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OPTIMIZING MU2E EXPERIMENT: BEAM SHADOWING WITH CHANNELING IN BENT CRYSTALS FOR ENHANCED EXTRACTION EFFICIENCY

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OVERVIEW

- Mu2e extraction
- Channeling in crystal and crystal assisted beam shadowing
- Bent crystal parameters
- Crystal production and characterizations

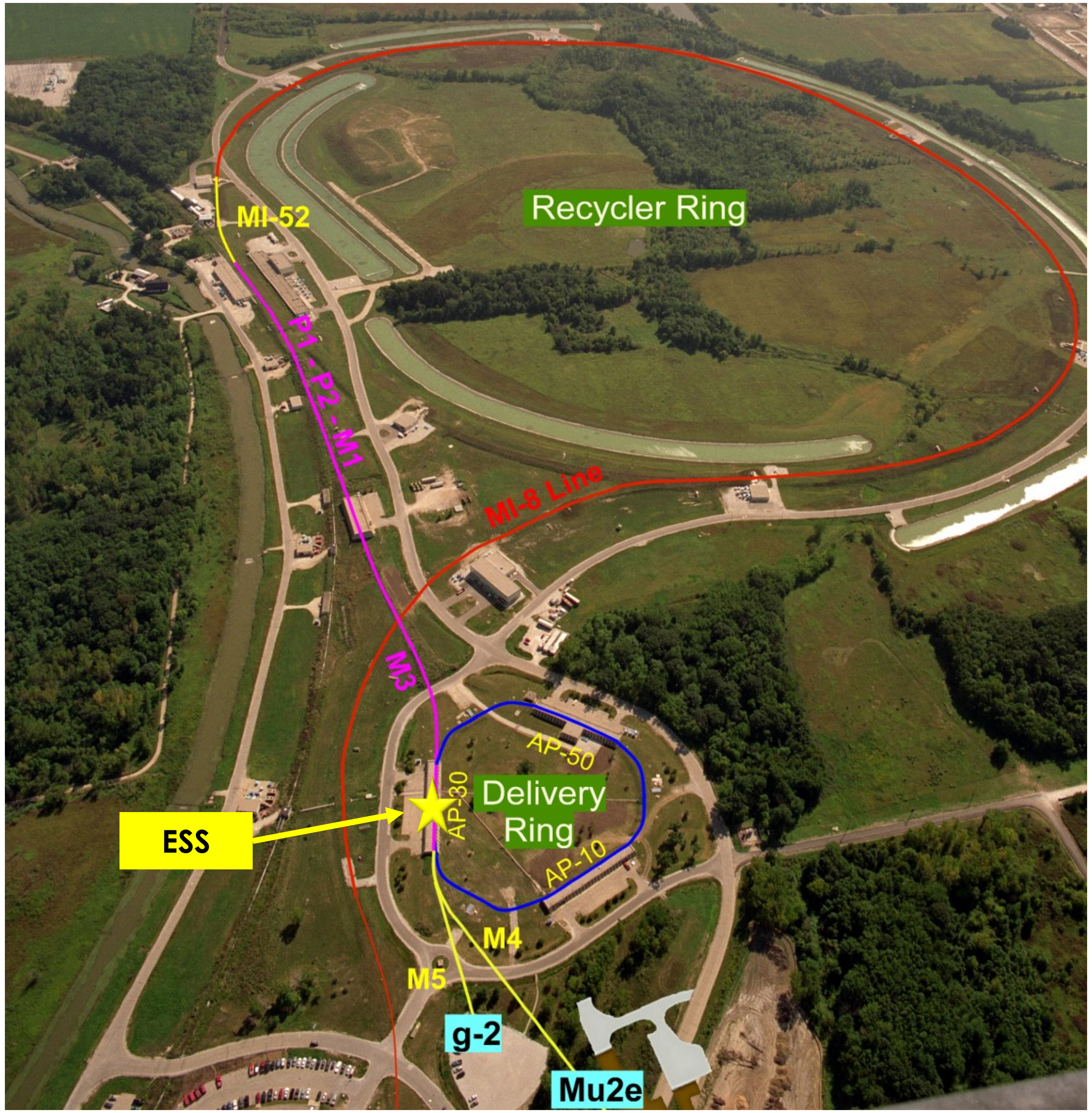
GOAL OF THE ACTIVITY

- Beam losses from interaction of beam with the septum can cause high level of radiation and consequent limitation of beam intensity

- The channeling phenomenon in a bent crystals allows to efficiently deflect positive particles while suppressing inelastic scattering wrt amorphous medium

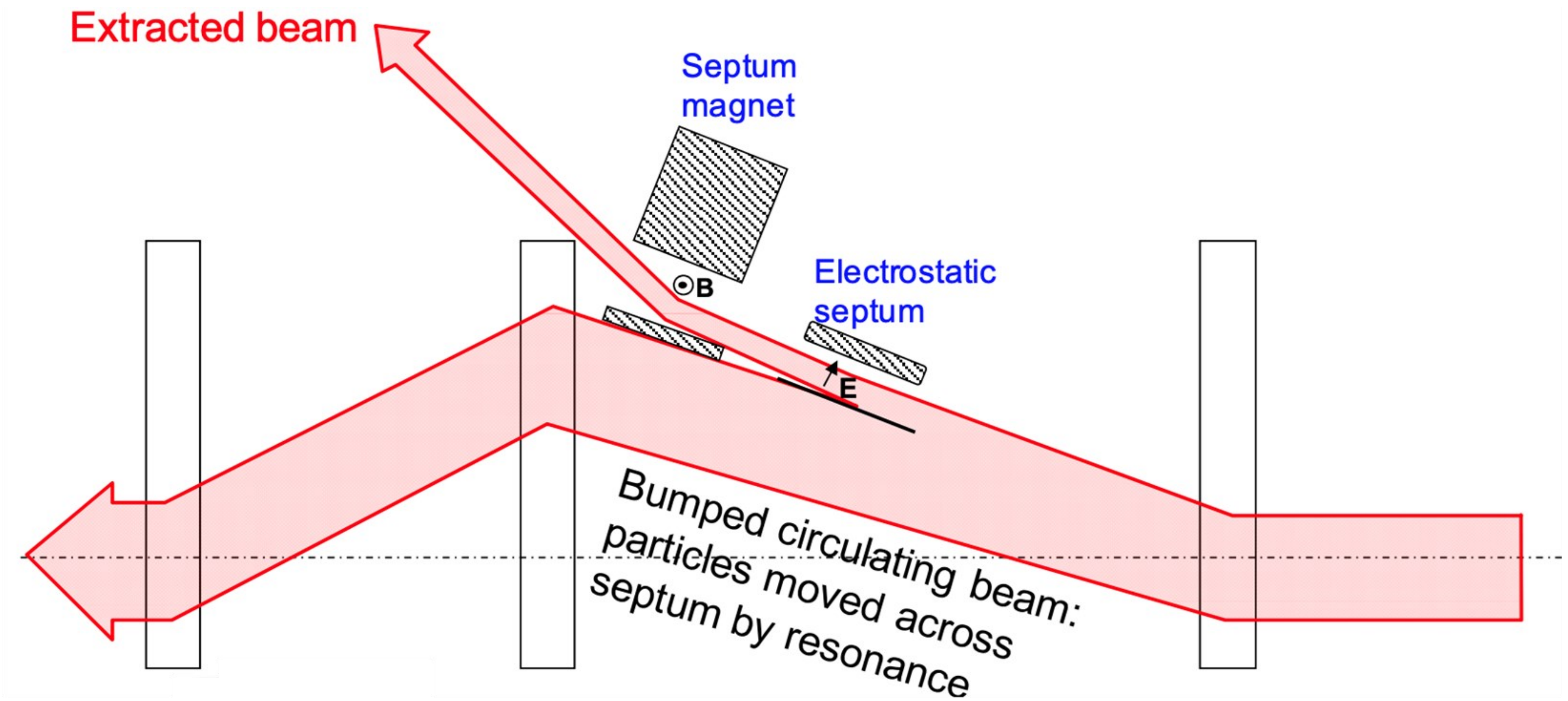
- An upstream bent crystal can thus be exploited to shield the septum by steering a small portion of the beam away from it

