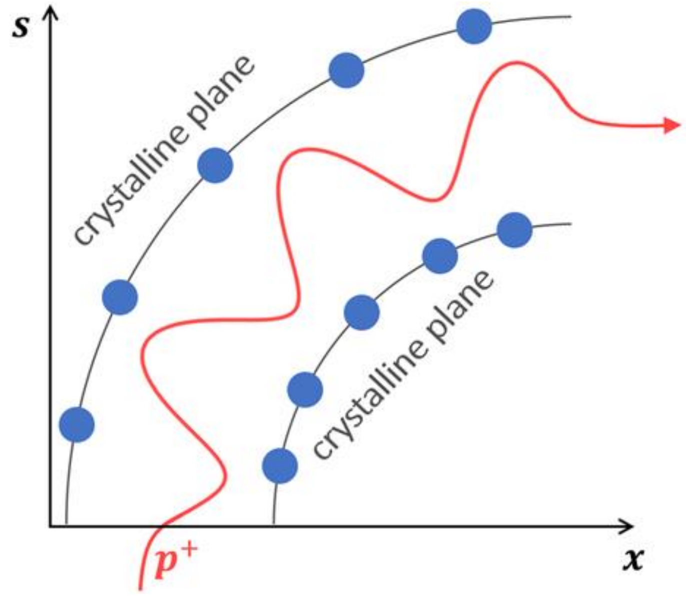


Channeling in bent crystals

- If we bent a crystal, channeled particles are forced to follow the curvature of the lattice plane

- A bent crystal can act as a sort of waveguide for channeled particle, steering them at angle depending on its geometry

- **Large steering power can be obtained in few millimeters of crystal**, equivalent to that of hundreds of Tesla magnetic dipole



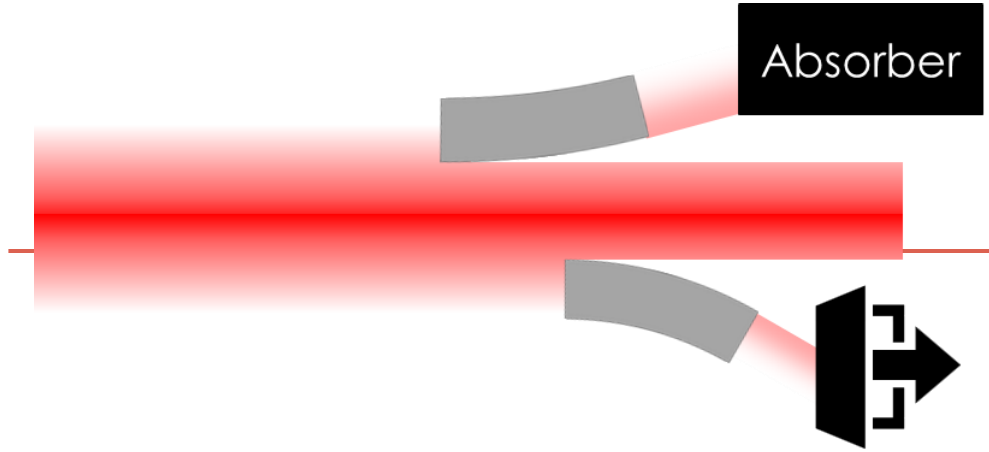
Energy (GeV)	Deflection (μrad)	Size (mm)	Equivalent dipole (T)	
6500	50	4	271	LHC
8	300-600	3	2.65-5.30	
8	300-600	2	4-8	Mu2e
2000	14000	70	1333	

Bent crystal application

Beam Collimation:

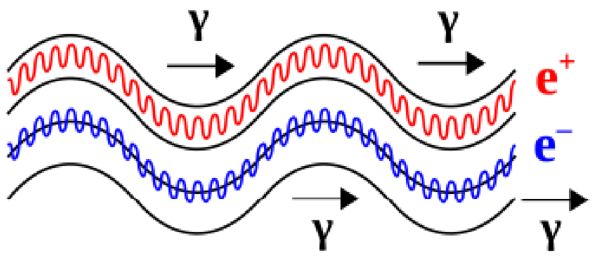
With crystal high control of beam halo separation from primary beam

Now baseline for HL-LHC ion collimation



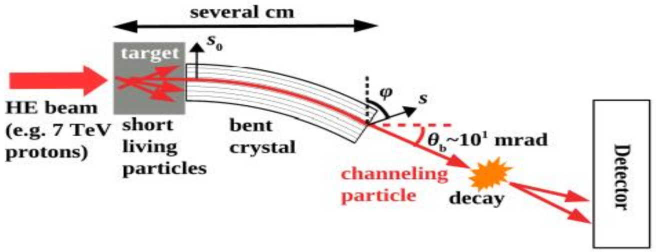
Novel radiation sources:

