INTRODUCING CHANNELING EFFECT

Enrico Bagli

on the behalf of G4CMP working group

Motivation

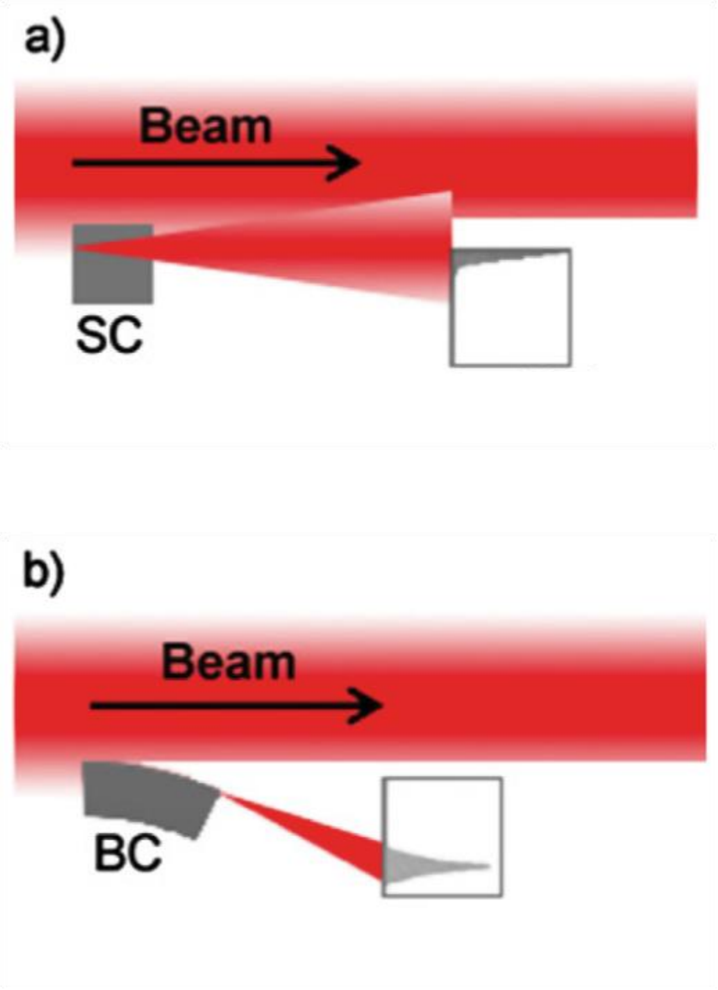
- *“Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science.”*
- In October 2012 the first Geant4 release with support for crystal structures was released.
- Processes of solid state physics can be implemented to obtain more realistic simulation of current experiments which use crystals in their experimental apparatus.
- Channeling can strongly affect physical process of charged particles in crystals.

Motivation

- Stand-alone software to simulate channeling do not allow to consider all the processes already implemented into Geant4.
- Geant4 is continuously updated and physics models have been extensively validated (no need to reinvent the wheel).
- Implementation of channeling into Geant4 can lead to:
  - evaluation of channeling influence on current simulation made with Geant4
  - addition of the Geant4 toolkit advantages to the simulation of current and new experiments based on channeling (e.g. beam collimation and extraction with crystal)

Crystal collimation

- Crystal can be used as a primary collimator to deflect particles of the halo toward a secondary collimator.
- Main advantage is the possibility to deflect the beam out and reduce the beam losses.

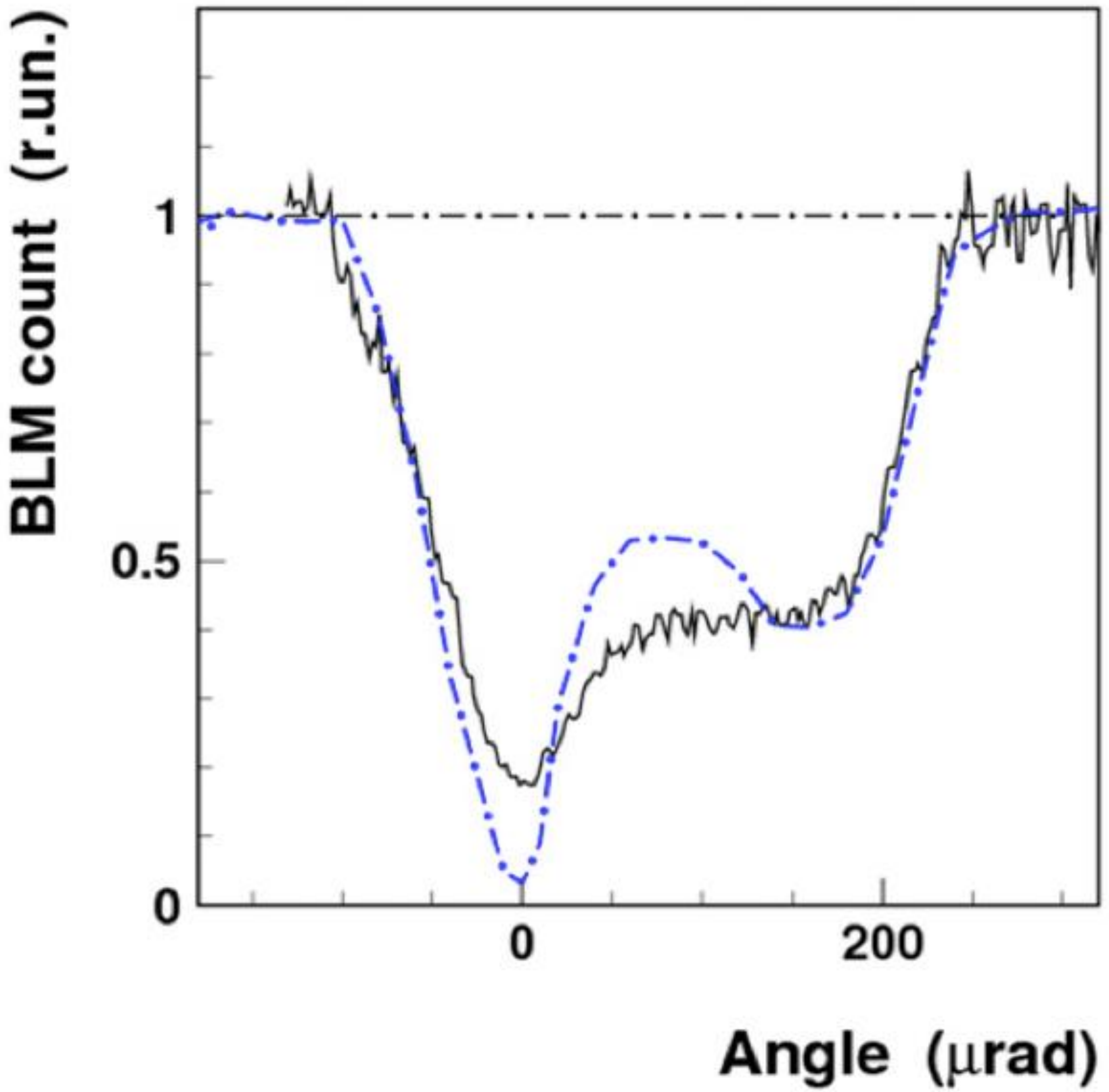


a) standard collimation system
b) crystal collimation system

W. Scandale et al. PLB 692, 72 (2010)

Beam loss reduction

Measurement of the ratio of the beam loss in the CERN SPS ring with 120 GeV/c protons and Si (110) crystal varying the crystal orientation with respect to beam direction.



W. Scandale et al. PLB 703, 547 (2011)

Crystal extraction

- Measurement of the extraction efficiency in the IHEP U-70 accelerator with short Si (110) crystals.

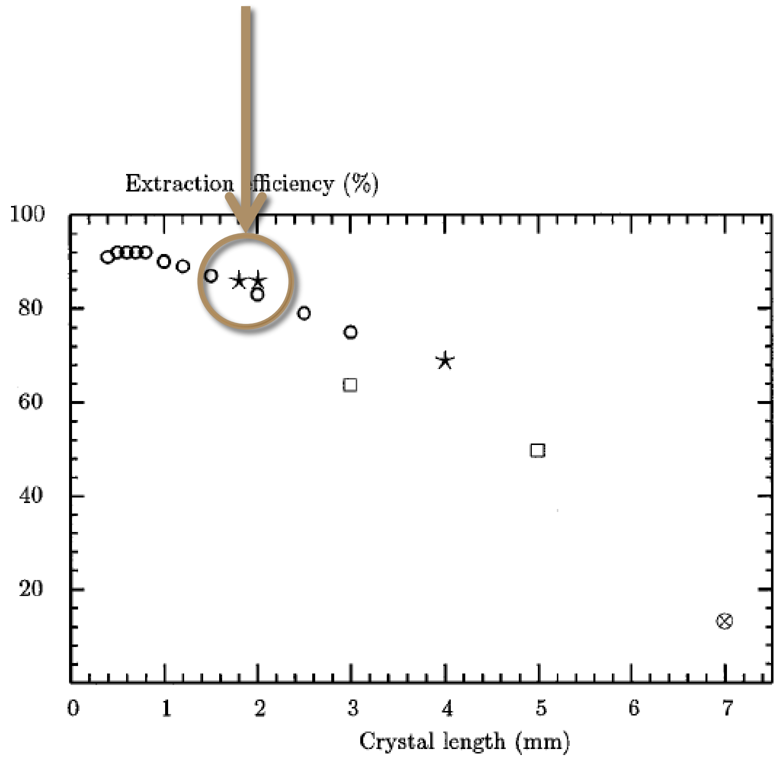


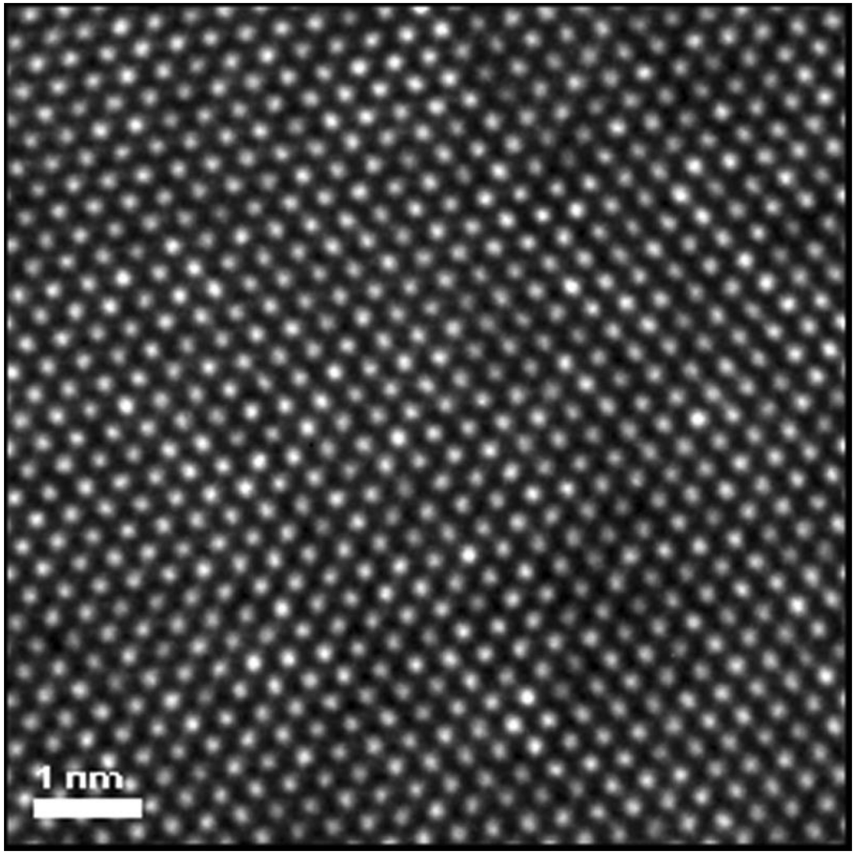
FIG. 3. Crystal extraction efficiency as measured for 70-GeV protons. Recent results [(★), strips 1.8, 2.0, and 4 mm], 1999–2000 [(□), O-shaped crystals 3 and 5 mm], and 1997 [(⊗), strip 7 mm]. Also shown (∘) is the Monte Carlo prediction for a perfect crystal with 0.9 mrad bending.

