FERMILAB-SLIDES-24-0015-AD

Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

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

V.Nagaslaev (Fermilab)

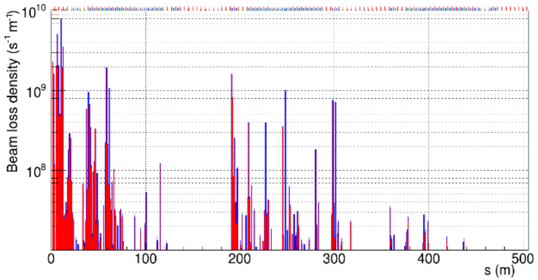
5th SX Workshop, Wiener Neustadt

February 13, 2024

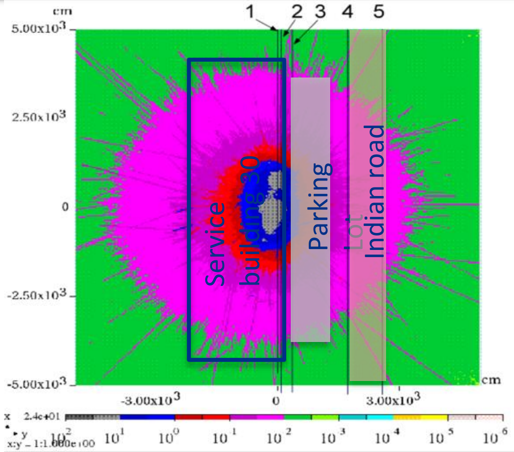
This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

# Slow Extraction from DR: Limitations from beam losses

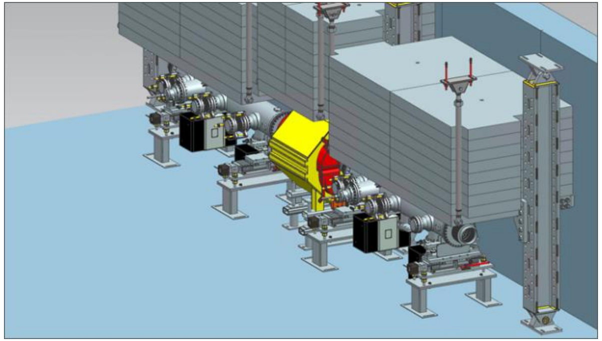
- 8kW average beam power
- Residual radiation
- Equipment activation and lifetime
- Radiation at public areas
- Deliver Ring (DR) shielding
- Impact to the Mu2e experiment
- Looking for additional mitigation

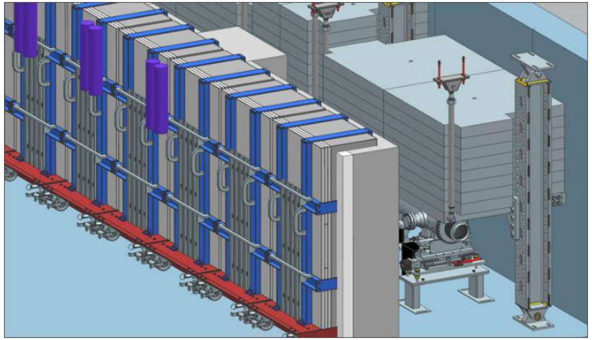



Losses in the Ring




Radiation levels on ground surface





In-tunnel shielding around the extraction septum



Fermilab

# 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 ?

# 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

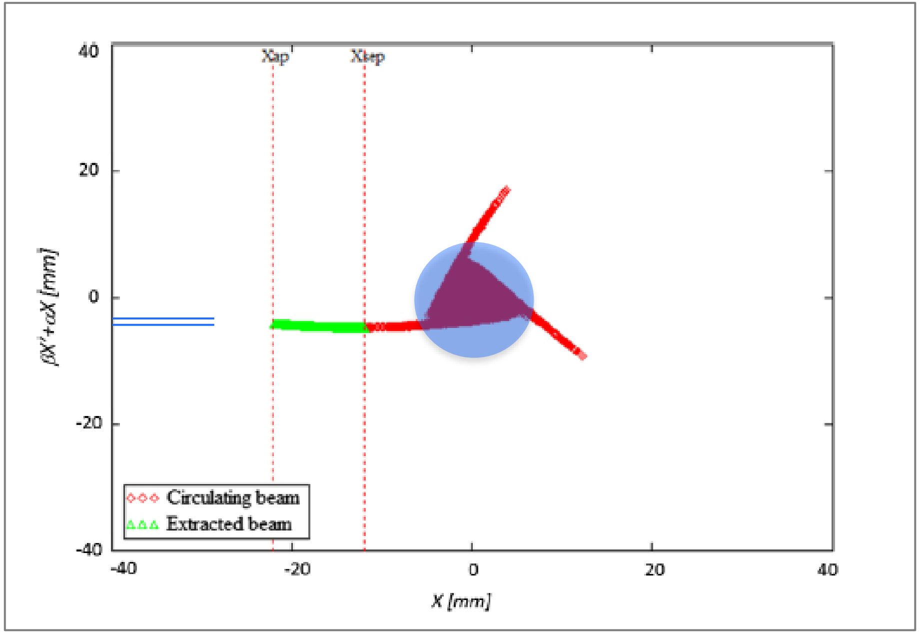
    Beam angular dispersion is higher

- Crystal:

    0.2mm x 0.4mm x 25mm ?