For channeled light particles (e+/e-) enhanced photon emission



Beam Extraction:

Surgical redirection of a beam portion, towards a precise location in the machine or in an external facility

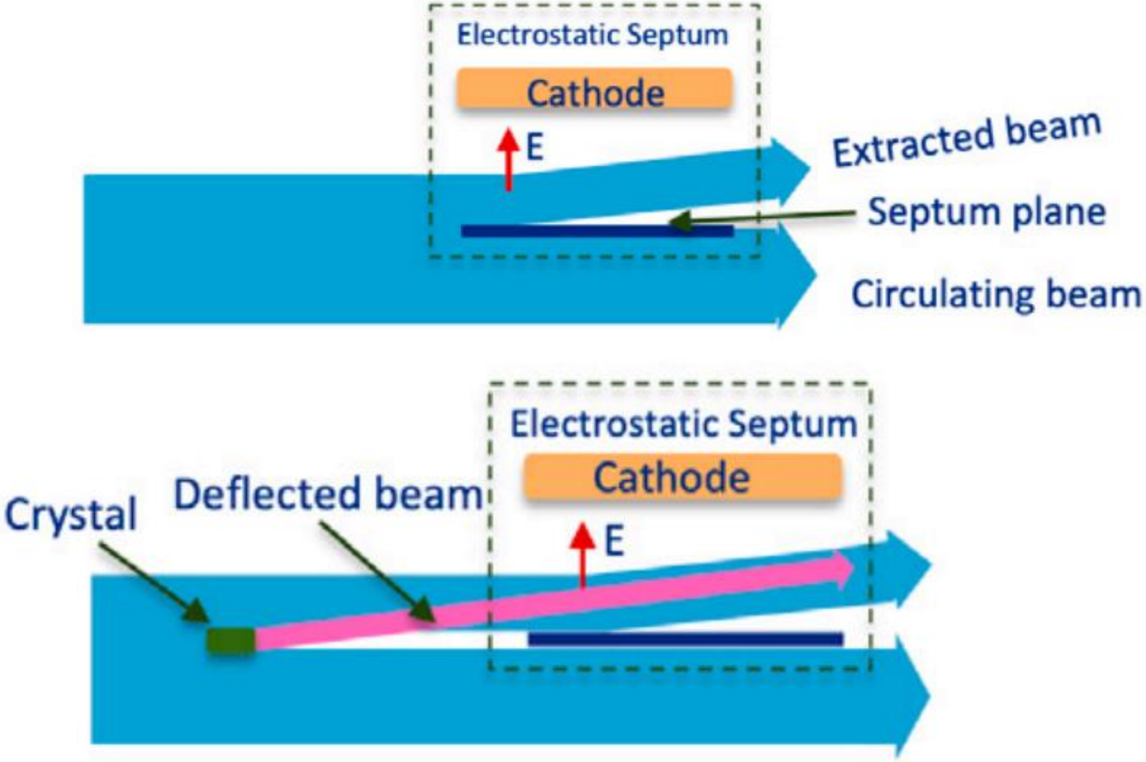


Spin precession:

Spin precession much faster in bent crystal wrt existing dipole magnets→EDM & MDM study of fast decaying particles (e.g. TWOCRYST experiment)

Bent Crystal for the Mu2e Experiment

- Idea: implement an optimized bent crystal upstream of the electrostatic septum (Silicon crystal oriented (110))
- Tested at SPS for 400 GeV proton
- Feasible also for 8 GeV proton of Mu2e beam

