# Crystal Channelling for Hadron Therapy Accelerators

SURE/CERN Summer Student Programme 2022

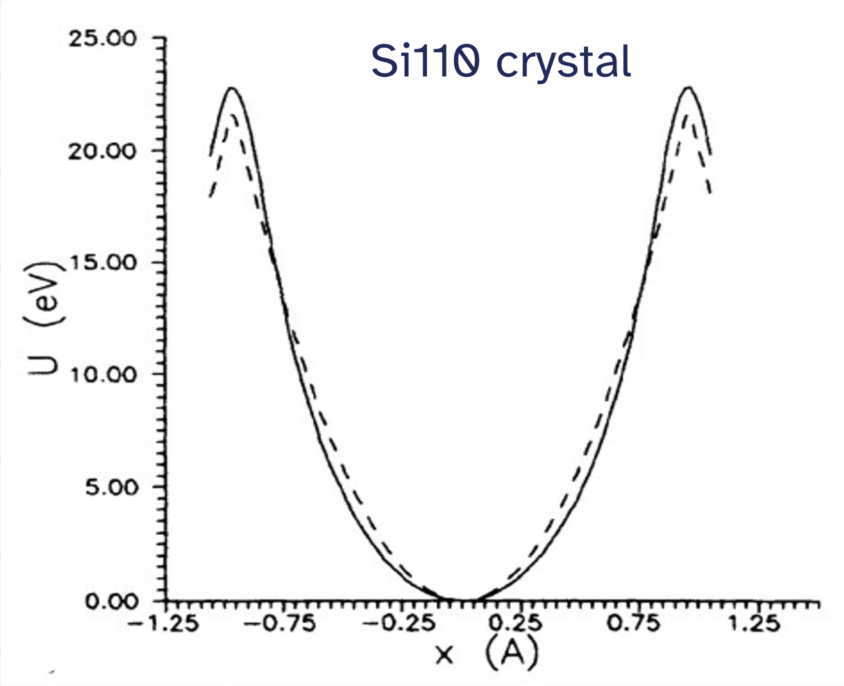
Boris Ng, 21/08/22

# 01

# Introduction

# Intro: Crystal Channelling

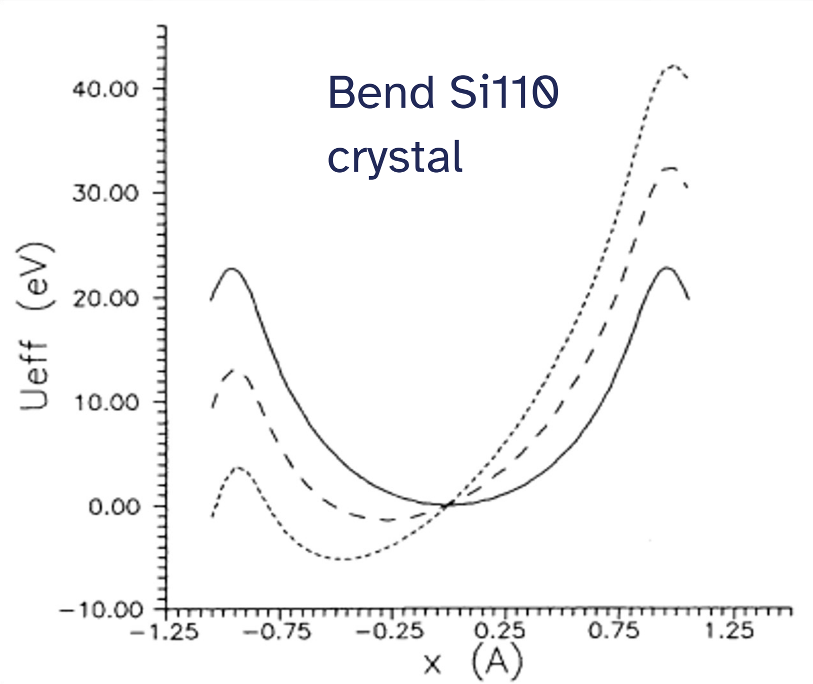
- In a crystal:
  - Periodic structure
  - Continuous potential well
  - Trap & guide particle
  - Pass through without much energy loss




Potential plot of Si110 crystal of different curvature. Adapted from: Biryukov, Chesnokov and Kotov (2013)