AERIAL VIEW TO THE ACCELERATOR BEAM LINES



SEPTUM MAGNET FOR SLOW RESONANT EXTRACTION

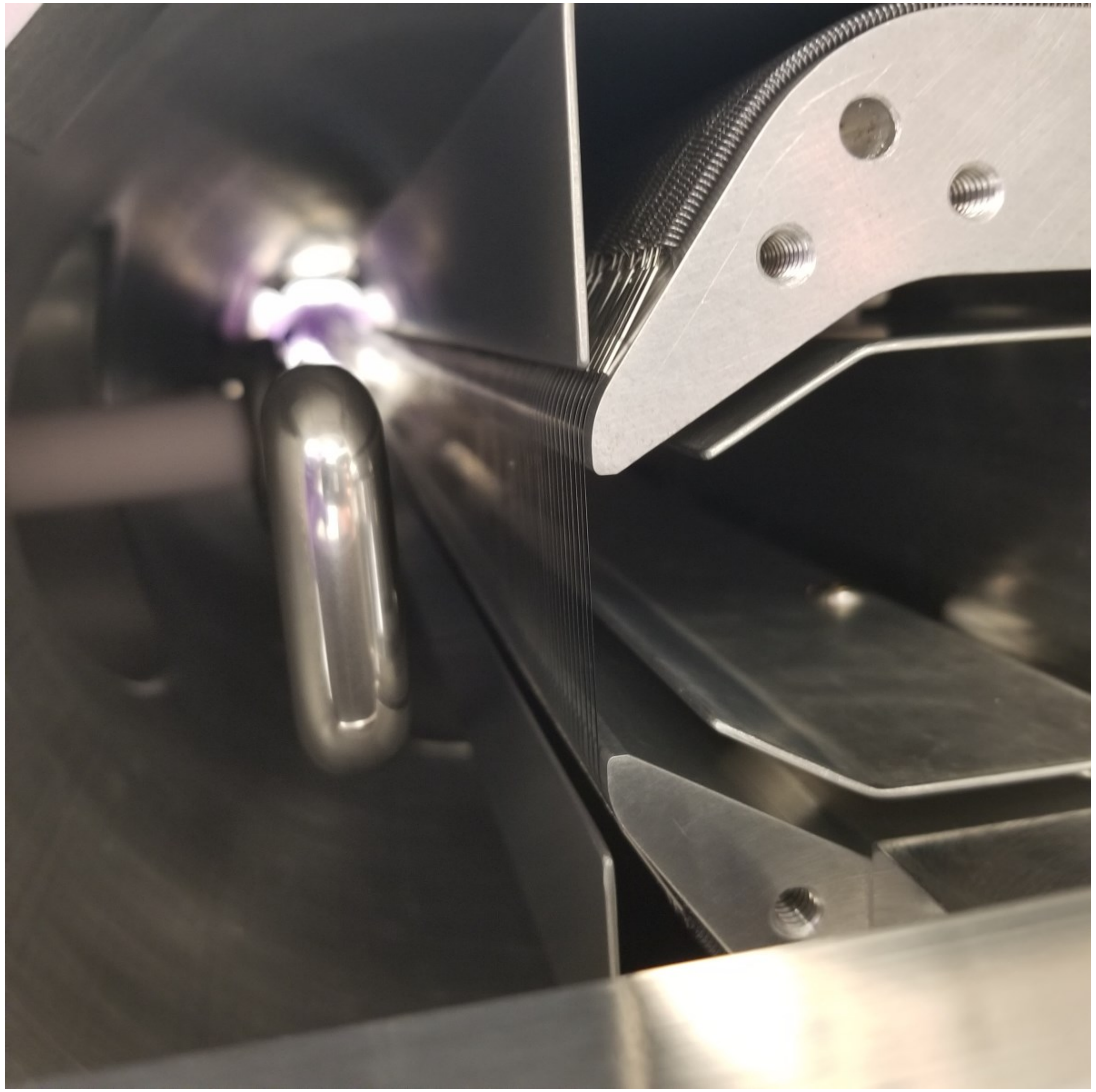
- Resonance is driven by sextupoles
- Largest oscillating particles are captured by the septum magnet yielding extraction
- A fraction of the particle beam interact with the matter in the septum and generates losses