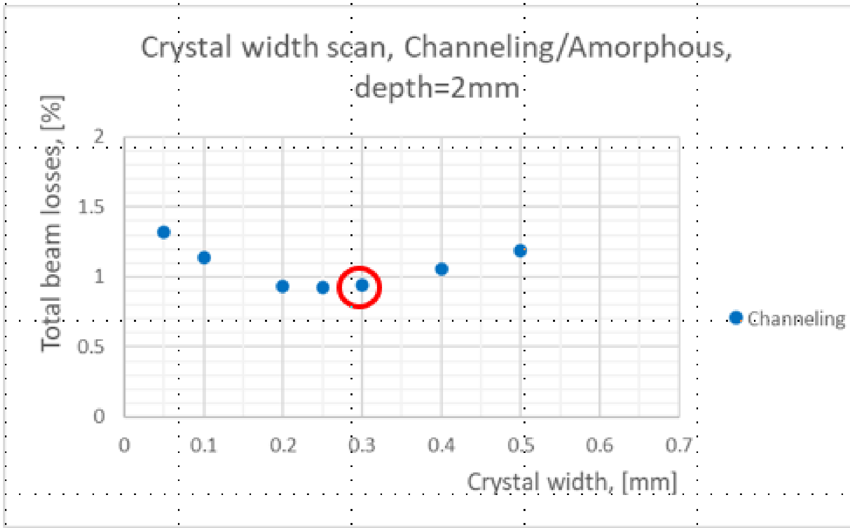


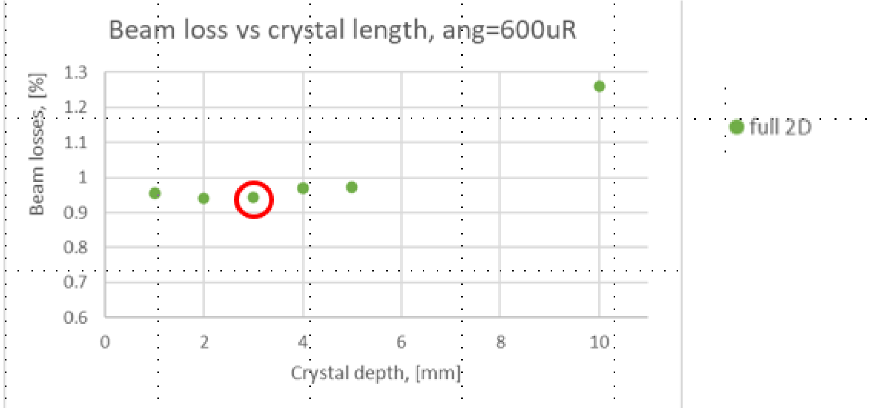
V. Nagaslaev, et al., Nucl. Instr. Meth. A, 1058 (2024) 168892.

F.M. Velotti, et al., Phys. Rev. Accel. Beams 22 (2019) 093502.

Optimizing Bent Crystal

- Preliminary *MARS15* simulations to check the shadowing functionality with the Mu2e beam and to instantiate the crystal parameters
- A preliminary beam loss **reduction of a factor 3** is estimated for a beam with 40μrad angular divergence
- **Reduction of 41%** for 80μrad angular divergence





Plots courtesy of Vladimir Nagaslaev (FNAL)

