Experiments on deflection of charged particles using silicon crystals at REFER ring (Hiroshima University) and Proton Synchrotron (KEK)

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Contents

1. Introduction to the channeling effect
2. Motivation
3. Experiment on electron beam deflection (REFER, Hiroshima University)
4. Experiment on proton beam deflection (Proton Synchrotron, KEK)
5. Conclusion
Introduction (channeling effect)

\[ \theta \] – angle of incident particle to the crystallographic plane

- \( \theta < \text{Lindhard angle} \) \rightarrow channeling effect
- \( \theta > \text{Lindhard angle} \) \rightarrow no channeling effect
Motivation

Application to deflection of high energy (50 GeV) and high intensity proton beam at J-PARC (Japan Proton Accelerator Research Complex):

- beam splitting in a slow-extraction beam,
- beam collimator,
- slow beam extraction from the synchrotron in the future.

Collimation of the ultra-low emittance beam at ILC (International Linear Collider).

Beam extraction from the REFER ring is within the scope.

Beam diagnosis by channeling effect (beam divergence and profile).
REFER ring @ Hiroshima University

- REFER (Relativistic Electron Facility for Education and Research)

150 MeV Electron beam

Beam extraction line
beam intensity: $1.0 \times 10^4 \, s^{-1}$
REFER ring @ Hiroshima University

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Experimental setup

Extraction line

vacuum: $1.0 \times 10^{-7}$ torr

QM3: for change of beam divergence

thickness of crystal: 16 $\mu$m
Extraction line
Setup

Beam

Si crystal

Mirror

IT & CCD

Goniometer
**Schematic view of the setup**

phosphor

Beam profile

<100> axis

θ direction

Si crystal

thickness of crystal: 16µm

electron beam

φ direction

beam divergence controlled by QM3
**Experiment: beam divergence**

- Beam divergence vs. QM3 current
  (➡️ measured beam profile and optics calculation)

- Vertical angle dependence of the profile is the point.

- Lindhard angle for <100> axis of Si : 0.7 mr
  - Beam divergence > Lindhard angle
Results: Beam Profiles

QM3: 2.0A \( \theta = 0 \), \( \phi = -1.5 \text{mr} \)  
Beam divergence: 3.0 mr

QM3: 2.6A \( \theta = 0 \), \( \phi = -1.5 \text{mr} \)  
Beam divergence: 5.2 mr
Analysis

- Beam divergence (vertical): 3.0 mr  QM3: 2.0 Å

Fitting with double Gaussian

Beam center ≅ weighted average in 2σ region
Results

- Beam divergence (vertical): 3.0 mr $\theta=0$ mr (QM3: 2.0 Å)

Deflection angle $\leftrightarrow$ change of beam center + 2.34 m

![Graph showing deflection angle vs. $\phi$](image)
Results

- Beam divergence = 3.8 mr \( \theta = 0 \) mr (QM3 : 2.2 A)
• Beam divergence : 5.2 mr $\theta = 0$ mr (QM3 : 2.6 A)
Results: deflection vs. beam divergence

- Deflection vs. beam divergence

The magnitude of the deflection, $\Delta$, was determined by fitting the plot with 1st derivative of Gaussian function.

Larger beam divergence $\rightarrow$ Smaller deflection
\[ U = \frac{2Ze^2}{d} \ln \sqrt{1 + \frac{3R^2}{\rho^2}} \]

**Lindhard string continuous potential**

- \( R \): Thomas-Fermi radius
- \( \rho \): Distance from \(<100>\) axis
- \( d \): Lattice constant in \(<100>\) axis
  
  \((5.43\text{Å for Si})\)
- \( Z \): Atomic number \((14\text{ for Si})\)

**Conditions for simulation**

- 4\(^{th}\) order of Runge-Kutta method
- Without consideration of multiple scattering and channeling radiation
- Energy of electrons: 150 MeV
- Thickness of the crystal: 16 μm
Simulation: trajectory

- Trajectory of an electron

Initial position: X=0Å, Y=0.3Å

Initial position: X=0Å, Y=0.5Å
Simulation

- Preliminary results

Beam divergence : 3.0 mr

Beam divergence : 5.2 mr

Larger beam divergence → Smaller deflection
• Comparison with experimental data
  – Beam divergence : 3.0 mr (QM3 : 2.0 Å)

The tendency of the deflection as a function of the vertical direction of the crystal (ϕ) is same. But, in quantitative comparison, the peak-to-peak difference of the deflection angle of the measurement is about 0.4 mr, while it’s around 0.04 mr for the simulation.
Simulation

- Comparison with experimental data
  - Beam divergence : 5.2 mr (QM3 : 2.6 A)

Experimental data agree with simulation qualitatively.
Study with more realistic beam profiles etc. is underway.
• Performed experiment on beam deflection at REFER with the 150-MeV electron beam.