SEPTUM

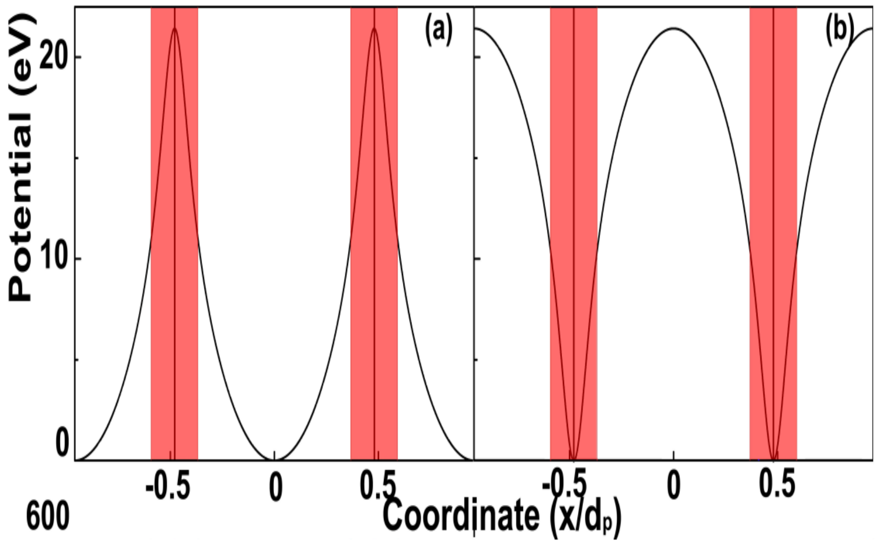
- W/Re foils 1mm/25mm
- Effective thickness 50mm
- Beam losses occur due to beam passing through the thin septum plane.

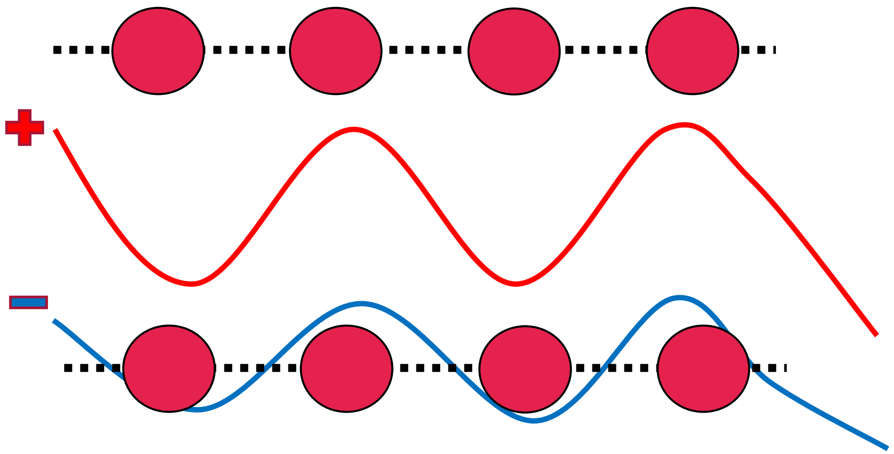
How to steer particles away from it?



CHANNELLING 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

- Channeled particle follows 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

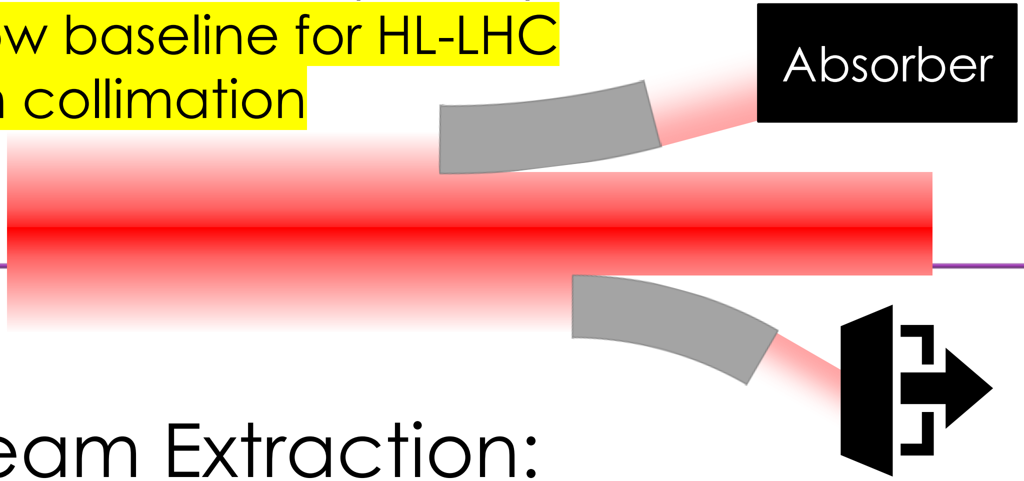
Energy (GeV)	Deflection	Size (mm)	Equivalent dipole
6500	50	4	276 T
0.855	1500	0.015	285 T
20.53	400	0.06	456 T
2000	14000	70	1134 T

BENT CRYSTAL APPLICATIONS

Beam Collimation:

With crystal high control of beam halo separation from primary beam

Now baseline for HL-LHC ion collimation

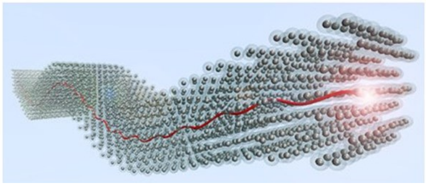


Beam Extraction:

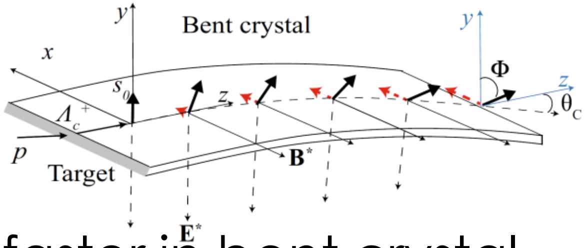
Surgical redirection of a beam portion, towards a precise location in the machine or in an external facility

Novel radiation sources:

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



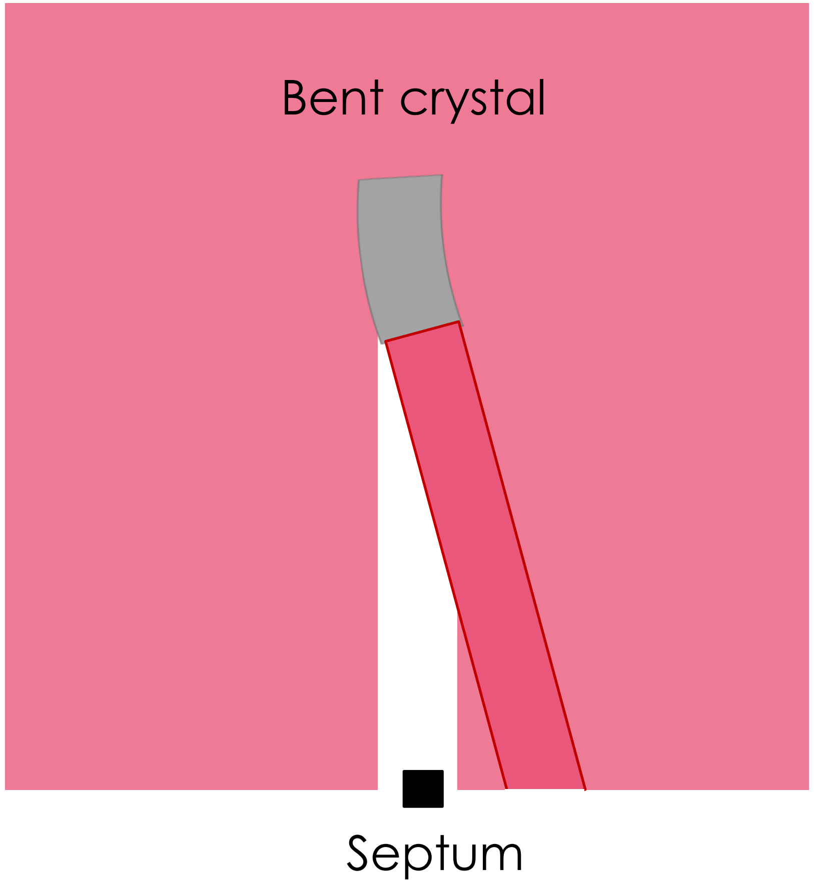
Spin precession:



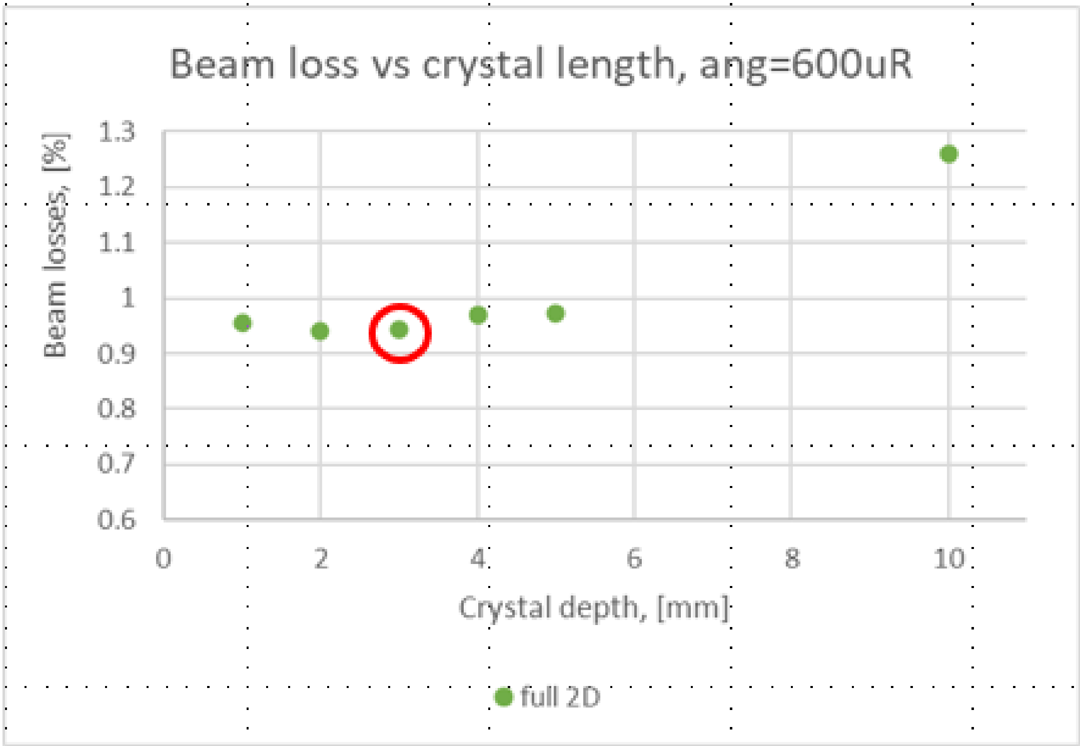
Spin precession much faster in bent crystal wrt existing dipole magnets→EDM & MDM study of fast decaying particles

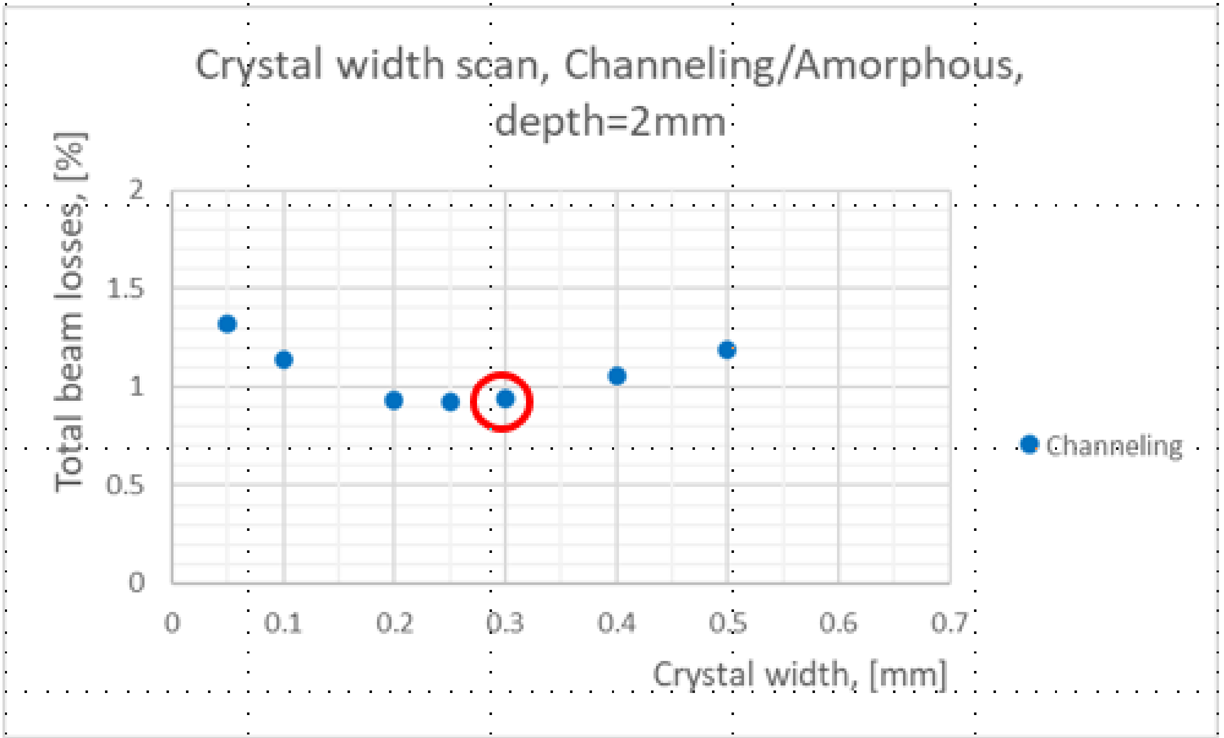
BEAM SHADOWING WITH A BENT CRYSTAL

- An upstream bent aligned wrt the beam deflect incoming particles
- Downstream the crystal, a footprint of depleted particles
- Tested at SPS for 400 GeV proton
- Feasible also for 8 GeV proton of Mu2e beam



