Mu2e – Italy meeting
May 11, 2023

Beam manipulation through channeling in bent crystals and application to Mu2e

V Guidi, L Bandiera, A Mazzolari, M Romagnoni, A Saputi
(senior staff members)

Istituto Nazionale di Fisica Nucleare

guidi@fe.infn.it

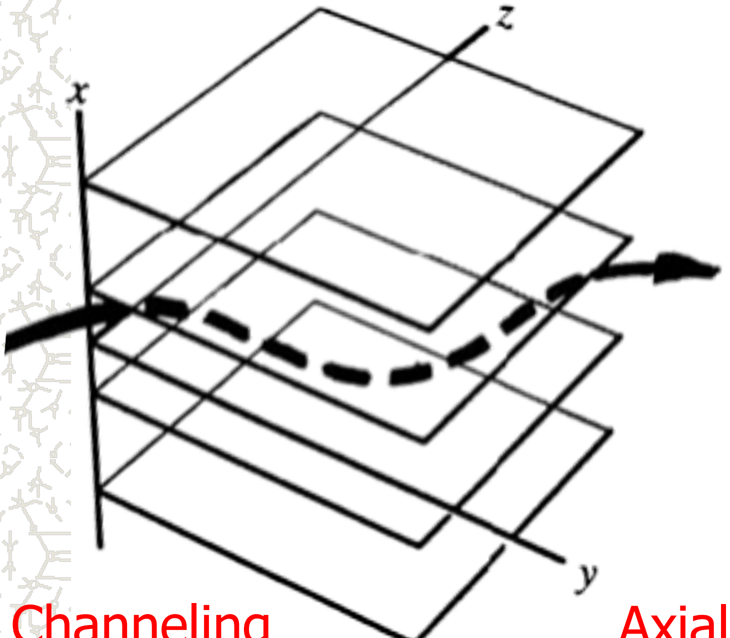
Università degli Studi di Ferrara

Outline

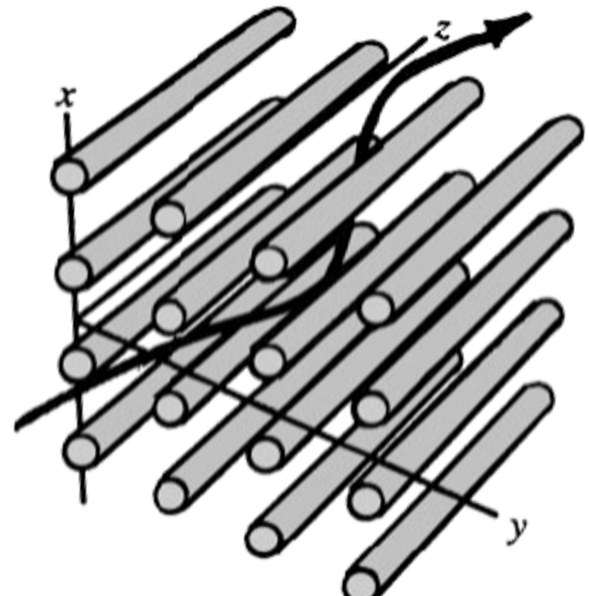
- Orientational coherent interactions in bent crystals
- Crystal fabrication and characterization
- Application of bent crystals to the Mu2e experiment
- Summary

Orientational coherent interactions in bent crystals

Channeling is the confinement of charged particles traveling through a crystal within atomic planes or strings



Planar Channeling



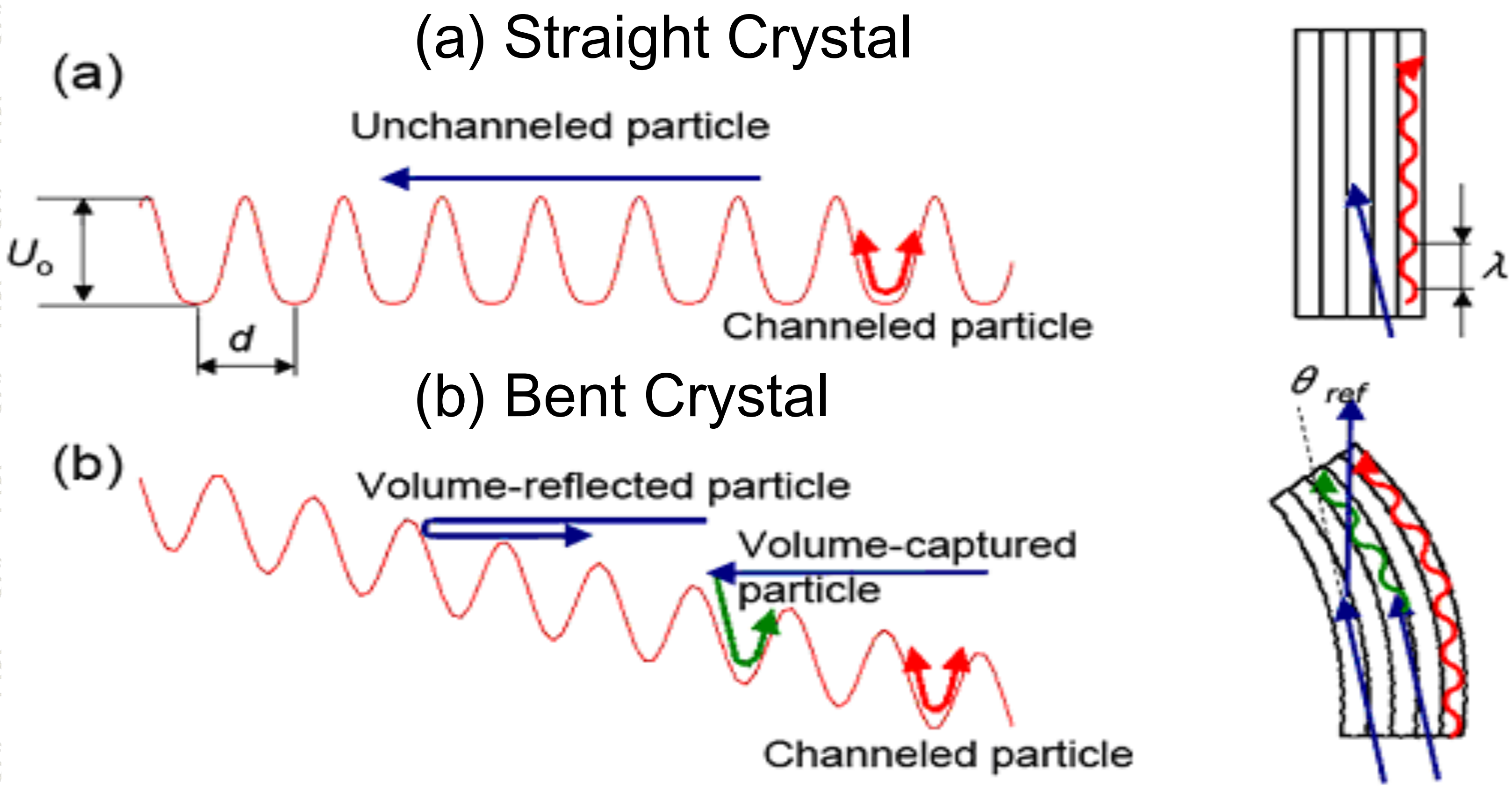
Axial Channeling

Channeling occurs as the trajectory of particles forms an angle lower than the critical angle [1]