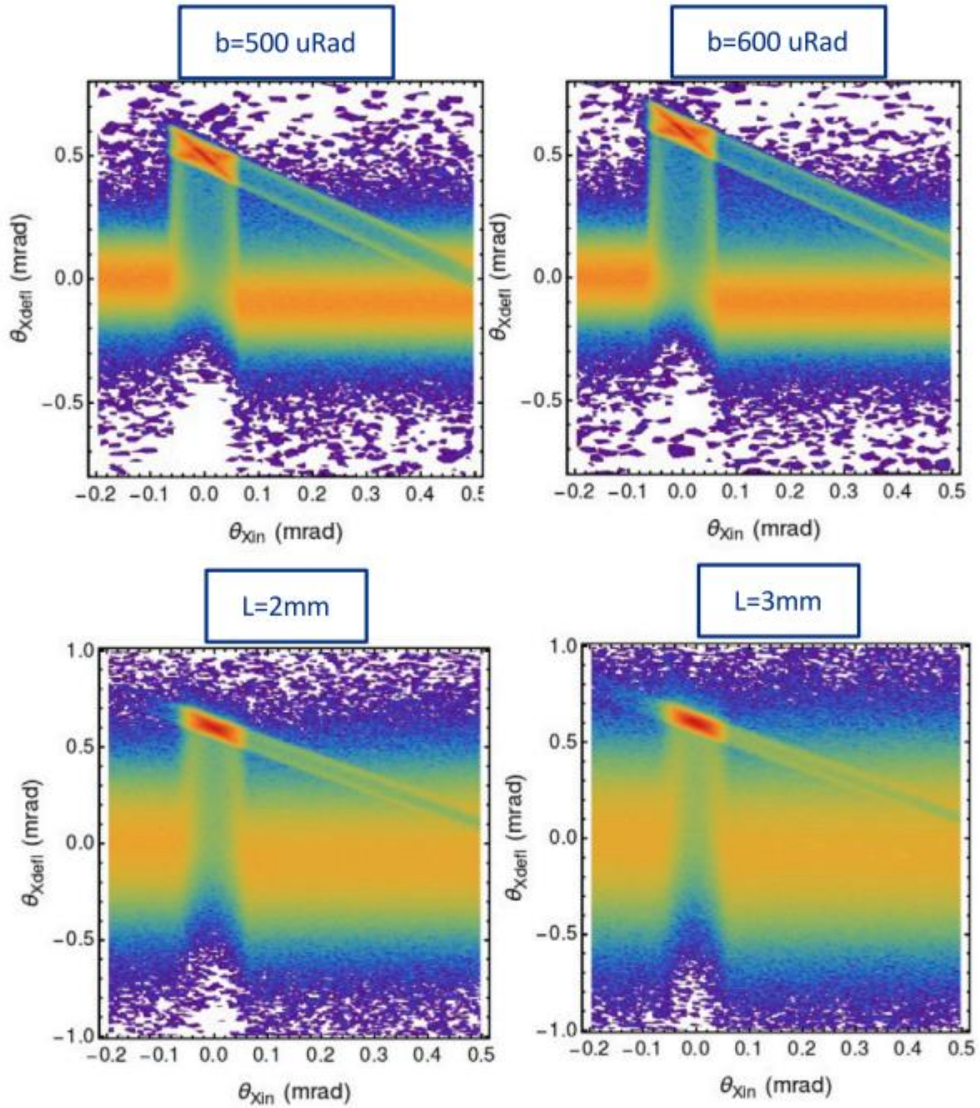
Geant4 Simulations

- Subsequent large set of Geant4 simulations were performed to optimize the beam losses,
- Found a new working point and freeze the crystal characteristics