# Intro: Crystal Channelling

- With slight bending:
  - Similar potential
    - Slightly lower by centrifugal force
  - Particles bend with crystal
  - Beam extraction
- Adv:
  - Smaller size
  - No power needed
  - Radiation hard




Potential plot of Si110 crystal of different curvature. Adapted from: Biryukov, Chesnokov and Kotov (2013)

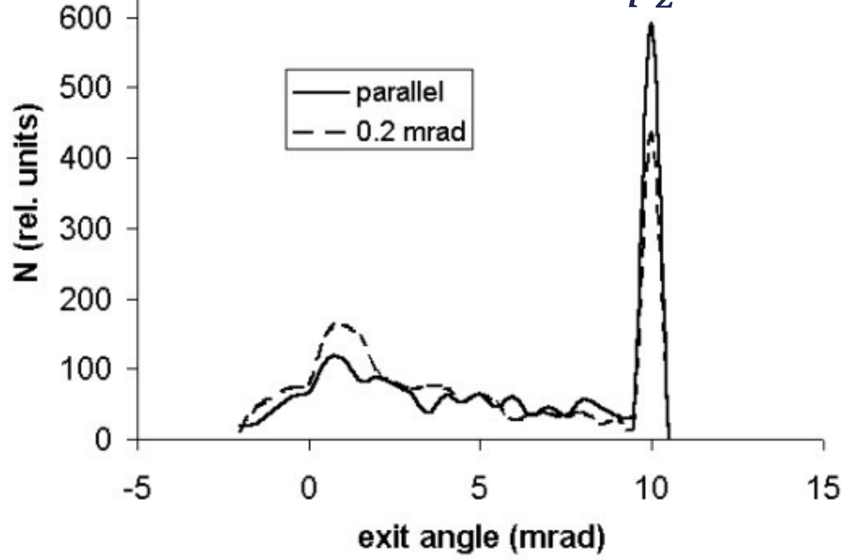
# Intro: Dechannelling

- Some particles will escape (dechannelled)
- Diffusion approach
  - Dechannelling Length $L_D(pv, R) \sim \frac{E_c(pv/R)}{E_c(0)}$
    - Decrease with $pv$
  - Fraction of channelled $\sim \exp(-z/L_D)$

| $p$ | $v$ | $E_c$ |
|---|---|---|
| Particle momentum | Particle velocity | Crystal Potential |

| $1/R$ | $z$ |
|---|---|
| Crystal Curvature | Distance travelled in Crystal |

Angle $\theta = \frac{dx}{dz} = \frac{p_x}{p_z} \stackrel{\text{def}}{=} x_p$




Histogram of exit angle combining channelling and dechannelling effect.
Adapted from: Bellucci and Biryukov (2007)

# Can crystal channelling be used for beam extraction in hadron therapy accelerator?

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# Crystal in Isolation

## Varying Energy

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# Isolation: Methodology

- **BDSIM** (program that simulate beam transportation and interaction)
- Setup:
  - **Proton square beam** (envelope:

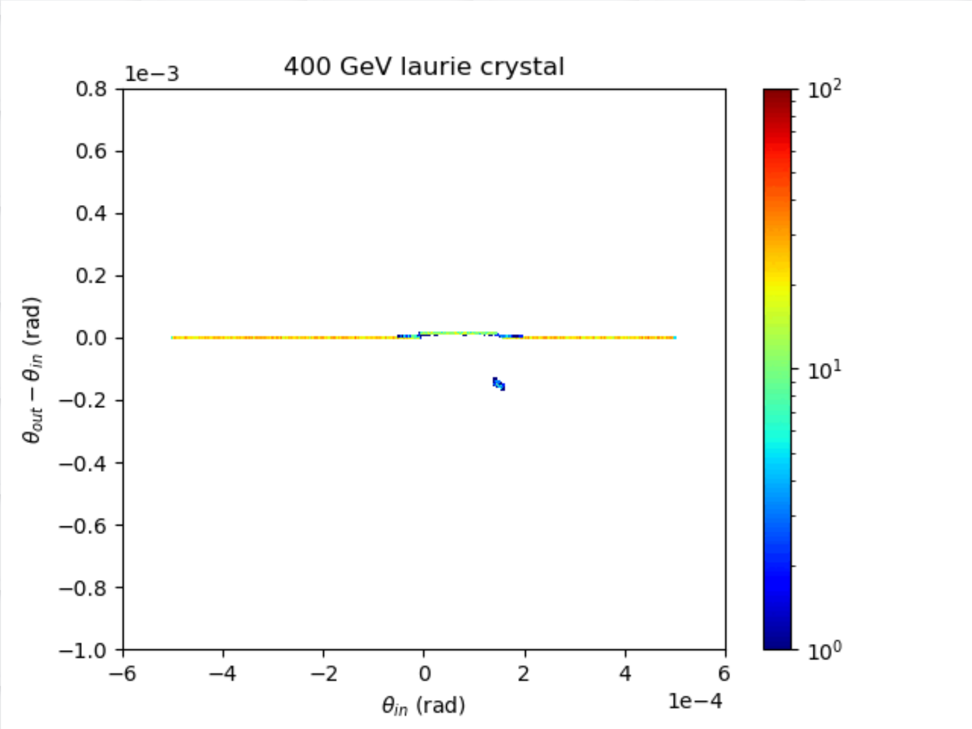
| $x$ | $x_p$ | $y$ | $y_p$ |
|---|---|---|---|
| 0.4cm | 5E-4 | 0 | 0 |

