Feasibility study for crystal shadowing in 8GeV Slow Extraction at Fermilab

V.Nagaslaev (Fermilab)
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Slow Extraction from DR: Limitations from beam losses

- 8kW average beam power
- Residual radiation
- Equipment activation and lifetime
- Radiation at public areas
- Deliver Ring (DR) shielding
- Impact to the Mu2e experiment
- Looking for additional mitigation
Using channeling in bent crystals at 8GeV

• Crystal shadowing successfully demonstrated at SPS
  Is it feasible at 8 GeV?

• Advantage:
  Higher acceptance (critical angle)
  Lower beam rigidity

• Concerns:
  Scattering is higher
  Dechanneling processes are stronger
  Beam angular dispersion is higher

• Crystal:
  0.2mm x 0.4mm x 25mm ?
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• Circulating beam in DR:
  • angle spread is 10 times the critical angle

• Extracted beam angles spread can be made very small

• Constraints on extraction:
  • Low chromaticity
  • Low D/D’
  • Beam angle dynamic control
Modelling the crystal collimation (shadowing)

1. Proof-of-principle study using the fixed crystal geometry
2. Explore the crystal parameter space
Modelling the effect of the crystal shadowing in the DR

Proposed tunnel location for the Crystal Collimator

- Space available
- Sufficient phase advance
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Proof-of-Principle Crystal Shadowing modeling – Phase I

Phase I
Transport in the crystal

- FLUKA model
- Compute the scattering PDF matrix
  - 220x120, 5x5 uRad bins
- Crystal parameters are fixed
  - L=0.4mm, 300uRad
- CERN-Fermilab collaboration
  - Luigi Esposito, CERN, November 2021
Phase II: Accelerator tracking using MARS

Delivery Ring “Extraction section”

Lattice elements:

- ESS1
- Q203
- ESS2
- Q204
- Lambertson
- C-Magnet
- Aperture details
- Crystal
  - Grossly exaggerated

No multi-turn tracking is needed
Efficiency calculations in the end of the Extraction section

Filter 1:
Pass through the Extraction section (survived in tracking)

Filter 2:
Stay in the aperture (within green ellipses)

Nominal Eff=98.5%
MARS tracking reproduces the design performance
Effect of crystal channeling for the beam design parameters

With beam divergence rms=40 uR, beam losses drop by over factor of 3
Conservative beam parameters: rms angle=80uRad

The minimum loss point shows the 41% beam loss reduction compared to no crystal configuration.
More details about Proof-of-Principle simulation

Detailed analysis of the Proof-of-Principle simulation studies is available online

Feasibility of using crystal channeling for the beam loss mitigation in slow extraction at 8GeV

V. Nagaslaev a,*, I. Tropin a, L. Esposito b, M. Fraser b, B. Goddard b, F. Velotti b, L. Bandiera c, V. Guidi c, A. Mazzolari c, M. Romagnoni c, A. Sytov d

a Fermi National Accelerator Laboratory, USA
b CERN, Switzerland
c Università di Ferrara, INFN Ferrara, Italy
d Università di Ferrara, INFN Ferrara, RISTI, South Korea
Crystal parameters optimization: WIP
Crystal parameter optimization

- To explore further the space of geometrical crystal parameters, we need PDF maps generated for each configuration.
- The PDF maps were provided by our Ferrara collaborators.
  - Computed using GEANT extension (A. Sytov)

![GEANT, b=300uR, L=0.4mm](image)

![FLUKA, b=300uR, L=0.4mm](image)
Bending efficiency comparison for 300uR bending crystal, FLUKA vs GEANT

Bending efficiency vs angle

- FLUKA
- GEANT

Incident angle, μRad

Efficiency, %
Scattering PDF maps, A.Sytov (GEANT) (not all of them!)

Crystal scattering PDF maps with $L=0.4\text{mm}$, $\text{bend}=100\text{-}1000\text{uRad}$

Crystal scattering PDF maps with $\text{bend}=600\text{uRad}$; $L=0.4\text{mm}\text{ -}5\text{mm}$
Beam loss comparison for L=0.4mm bending crystal, varying bending angle
Beam loss comparison for L=2mm crystal, 600uR bending; variable hor. width

![Graph showing beam losses as a function of crystal width.](image)
Beam loss comparison for 600uR bending crystal, variable length

- Amorphous scattering:
  - Full MS, no channeling
- Horizontal PDF maps:
  - Channeling, no vert. MS
- Full scattering maps:
  - Horz&Vert - TBD
- Mixed scattering:
  - Horz PDF + amorphous
Conclusions

• Using crystal shadowing for beam loss mitigation at 8GeV is feasible
• Beam losses reduction over x3 is possible if extracted beam angle spread is kept within the CA.
• Strict requirements on the mean angle spread limit the choice of extraction scheme.
• Beam losses reduction over 40% with conservative beam parameters is achievable.
• Optimal crystal parameters are well within the reach of technology.
Back-up
Particle sample for MARS tracking

- Beam sample generated based on the full spill tracking simulations with PyOrbit
- Beam sample represents one spiral step size
- Only narrow part around the septum plane is used, the rest does not contribute to losses
Crystal collimation efficiency – first trial

Crystal at Z=0.3m (1.3m US of foils)

Proton angles at the crystal entrance and exit

Efficiency improvement is modest – about 10%

Projected beam profile at the septum entrance

Volume reflection
Channeling

No scattering profile
Effect of scattering
Septum width
Mixing in the beam phase space at septum

Beam transition from crystal to septum, crystal width=100u

A lot of destructive mixing due to the angle spread

Phase space (X-X’ plane) at crystal exit

Phase space (X-X’ plane) at septum entrance
Mixing in the beam phase space at septum – new location & width

Crystal at $Z=0.7m$ (0.9m US of foils), width=200um

Phase space ($X-X'$ plane) at crystal exit

Phase space ($X-X'$ plane) at septum entrance
Crystal angle alignment scan, beam rms=80uRad

**Conservative beam parameters:**
angle spread rms=80uR

Beam losses vs crystal alignment angle, d=200u

Yellow points: channeling off, crystal in the beam