SIMULATION OF BEST CRYSTAL CONDITION

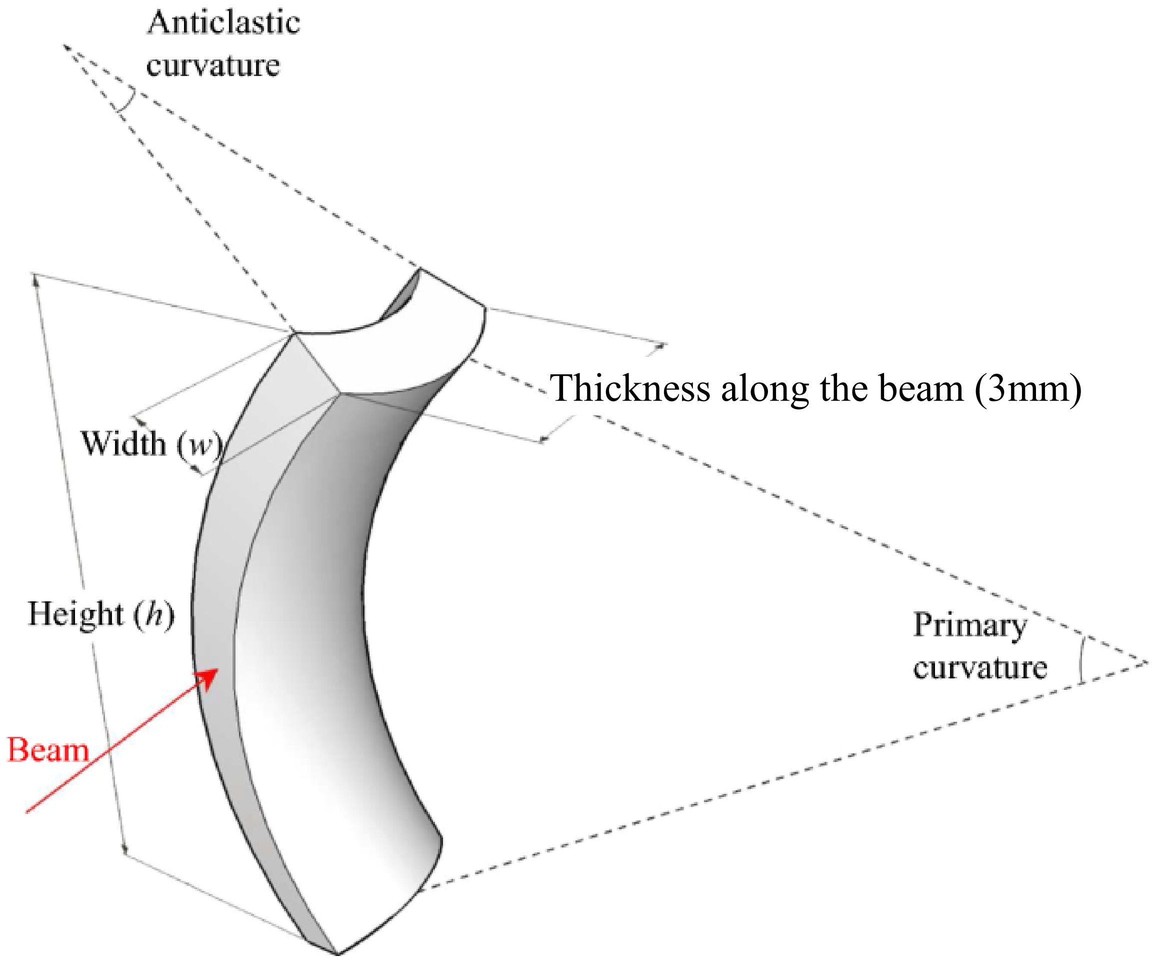




Courtesy of Vladimir Nagaslaev (FNAL)

CRYSTAL BENDING SCHEME

- Secondary anticlastic curvature occurs spontaneously in all materials with aspect ration
- Advantages:
    - thin crystal width
    - Crystal holder at edges of crystal: far from beam
    - large and uniform bending achievable



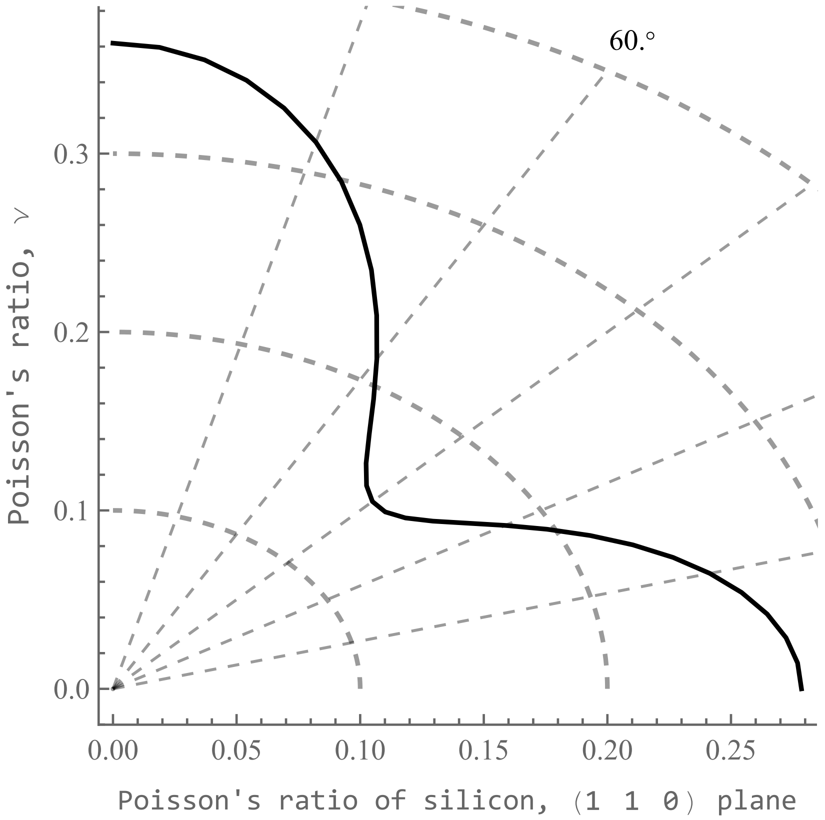
ELASTIC THEORY CALCULATION

- In order to achieve deflection θ=600μrad with crystal thickness along the beam of t=3mm, the anticlastic radius of curvature is