Parameters for Silicon bent crystals

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

S. Miscetti, et al., Nucl. Instr. Meth. A, 1073 (2025) 170257.

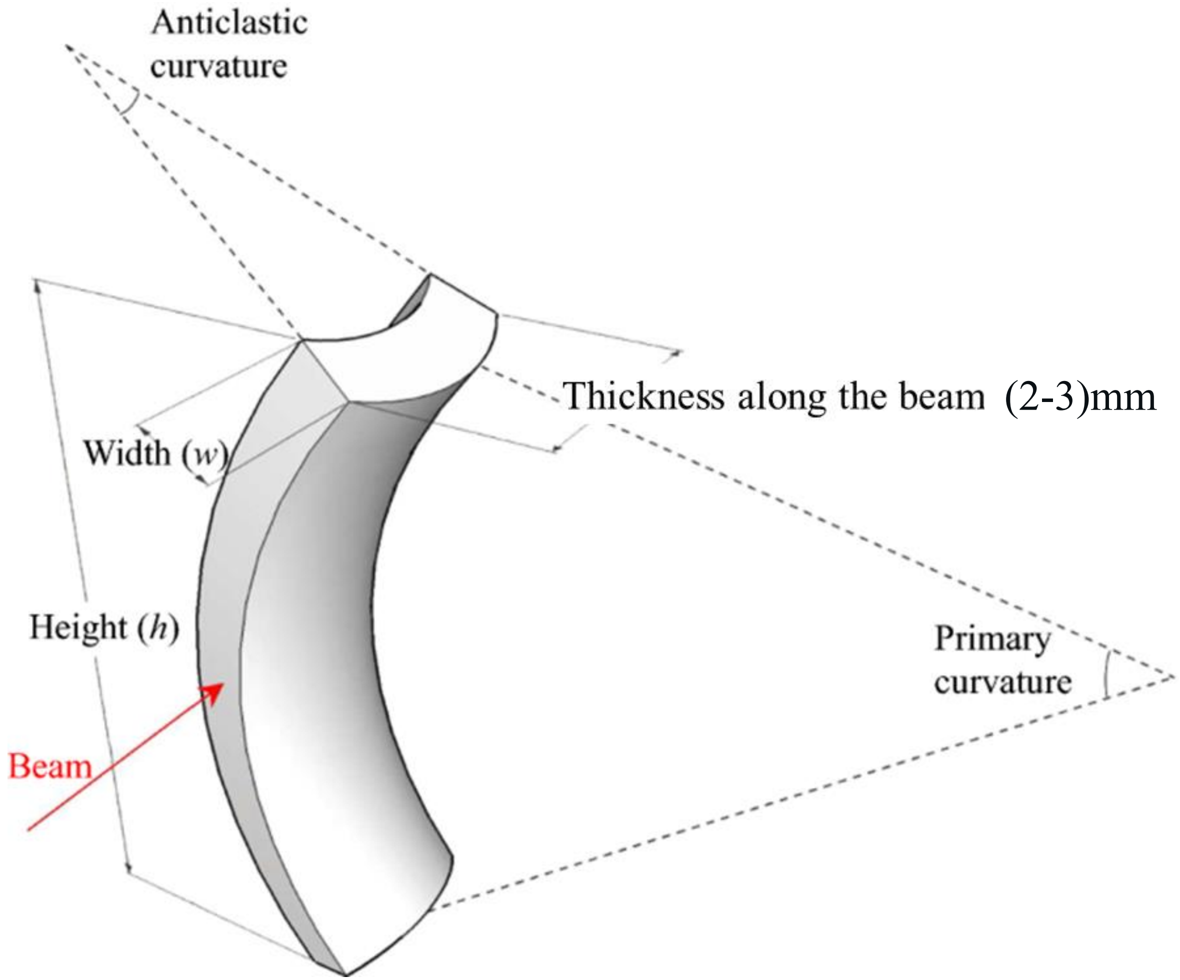


Fixed thick L= 3mm

Fixed bending radius b=600μrad

Creating a bent crystal

- **Secondary anticlastic curvature** naturally appears in any material with a high aspect ratio.
- **Benefits include**:
    - Narrow crystal width
    - Crystal holder positioned at the edges: distant from the beam path
    - Enables significant and uniform bending



Elastic theory calculation

To achieve deflection of (300-600)µrad with crystal thickness L=(2-3)mm, the anticlastic radius of curvature must be:

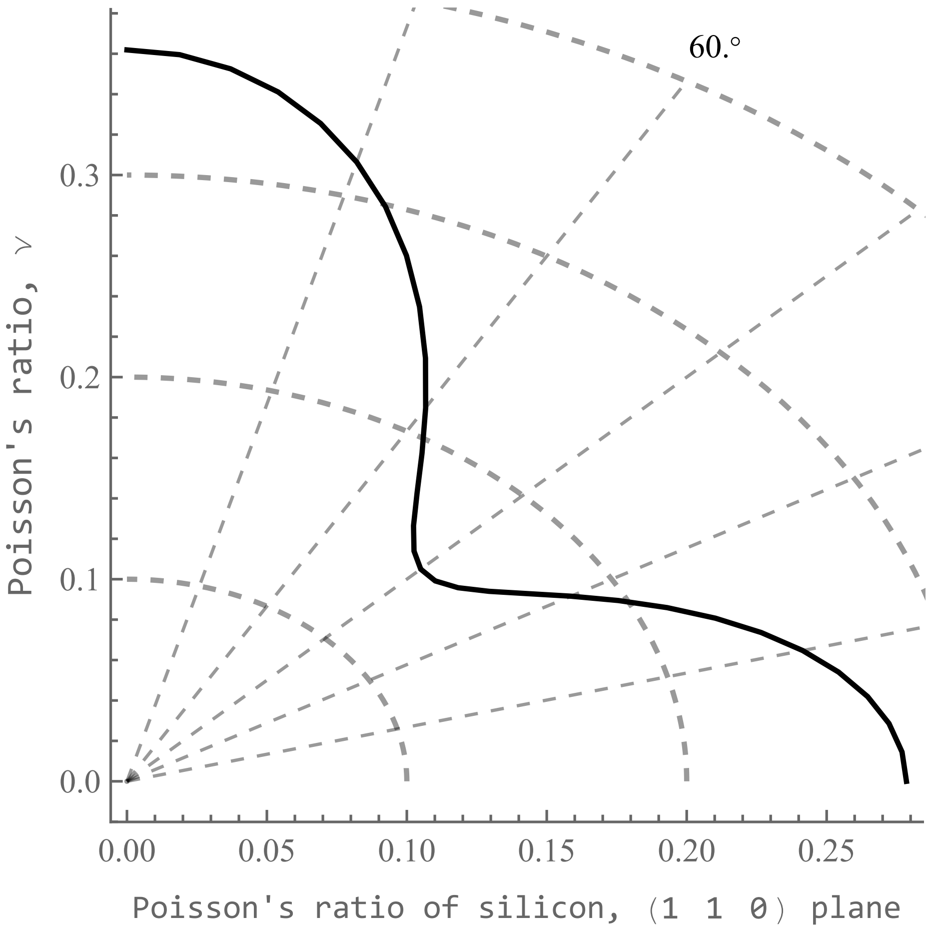
$$R_{Anticlastic} = \frac{Thickness\,[m]}{Deflection\ angle[rad]}$$

