Crystal Possibilities at FACET?

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Outline

• Introduction
  – The Basics

• Ongoing Experiments
  – FNAL T980, CERN UA9, Mainz, others
  – Some open Questions

• Potential Applications
  – Beam Collimation
  – X-(\(\gamma\)-) Ray Generation
Channeling in Crystals

- **Discovered in the 60s:**
  - Atoms lined up in strings or planes, give rise to strong fields.
  - Beam particles can pass in between, guided by these fields.
  - Nuclear Potential:
    
    \[ V(\vec{r}) = \frac{Z_1 Z_2 e^2}{r} \left( 1 - \frac{r}{\sqrt{r^2 + C^2 a^2}} \right) \]
    
    - \( C \approx \sqrt{3}, a: \) screening length
    - In reality more complicated (thermal vibr., defects etc.)
  - 1 nucleus: \( 2 \times 10^{12} \) V/cm @ 0.1 Å
    <110> string: \( 1.3 \times 10^{10} \) V/cm (Si) (equiv. 4000 T B-field!)
• Critical angle (for Si <111> axial, (110) planar):

\[ \Psi_1 = \sqrt{\frac{4Z_1Z_2e^2}{pvd}} \]

\[ \Psi_p = \sqrt{\frac{4Z_1Z_2e^2Nd_pCa}{pv}} \]

- (d: atom spacing, no thermal vibrations)
- or about 15 \( \mu r/\sqrt{p} \) and 5 \( \mu r/\sqrt{p} \), resp. (p in [TeV/c])
- beyond these, particle escape transversely
  -> amorphous behaviour.
**Bent Crystals (Tsyganov)**

- **Channeled particles may follow a bend in a crystal**
  - if $\rho$ not too small, else again transverse energy gets too high

  \[ R_c = \frac{p\nu}{\pi Z_1 Z_2 e^2 N d_p} \]

  - for Si (110), 1 TeV/c: $R_c \approx 0.4$ m
  - In practice, experiments seem to run at maybe 10 $R_c$
Ongoing experiments

• **Protons, Ions:**
  – Fermilab T980
  – CERN H8 (ext. beam line)
  – CERN UA9 (SPS)
  – ...

• **Electrons/Positrons**
  – Mainz
  – LNF (Frascati)
  – (also secondary e⁻ and e⁺ at CERN)
  – …
H8-RD22 experiment (2006-'09)

Goniometer with crystal holders

Si microstrips (AMS)

Si microstrips (AGILE)

70 m

Scandale et al.
Strip crystals
Built at IHEP - Protvino and at INFN - Ferrara

The main curvature due to external forces induces the anticlastic curvature seen by the beam

Crystal size: 0.9 x 70 x 3 mm³

Main radius of curvature

Radius of anticlastic curvature

Scandale et al.
Goniometer
Assembled at INFN/LNL - Legnaro

- Two motors for translations
  - 2 μm repeatability
  - 102 mm range (upper stage)
  - 52 mm range (lower stage)

- One motor for rotations
  - 360° range
  - 1.5 μrad precision
  - 1 μrad repeatability
Angular beam profile as a function of the crystal orientation

9mm long Si-crystal deflecting 400GeV protons

The angular profile is the change of beam direction induced by the crystal.

The rotation angle is the angle of the crystal respect to the beam direction.

The particle density decreases from red to blue.

1 - "amorphous" orientation
2 - channeling (50 %)
3 - de-channeling (1 %)
4 - volume capture (2 %)
5 - volume reflection (98 %)

Scandale et al.
Particle-crystal interaction

Possible processes:
- multiple scattering
- channeling
- volume capture
- de-channeling
- volume reflection

Volume reflection
Prediction in 1985-’87 by A.M. Taratin and S.A. Vorobiev,
First observation 2006 (IHEP - PNPI - CERN)
Motivation:
- Use crystals as primary beam collimator at the LHC
- Hope to increase collimation efficiency dramatically by deflecting rather than scattering in 1st collimator

Experiment is setup in the SPS
- can directly verify the collimation efficiency.
The underground experiment in the SPS

Approved by the CERN Research Board of the 3 Sept 2008

Goals:
- Demonstrate high efficiency collimation assisted by bent crystals (loss localization)
- Follow single particle dynamics in crystal-collimation system

Scandale et al.
UA9 layout

Scandale et al.
Scandale et al.

U. Wienands, SLAC & LARP
FACET Users Mtg, 18-Mar-10
Expts. with Positrons & Electrons

• Positrons can basically channel like protons
  – quantitative differences possible due to q.m.
• Electrons see a very different potential
  – nuclei attract rather than repel
  – expect channeling to be less effective
• Both will radiate strongly (short bending radii)
  – high-energy X-rays expected and seen
  – even protons emit significant X-rays
  – thoughts and ongoing work assessing the possibility of an x-ray laser with crystal(s).
$e^+ / e^-$ Difference

positive harmonic potential

negative potential

Carrigan, Channeling 2008

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Other results of H8RD22

PROTON BEAM (400GeV/c),
◆ Volume reflection dependence from the curvature of the crystal
◆ Axial channeling

ELECTRON/POSITRON BEAM (180GeV/c),
◆ Volume reflection with electrons and positrons
◆ Radiation emission with e+/e- beams in channeling condition

Channeling from secondary crystal planes
Vertical beam profile

Modulated VR & y scan

Cradle alignment

POSITRONS

ELECTRONS

e+/e- having lost energy via radiation emission

The crystal is not ideal but it’s there!!!!!!