$$R_{Anticlastic} = \frac{3000\mu m}{600\mu rad} = 5m$$

- Thus, the primary bending radius would be

$$\frac{R_P}{R_A} = Poisson\ Ratio = 0.2786 \rightarrow R_P = 1.39m$$

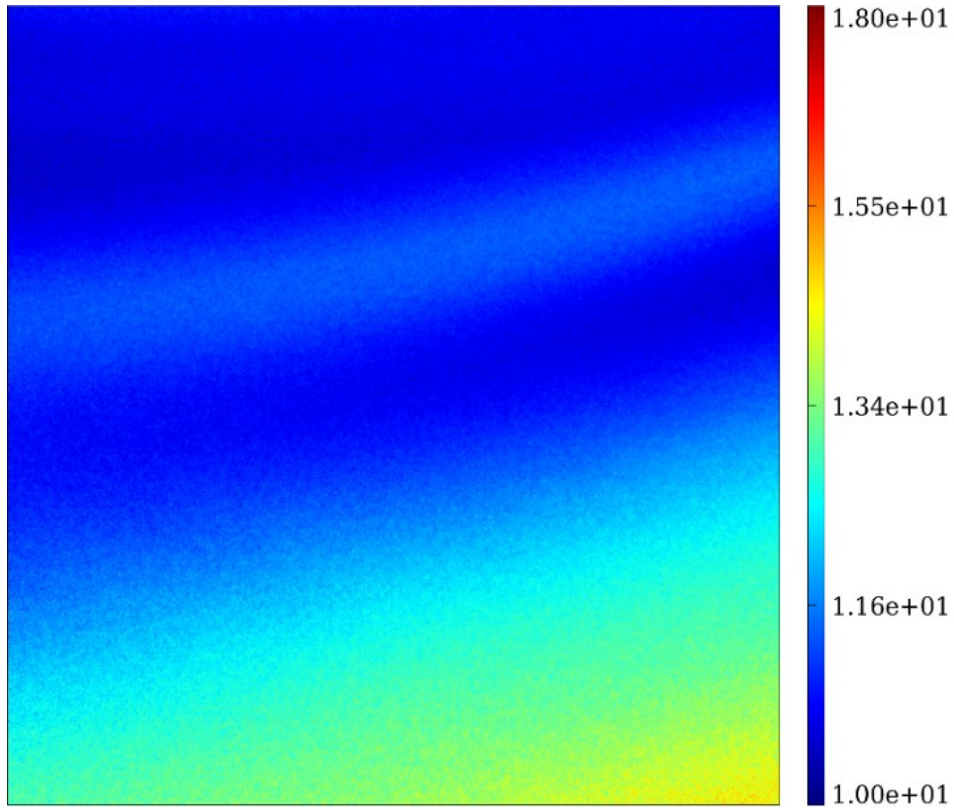


SAMPLE FABRICATION STEPS

- Crystalline quality control of prime material
- Sample shaping
- Mechanical bender design
- Bending characterization

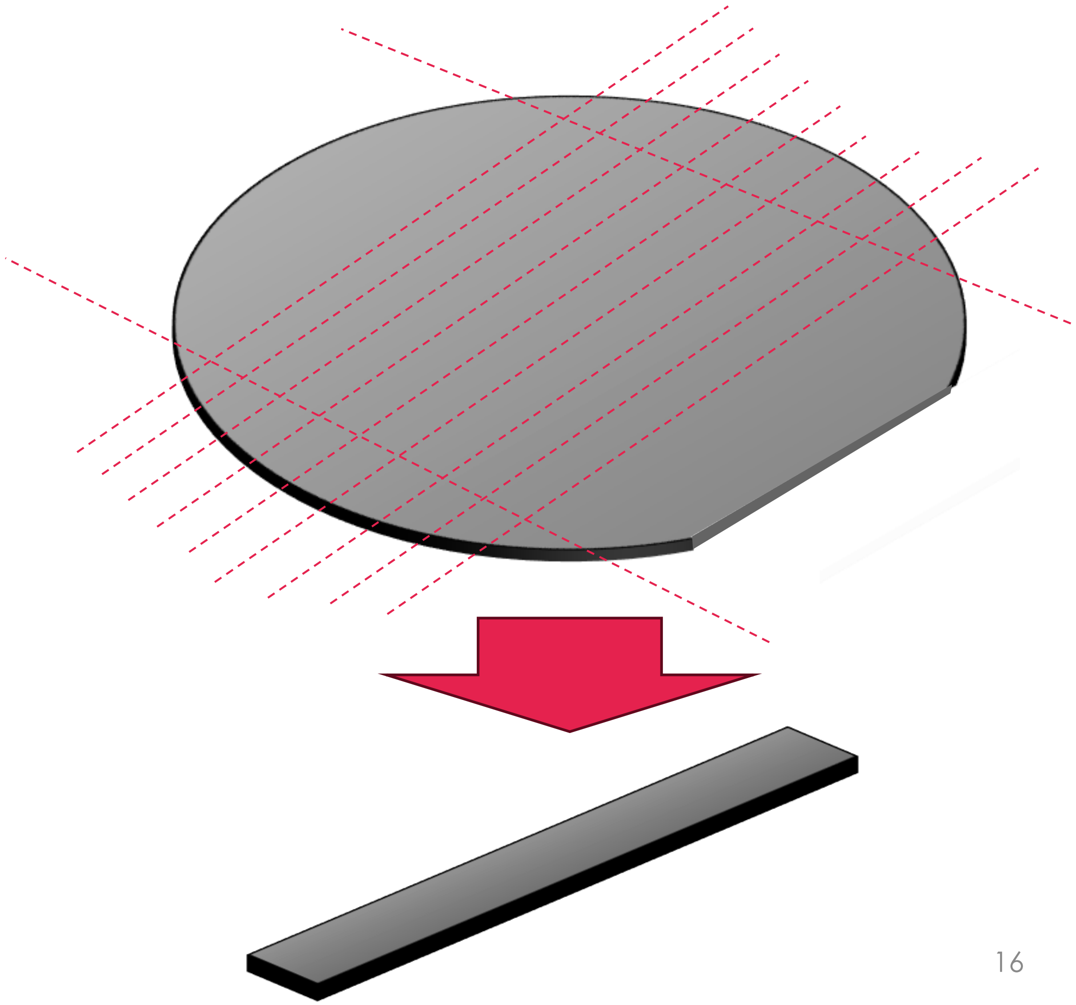
WAFER PREPARATION: ESRF CHARACTERIZATION