A. G Afonin et al. PRL 87, 094802 (2001)

Channeling phenomenon

Crystal

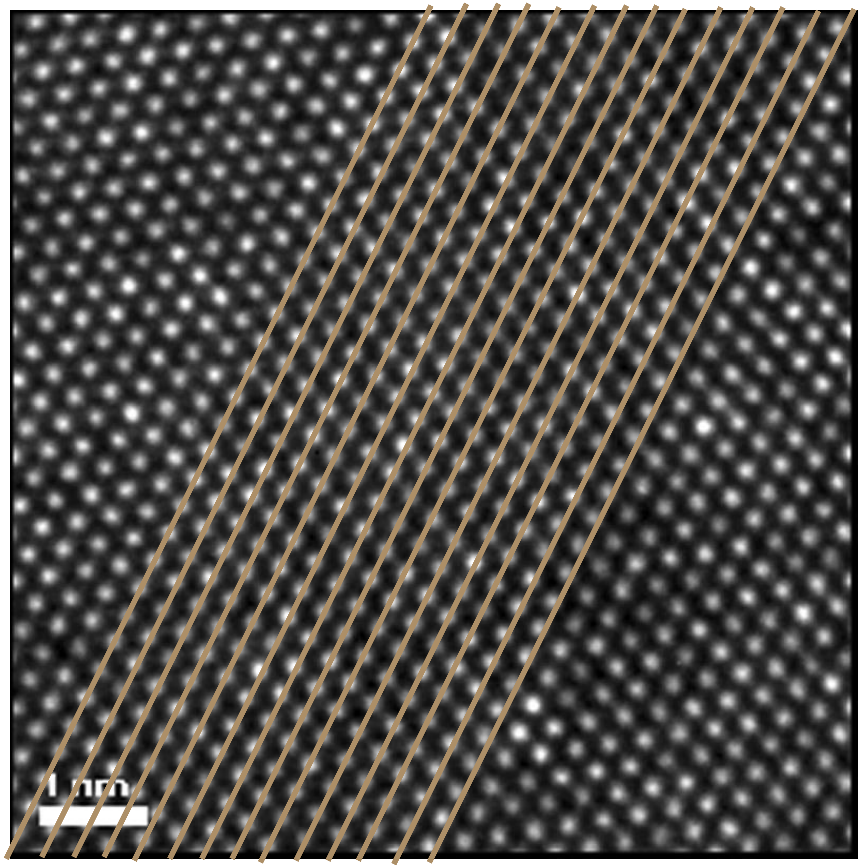
- Ordered pattern of atoms.



Ki-Bum Kim, SPIE Newsroom, DOI: 10.1117/2.1200812.1396

Crystal

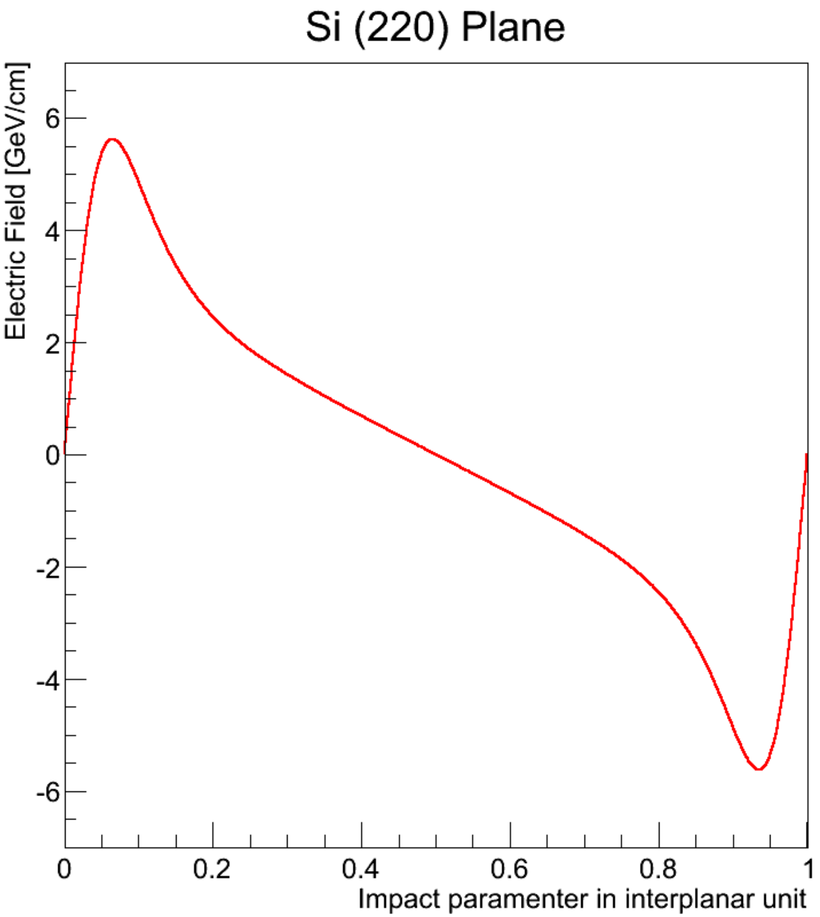
- Ordered pattern of atoms.
- Aligned atoms can be seen as planes or axes.



Ki-Bum Kim, SPIE Newsroom, DOI: 10.1117/2.1200812.1396

Crystal

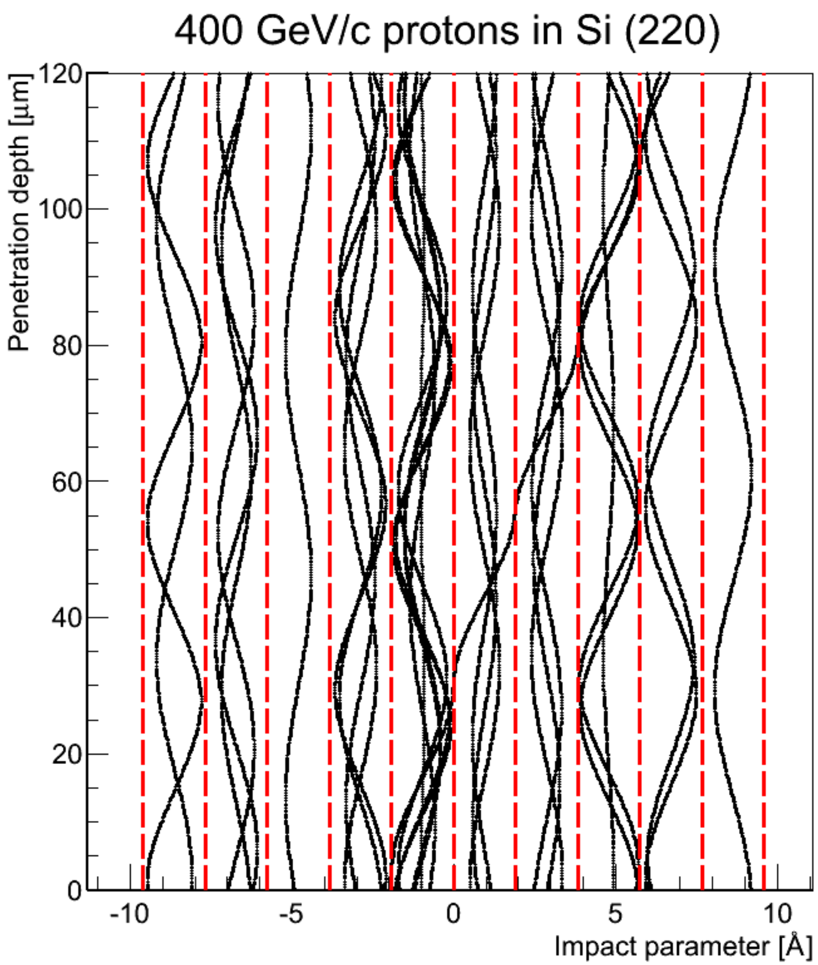
- Ordered pattern of atoms.
- Aligned atoms can be seen as planes or axes.
- Strong electromagnetic field between planes and between axes (GeV/cm).



ECHARM - E. Bagli, V. Guidi, V. A. Maisheev, PRE 81, 026708 (2010)

Crystal

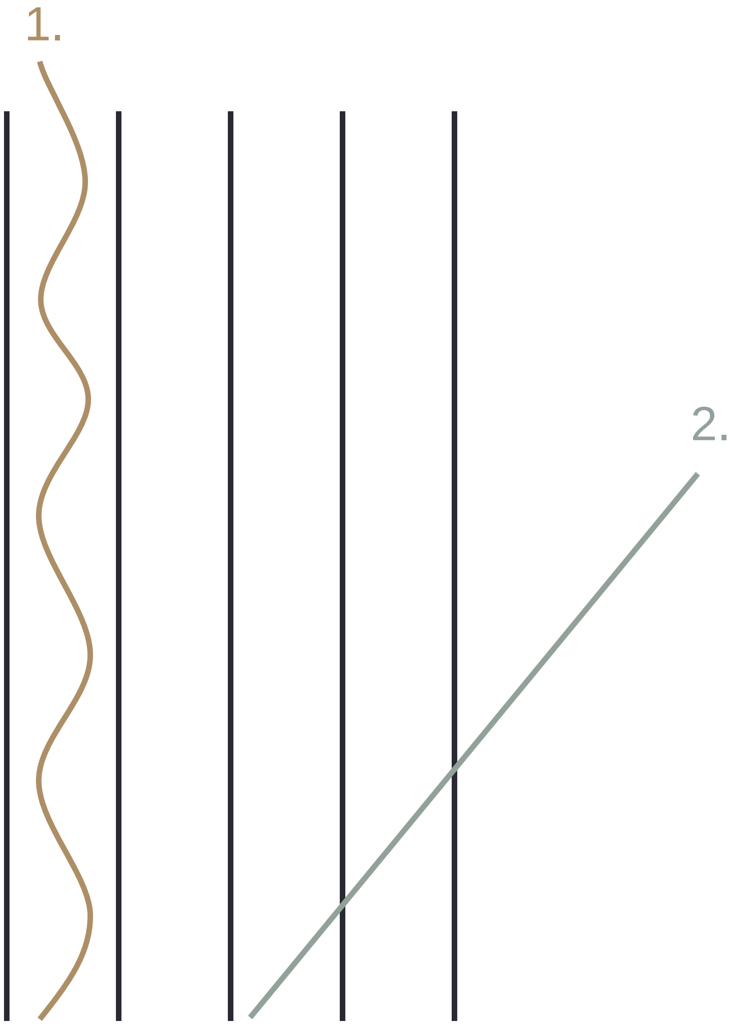
- Ordered pattern of atoms.
- Aligned atoms can be seen as planes or axes.
- Strong electromagnetic field between planes and between axes (GeV/cm).
- Channeling if particle direction aligned with planes or axes



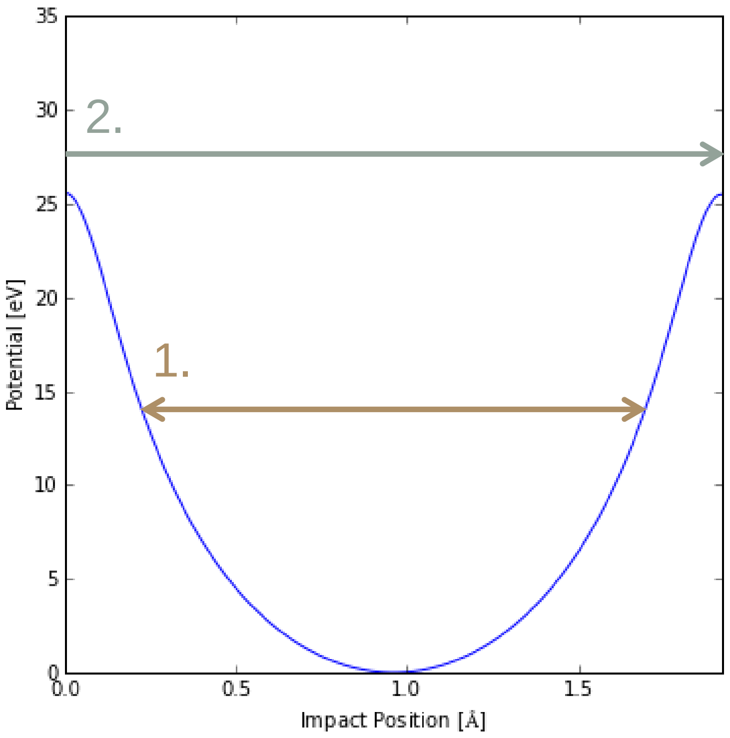
DYNECHARM++ - E. Bagli, V. Guidi, NIMB 309, 124 (2013)

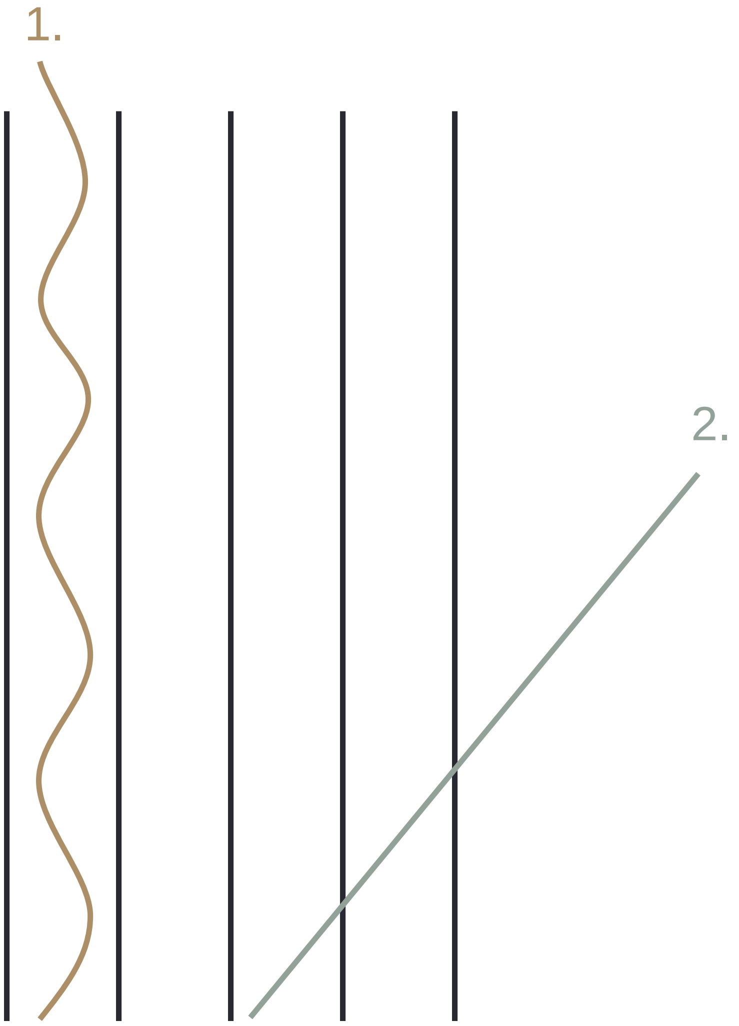
Straight crystal

- Particle whose direction of motion is aligned with crystal planes are captured in channeling.