Scandale et al.
Radiative Energy Loss

Bolognini, Thesis

U. Wienands, SLAC & LARP
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Mainz Group (MAMI & LNF BTF)

- Use $e^+$ at BTF and $e^-$ at MAMI ($\leq 1.5$ GeV)
- Detection of X-rays
  - dechanneling length measurements
  - X-rays from “crystal undulator” (Aarhus)
**Dechanneling length**

- Deduce $e^-$ dechanneling length from channeling radiation using a Fokker-Planck ansatz.
  - $21\mu$m/GeV
    - flat crystal, planar
  - Sets scale for deflection expts.
  - Sets scale for any coherent effects

(valid for which energies?)

*Backe et al. NIM 2008*
Undulator Radiation at Positron/Electron Channeling in a Single Crystal

A. Solov’yov, A. Korol, W. Greiner et al.
Positron Channeling in Si-Undulator Crystal

\[ x = A \cdot \cos \left( \frac{2\pi}{\lambda_u} z \right) \]

\[ A = 9 \, \text{Å}, \quad \lambda_u = 50 \, \mu\text{m}, \quad N_U = 4 \]

Beam Energy \( E = 600 \, \text{MeV}, \quad \gamma = 1175.2 \)

\[ K = \gamma \cdot A \cdot \frac{2\pi}{\lambda_u} = 0.133 \]

Photon energy

\[ \hbar \omega = k \frac{4\pi \cdot \gamma^2 \hbar c}{\lambda_u (1 + K^2 / 2 + \gamma^2 (\theta_x^2 + \theta_y^2))} = 67.9 \, \text{keV} \]

at \( \theta_x = \theta_y = 0 \), and first order \( k = 1 \)
Experimental Setup @1.5GeV

Lauth et al. 
Channeling 2008

Nal Detector 
(10"Ø × 10" length)

Undulating crystal
Flat crystal
Scan around the vertical axis $\Phi$
Flat crystal

Lauth et al.
Channeling 2008
Scan around the vertical axis $\Phi$
Bent crystal

Aarhus-Kristall
28-08-08
wipp=-1.8°
Psi=178°
Phi=-10°->10°
0.1°/s

(100)
(111)
(110)

no Channeling

Signal Ionisation Chamber (log) [V]
Difference Spectra Bent-Flat

Lauth et al.
Channeling 2008
Some Observations

- **Proton data (at least single path) of high quality**
  - Lepton data much less so
  - There is interest in the X-ray production aspect.
  - Lack of good e+ beams does not help…

The possibility to produce undulator-like radiation in the hundreds of keV up to the MeV region by means of positron channeling is well known and was discussed in a number of papers, … However, the demonstration and utilization of such devices hampers from the fact that high quality positron beams in the GeV range are not easily available, in contrast to electron beams.

Backe et al.
NIM 2008
@ FACET

- High-quality e− and e+ beams up-to 24.5 GeV

- What else is needed:
  - Beampipe insert(s) to setup crystal(s) and detectors, possibly spectrometer magnet(s)
  - drift length to measure deflections accurately
  - possibility to taylor beam size & power density (and beam energy) to requirements
**Experimental Thrust**

- **Motivation for experiments:**
  - LC need efficient beam collimation
  - X-Ray generation may be of interest to the s.r. community
  - … and the processes themselves, while mostly qualitatively understood, need more quantitative understanding.
With the anticipated FACET start-up at SLAC in March 2011, we are studying the feasibility of two related crystal experiments:

- **Physics of volume reflection (VR) by e- and e+ in crystals.**
  - This will test the standard continuum model of VR for light particles of both charge signs
  - Explore the harmful effects of multiple scattering on VR
  - Possible application of VR to beam halo cleaning in Linear Colliders

- **Physics of volume reflection radiation by e- and e+ in crystals.**
  - This will test the radiation models for channeled light particles in the regime where “undulator parameter” $K = E/m \times \text{deflection angle} \sim 1$
  - Explore possible applications of VR as a new photon source and an energy degrader/collimator for halo particles in colliders
FACET 23 GeV electrons VR Output Angle Plot 0.65mm Si, R=1.3 m

- Crystal Rotation Angle
- VR rms = 0.04 mrad (Multiple Scattering is main contribution $\theta_{ms}$=1/E)
- VR angle = - 0.03 mrad

23 GeV: $\theta_{c0}$ ($\sim E^{-1/2}$) = 0.044 mrad, $R_{crit}$ ($\sim E$) = 0.05 m, $L_{dech}$ ($\sim E$) = 0.75 mm
Summary

1. We have begun a study of possible VR physics and radiation experiments at the planned FACET facility of SLAC, with beam expected in March 2011.

2. FACET 23 GeV e- and e+ beams will have $\theta_{\text{rms}} \sim 10-100 \ \mu\text{rad}$ for 100-10 $\mu\text{m}$ spot sizes, well-matched to the channeling critical angle in Si, and a good probe for VR effects.

3. If we use the IHEP-NPI Si crystal, 0.65 mm thick, R= 1.3 m, the VR angles are about 30 $\mu\text{rad}$, but multiple scattering gives an rms spread of 40 $\mu\text{rad}$. VR angle can still be clearly identified from the distributions.

4. The VR radiation spectrum for this case is estimated to have photons in the range 200 – 600 MeV using a simple wiggler model, with about 20 channel wiggles providing most of the radiation.
Si Undulator

- If we used the Aarhus crystal undulator
  - at 24 GeV: $\hbar \omega = 7.24\,\text{MeV}$, $k = 5.31$
- With 150 $\mu$m period:
  - $> 14\,\text{MeV}$, $k = 1.75$,
- … and we can do $e^+$ and $e^-$…
For this Working Group

• Think about measurements one might want to do in a first round of measurements.
• What experimental apparatus might be needed and how much space?
• What would be the crystal parameters desired?
• What would be the beam parameters desired?
• How to get suitable crystals?
• Get organized!