$$\theta_{max} = \sqrt{\frac{2U}{E}}$$

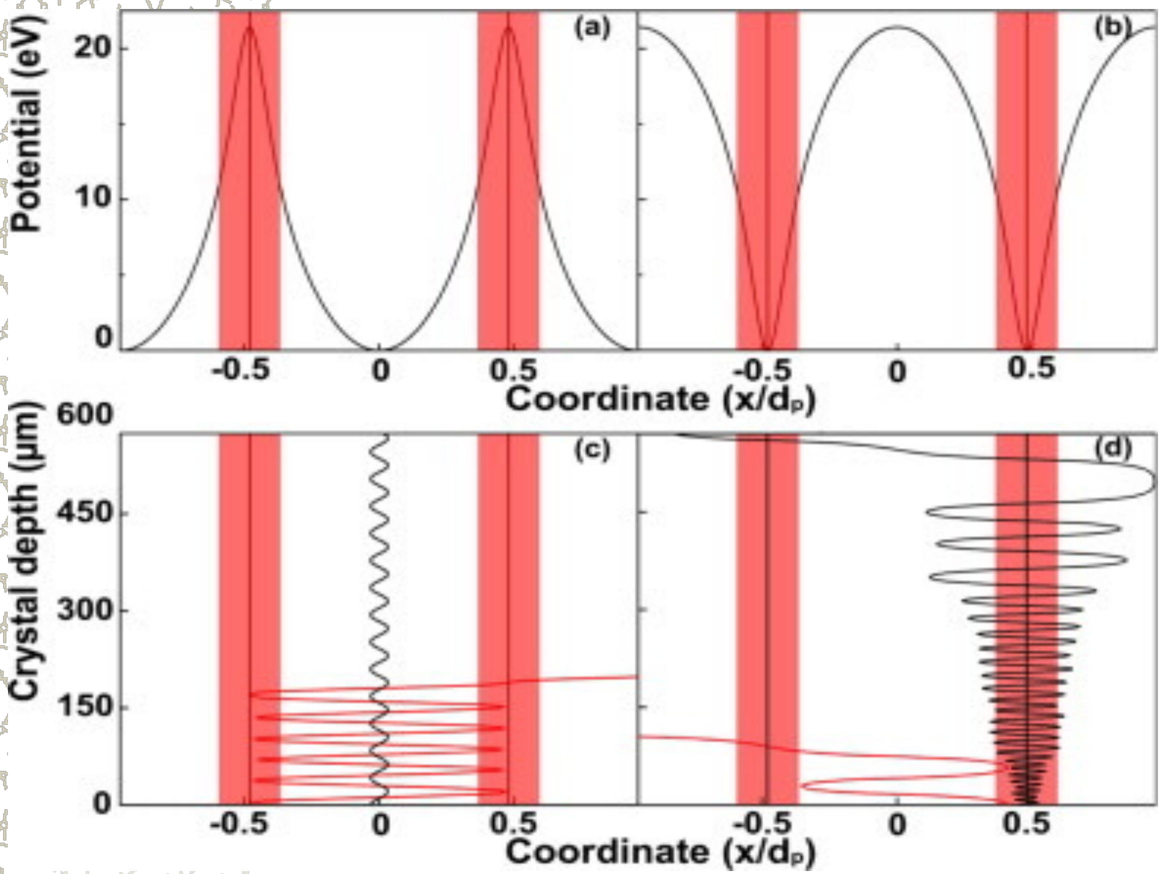
[1] J. Lindhard, K. Dan. Vidensk. Selsk. Mat. Fys. Medd. 34 (1965) 14.

Planar phenomena



Volume reflection was predicted by Taratin and Vorobiov in 1988

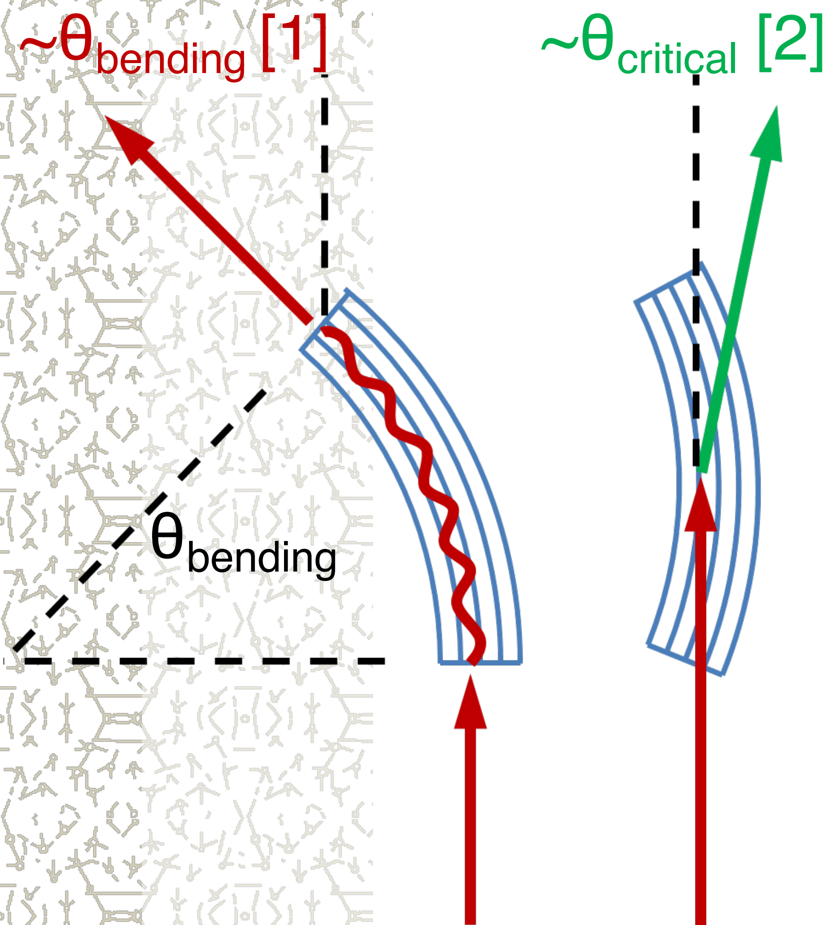
Positive- vs. negative-particle dechanneling



Channeled negative particles are dechanneled faster than positive ones due to higher probability to suffer incoherent scattering with nuclei.

Thinner bent crystals are required for efficient deflection of negative particles

Beam trajectory manipulation via channeling and volume reflection



- Bent crystals can be used in an accelerator for particle beam manipulation:
  - extraction of particles from the circulating particle beam;
  - collimation of the beam;
  - focusing
  - splitting

- With short bent crystals (~ mm), it is possible to deflect ultra-high-energy particles in CERN (SPS or LHC) with angles (100 μrad – 1mrad) achievable by 1000 Tesla magnets having a similar size.

[1] Tsyganov (1976)
[2] Taratin and Vorobiov (1988)

How strong would the equivalent dipolar magnetic field be?

Goal	Particle	Energy	Deflection	Thickness	Field of equivalent dipole
LHC collimation	Ions / protons	6.5 TeV	50 μrad	4 mm	292 T
LHC extraction (Crysbeam)	Protons	6.5-7 TeV	Few hundred μrad	Few cm	10^2 T
LHC extraction (SELDOM)	Protons	7 TeV	150 μrad	12 mm	292 T
Dipole precession (SELDOM)	Charmed Baryons	~ 1 TeV	17 mrad	80 mm (Si) 50 mm (Ge)	708 T 1133 T

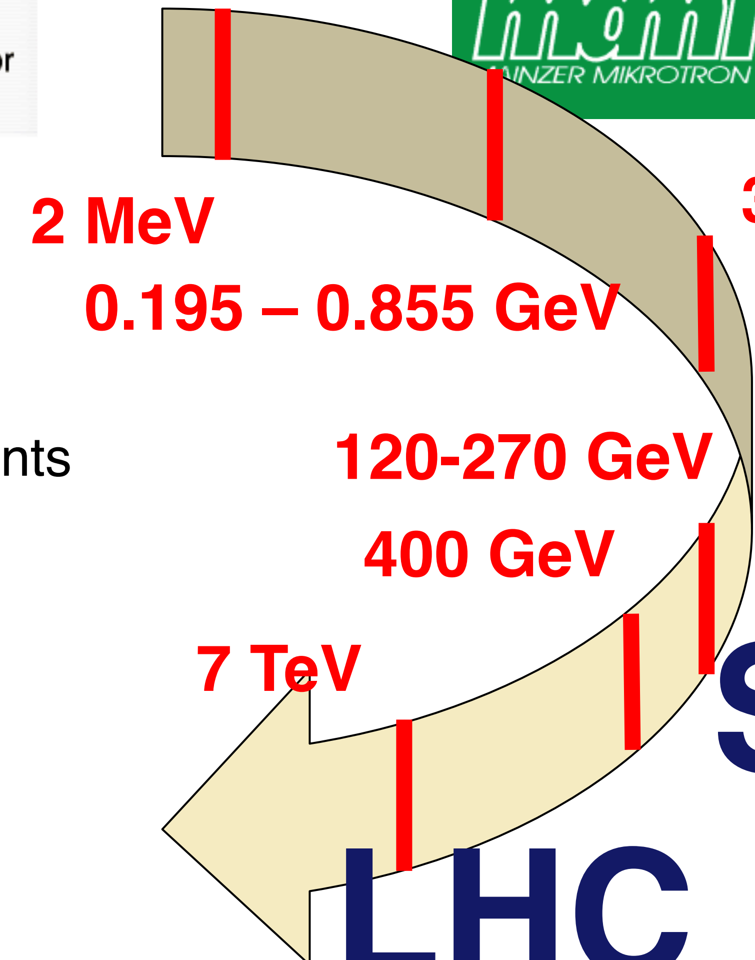
Neither supercurrents nor cooling needed