- For high channeling efficiency is critical lattice quality
- X-rays tomography allows to detect defects in the bulk of the crystal
- In the silicon wafer showed no dislocation



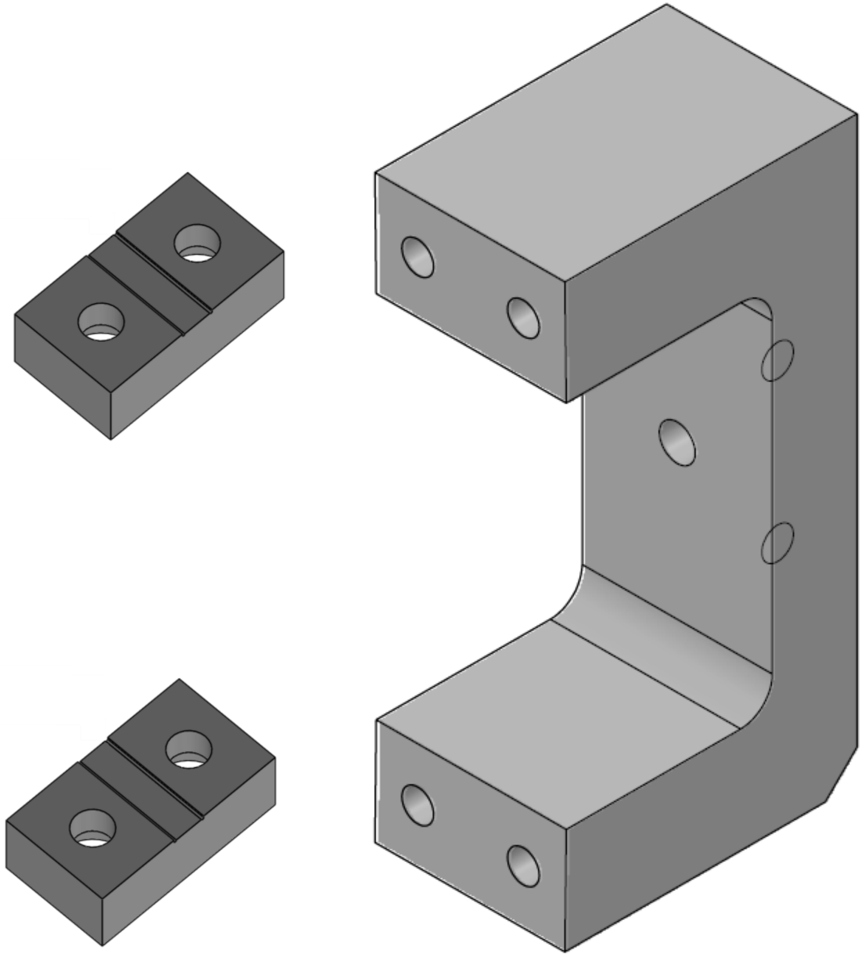
PREPARATION CUTTING PROCEDURE

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



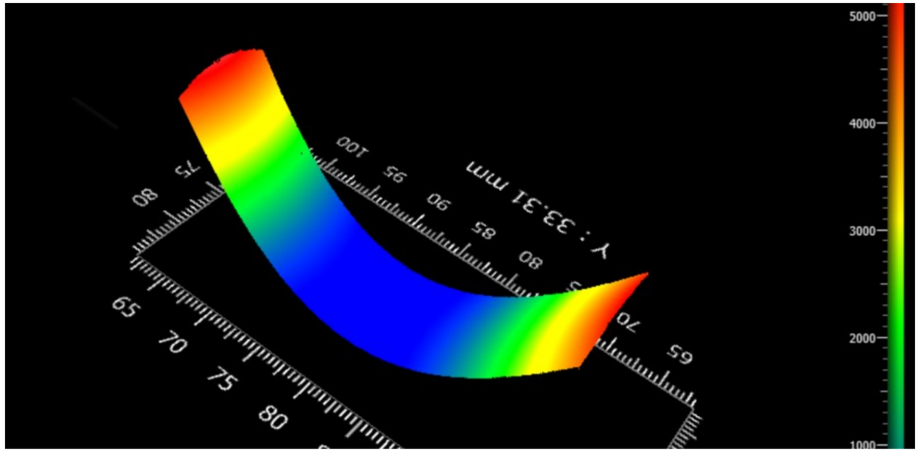
FINAL HOLDER

- Holder was designed with inclined support surfaces
- The angle of inclination is obtained with high precision using Electrical Discharge Machining
- The crystal sample is mounted and forced into arched position with radius of curvature Rp=1.39m,