)
  - **Silicon 110 crystal** (cross section: 4cm x 4cm)
    - In the middle of a collimator (length: 30 mm)
    - Rotated by half the bending angle
  - 3 drift tubes (length: 1cm)
  - 1 drift tube (length: 3m, radius: 1.5m)

# Isolation: Results

- Beam energy from 400 to 1.078 GeV (KE: 140MeV) (in uneven steps)
- Diamond-shaped channelled region
- Dechannelled region (y value >0)

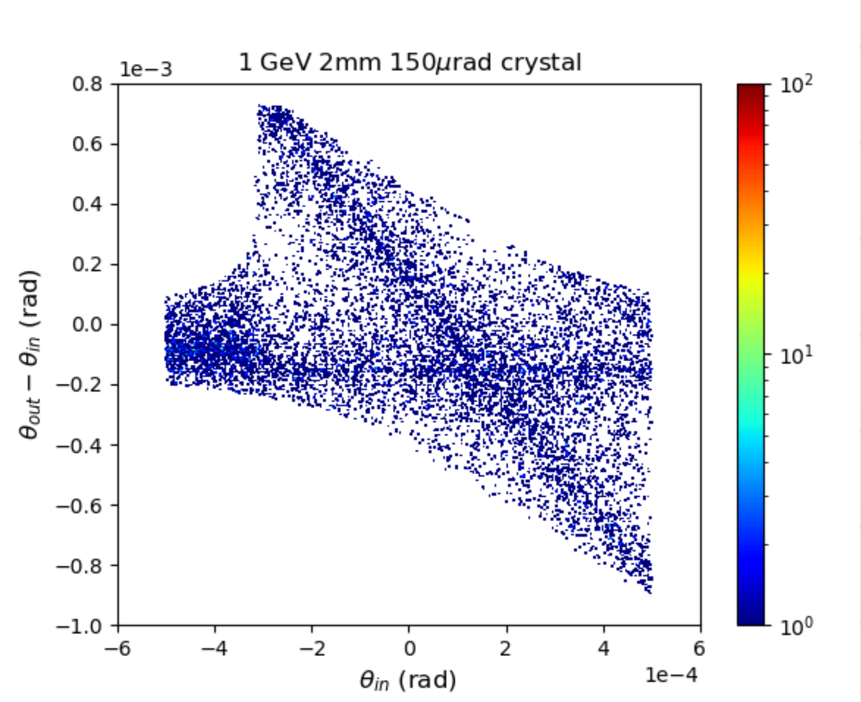
- Channelled region:
- Higher energy
  - Smaller spread in $\theta_{in}$
  - Smaller spread in $\theta_{out} - \theta_{in}$




$\theta_{out} - \theta_{in}$ against $\theta_{in}$ plot at different energies.

