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.
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
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 follow 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
The crystal object is built by 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.
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 processes.

As an example, channeled positive particles oscillate between atomic planes, interacting less frequently with nuclei and core electrons.
**Condition for channeling**

**Straight crystal**

\[ E_T < U_{\text{max}} \]

\[ E_T = \frac{p}{2}^2 + U(x) \]

**Bent crystal**

\[ E_T' < U_{\text{max}}' \]

\[ E_T' = \frac{p}{2}^2 + U'(x) \]
Dechanneling & Volume Reflection

Dechanneling

\[ E_T > U_{\text{max}} \]

![Graph showing potential vs. impact position](image)

\[ E_T = \left( \frac{p}{2} \right)^2 \]
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 ($\rho$) of the material.

Continuous processes

• Material density ($\rho$) 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⁻
Observation of nuclear dechanneling for high-energy protons in crystals


Abstract

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% was recorded, which is close to the maximum value expected for a parallel beam and exceeds the previously known limitation of detection efficiency for long crystals.
Experimental setup

400 GeV/c protons

Si (110)
R = 38.4 m
L = 1.94 mm

Goniometer
2 μrad resolution

Strip detector x-z
Nuclear dechanneling length


Channeled

Not channeled

\[ L_n = (1.53 \pm 0.35 \pm 0.20) \text{ mm} \]

- 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


\[ L_n = (1.53 \pm 0.35 \pm 0.20) \text{ mm} \]

\[ L_n = (1.31 \pm 0.05) \text{ mm} \]
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.

\[ L_n = (1.31 \pm 0.05) \text{ mm} \]
Channeling efficiency vs. incoming angle


Geant4 Channeling

Experimental measurements (a)
UA9 collaboration simulations (a)
Geant4 Simulations (b)
Channeling efficiency vs. incoming angle

- Shape of the channeling efficiency well fit experimental measurements.
- Better description of the tails.
- Lower efficiency due to shorter nuclear dechanneling length.
Inelastic interaction rates under channeling for protons


CERN, European Organization for Nuclear Research, CH-1211 Geneva 23, Switzerland
INFN Sezione di Ferrara, Dipartimento di Fisica, Universita' di Ferrara, Via Saragat 1, 44100 Ferrara, Italy
INFN Laboratori Nazionali di Legnaro, Viale Universita' 2, 35020 Legnaro (PD), Italy
INFN Sezione di Torino, Via Pietro Giuria 1, 10125 Torino, Italy
IFNI Sezione di Trieste, Via Valerio 2, 34127 Trieste, Italy
Ph. Inst. of High Energy Physics, Moscow Region, 142294 Protvino, Russia
Joint Institute for Nuclear Research, Dubna, Moscow Region, Russia
Petersburg Nuclear Physics Institute, Gatchina, Leningrad Region, Russia
Universita' dell'Insubria, Via Valutino 11, 22100 Como, Italy
INFN Sezione di Milano Bicocca, Piazza della Scienza 3, 20126 Milano, Italy

ARTICLE INFO
Article history:
Received 30 June 2010
Available online 11 July 2010

Keywords:
Crystal
Channeling
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 channelled 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 then 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.

© 2010 Elsevier B.V. All rights reserved.
Experimental setup

400 GeV/c protons

Secondary particles

Si (110)
R = 10.3 m
L= 1.94 mm

Goniometer
2 μrad resolution

Scintillator

Strip detector x-z
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

W. Scandale et al., NIMB 268 (2010) 2655
Interaction rates vs. integration angle

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

**Geant4 Channeling**

1. Geant4
2. Geant4 + Channeling
3. Geant4 without crystal
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.
Dechanneling length for $\pi^-$

Measurement of the dechanneling length for high-energy negative pions


ARTICLE INFO
Article history:
Received 14 November 2012
Received in revised form 17 December 2012
Accepted 26 December 2012
Available online 28 December 2012
Editor: L. Rolandi

Keywords:
Crystal
Channeling
Beam manipulation

ABSTRACT
We studied the dechanneling length of 150 GeV/$c\pi^-$ interacting with a short bent silicon crystal. Dechanneling length measures the rate and the strength of incoherent interactions of channelled 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 $\pi^-$


\begin{align*}
L &= (0.93 \pm 0.05) \text{ mm} \\
\varepsilon_{ch} &= (12.5 \pm 1.0) \% \\
\theta_{ch} &= (99.6 \pm 0.2) \mu\text{rad}
\end{align*}

Geant4 Channeling

\begin{align*}
L &= (0.60 \pm 0.05) \text{ mm} \\
\varepsilon_{ch} &= (4.5 \pm 0.2) \% \\
\theta_{ch} &= (95.6 \pm 0.6) \mu\text{rad}
\end{align*}
Dechanneling length for $\pi^-$

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.

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

...