Thus, the primary bending radius would be

$$\frac{R_P}{R_A} = 0.2786$$

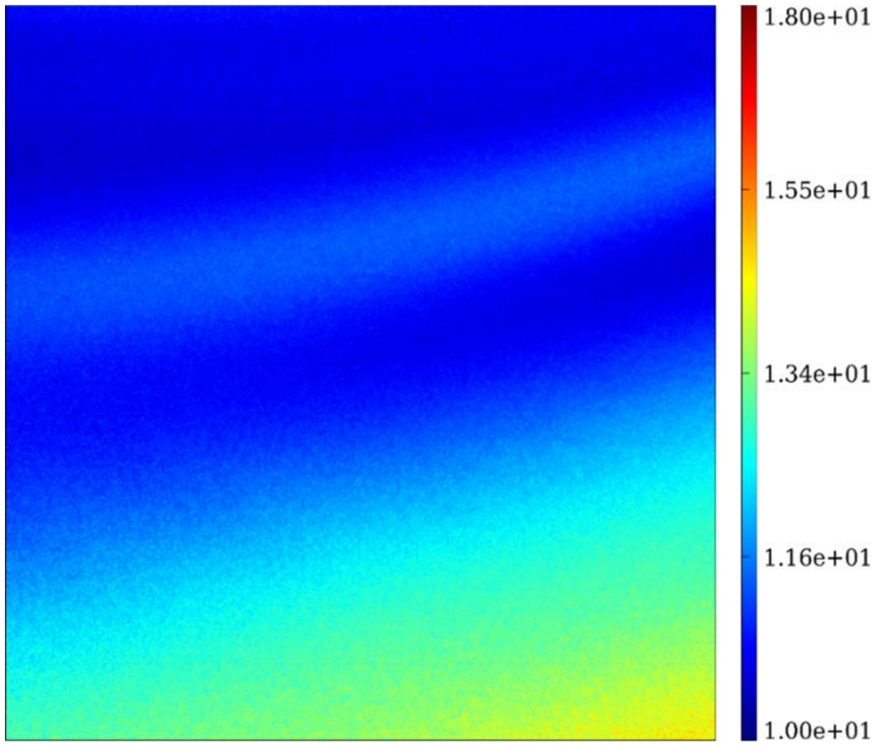
Posson ratio of Silicon (110)

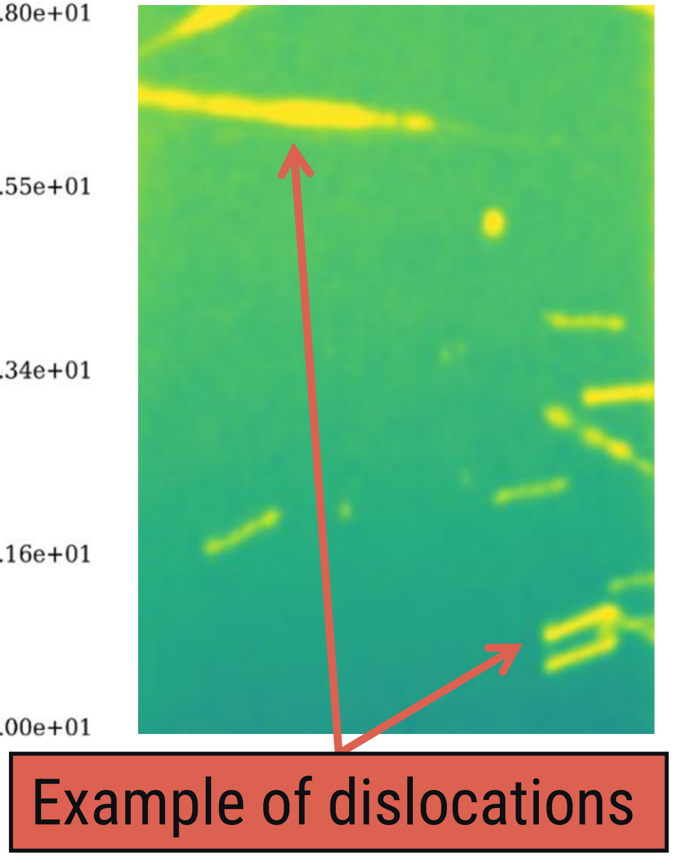
b \ L	2mm	3mm
300 μrad	R_p=1.86m	R_p=2.79m
600 μrad	R_p=0.93m	R_p=1.39m