# Using channeling in bent crystals at 8GeV

- 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



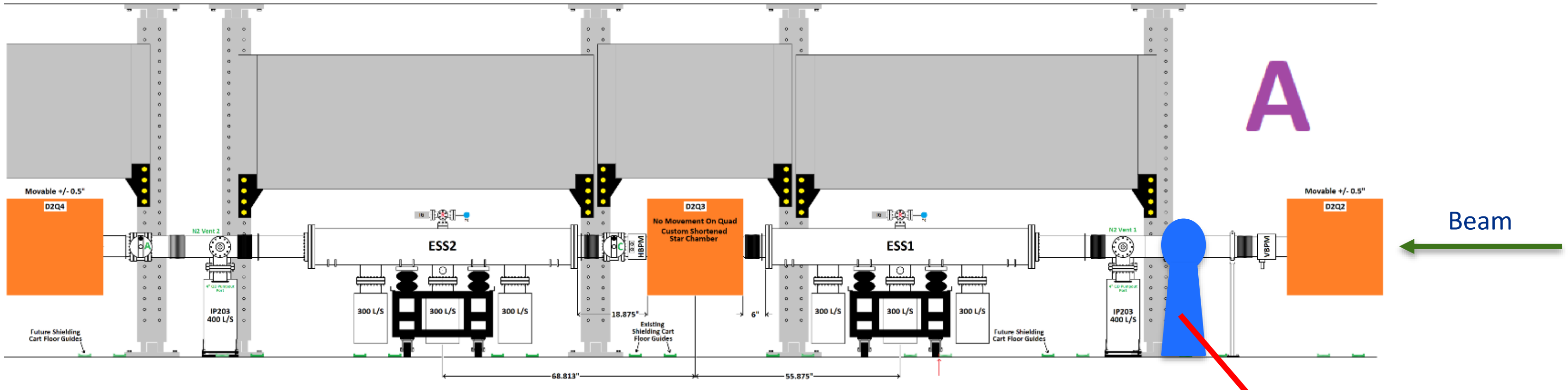


Fermilab

# Modelling the crystal collimation (shadowing)

1. Proof-of-principle study using the fixed crystal geometry
2. Explore the crystal parameter space

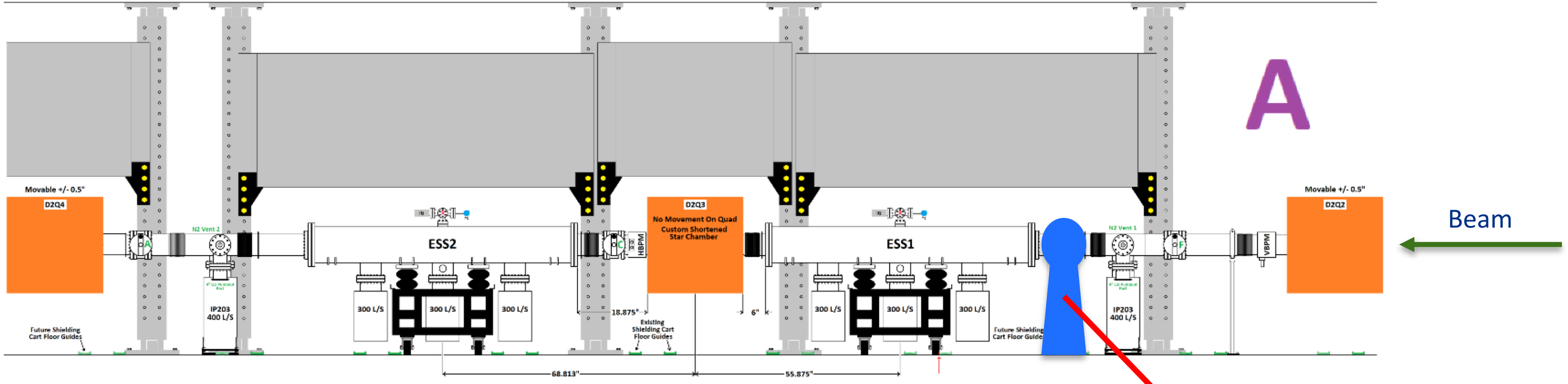
# Modelling the effect of the crystal shadowing in the DR




Proposed tunnel location for the Crystal Collimator

- Space available
- Sufficient phase advance

# Modelling the effect of the crystal shadowing in the DR




Proposed tunnel location for the Crystal Collimator

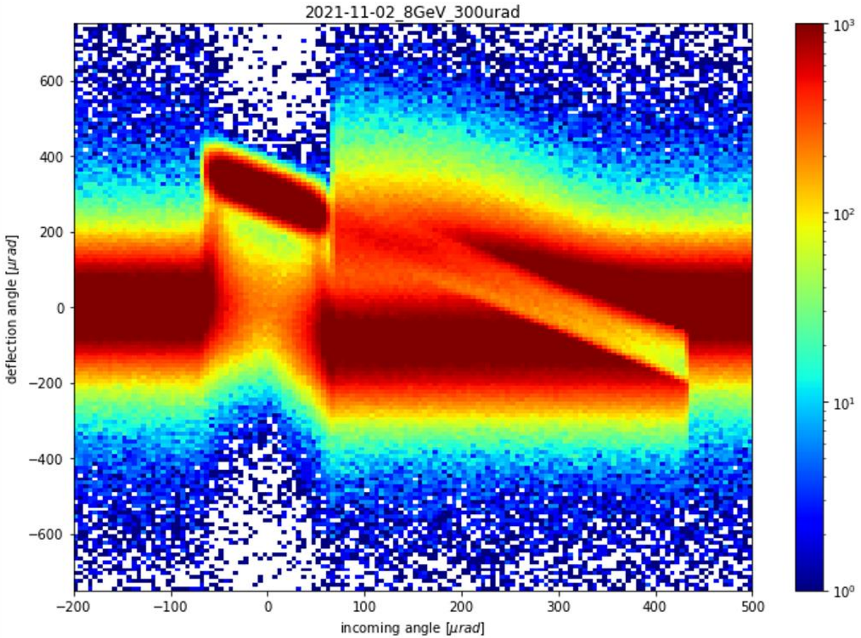
- Space available
- Sufficient phase advance