Labs for channeling experiments

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

Sensor and Semiconductor Laboratory

Mainzer Mikrotron



SLAC

SPS

LHC

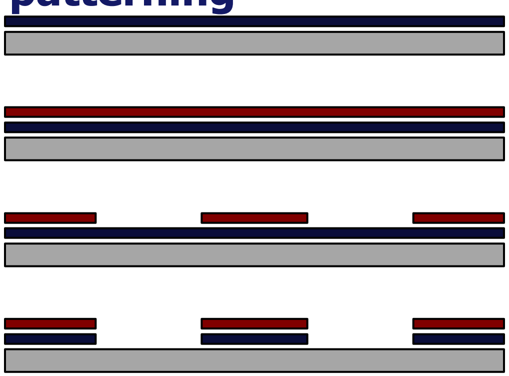
CERN

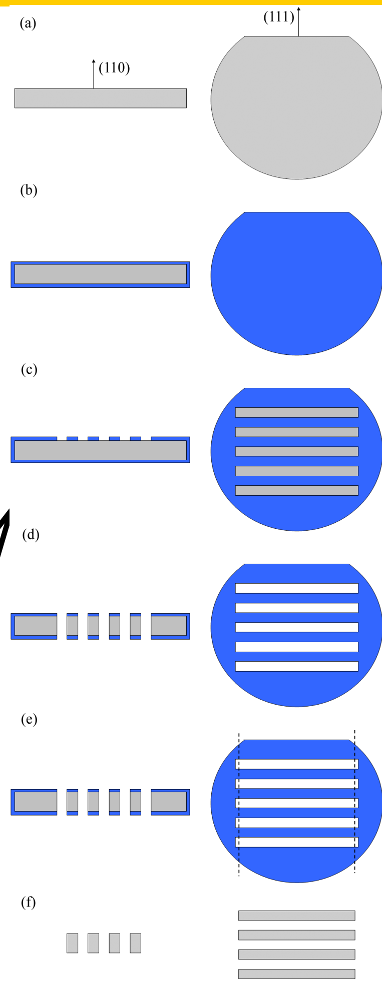
INFN experiments since 2003

Crystal fabrication

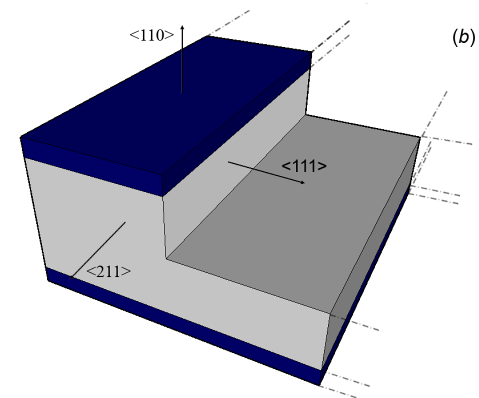
LPCVD deposition of silicon nitride thin layer

Silicon nitride patterning

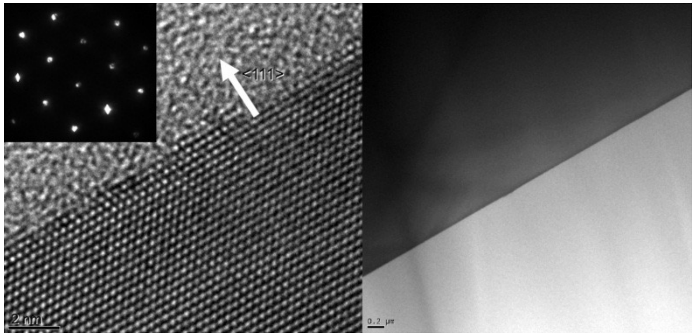




Anisotropic etching: Etching rate on different silicon planes for KOH 20% at 40 °C

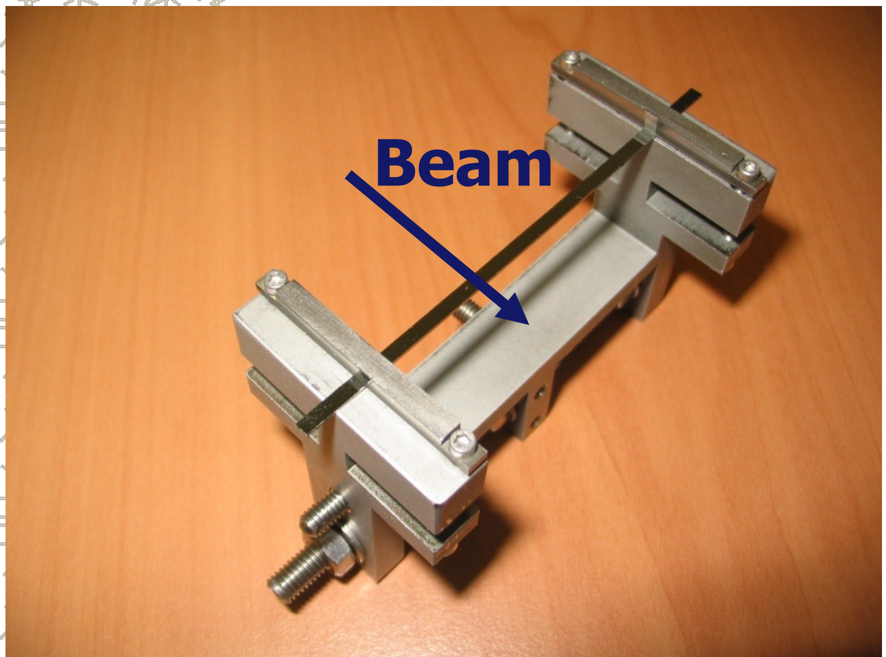


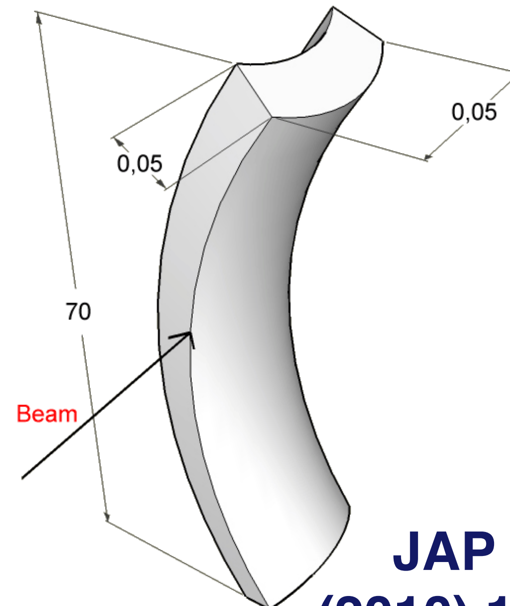
Crystalline surfaces



[1] S. Baricordi et al., Journal of Physics D: Applied Physics 41 (24), 245501
[2] S. Baricordi et al., Applied Physics Letters 91 (6), 061908