Straight crystal

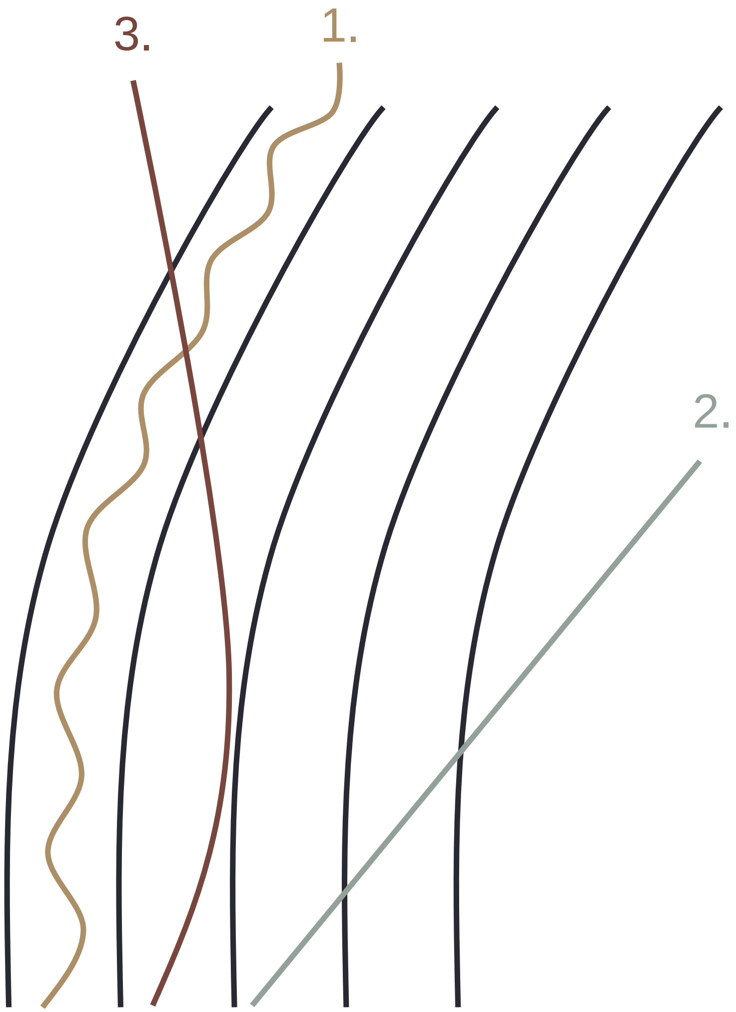




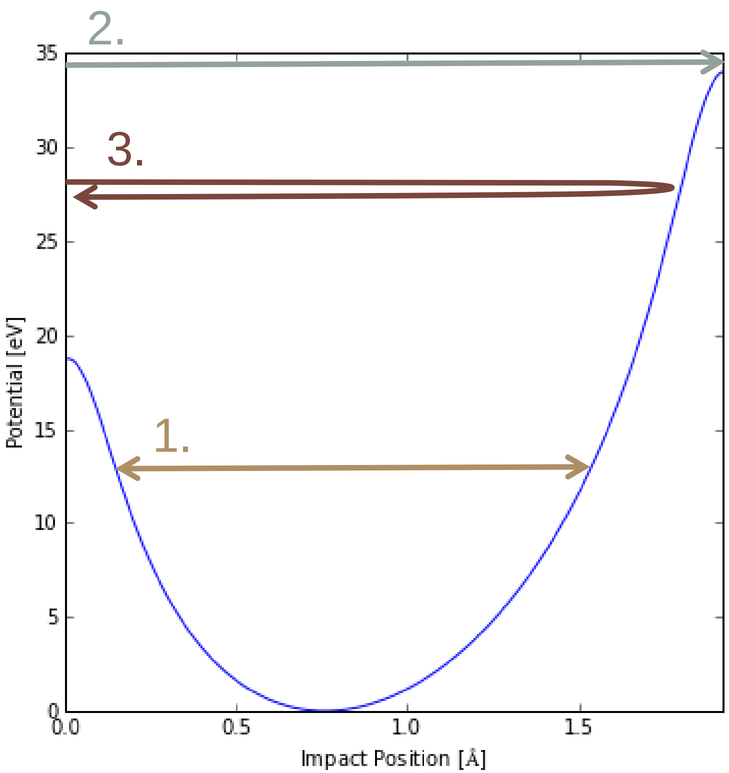
1. Channeled
2. Not channeled

Bent crystal

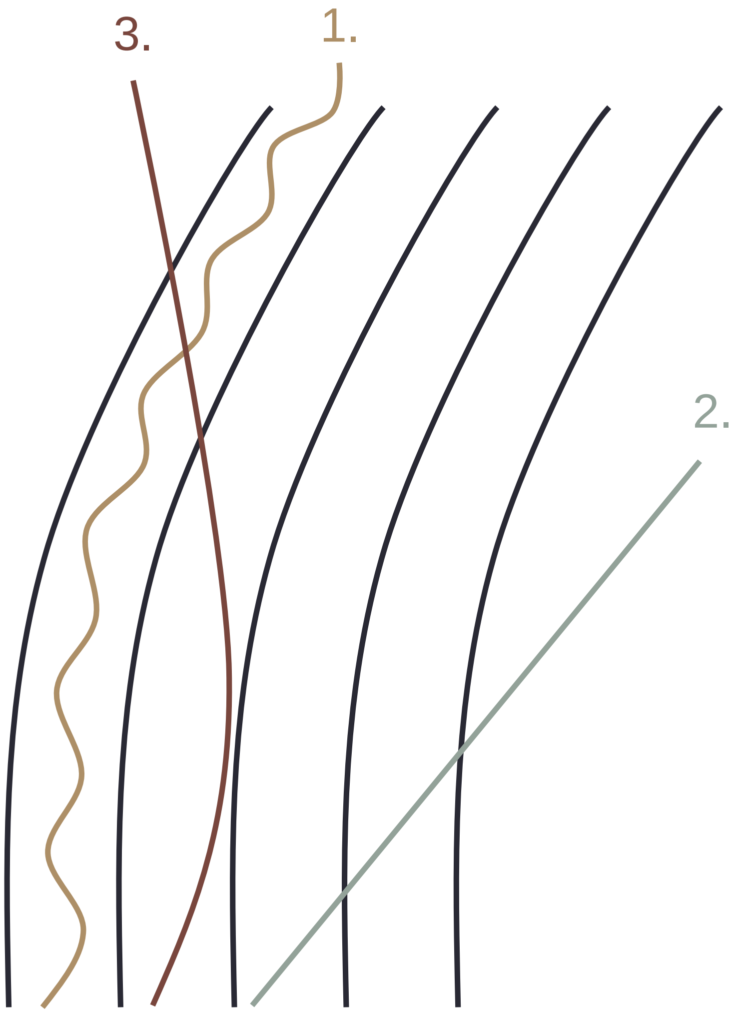
- Channeled particles follows the crystal curvature and are deflected (1.).
- Particle whose trajectories is tangent to crystalline planes are “reflected” by the potential barrier (3.)



Bent crystal



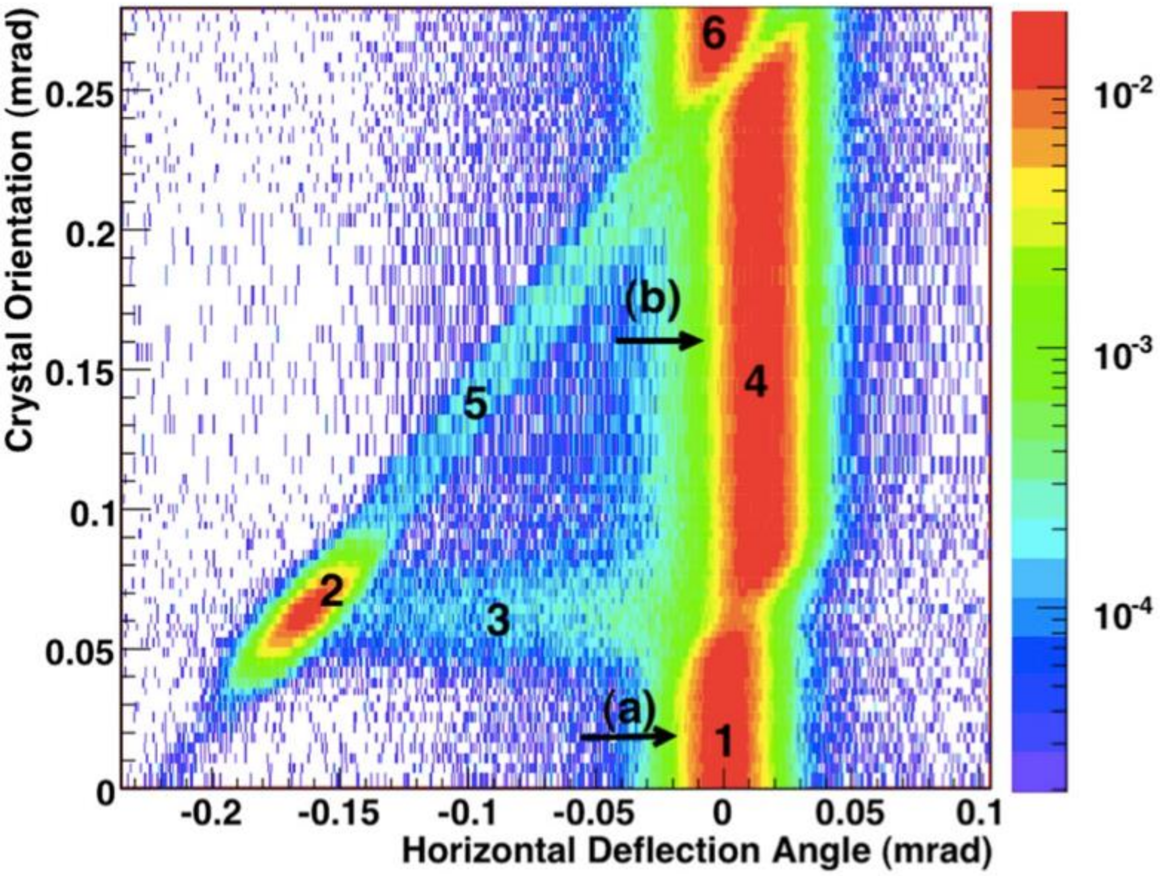
1. Channeled
2. Not channeled



Bent crystal

Varying the crystal orientation with respect to the beam direction orientational effects are observed:

1. No effect
2. Channeling
3. Dechanneling
4. Volume reflection
5. Volume capture
6. No effect

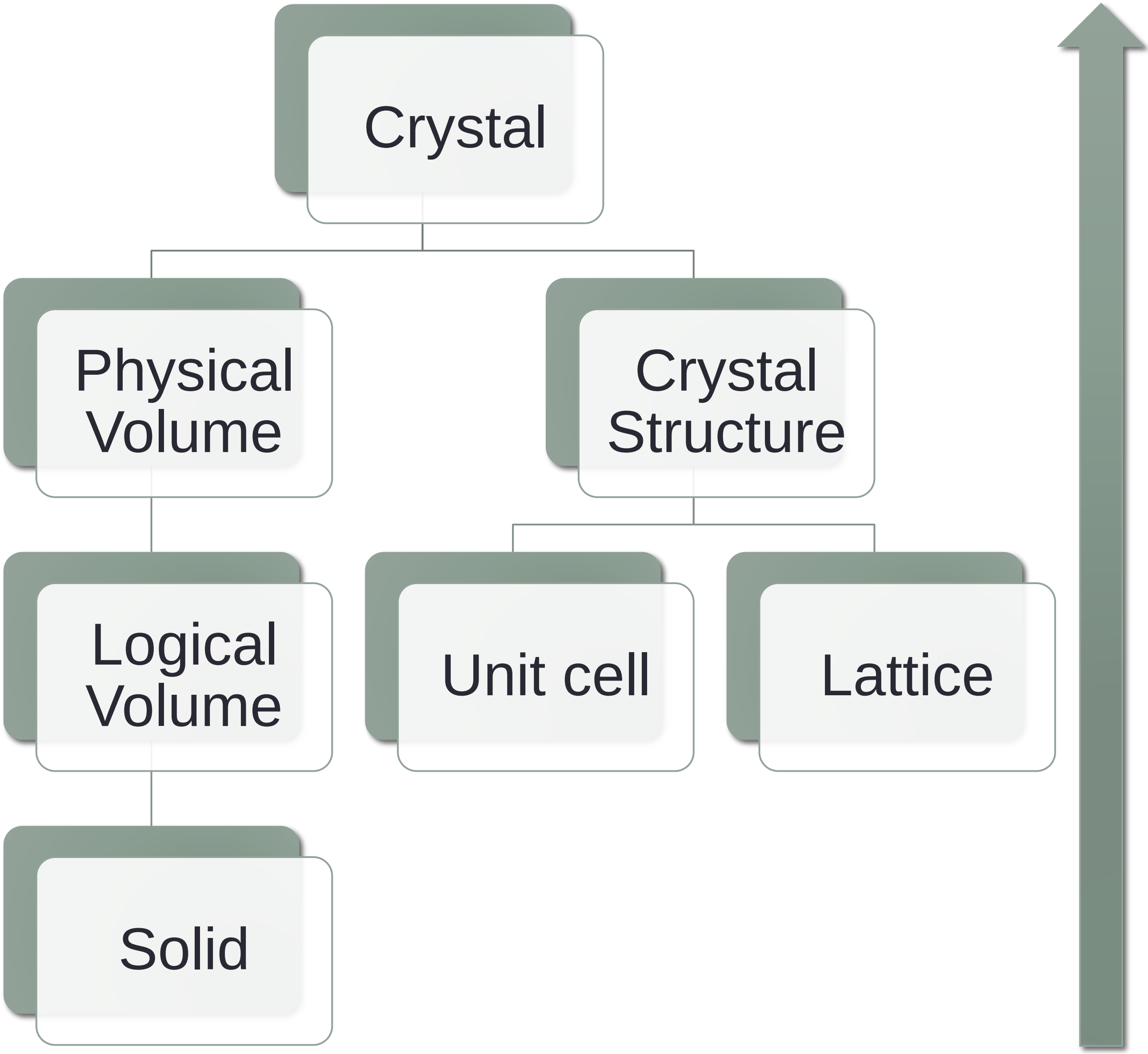


W. Scandale et al., PRL 98, 154801 (2007)

Geant4 implementation

Crystal

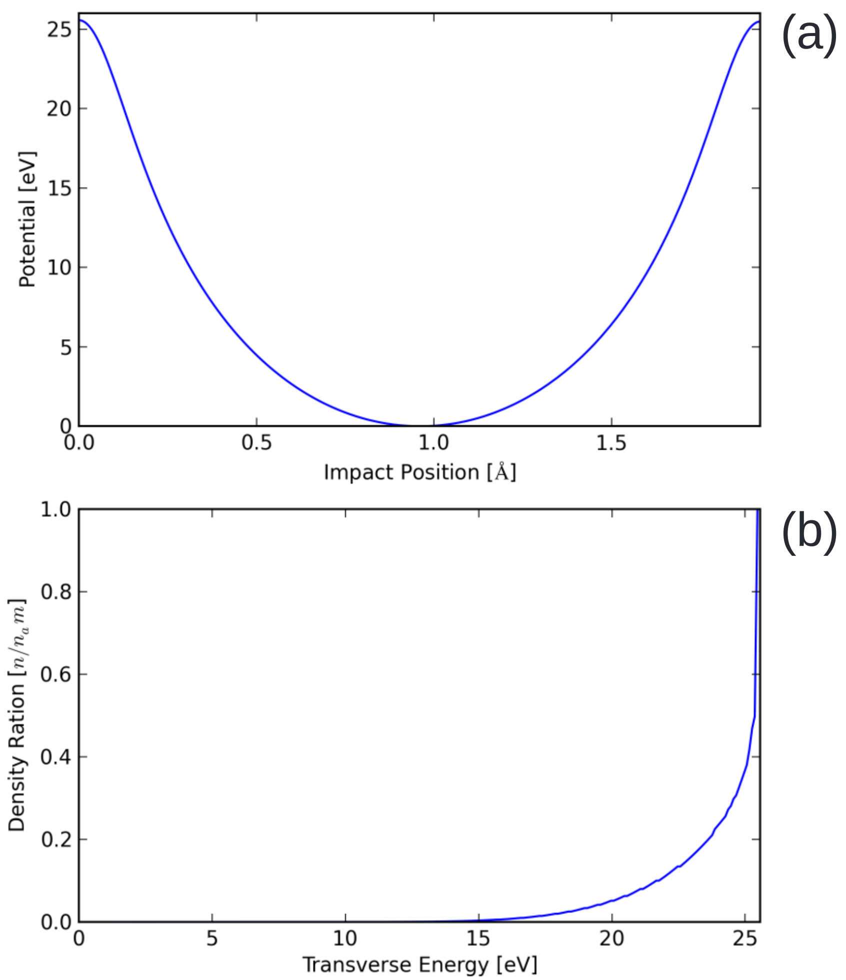
The crystal object is built adding to the standard Physical Volume the Crystal Structure in which the Unit Cell and the Lattice are defined.



Electric characteristics

The crystal structure is used to compute the electrical characteristics of the crystal itself.

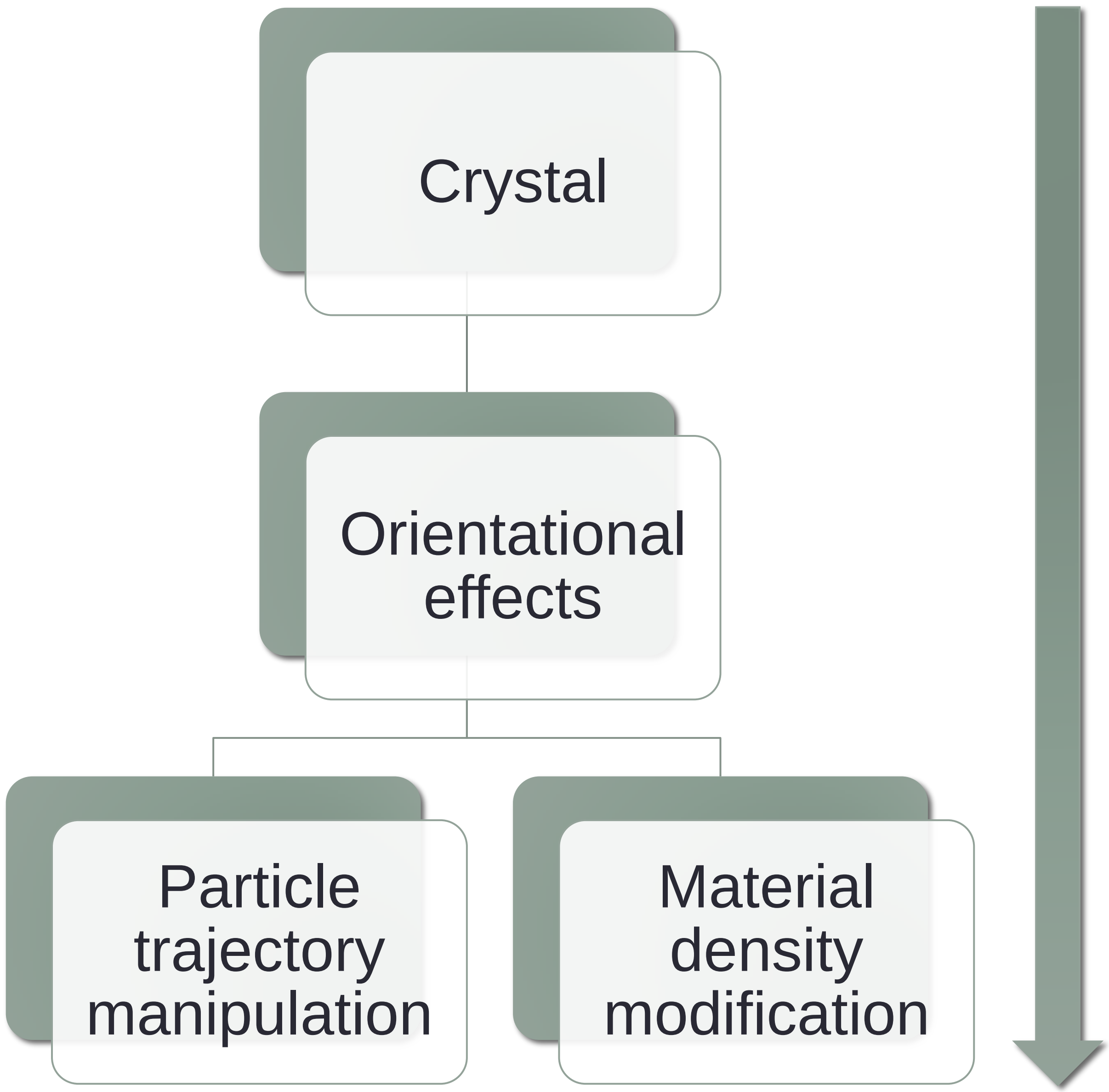
In particular the interplanar potential (a) and the integrated density (b) are initialized for one plane (in the example Si (110)) and used during the simulation.



Geant4 processes modification

By modifying the trajectory of the particle and the density of the material "seen" by the particle the orientational effects in a crystal affect all the Geant4 physical process

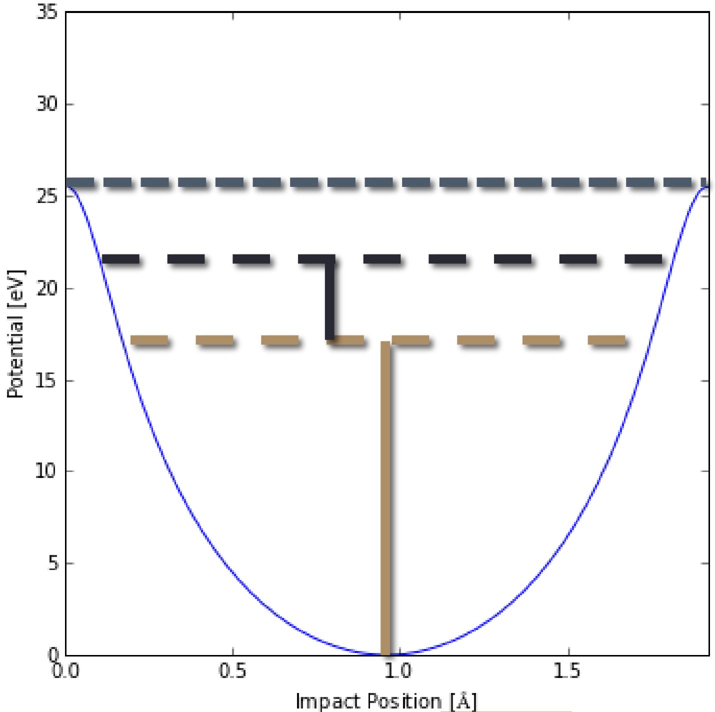
As an example channeled positive particles oscillate between atomic planes interacting less frequently with nuclei and core electrons.