# 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*



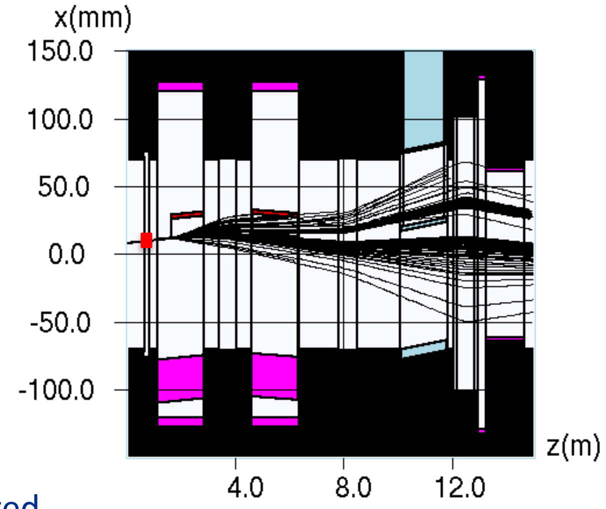

Fermilab

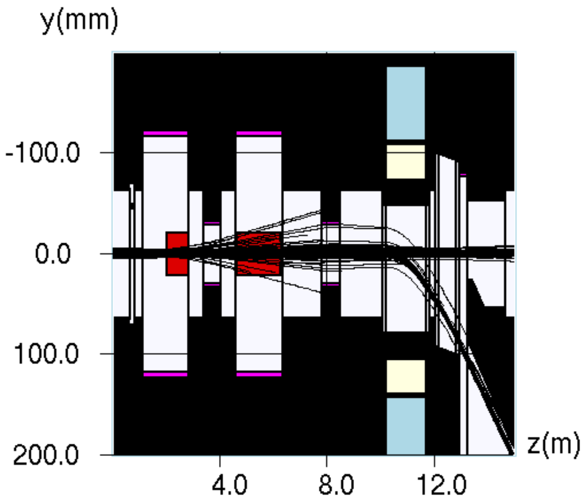
# Phase II: Accelerator tracking using MARS

## 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:

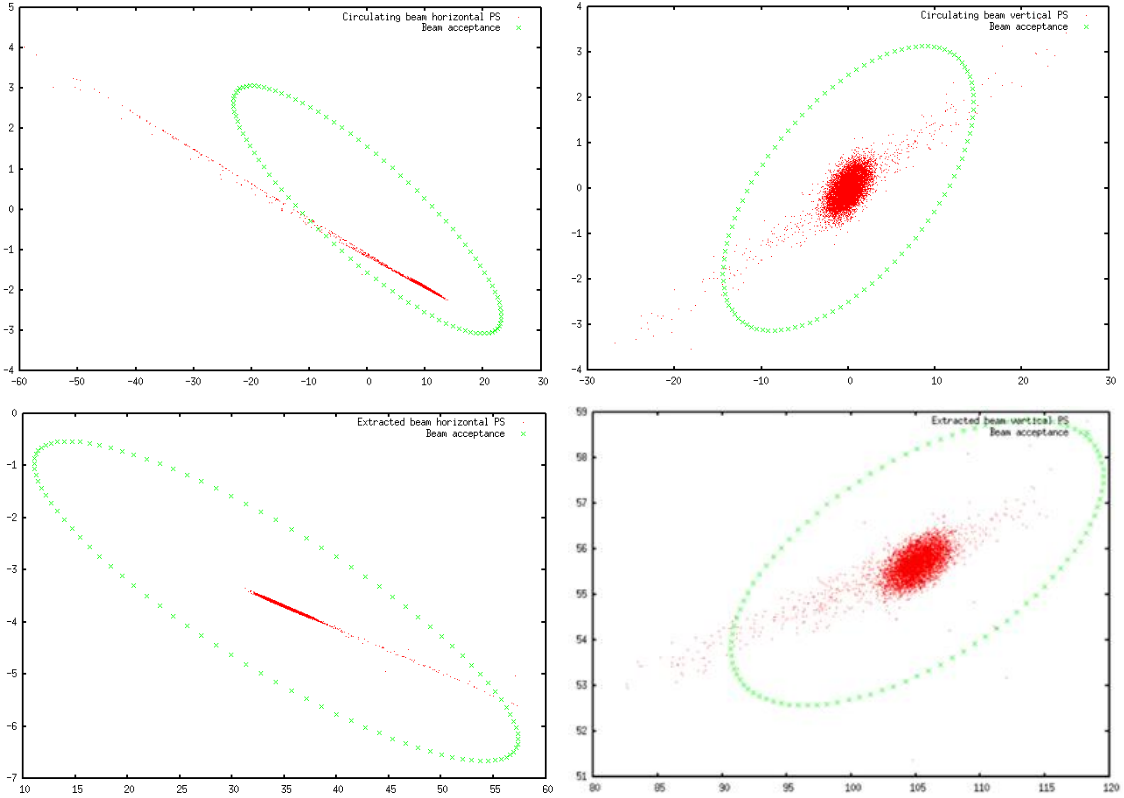
Pass through the Extraction section (survived in tracking)

Filter 2:

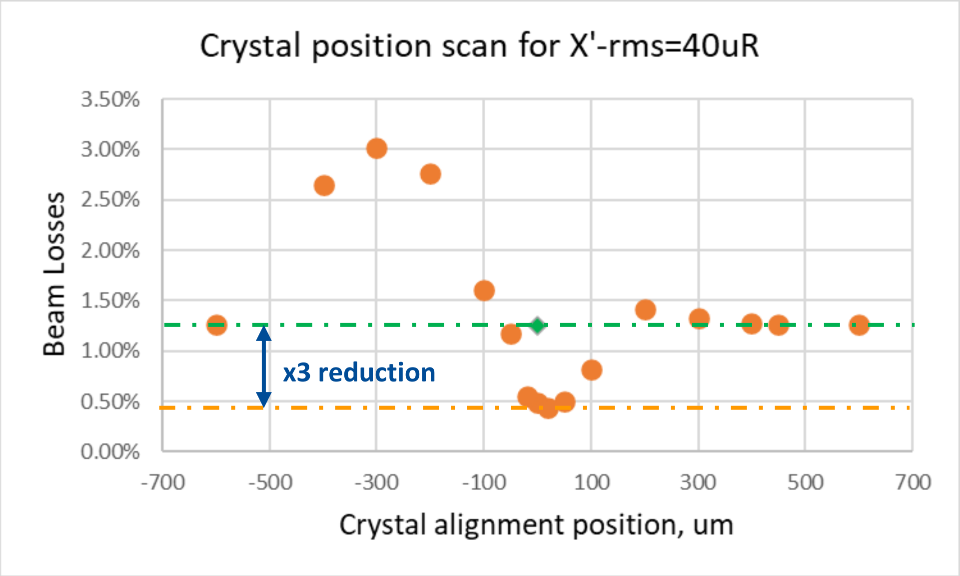
Stay in the aperture (within green ellipses)