Crystalline quality control of prime material

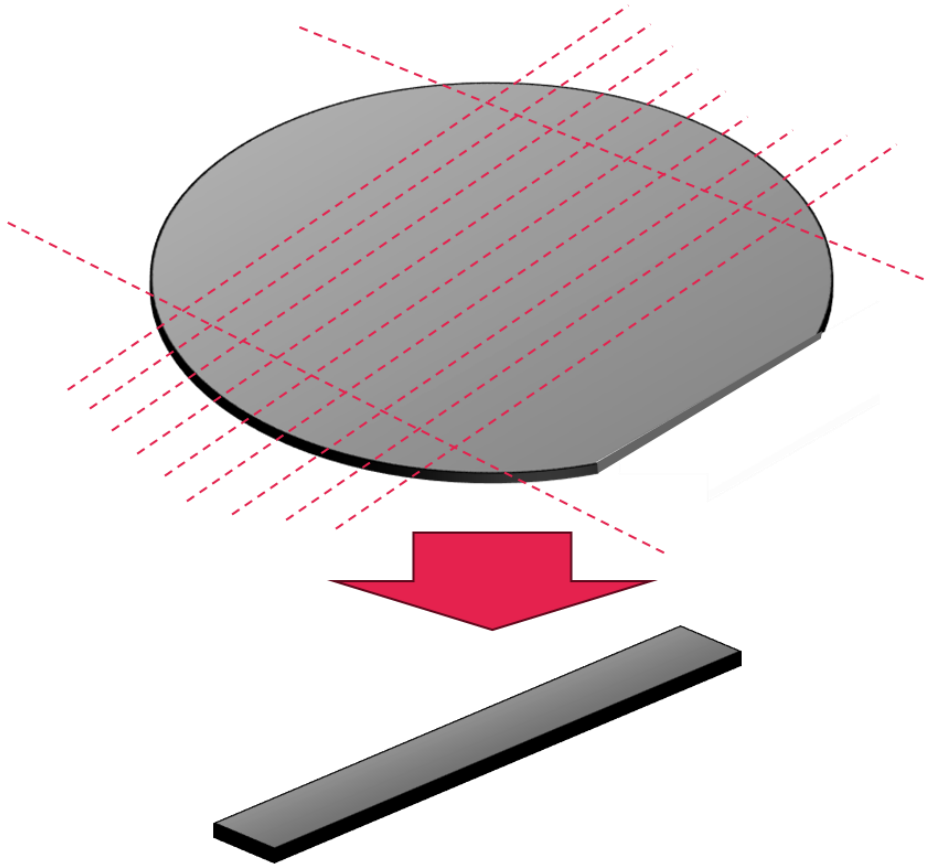
- High channeling efficiency critically depends on the **crystal's lattice quality**.
- X-ray tomography makes it possible to detect defects within the bulk of the crystal.
- In the examined silicon wafer, measured at BM05 at ESRF, **no dislocations were observed**.





Cutting Procedure

- From the wafer, samples with parallelepiped shape are obtained by cutting with **micrometric precision.**
- Process was conducted with dicing blades bonded with micro-diamonds.
- Cut surfaces are lapped and polished to provide pristine material in the beam entrance face.



Holder finalization

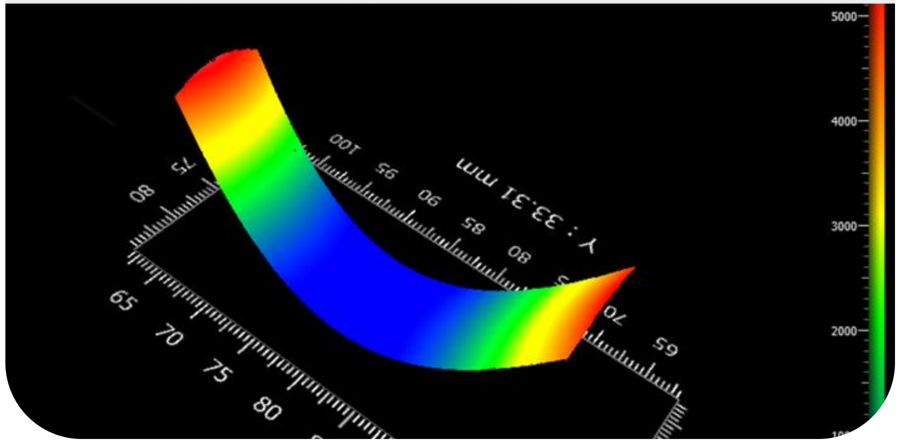
- Holder was designed with inclined support surfaces
- The angle of inclination is obtained with high precision using Electrical Discharge Machining at mechanical workshop of INFN Ferrara
- The crystal sample is mounted and forced into arched position to obtain the anticlastic bending used to deflect particles in channeling