• Systematic investigation of the beam deflection as a function of the beam divergence.

• Preliminary comparison with simulation:
  – Qualitative agreements
  – Quantitative comparison … being studied
Prospect

- Experiment at KEK-ATF (Accelerator Test Facility)
  - $E = 1.28$ GeV
  - Normalized emittace: $\varepsilon_x = 3.4 \times 10^{-6}$ m, $\varepsilon_y = 4.5 \times 10^{-8}$ m
  - Just a similar experiment at ATF as the REFER experiment
  - See channeling effects with the super-low emittance beam.
Experiment at KEK–PS

12 GeV Proton Synchrotron

North counter hall

EP2 line

Experiment was done in EP2 line

East counter hall
**Experimental setup**

- Crystal
- Goniometer \( \pm \theta \)
- Fluorescence plate
- Al plate
- CsI plate
- Distance 145 cm
- Distance \( \pm 20 \text{ cm} \)
Crystal, proton beam

Parameters of crystal

Material: Silicon
Size: 3 x 0.3 x 10 mm
Bending angle: ~ 32.6 mrad
Plane: (111)
Lindhard angle: 0.066 mrad

Parameters of the proton beam

Energy: 12 GeV
Intensity: $10^{12}$ protons/spill
Size: 15 x 12 mm
Divergence: < 5 mrad

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Schematic drawing of the experiment

View from above

Crystal

Deflection angle

CsI plate (5x2.5cm)

Deflected beam

Main beam

Bent crystal

Goniometer

Fluorescence plate (10x10cm)

12 GeV protons

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Typical pictures

- Image after background subtraction
- Raw image
- CsI plate
- Fluorescence plate
- Primary beam
- Deflected beam

- Intensity of deflected beam
- Bending angle
- Crystal efficiency
Results

Such dependence agrees with estimations.
Results

The diagram shows the deflection of protons in a crystal. The beam of protons ($10^{12}$) is incident on the crystal, resulting in a deflection of approximately $10^7$ protons. The angle between the crystal and beam axis is indicated in milliradians (mrad).

**N deflected** ~ $10^7$

**N beam** $10^{12}$
Crystal efficiency

\[ N_{\text{deflected}} = \text{Crystal Efficiency} \times \text{Angle Efficiency} \times N_{\text{incident upon the crystal}}. \]

Crystal Efficiency could be:

- 100% → at 5 mrad
- 26% → at 1 mrad
- 13% → at 0.5 mrad

Incident particles within critical (Lindhard) angle to the crystallographic plane.
At the beam divergence <5 mrad and Lindhard angle 0.066 mrad, angle efficiency is > 1%

Only small part of all protons hits crystal, that is 0.3%

N incident upon the crystal = 3 x 10^9

N deflected = 4 x 10^7 protons
Simulation

picture at the distance 145 cm from the crystal

“Catch” code

Initial parameters

Beam
Energy: 12 GeV
Size: 15 x 12 mm
Divergence: 0.3, 0.5, 1, 5 mrad

Crystal
Size: 3 x 0.3 x 10 mm
Bending angle: ~ 32.6 mrad
Plane: (111)
Simulation

\[ N \text{ deflected} = \text{Crystal Efficiency} \times \text{Angle Efficiency} \times N \text{ incident upon the crystal.} \]

Crystal Efficiency is 15%
Simulation vs. Experimental data (1)

Position of the deflected beam at the distance 145 cm from the crystal, (mm)

- Experimental data
- Simulation
Simulation vs. Experimental data

- 5 mrad
- 0.5 mrad
- 1 mrad
- 0.3 mrad
Crystal efficiency

At the beam divergence 0.3 - 0.5 mrad

crystal efficiency in experiment was 8 - 13%

From the simulation it is 15%
Summary

• Experiment on the deflection of proton beam by the bent crystal was successfully done.

• The crystal shows good deflection efficiency which is 8\% - 13\%.

• Performed Monte-Carlo simulation proves the experimental data
Future projects

Next experiment on the channeling of ultra-low emittance electron beam will be performed at KEK-ATF (Autumn, 2006).

Participation at the experiment on proton collimation at the Fermilab.

Experiment at the REFER ring, Hiroshima University with the 150 MeV electron beam (channeling radiation)

Application for the J-PARC