Nominal Eff=98.5%

MARS tracking reproduces the design performance

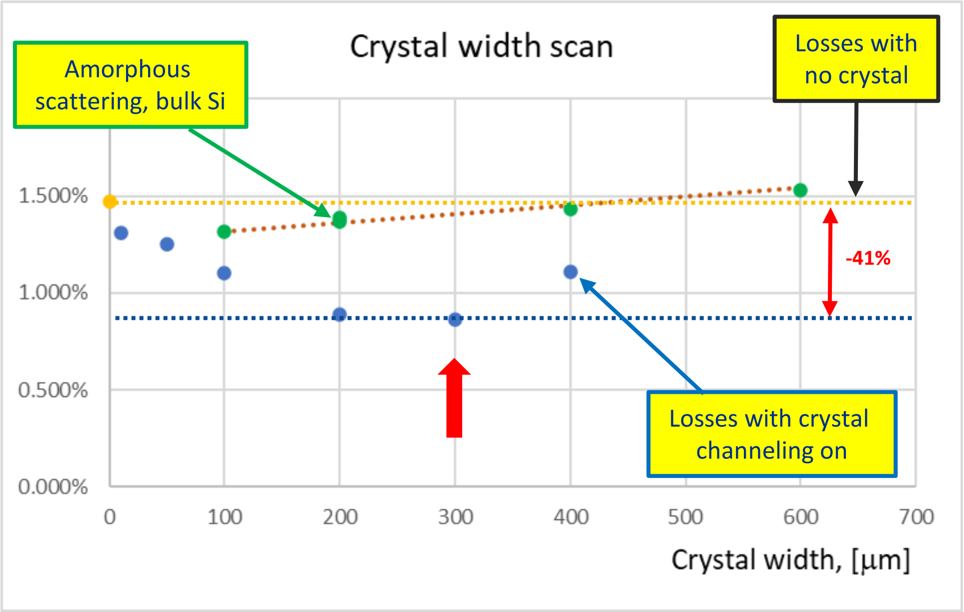


# Effect of crystal channeling for the beam design parameters




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

Nuclear Instruments and Methods in Physics Research A 1058 (2024) 168892

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

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

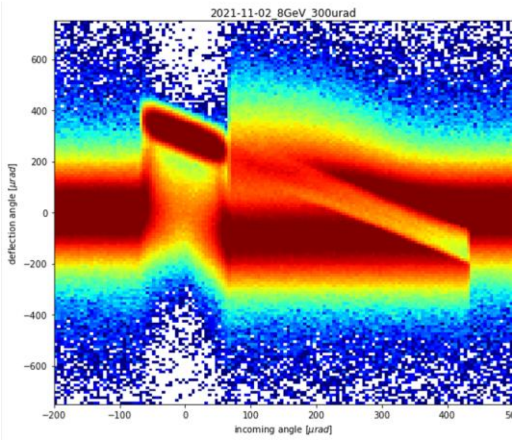
V. Nagaslaev [a,*], I. Tropin [a], L. Esposito [b], M. Fraser [b], B. Goddard [b], F. Velotti [b], L. Bandiera [c], V. Guidi [c], A. Mazzolari [c], M. Romagnoni [c], A. Sytov [d]

[a] *Fermi National Accelerator Laboratory, USA*
[b] *CERN, Switzerland*
[c] *Università di Ferrara, INFN Ferrara, Italy*
[d] *Università di Ferrara, INFN Ferrara, KISTI, South Korea*