# Isolation: Results

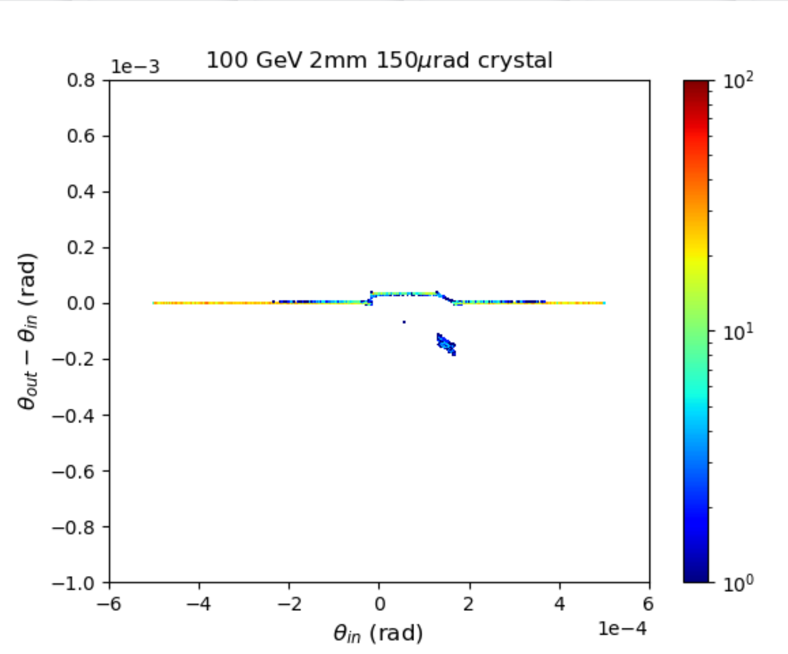
- 1.078 GeV (KE = 140 MeV):
  - Typical energy in hadron therapy accelerator
  - Only 1 diamond region
  - Very large spread
    - Difficult to extract correctly bended
    - Not useful
- ✗ crystal channeling for typical hadron therapy




$\theta_{out} - \theta_{in}$ against $\theta_{in}$ plot at 1.078 GeV.