Crystal bending

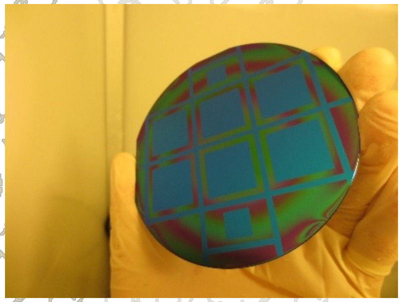


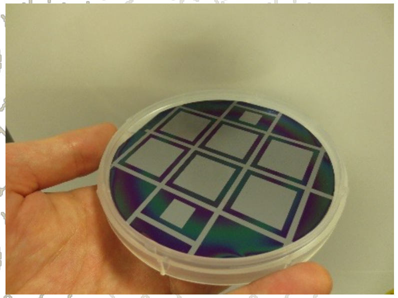


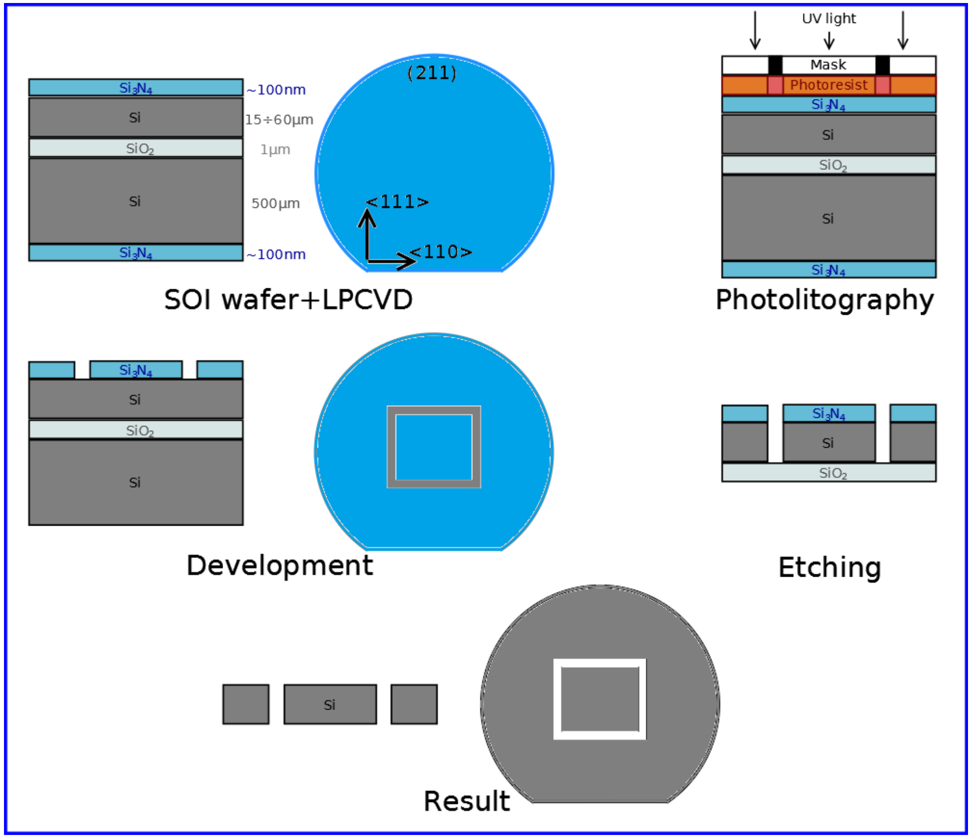
JAP 107 (2010) 113534

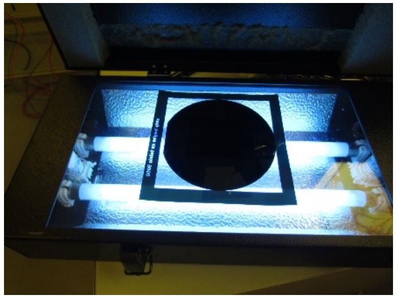
- A primary curvature is imparted by mechanical external forces, which result in a secondary (anticlastic) curvature.
- The mechanical holder imparts a primary strain and can be set far apart from the beam hence reducing unwanted interaction with the beam.

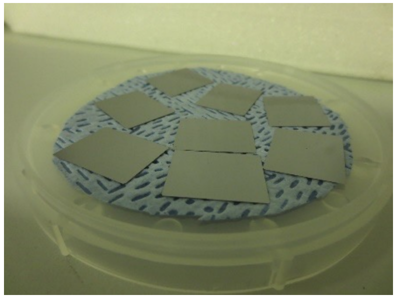
Quasi-mosaic crystal fabrication





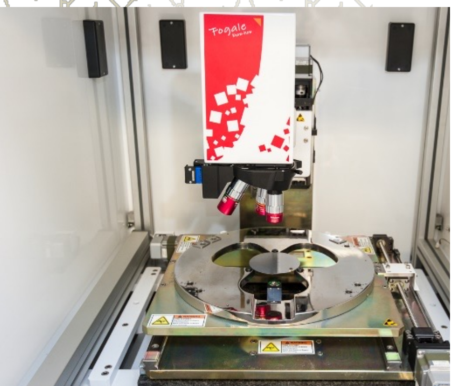


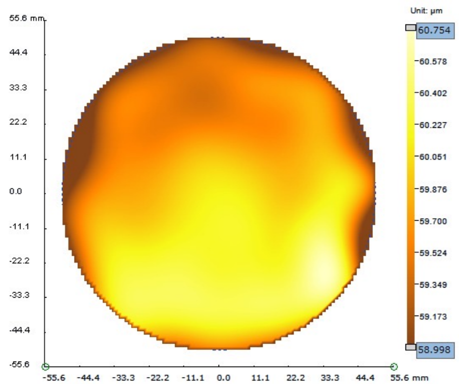




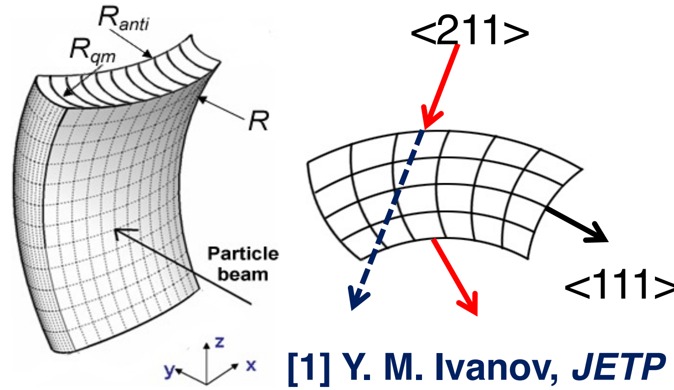
G. Germogli, A.Mazzolari et al., Nucl. Instr. Meth. B 355 (2015)

Crystal bending and characterization





FOGALE TMAP 4: thickness measurement

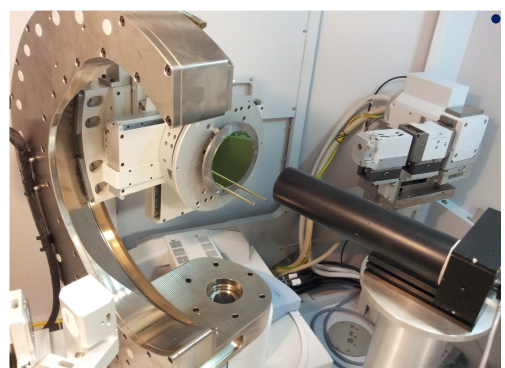


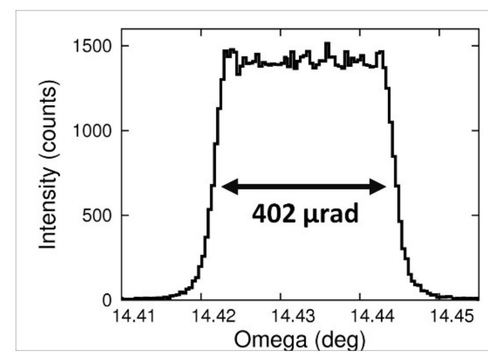
[1] Y. M. Ivanov, *JETP Lett.* (2005).

Quasi-mosaic crystal [1]:

- **Anticlastic curvature suppressed due to strong bending along principal direction**

Crystal mounted onto bending holder





Panalytical X'pert Pro x-rays: bending angle estimation

Experimental Setup on CERN-SPS external beamline (H8-H4)

Double sided silicon detectors*

DsX (300μm)