Condition for channeling

Straight crystal

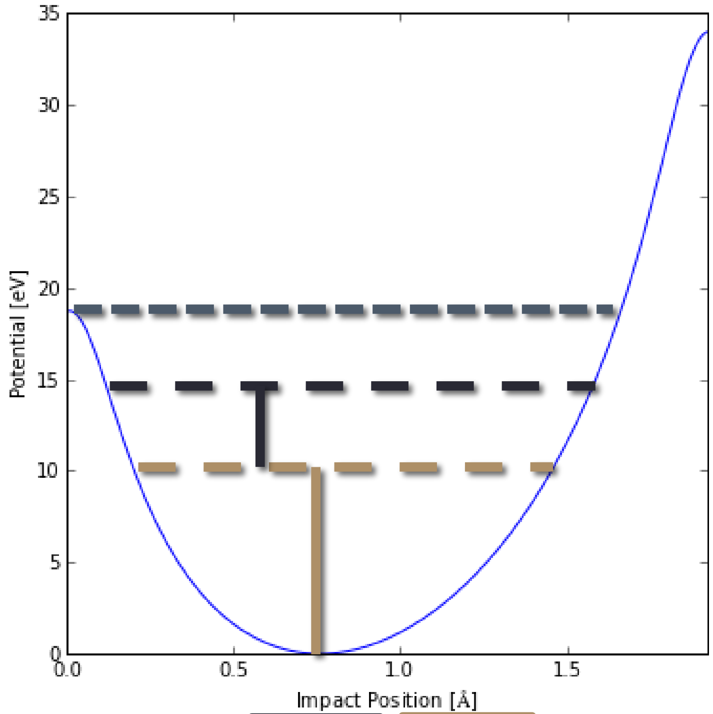
$$E_T < U_{max}$$



$$E_T = \frac{pb}{2} q^2 + U(x)$$

Bent crystal

$$E_T' < U_{max}'$$

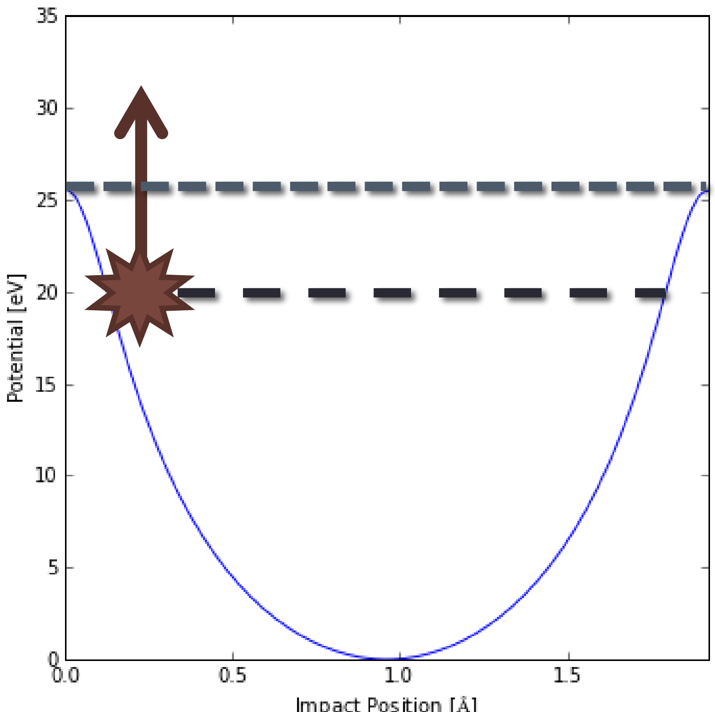


$$E_T' = \frac{pb}{2} q^2 + U'(x)$$

Dechanneling & Volume Reflection

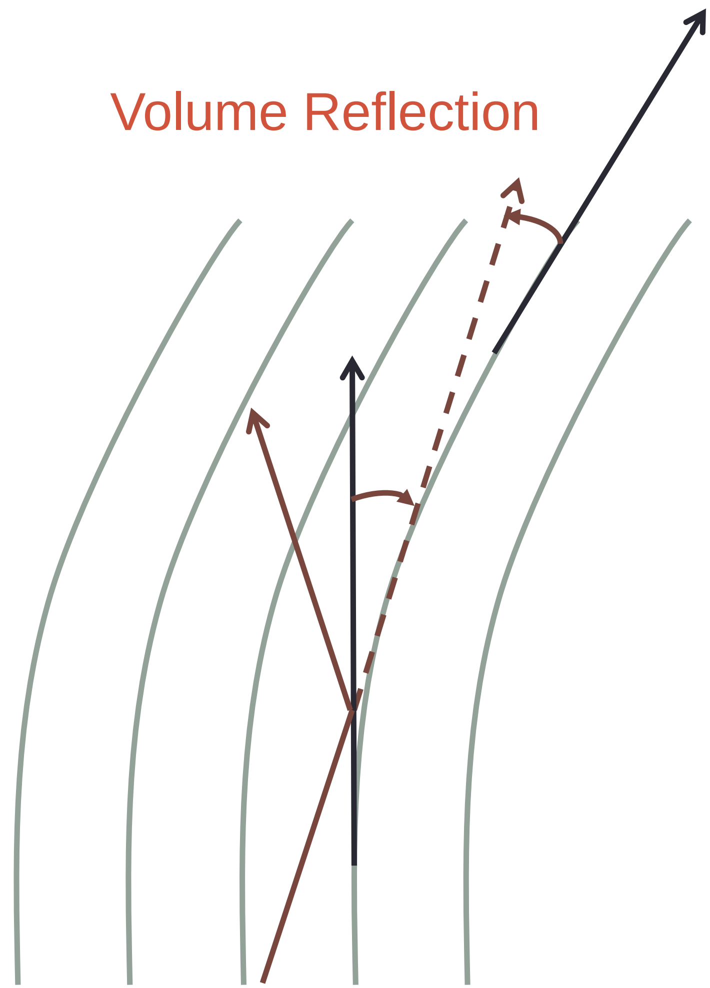
Dechanneling

$$E_T > U_{max}$$



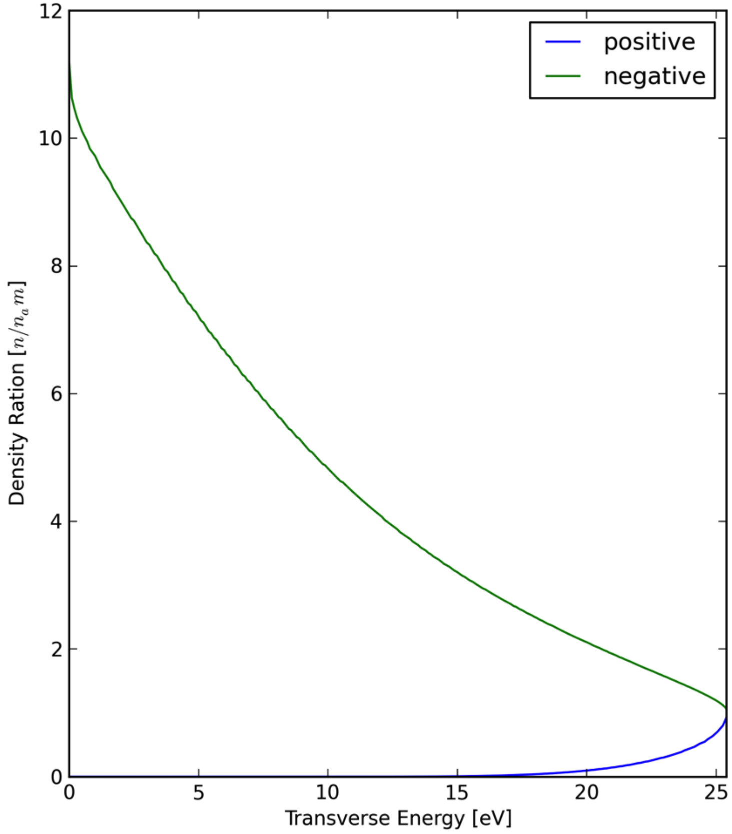
$$DE_T = D\left(\frac{pb}{2}q^2\right)$$

Volume Reflection



Modified density

- Nuclei and electron density tables are computed for positive and negative particles as a function of the particle transverse energy.
- This approach can be used for crystal with dimension parallel to the beam much longer than the channeling oscillation period.



Geant4 processes

Discrete processes

- The mean free path of the discrete processes is recomputed at each step using the modified density because it is directly proportional to the density (ρ) of the material.

Continuous processes

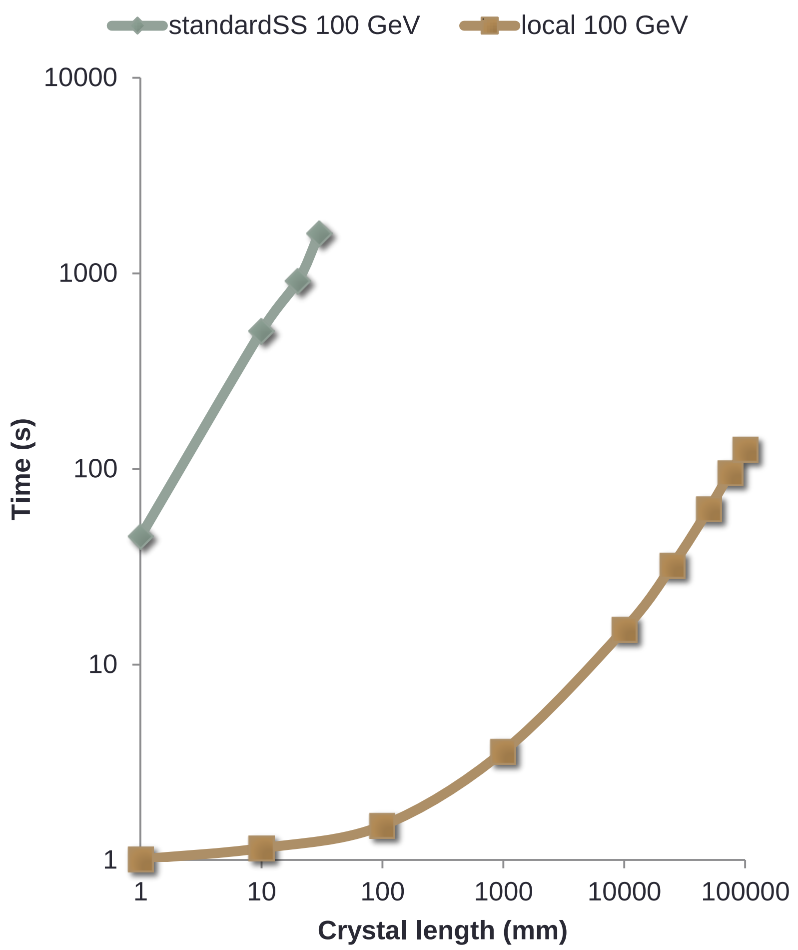
- Material density (ρ) for the calculation of continuous energy loss (dE/dx) is modified at each step ($dx=\rho dz$) to enable the reduction or the enhancement of the energy loss due to channeling.

Geant4 Multiple Scattering

Prefer Single Scattering approach to Multiple Scattering:

- pro: simpler implementation and easier integration with channeling code.
- con: very large CPU penalty

Possible alternatives being investigated



Model validation

Model validation

- Simulation of experiments in which the crystal role is predominant
- Experiment with single-pass beam instead of multi-turn beam to reduce the complexity of the simulation.
- Three measurements selected:
  - Nuclear dechanneling and channeling efficiency for protons
  - Inelastic interaction rates under channeling for protons
  - Dechanneling length for π^-

Nuclear dechanneling and channeling efficiency for protons

Physics Letters B 680 (2009) 129–132

Contents lists available at ScienceDirect

Physics Letters B

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Observation of nuclear dechanneling for high-energy protons in crystals

W. Scandale[a], A. Vomiero[b], S. Baricordi[c], P. Dalpiaz[c], M. Fiorini[c], V. Guidi[c], A. Mazzolari[c], R. Milan[d], Gianantonio Della Mea[e], G. Ambrosi[g], B. Bertucci[f,g], W.J. Burger[f,g], P. Zuccon[g], G. Cavoto[h], R. Santacesaria[h], P. Valente[h], E. Vallazza[i], A.G. Afonin[j], Yu.A. Chesnokov[j], V.A. Maisheev[j], I.A. Yazynin[j], A.D. Kovalenko[k], A.M. Taratin[k,*], A.S. Denisov[l], Yu.A. Gavrikov[l], Yu.M. Ivanov[l], L.P. Lapina[l], L.G. Malyarenko[l], V.V. Skorobogatov[l], V.M. Suvorov[l], S.A. Vavilov[l], D. Bolognini[m,n], S. Hasan[m,n], M. Prest[m,n]

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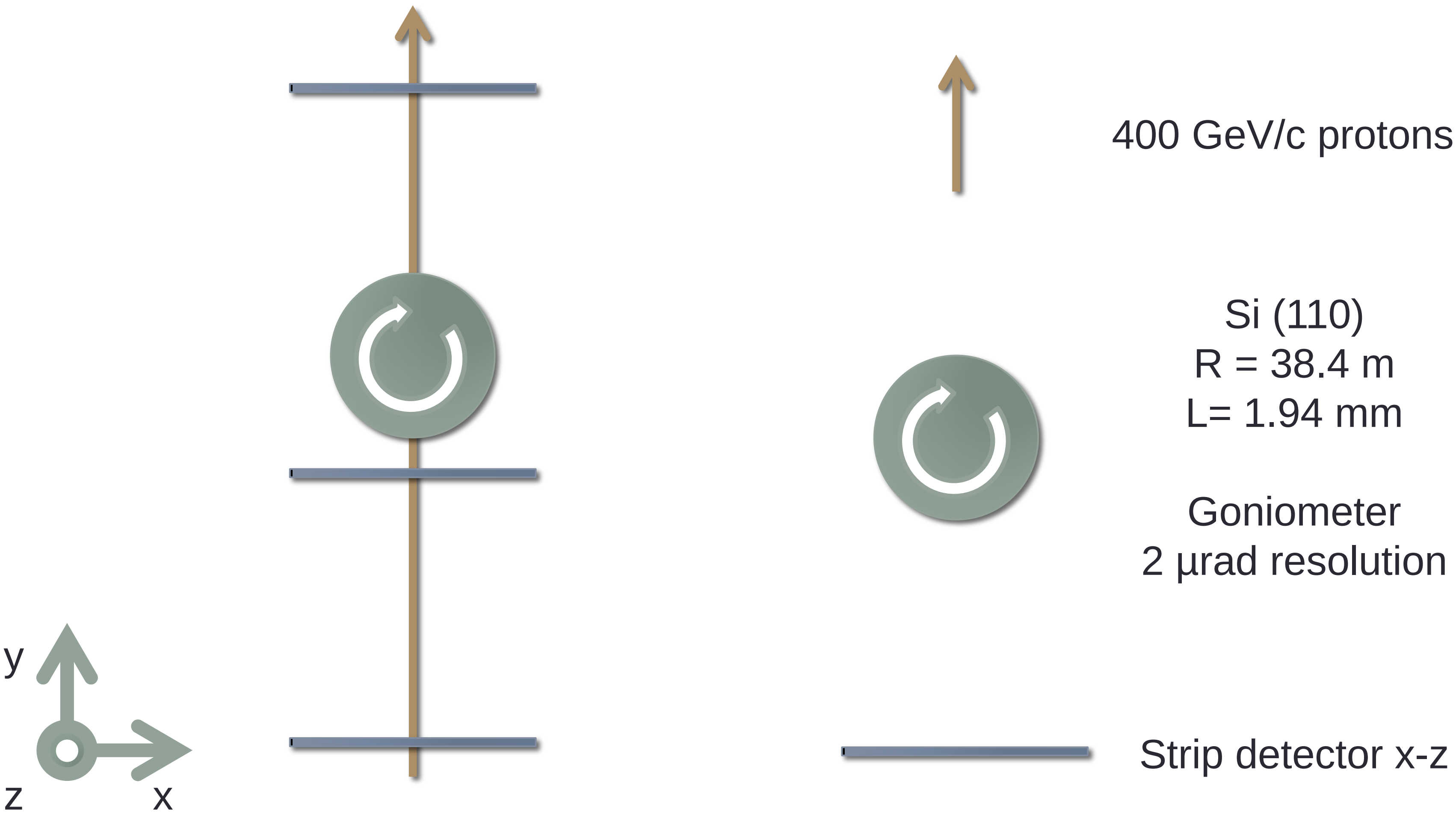
A B S T R A C T