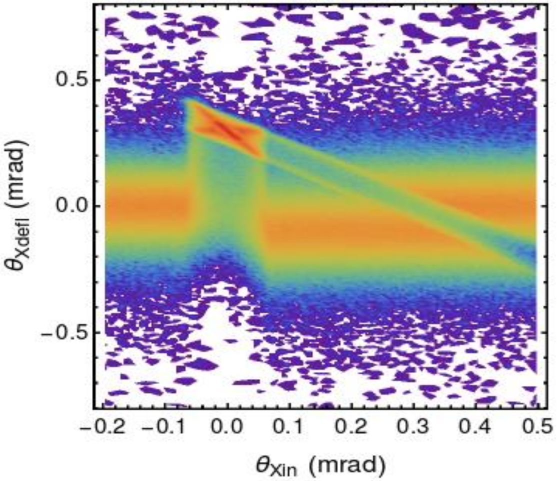
# Crystal parameters optimization: WIP

# 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)

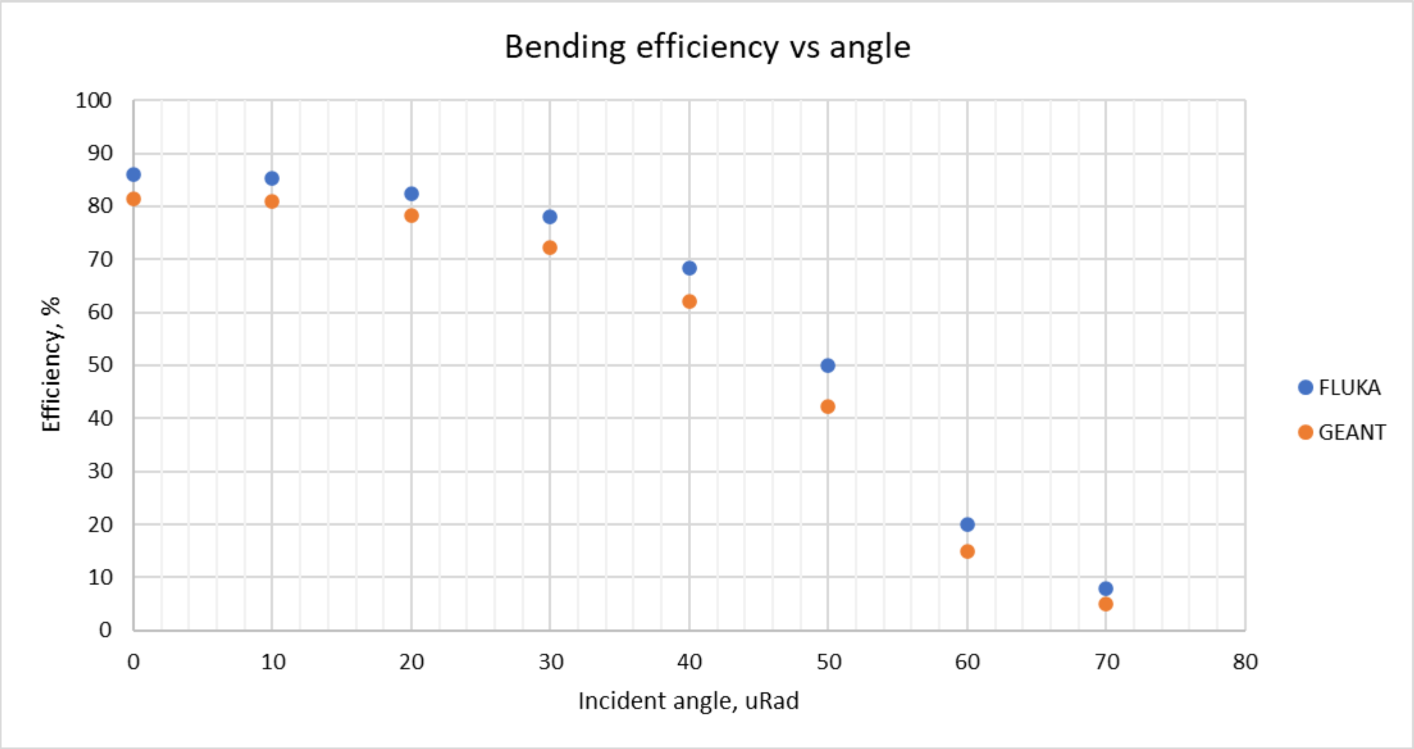



GEANT, b=300uR, L=0.4mm

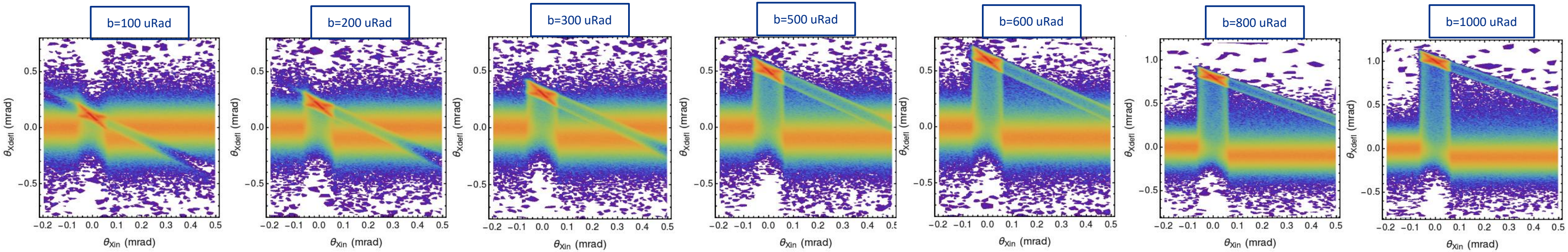



FLUKA, b=300uR, L=0.4mm

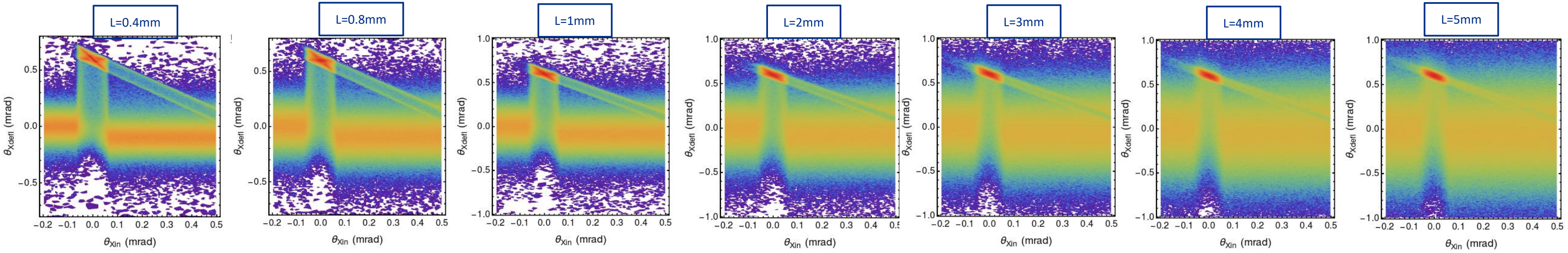
# Bending efficiency comparison for 300uR bending crystal, FLUKA vs GEANT