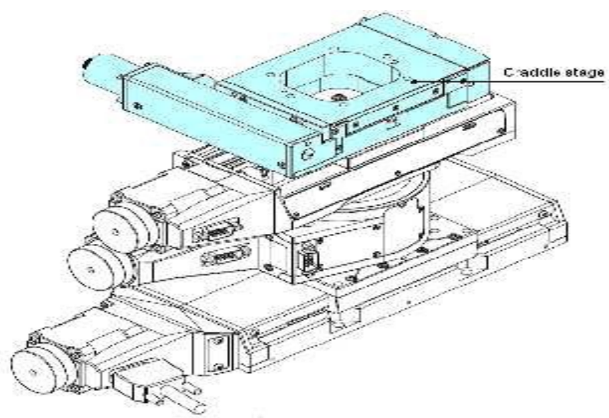
Spatial resolution

~5 μm

Angular Resolution

~1 μrad

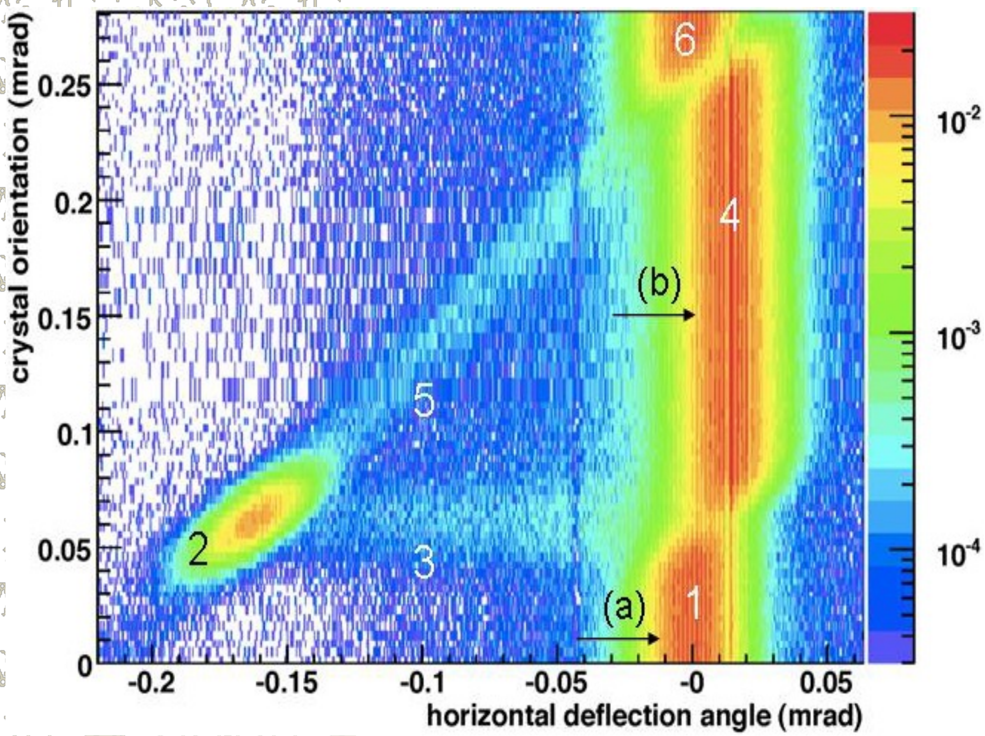
High-precision goniometer



Goniometer resolution

~1 μrad

Planar case: 400 GeV/c protons



1. Unperturbed beam
2. Channeling
3. Dechanneling
4. Volume reflection
5. Volume capture
6. Unperturbed beam

PRL 98 (2007) 154801

Channeling

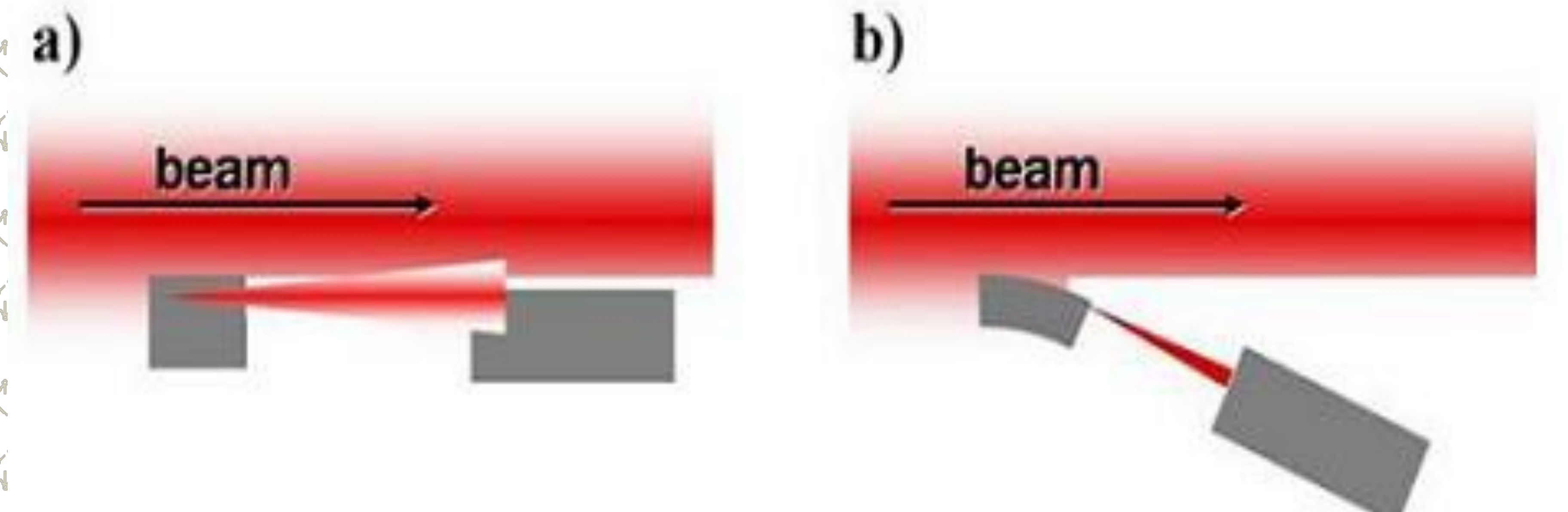
- ✓ Deflection angle: full bending angle, i.e. 170 μrad
- ✓ Efficiency: ~ 70 - 80%
- ✓ Limited angular acceptance

Volume reflection

- ✓ Deflection angle: 13.5 μrad
- ✓ Efficiency: > 95%
- ✓ Large angular acceptance equal to the bending angle

Crystal assisted beam collimation

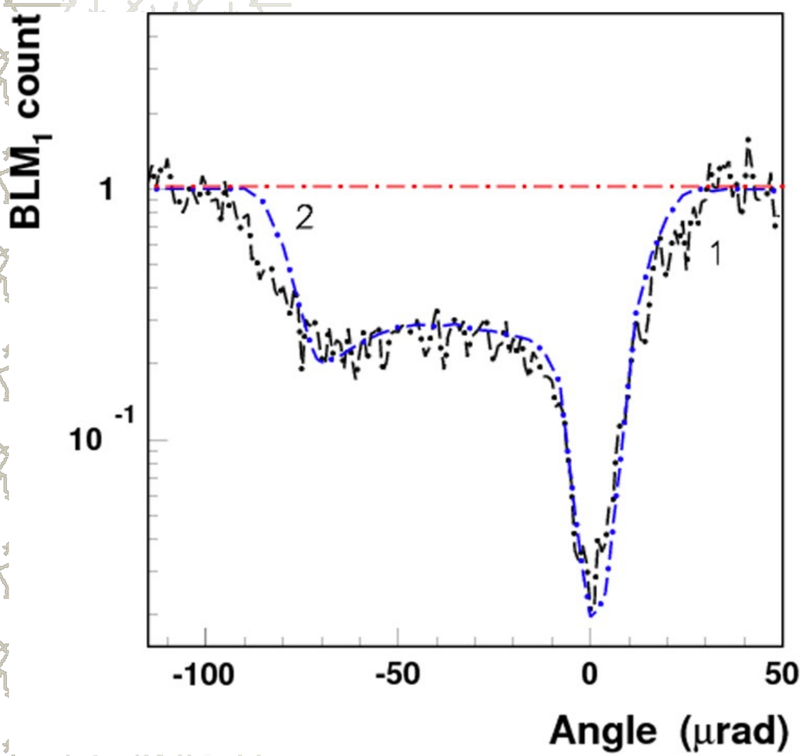
A bent crystal may serve as “smart target”,
which kicks most particles toward only one direction



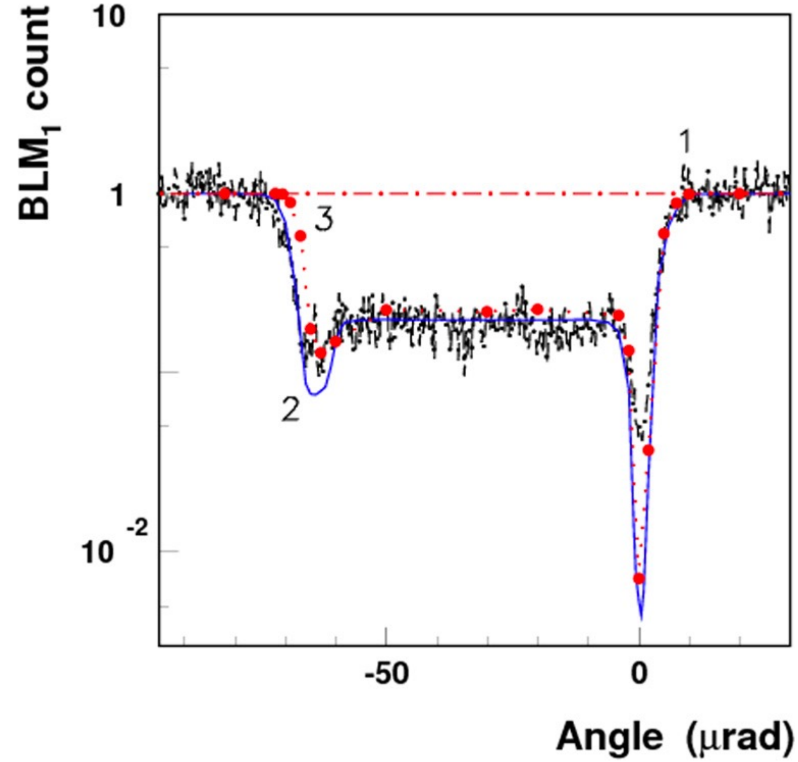
a) multi-stage collimation system: an amorphous material spread the primary halo so that it can be intercepted by a secondary collimator.
b) crystal-assisted collimation: a curved crystal deviates the halo directly to the primary absorber.
c) Essential tool for halo collimation in the LHC with 7 TeV protons