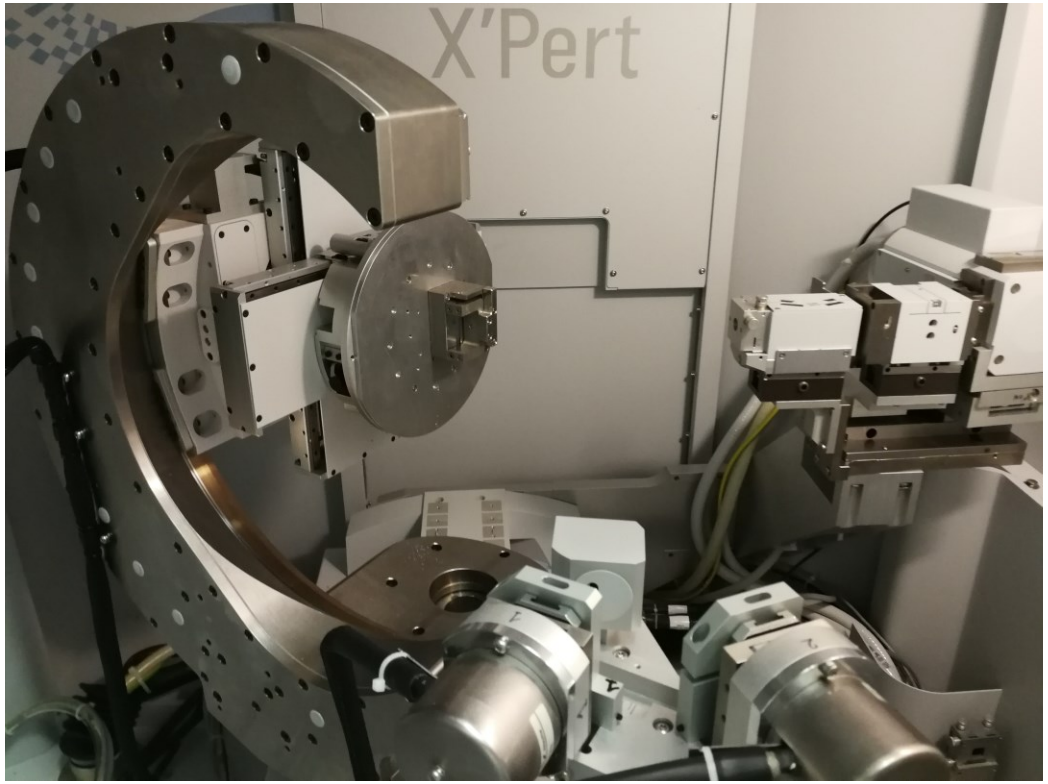
CURVATURE CHARACTERIZATION (1)

- 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
- In Ferrara 2 instruments are available:
  - Zygo VeriFIRE HDX, for measure of large sample in 1-shot measurses
  - Zygo NexView NX2, high resolution in small field of view



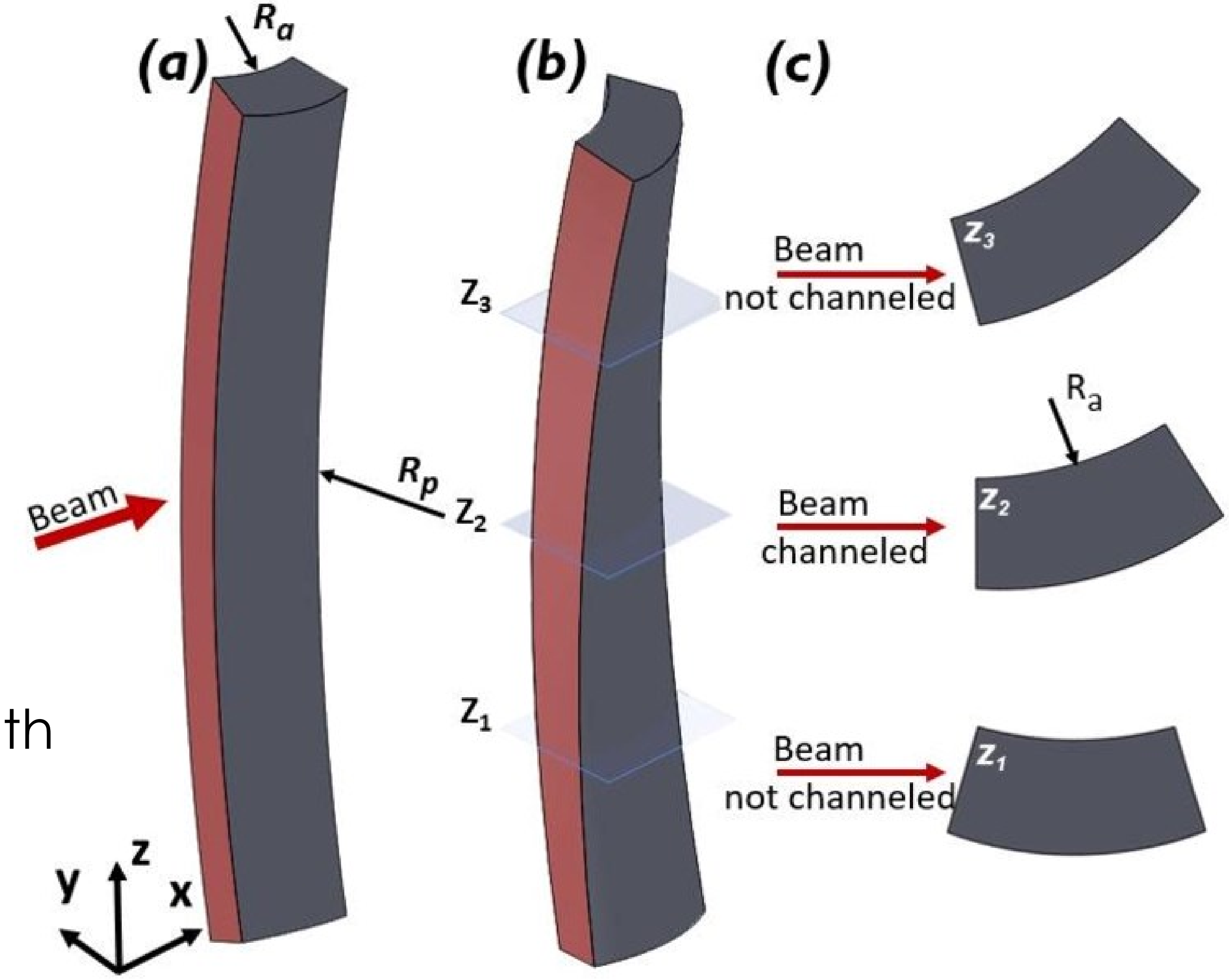
CURVATURE CHARACTERIZATION (2)

- Direct measure of lattice planes curvature can be achieved via x-rays diffraction
- In Ferrara Labs, a Panalytical X'Pert PRO MRD XL High Resolution diffractometer is used
- Measure of local orientation of lattice planes with 0.0001° resolution
- Angular shift allows to reconstruct the curvature along a direction



TORSION CHARACTERIZATION

- When flexed, a crystal may be subjected to torsion
- Torsion changes alignment between crystal and beam along the vertical direction, decreasing the total channeling efficiency
- X-rays diffraction allows measure of torsion, <10μrad/mm is compatible with good steering efficiency



CONCLUSIONS

- Beam losses at extraction may hinder Mu2e operation
- Mitigation by beam shadow technique with bent crystal can reduce beam losses
- Design of bent crystal finalized
- Preliminary test on prime material completed
- Final sample ready within 2024