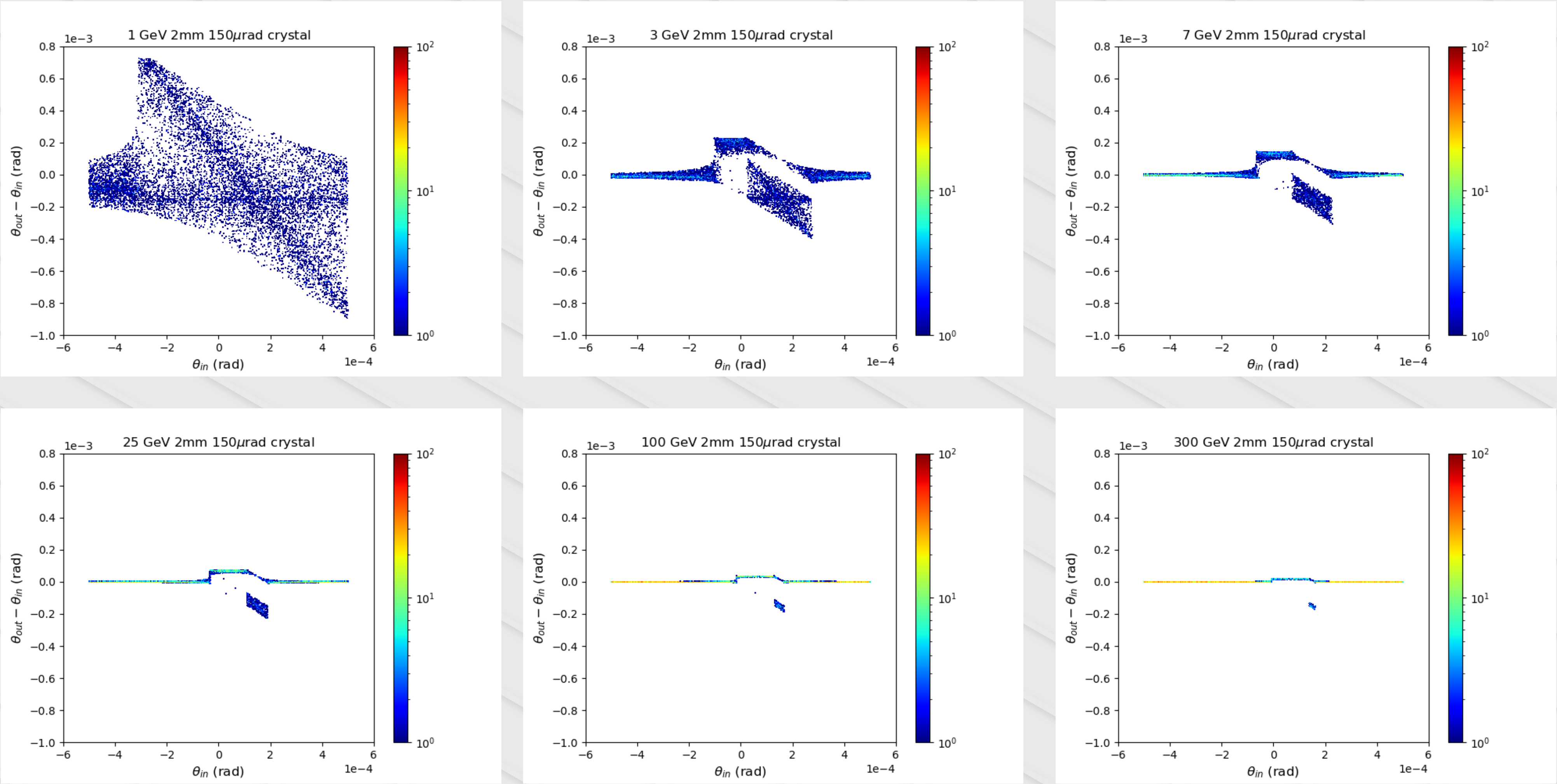
# Isolation: Results

- High energy:
  - Distinct (de)channelling regions
  - ⇒Can make use of channelling
  - More particles get dechannelled
  - ⇒Dechannelled region may be more useful



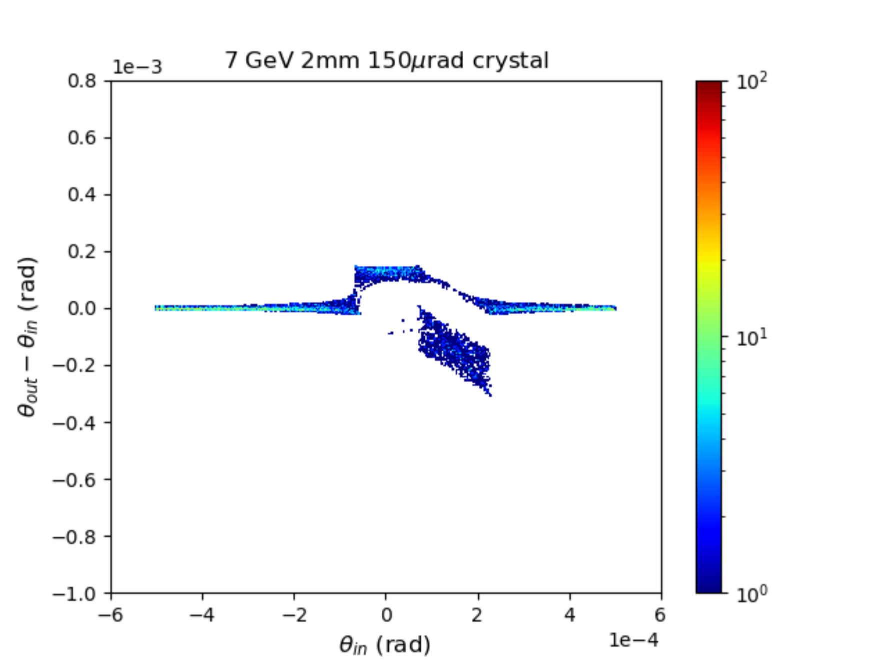

$\theta_{out} - \theta_{in}$ against $\theta_{in}$ plot at 100 GeV.

# Isolation: Results



# Isolation: Discussion

- Spread in $\theta_{in}$: volume capture
  - Dechannelled particles can be capture
  - Probability $w_S = const \frac{R}{(pv)^{3/2}}$
  - More likely at low energies
  - Low energy : Higher spread in $\theta_{in}$




$\theta_{out} - \theta_{in}$ against $\theta_{in}$ plot at 7 GeV.