UA9: Crystal channeled the 6.5 TeV proton beam in the LHC

Beam losses vs. orientation



Operation at injection 450 GeV



Operation at 6.5 TeV

W. Scandale et al. PLB 758 (2016) 129

Crystals for the LHC

Contract to supply bent crystals to CERN for halo collimation for HL-LHC upgrade for ion beam collimation (contract INFN KE4350/EN/HL-LHC)

Thickness along the beam: 4.0±0.1 mm
Height < 55 mm.
Weight < 150 g
Channeling plane: (110)
Channeling axis: <111> or <110>
Miscut for axial channeling: 0±18 mrad

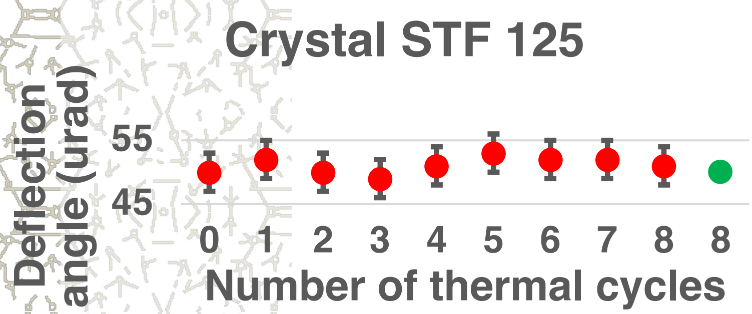
Miscut for planar channeling: < 10 μrad.
Torsion: < 1 μrad/mm
Bending angle: 47.5-52.5 μrad
Dislocation density < 1 cm^2

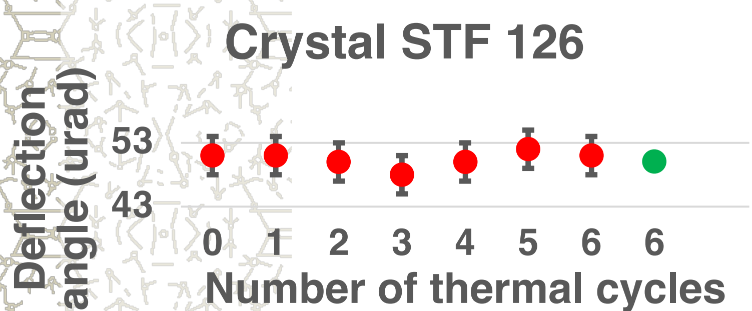
Bake out

- Bake out temperature = 250°C
- heating ramp = 50°C/h
- Bake out time = 48 h
- Number of thermal cycles = 3 at least
- Maximum allowed total outgassing after each bake out = $1*10^{-7}$ mbar·l·s^{-1}

Compliance of the mechanical properties of the crystal assemblies to the above specifications, in particular the bending angle, must be assessed after at least 3 thermal cycles.

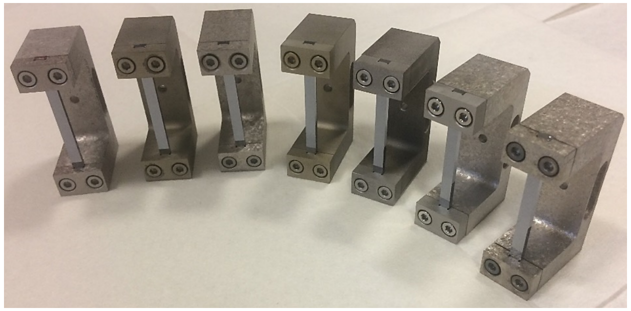
Crystals for the LHC



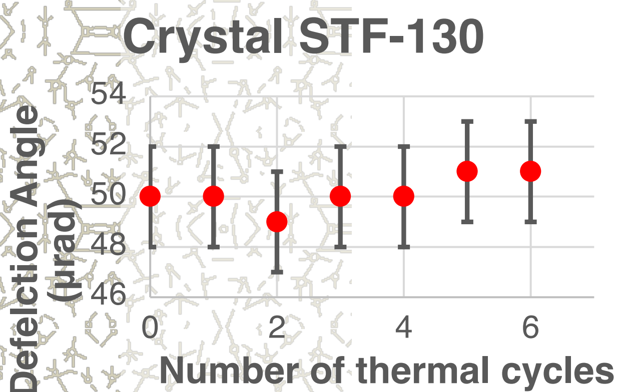


● HR-XRD@INFN-FE ● 180GeV π^+@CERN

Crystal code	Bending angle	Miscut	Bakeable
STF117	51±1	6±1	YES
STF118	53±1	6±1	YES
STF119	53±1	6±1	YES
STF120	52±1	6±1	YES
STF121	47±1	6±1	YES
STF122	46±1	6±1	YES
STF123	51±1	6±1	YES
STF124	49±1	6±1	YES
STF125	50±1	6±1	YES
STF126	50±1	6±1	YES