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

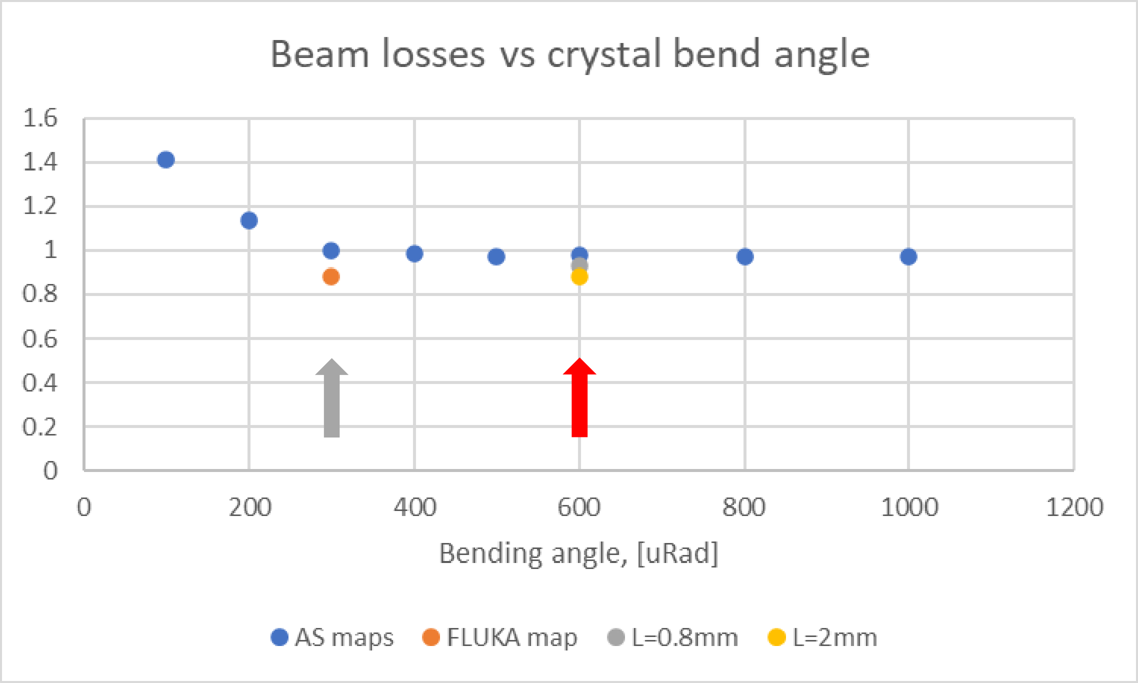



Crystal scattering PDF maps with L=0.4mm, bend=100-1000uRad

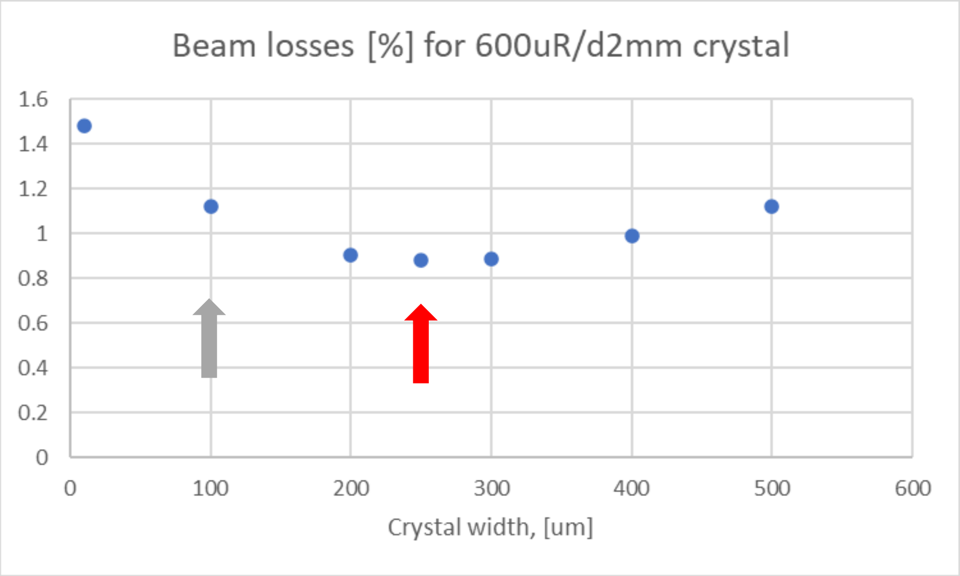



Crystal scattering PDF maps with bend=600uRad; L=0.4mm -5mm

# Beam loss comparison for L=0.4mm bending crystal, varying bending angle

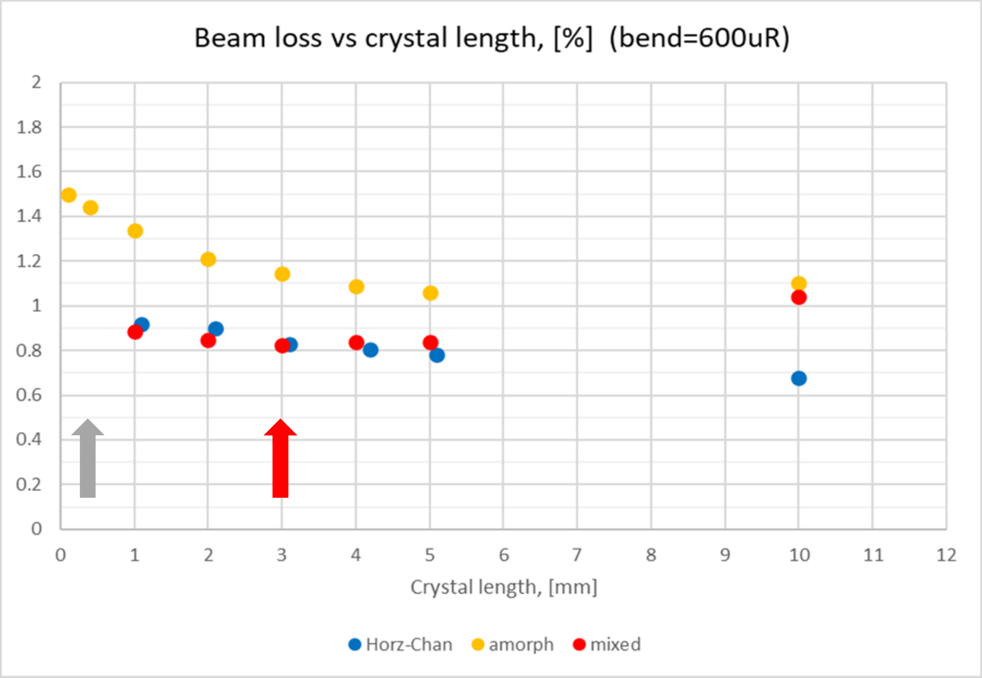


# Beam loss comparison for L=2mm crystal, 600uR bending; variable hor. width



# 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



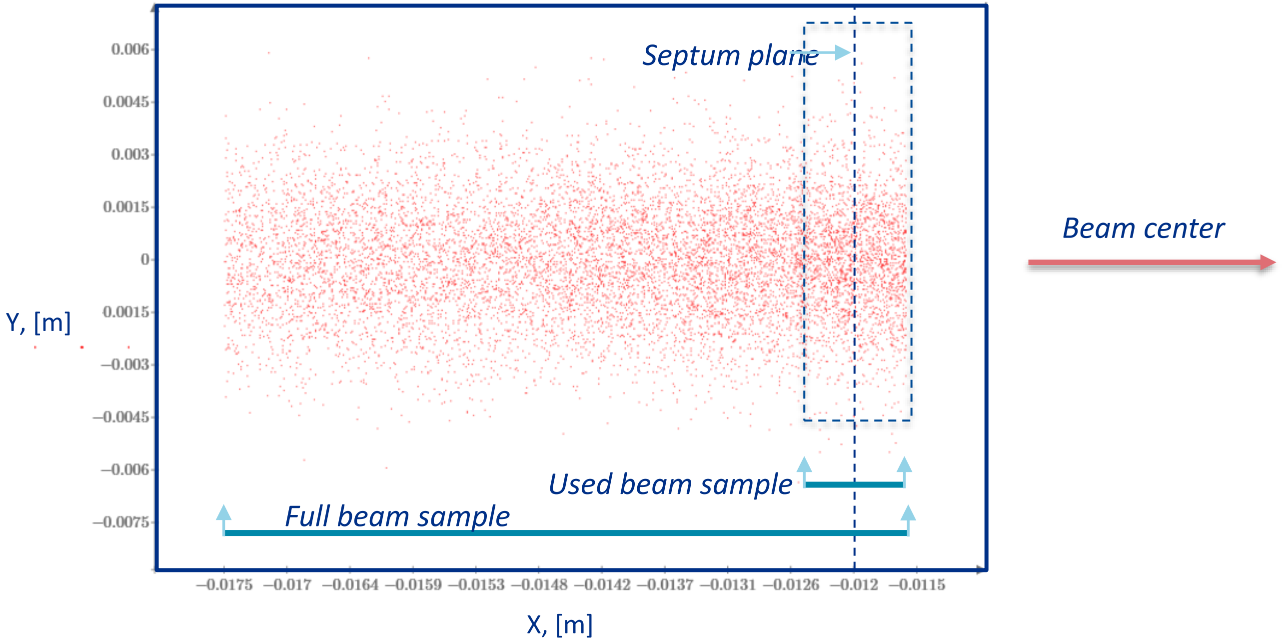