Curvature Characterization

- Characterization of curvature is of utmost importance for control of the channeled particle deflection

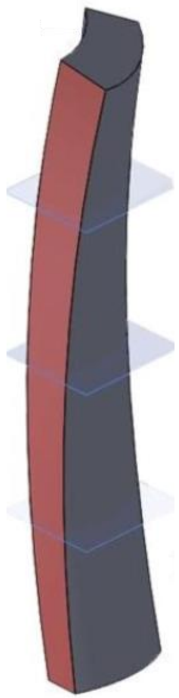
- 2D measure of surface profile can be achieved with **nanometric precision** with interferometric profilometer

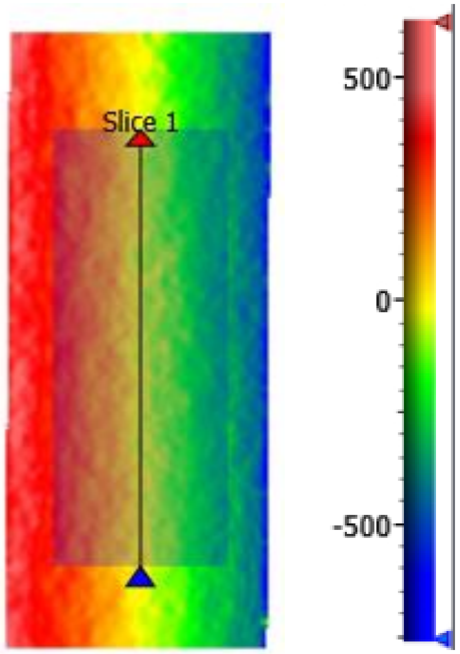
- First two samples 3mm long have been developed respectively with expected deflection angle of 590urad and 400urad

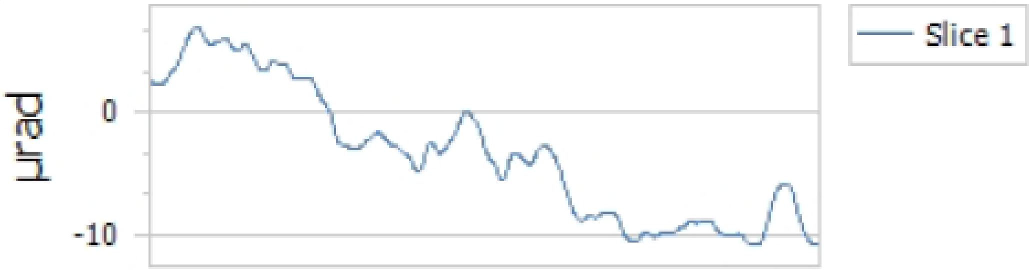


Torsion Characterization

- When flexed, a crystal may be subjected to torsion reducing channeling efficiency
- Fermilab experts requested a crystal with torsion ≤10μrad/mm for a good steering efficiency
- The optical characterization estimates **~5μrad/mm**



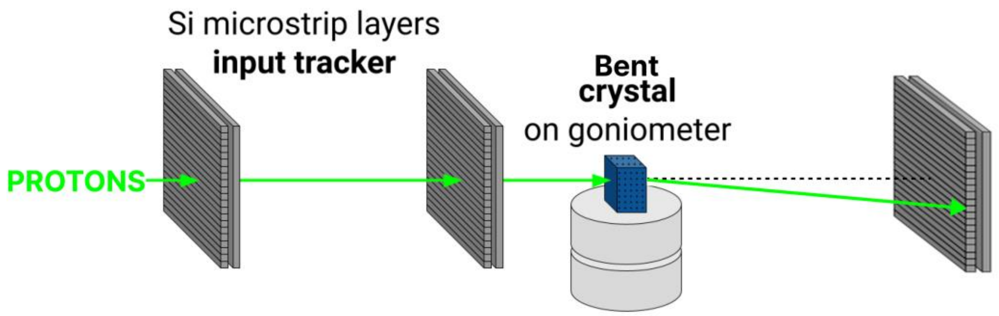




Next Steps

NEW DEVELOPMENTS:

- Finalizing the design of new possible crystals
  - Crystal thick L=2mm and L=3mm
  - Angle of deflection b=300 μrad and b=600μrad
  - Torsion <10μrad/mm
- First beam test **scheduled August 2025 at CERN SPS H8.**



Acknowledgments

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The Mu2e Collaboration
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