# Isolation: Discuss

- Spread in $\theta_{out} - \theta_{in}$: Diffusion approach
  - Fraction of channelled particle $\sim\exp(-z/L_D)$
  - $L_D$ decrease with beam energy
  - Low energy:
  - More dechannelling
  - High Spread in $\theta_{out}$ & thus $\theta_{out} - \theta_{in}$

From Introduction

- Diffusion approach
  - Dechannelling Length $L_D(pv, R) \sim \frac{E_c(pv/R)}{E_c(0)}$
    - Decrease with $pv$

# Isolation: Discuss

- ✗ crystal channeling for typical hadron therapy acceleartors
- But...
- Higher energy radiotherapy exist (FLASH therapy)
- Still not high enough though
- Channelling maybe useful in the future

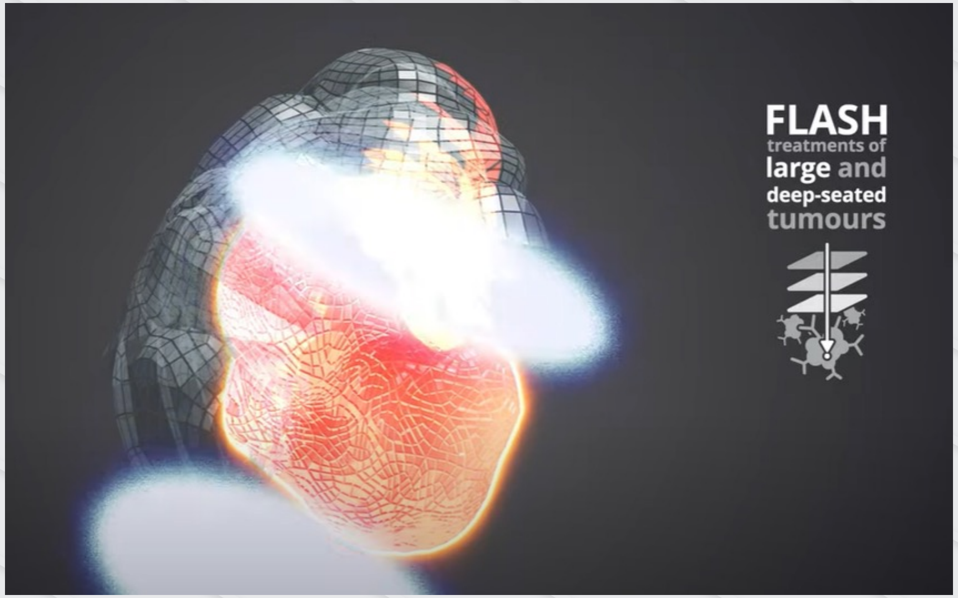



Illustration of FLASH therapy.
Adapted from: CERN (2021).

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# 03

# Crystal in PIMMS

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# PIMMS: Methodology

- PIMMS lattice model from Rebecca
- **BDSIM**
- Beam energy: **KE=1.2GeV** (**max energy** PIMMS can deliver)
- Replace the extraction septum magnetic with
  - **Crystal**: Si110, Length 2 mm, Bending angle 150 µrad, Cross section 4cm x 4cm, in the middle of an 80cm collimator
  - **Drift tube**: Length 80 cm
- 50 turns, 2k particles