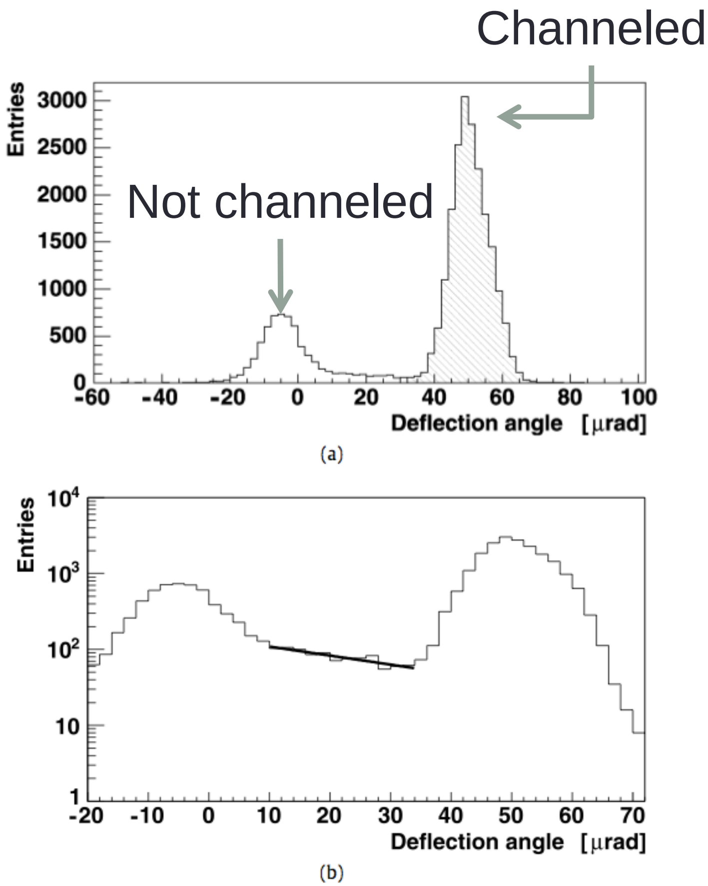
Channeling in a short bent silicon crystal was investigated at the CERN SPS using 400-GeV/*c* protons with an angular spread much narrower than the critical channeling angle. Particle dechanneling due to multiple scattering on the atomic nuclei of the crystal was observed and its dechanneling length was measured to be about 1.5 mm. For a crystal with length comparable to such dechanneling length, an efficiency of 83.4% was recorded, which is close to the maximum value expected for a parallel beam and exceeds the previously known limitation of deflection efficiency for long crystals.

Experimental setup



Nuclear dechanneling length

W. Scandale et al., Phys. Lett. B 680 (2009) 129



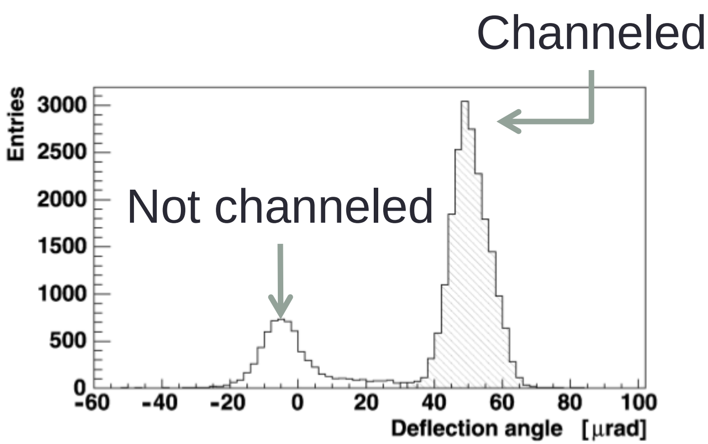
$L_n = (1.53 \pm 0.35 \pm 0.20)$ mm

W. Scandale et al., Phys. Lett. B 680 (2009) 129

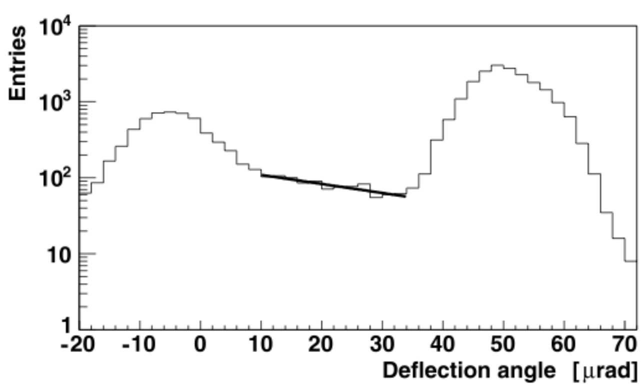
- Nuclear dechanneling length is the “decaying length” of channeling process for short crystal.
- It depends on the strength of incoherent interactions suffered by channeled particles.

Nuclear dechanneling length

W. Scandale et al., Phys. Lett. B 680 (2009) 129



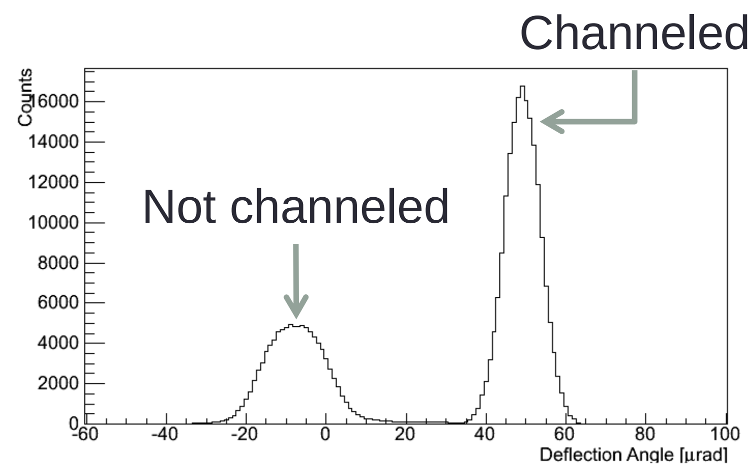
(a)

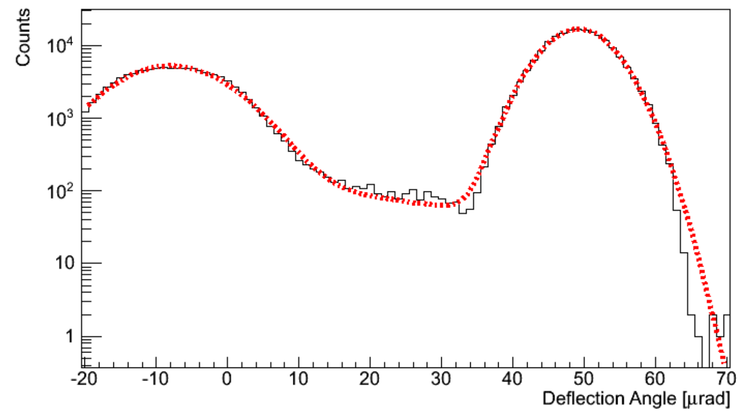


(b)

$L_n = (1.53 \pm 0.35 \pm 0.20)$ mm

Geant4 Channeling





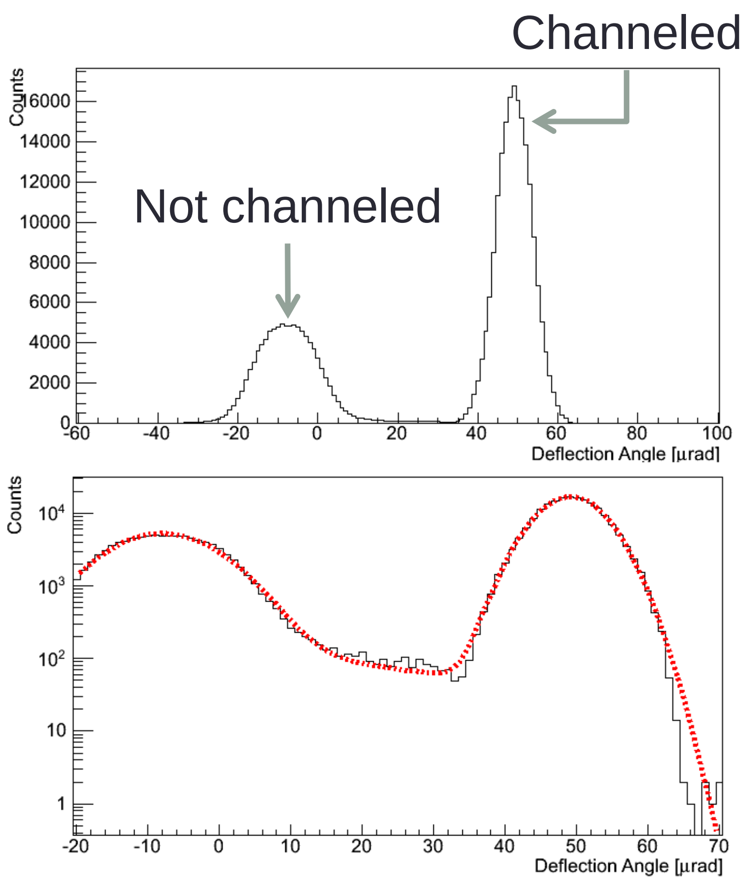
$L_n = (1.31 \pm 0.05)$ mm

Nuclear dechanneling length

Geant4 Channeling

- Lower nuclear dechanneling length means less deflection efficiency due to channeling.
- Usage of single scattering process for channeling needs further investigation and tuning.