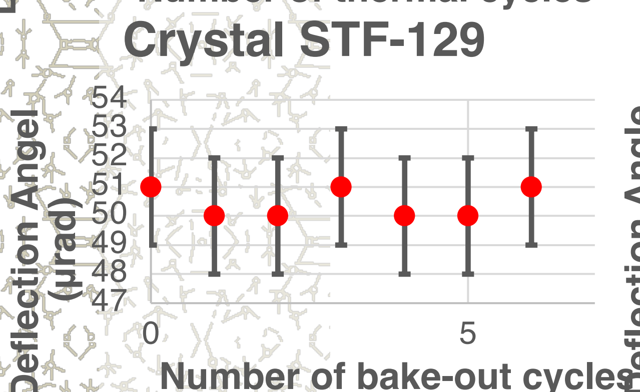


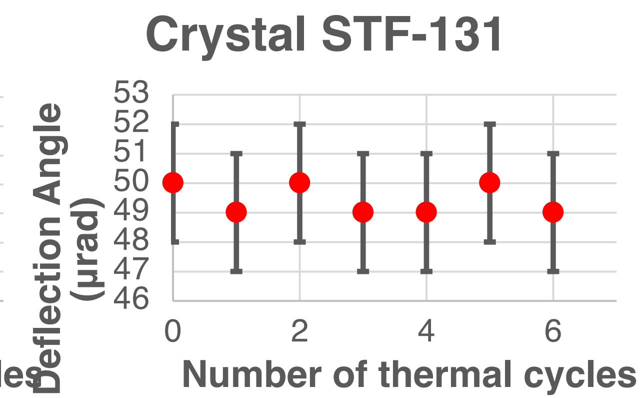
Crystals for the LHC

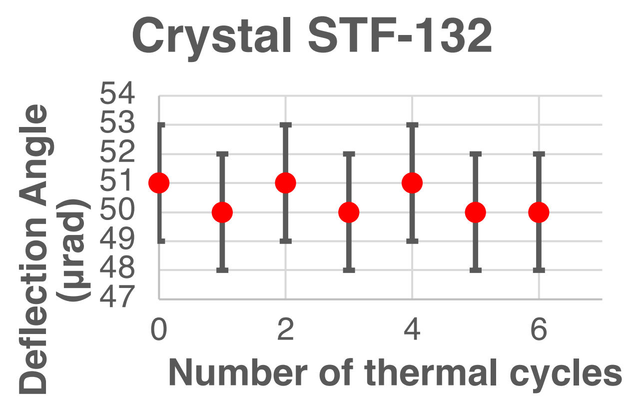


Selected for installation in LHC

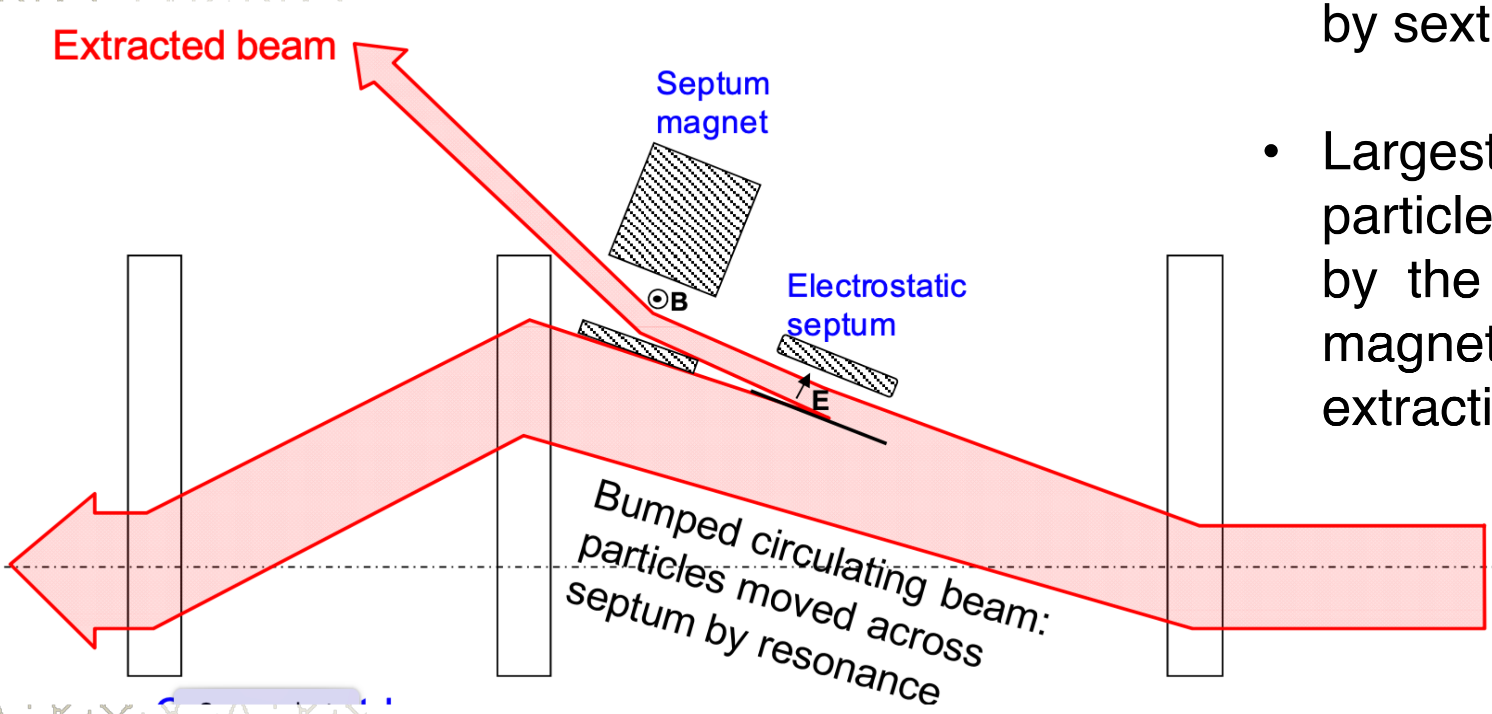
Crystal code	Bending angle	Miscut	Bakeable
STF129	50±1 μrad	1±1 μrad	YES
STF130	50±1 μrad	1±1 μrad	YES
STF131	49±1 μrad	1±1 μrad	YES
STF132	52±1 μrad	1±1 μrad	YES







Septum magnet for slow resonant extraction

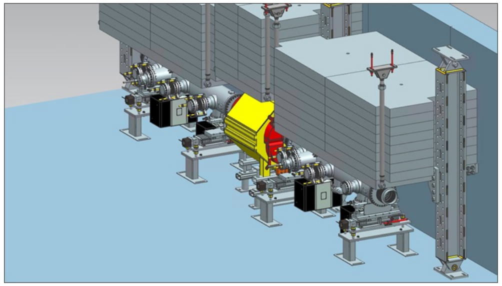


- Resonance is driven by sextupoles
- Largest oscillating particles are captured by the septum magnet yielding extraction

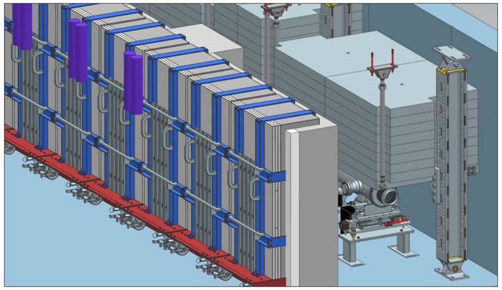
A fraction of the particle beam interact with the matter in the septum and generates losses

Motivation to reduce beam losses for Mu2e

- Slow Extraction (SX) is an inherently lossy process
- Design total beam losses for SX are 1.5%, equivalent to 120W radiation power
- Up to 1R/hr surface activation
- Significant shielding is necessary at the points of known losses
- Unknown losses – may require significant time to understand and mitigate
- Expect significant commissioning time to bring losses down to the design level
- This may reduce the beam power available for the experiment and effective run time
- Accelerator team is actively looking at the possibilities to reduce beam losses