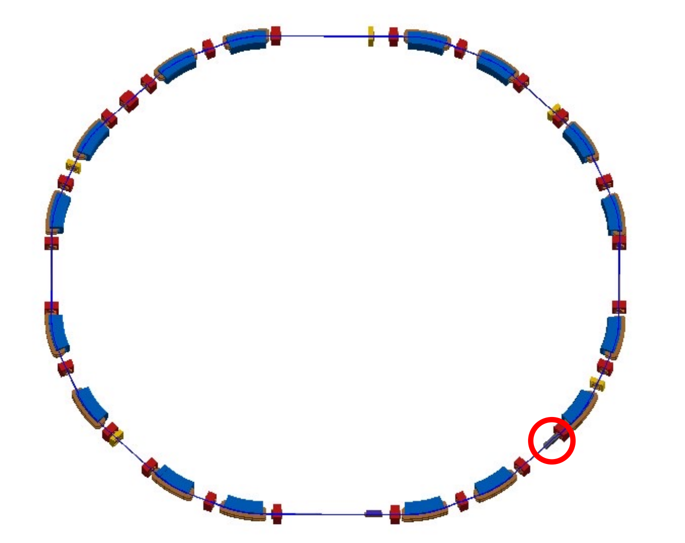
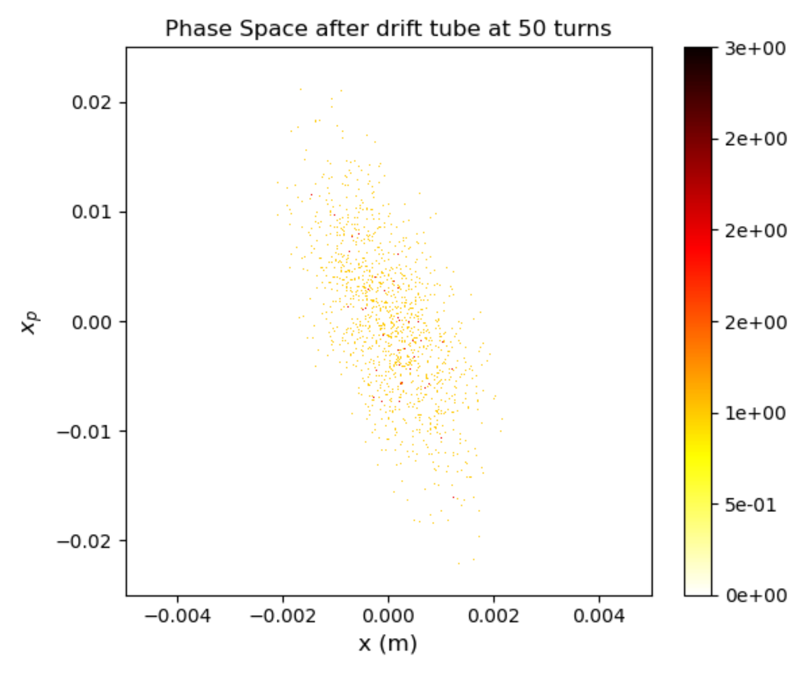
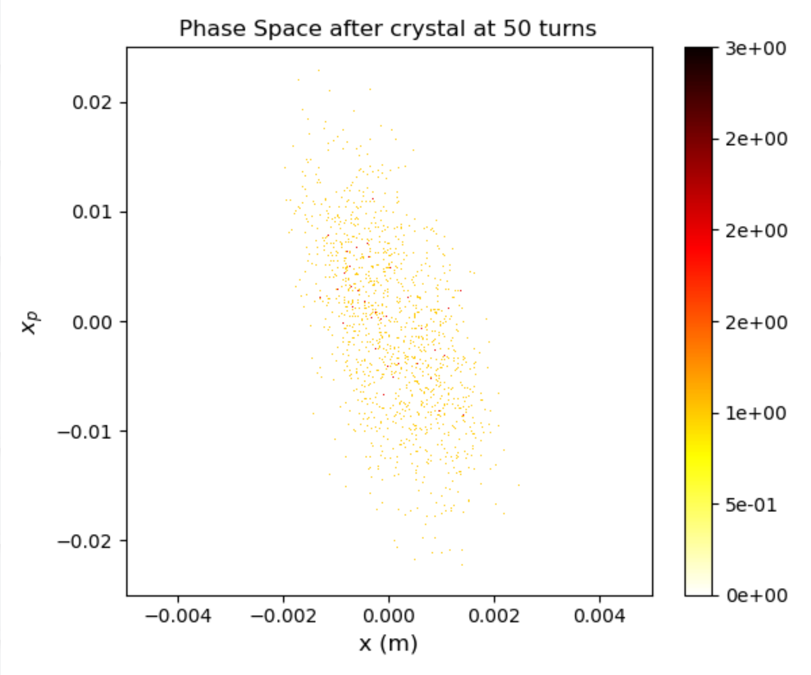


Illustration of PIMMS.