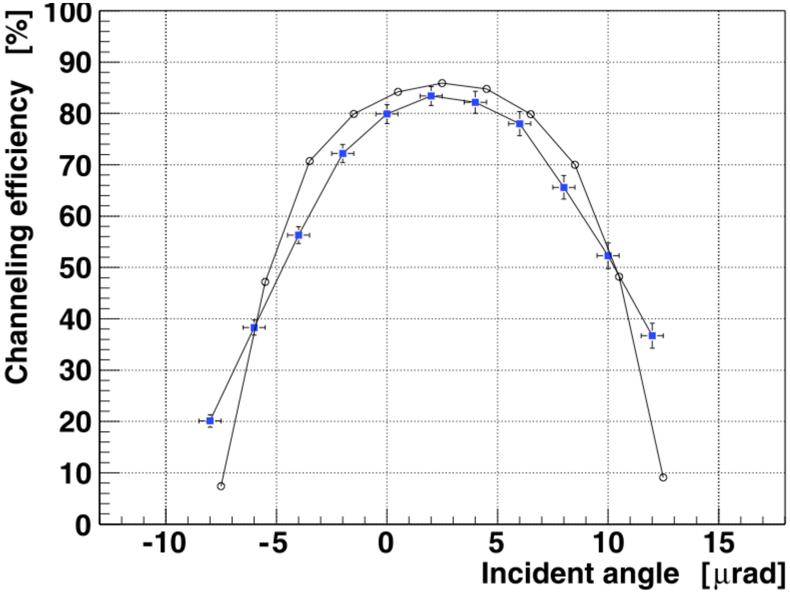
Geant4 Channeling



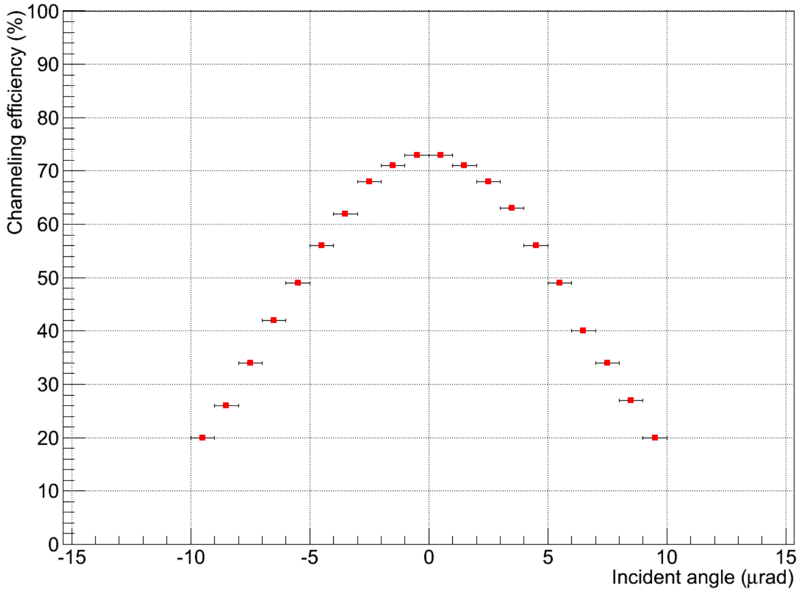
$L_n = (1.31 \pm 0.05)$ mm

Channeling efficiency vs. incoming angle

W. Scandale et al., Phys. Lett. B 680 (2009) 129



Geant4 Channeling



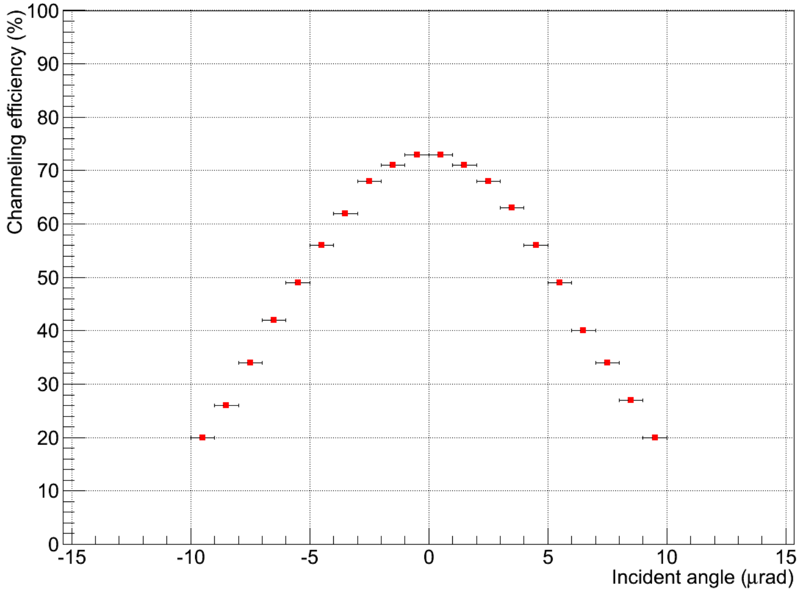
- Experimental measurements (a)
- UA9 collaboration simulations (a)
- Geant4 Simulations (b)

Channeling efficiency vs. incoming angle

Geant4 Channeling

- Shape of the channeling efficiency well fit experimental measurements.
- Better description of the tails.
- Lower efficiency due to shorter nuclear dechanneling length.

Geant4 Channeling



Inelastic interaction rates under channeling for protons

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BEAM INTERACTIONS WITH MATERIALS AND ATOMS

Probability of inelastic nuclear interactions of high-energy protons in a bent crystal

W. Scandale [a], R. Losito [a], M. Silari [a], E. Bagli [b], S. Baricordi [b], P. Dalpiaz [b], M. Fiorini [b], V. Guidi [b], A. Mazzolari [b], D. Vincenzi [b], R. Milan [c], Gianantonio Della Mea [d], E. Vallazza [e], A.G. Afonin [f], Yu.A. Chesnokov [f], V.A. Maisheev [f], I.A. Yazynin [f], S.V. Afanasiev [g], A.D. Kovalenko [g], A.M. Taratin [g,*], V.V. Uzhinsky [g], A.S. Denisov [h], Yu.A. Gavrikov [h], Yu.M. Ivanov [h], L.P. Lapina [h], L.G. Malyarenko [h], V.V. Skorobogatov [h], V.M. Suvorov [h], S.A. Vavilov [h], D. Bolognini [i,j], S. Hasan [i,j], M. Prest [i,j]

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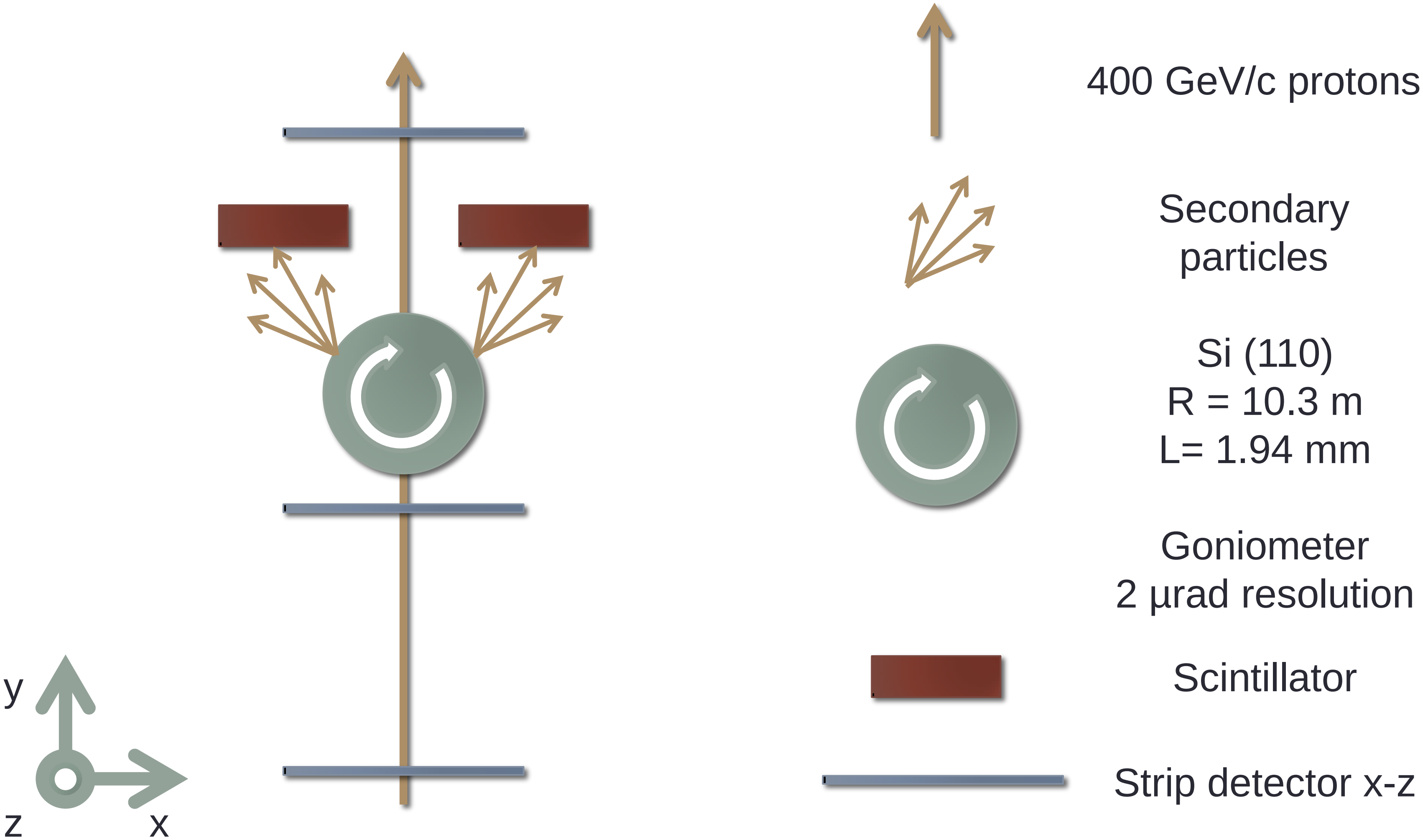
Volume reflection
Nuclear interactions

ABSTRACT

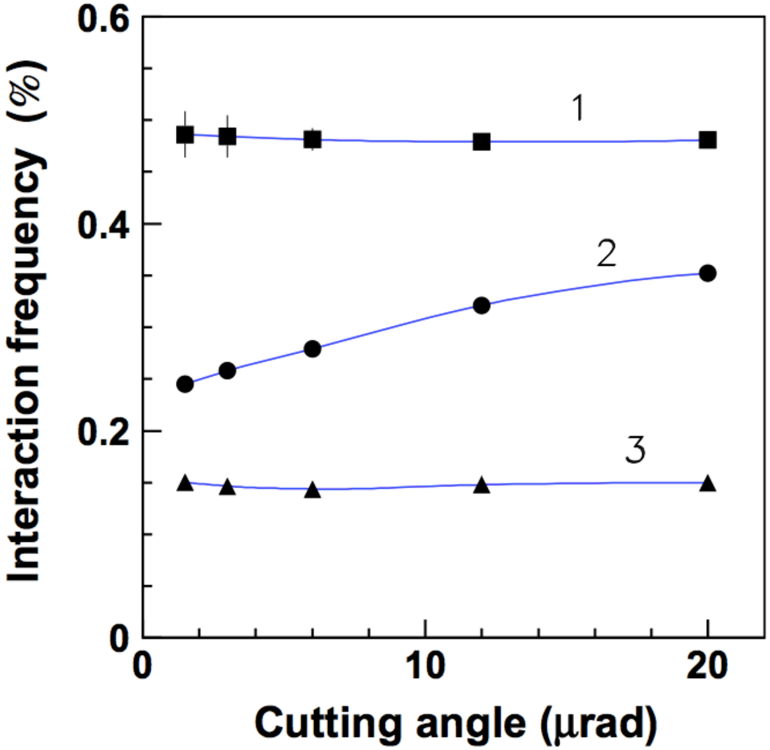
Probability of inelastic nuclear interactions in a short bent silicon crystal for its orientations optimal for channeling and volume reflection was investigated using 400 GeV/c protons of the CERN SPS. The contribution of nuclear interactions from channeled protons was observed to be about 3–4% of the probability for the amorphous orientation. For the crystal orientation optimal for volume reflection the nuclear interaction probability of protons was a few percents larger than in the amorphous case. It was shown that in the limiting case of a quasi parallel beam realizing for the collider beam halo the inelastic nuclear losses should decrease by more than five times, which is an additional advantage of a crystal as a primary collimator for the LHC collimation system.

Experimental setup



Interaction rates vs. integration angle

W. Scandale et al., NIMB 268 (2010) 2655

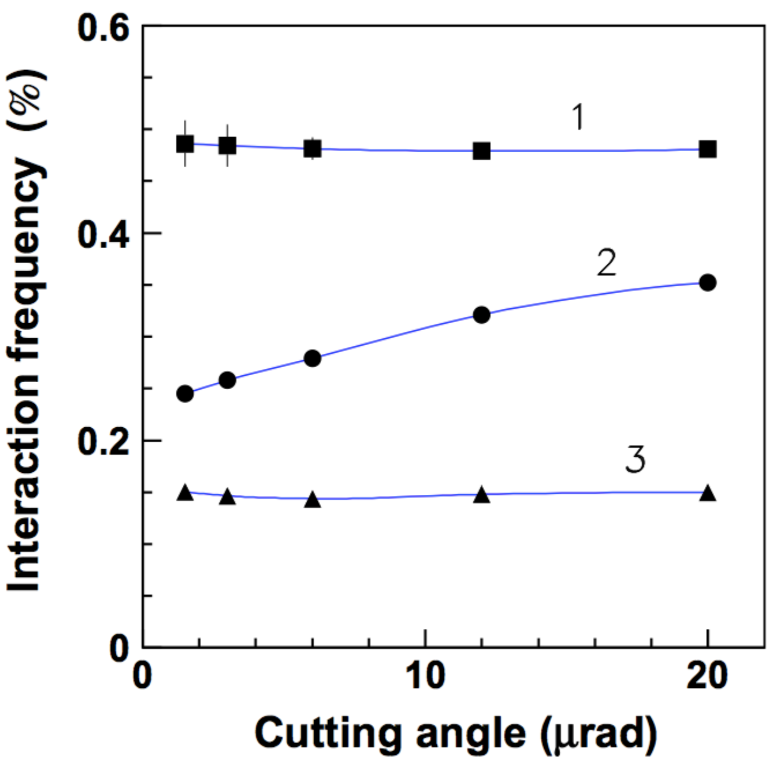


W. Scandale et al., NIMB 268 (2010) 2655

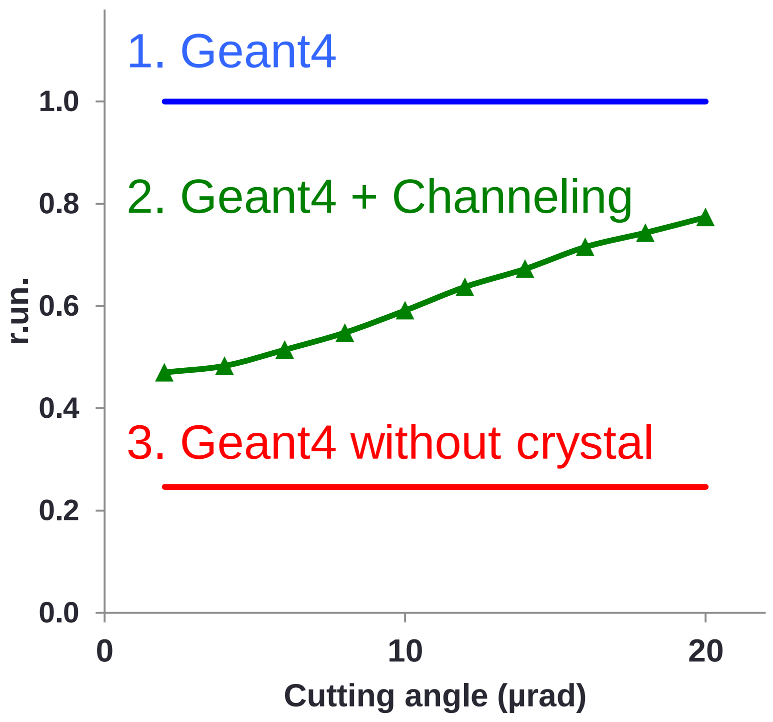
- Beam loss after collimation is directly proportional to the rate of inelastic interaction.
- By using the crystal in channeling mode the inelastic interaction rate is strongly reduced.
- In the experiment:
  1. Crystal not in channeling
  2. Crystal in channeling
  3. No crystal