Partial shielding around the septa in D30

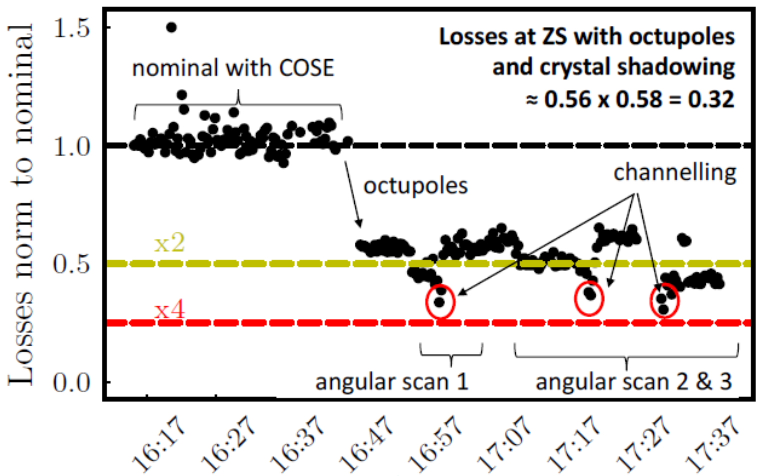


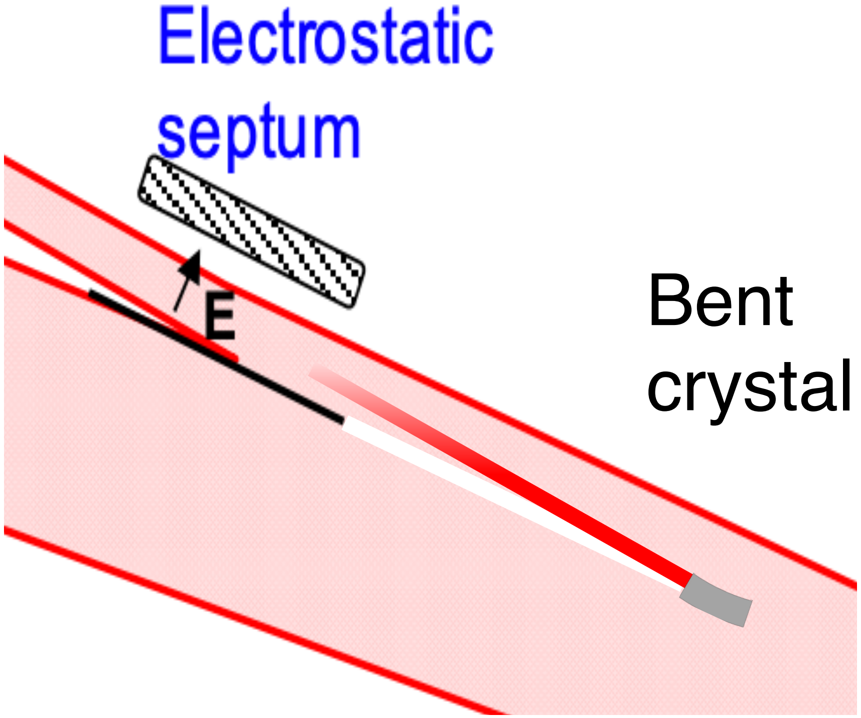
Full shielding around the septa in D30

Courtesy of Vladimir Nagaslaev

Slow extraction at CERN-SPS

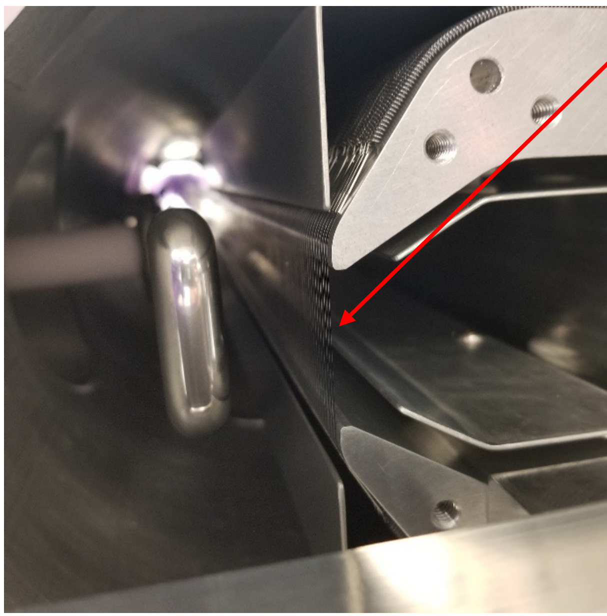
- Experiment performed in SPS ring with 400 GeV proton beam
- Reduction of beam losses by over 40% by using planar channeling
- Reduction of beam losses by over 25% by using volume reflection



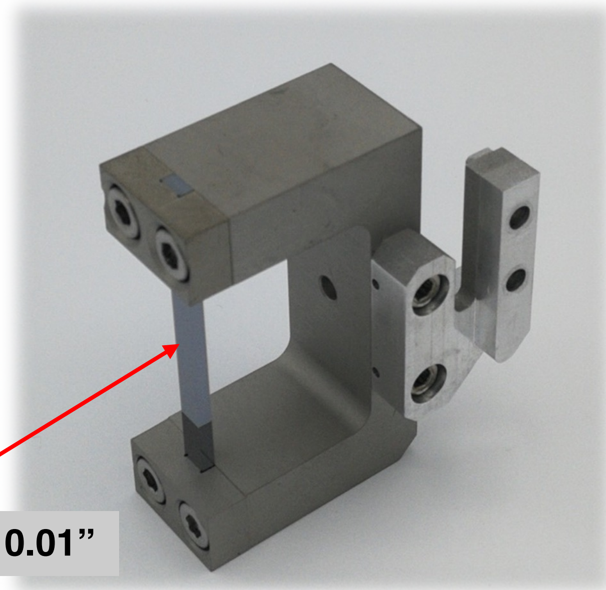


Schematic of crystal shadowing

Reminder – crystal "shadowing" concept



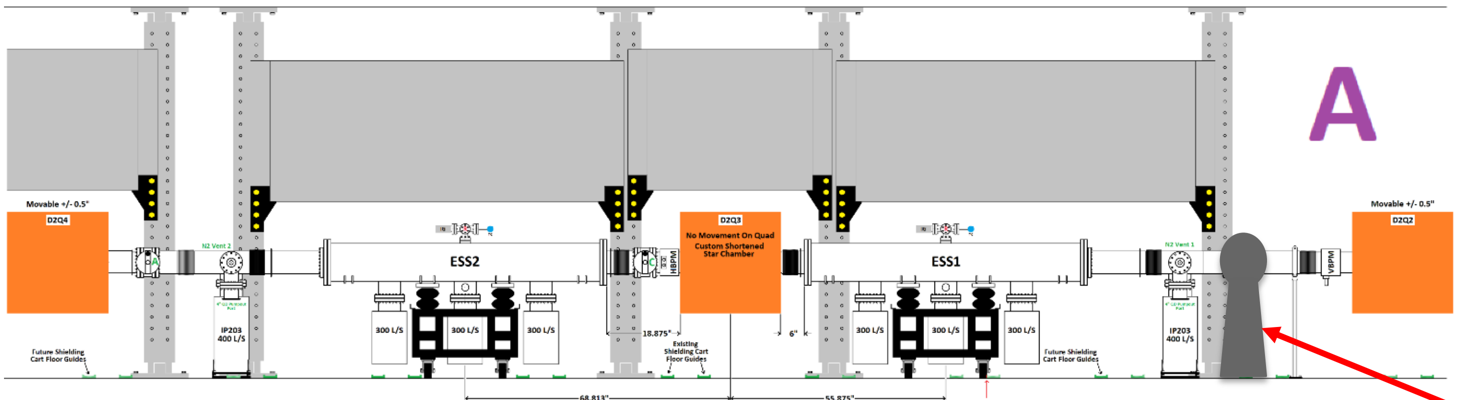
Electrostatic septum for SX
Losses occur in the foil plane



Typical Crystal fixture
To deflect the beam from the foil plane

Curtesy of Vladimir Nagaslaev

Tunnel view of the septa setup



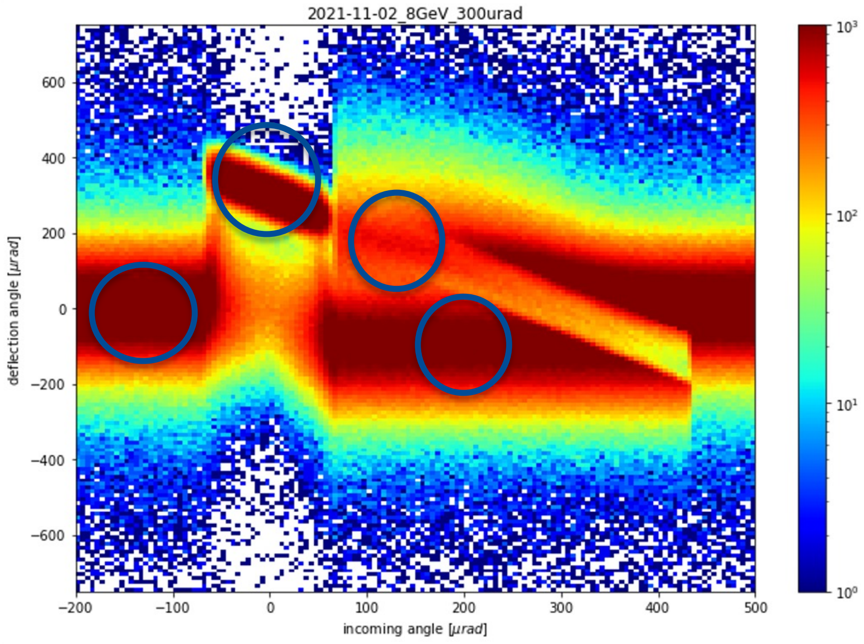
Proposed tunnel location for the Crystal Collimator

- **Purpose: bend the beam away from the septum**
- **Super-precise mechanism for crystal alignment (goniometer)**

Curtesy of Vladimir Nagaslaev

Phase I
Transport in the crystal

- Compute the scattering PDF matrix
  - 220x120, 5x5 uRad bins
- Crystal parameters are fixed
  - 0.4mm, 300uRad
- Produced by the CERN-Fermilab collaboration
- Courtesy: *Luigi Esposito, CERN, November 2021*
- Independent modeling by Ferrara would be very helpful



Curtesy of Vladimir Nagaslaev

Phase II
Transport in the Extraction channel to determine the extraction efficiency

- Use MARS: modelling both scattering and accelerator transport
- Fermilab owned tool (chances for support)
- Extensive model of the Delivery Ring exists
- Good experience with modelling the septum losses
- New potentials and overheads: MADX/PTC, ROOT, Fermigrid

Curtesy of Vladimir Nagaslaev

Conclusions

- Effect of the crystal with bending angle 300uRad modeled using the provided PDF matrix and Extraction section MARS model
- Beam loss reduction of x3 observed with beam design parameters
- Beam loss reduction of 40% obtained with more conservative beam parameters
- Crystal alignment and stability required at the level: +-50um horizontally and +-100uRad in rotation angle.
- These are the preliminary studies. Further improvements are possible upon the geometry optimization

Curtesy of Vladimir Nagaslaev

Expertise of Ferrara for Mu2e

- Simulation to optimize crystal geometry
- Fabrication of crystal
- Design and fabrication of bending holder
- Assembling of crystal and holder
- Bending characterization
- Assistance for installation at FNAL

Ferrara, world heritage by UNESCO since 1995

Thank you for your attention