# Conclusions

- 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

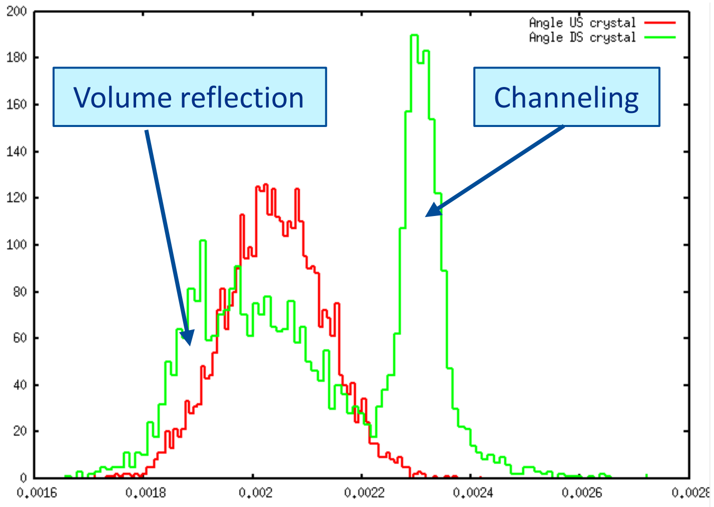




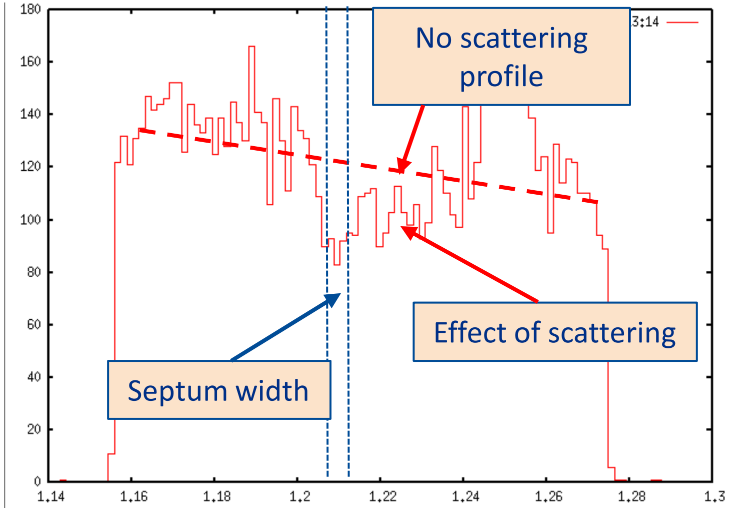

Fermilab

# Crystal collimation efficiency – first trial

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




Proton angles at the crystal entrance and exit

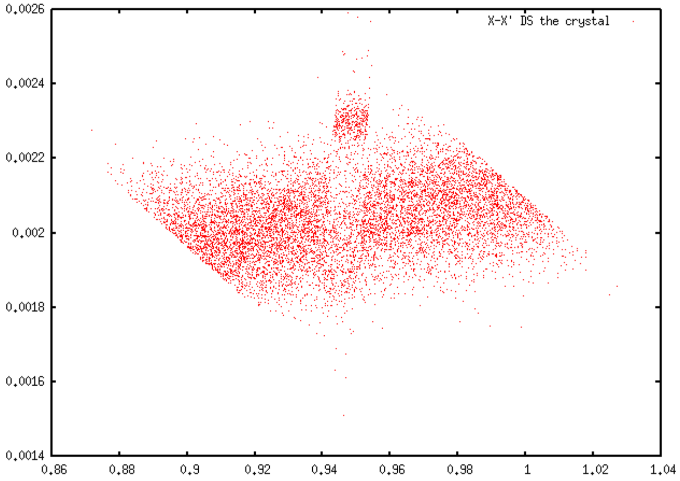



Projected beam profile at the septum entrance

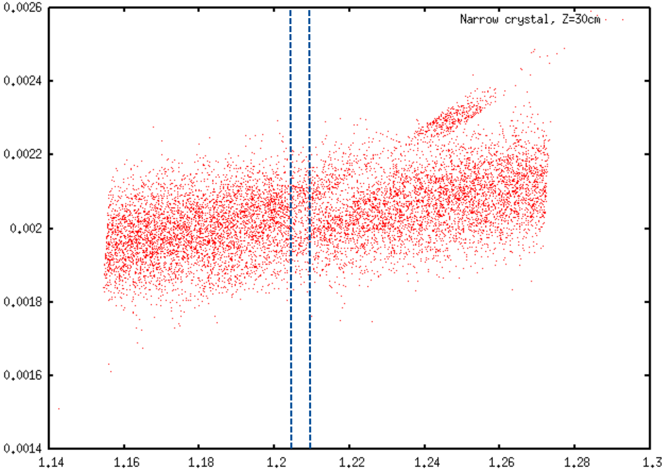
Efficiency improvement is modest – about 10%