# PIMMS: Results

- Phase diagram
  - Mostly similar
  - Slightly larger spread in $x$ for PIMMS lattice with crystal

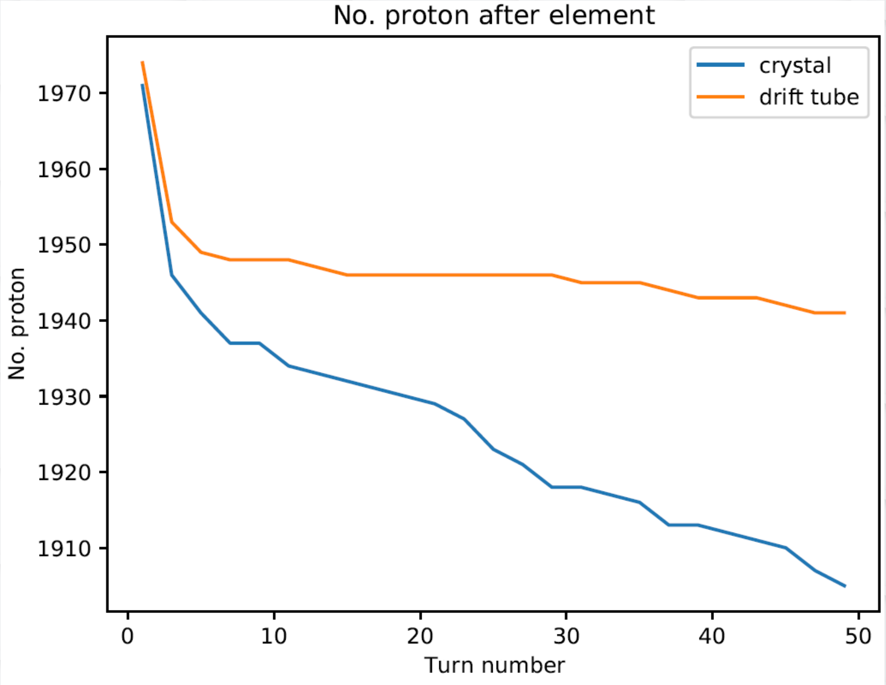



Phase diagram of particles corresponding to PIMMS with drift tube and crystal.

# PIMMS: Results

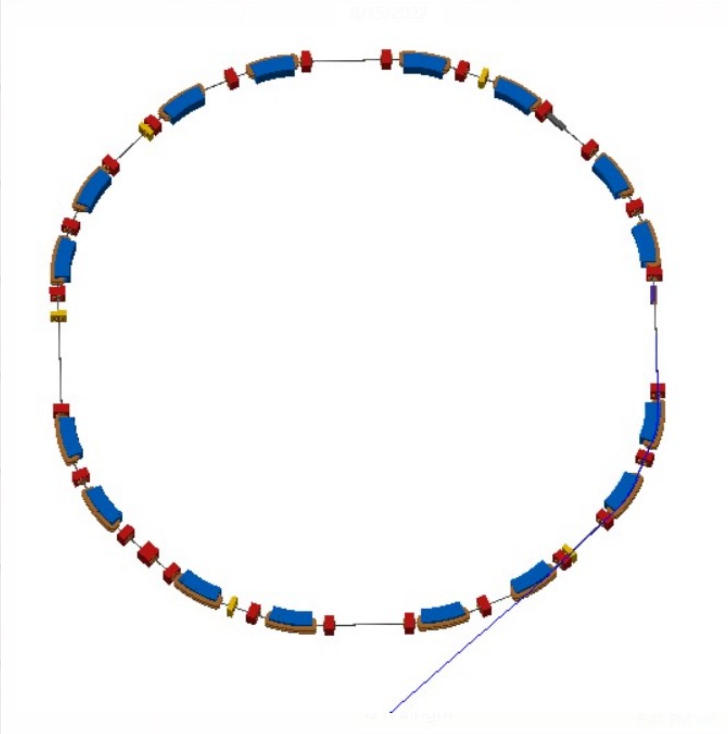
- Number of particle pass through
  - Crystal has sig. less particle
  - Maybe applicable for future high energy medical accelerator




Number of particles against turn number plot corresponding to PIMMS with drift tube and crystal.

# PIMMS: Points to Note

- Small no. particle
- Highly dependent on initial condition
  - Sometimes escape without even completing the 1st loop
  - Need more run to verify the result
- Small turn number (50)
- Crystal parameters not optimized



# 04

# Conclusion

# Conclusion

- For the parameter space covered, crystal channelling is not applicable in current hadron therapy accelerator
- However...
- At high energy, channelling has practical use

- If even higher energy therapy method is developed
- ⇒ Crystal channelling maybe useful in the future

# Reference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# THANKS

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