Interaction rates vs. integration angle

W. Scandale et al., NIMB 268 (2010) 2655



Geant4 Channeling

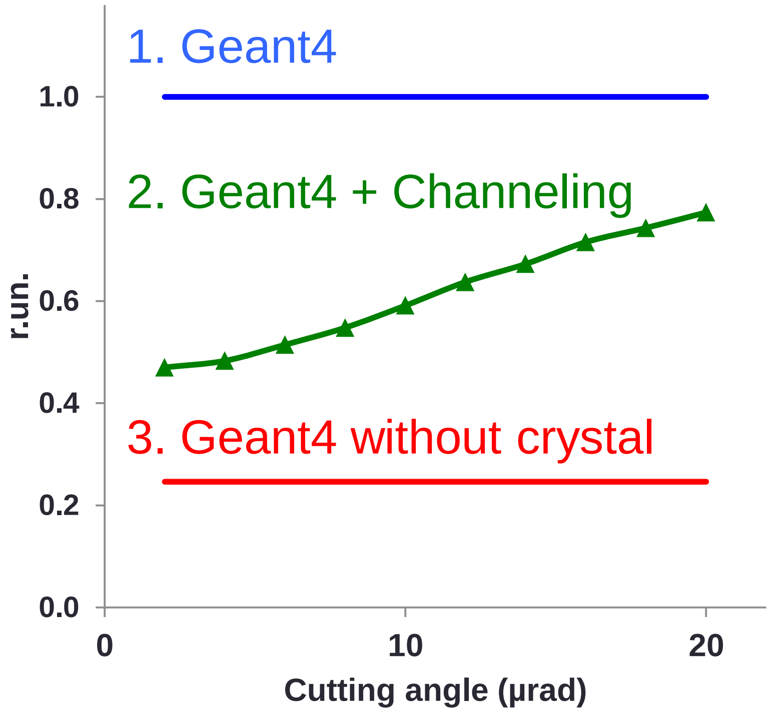


Interaction rates vs. integration angle

Geant4 Channeling

- Variation of the inelastic interaction rate as a function of the cutting angle.
- Results consistent with experimental measurements.
- Difference of the second derivative for low angle cuts needs further investigation.

Geant4 Channeling



Dechanneling length for π⁻

Physics Letters B 719 (2013) 70–73

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Measurement of the dechanneling length for high-energy negative pions

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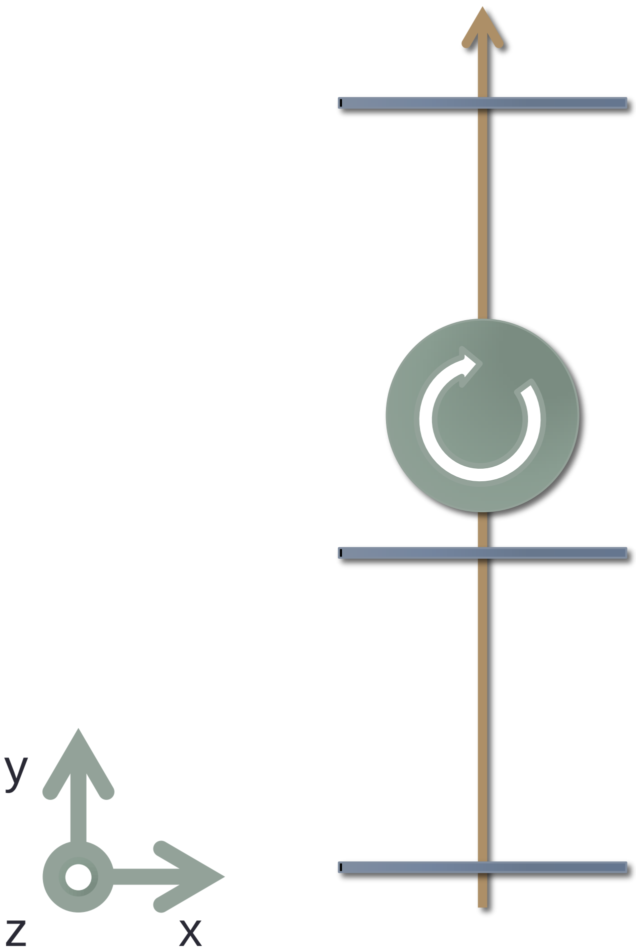
A B S T R A C T

We studied the dechanneling length of 150 GeV/c π^- interacting with a short bent silicon crystal. Dechanneling length measures the rate and the strength of incoherent interactions of channeled particles in a crystal. The mechanism of dechanneling of negatively charged particles has been elucidated through simulation and experiment. It was found that the dechanneling length for negative particles is comparable to the nuclear dechanneling length for positive charges. Indeed, dechanneling of negative particles occurs as a result of incoherent interactions with the nuclei because the trajectories of such particles always intersect atomic planes, explaining the lower channeling efficiency for such particles. Obtained results can be useful for the design of crystals for manipulating high-energy negative particle beams through channeling.

Experimental setup



150 GeV/c π^-

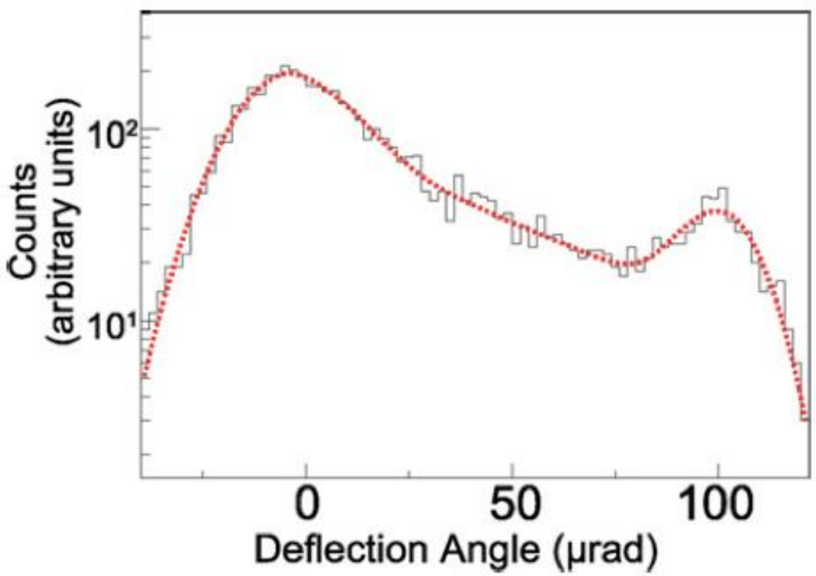
Si (110)
R = 19.2 m
L= 1.91 mm

Goniometer
2 µrad resolution

Strip detector x-z

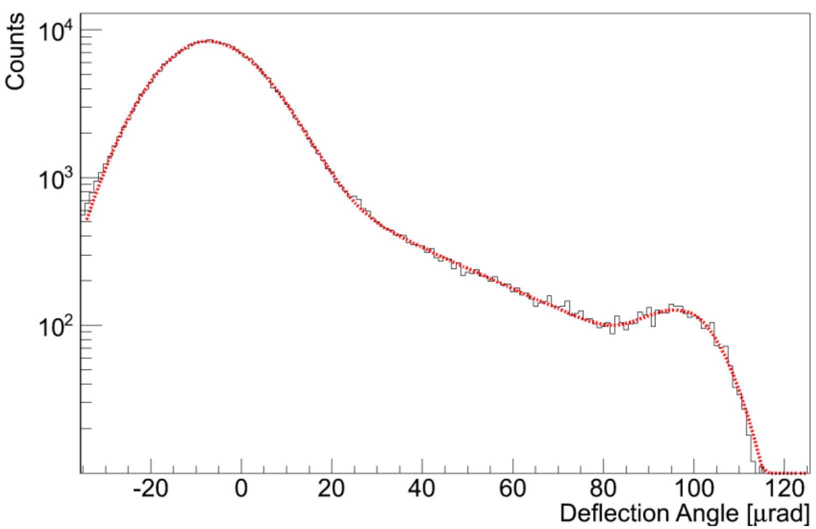
Dechanneling length for π^-

W. Scandale et al., Phys. Lett. B 680 (2009) 129



$L = (0.93 \pm 0.05)$ mm
$\varepsilon_{ch} = (12.5 \pm 1.0)$ %
$\theta_{ch} = (99.6 \pm 0.2)$ µrad

Geant4 Channeling



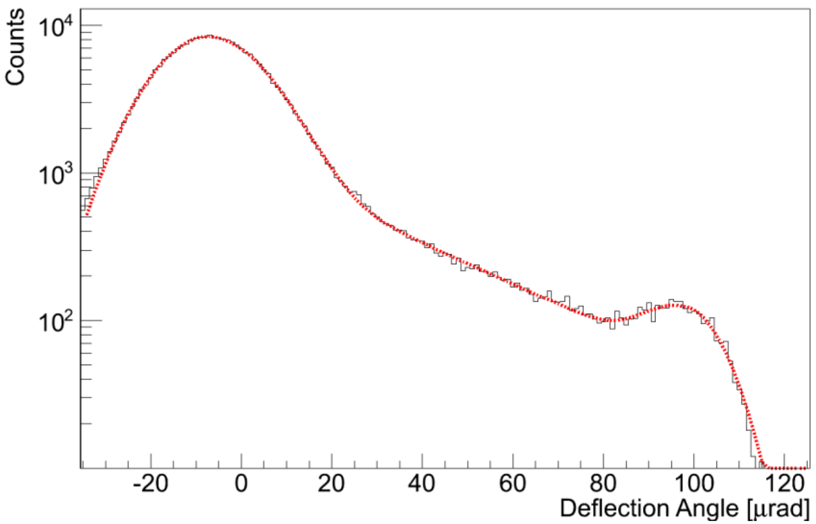
$L = (0.60 \pm$- $0.05)$ mm
$\varepsilon_{ch} = (4.5 \pm 0.2)$ %
$\theta_{ch} = (95.6 \pm 0.6)$ µrad

Dechanneling length for π^-

Geant4 Channeling

- Channeling of negative particles has been simulated.
- The lowering of the channeling efficiency with respect to positive particle has been reproduced.
- Usage of single scattering process for channeling needs further investigation and tuning as for positive particles.

Geant4 Channeling



L = (0.60 ±- 0.05) mm

ε_{ch} = (4.5 ± 0.2) %

θ_{ch} = (95.6 ± 0.6) μrad

Summary

Summary

- Planar channeling for particle channeled in straight and bent crystal has been added to Geant4.
- Calculation of electrical properties for planar channeling has been added to Geant4.
- Modification of Geant4 processes has been obtained.
- The channeling process has been proved to reproduce qualitatively the experimental result for bent crystal at high energies.
- Channeling of both positive and negative particles can be simulated.
- Implementation of single scattering still further investigation and tuning.

Possible expansions

- General framework for the computation of the electrical characteristics of crystals under continuum approximation.
- Precise calculation of the density.
- Computation of particle trajectory.
- Orientational phenomena for the interaction with axes.
- Radiation effects:
  - Planar channeling radiation
  - Coherent bremsstrahlung
  - Volume reflection radiation
  - …
- Ondulator crystal.
- Low energy channeling
- …