# Mixing in the beam phase space at septum

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




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

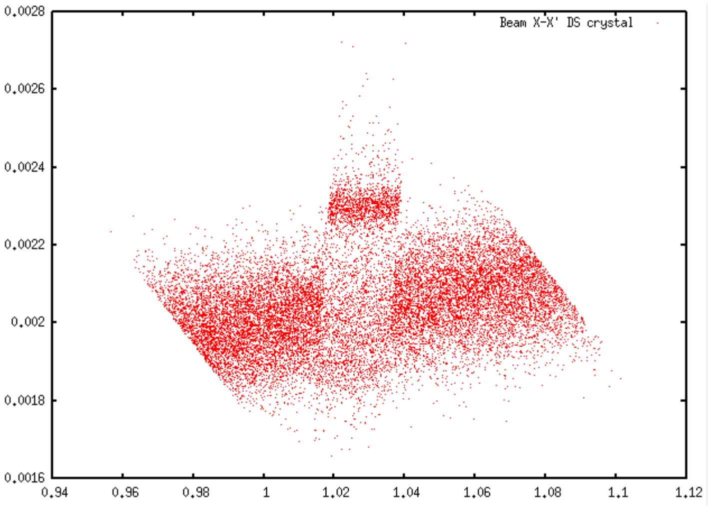



Phase space (X-X' plane)
at septum entrance

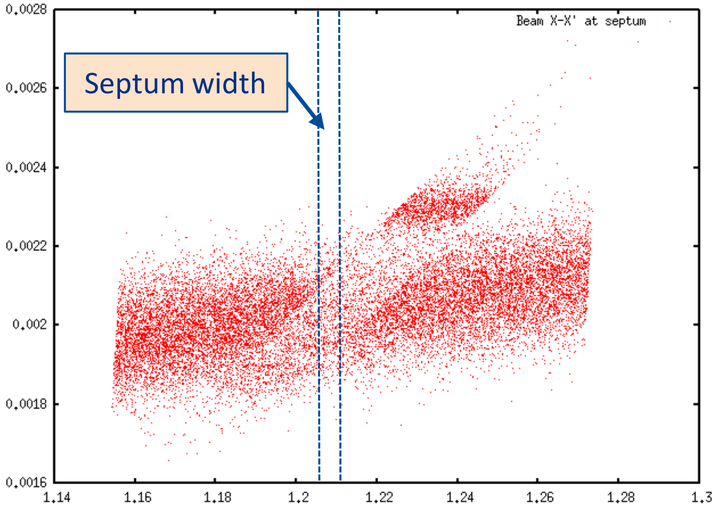
A lot of destructive mixing due to the angle spread

# Mixing in the beam phase space at septum – new location & width

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



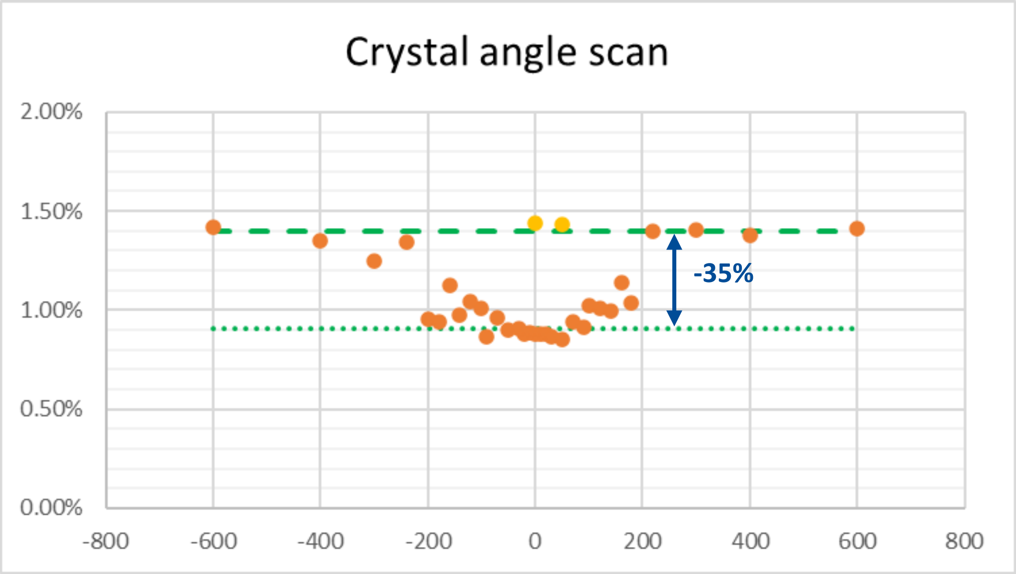

Phase space (X-X' plane)
at crystal exit




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