OBSERVATION OF PROTON REFLECTION ON BENT SILICON CRYSTALS AT THE CERN-SPS

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Outlook

♦ Why using crystals in hadron colliders
♦ The H8-RD22 experiment at CERN
  ♦ Experimental layout
  ♦ High precision goniometric system
  ♦ Tracking detectors
  ♦ Silicon crystals
♦ The results of the 2006 run
  ♦ Crystal Angular Scans (Strip and Quasi-Mosaic Crystals)
  ♦ deflection
  ♦ Efficiency
♦ Breaking news from the 2007 run
Why using crystals in hadron colliders

Crystal collimation: a smart approach for primary collimation

- A bent crystal deflects halo particles toward a downstream absorber:
  - the **selective and coherent scattering** on atomic planes of an aligned Si-crystal may replace more efficiently
  - the **random scattering** process on single atoms of an amorphous scatterer.
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)
The H8RD22 apparatus

- The scintillators S1-S6 produce the trigger
- The Si microstrips (AMS & AGILE) give the particle tracks
- The gas chamber (GS) and the hodoscope (H) provide a fast beam profile
- The goniometer orients the crystal respect to the incoming beam direction
Si microstrips

AMS

AGILE

Built at INFN - Perugia

pitch 110 μm, σ =14μm

Built at INFN - Como & Trieste

pitch 242 μm, σ =22μm

Mean   -0.00011
RMS    0.0315
χ² / ndf 298 / 144
Norm0     14 ± 1.58e+03
Mean0     0.000108 ± 0.000532
Sigma0    0.0001 ± 0.0137
Norm1     8.0 ± 239
Mean1     0.000404 ± -0.000114
Sigma1    0.0005 ± 0.0419

Sigma: 21.537 ± 6.536
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

Goniometer
Assembled at INFN - Legnaro
The main curvature due to external forces induces the anticlastic curvature seen by the beam.

Crystal size: 0.9 x 70 x 3 mm$^3$
Quasi-Mosaic effect (Sumbaev, 1957)

- The crystal is cut parallel to the planes (111).
- An external force induces the main curvature.
- The anticlastic effect produces a secondary curvature.
- The anisotropy of the elastic tensor induces a curvature of the crystal planes parallel to the small face.

Crystal size: 0.7 x 30 x 30 mm$^3$
Data taking

- Pre-alignment of the crystal respect to the beam line using optical methods

- Fast alignment of the crystal to the beam direction through the hodoscope (pitch 2 mm): the channeling peak is well visible at about 1 cm from the non-deflected beam

- Fast angular scan using the gas chamber (pitch 200 μm) and a high intensity beam ($10^8$ proton per SPS pulse): the reflection region is well visible.

- High statistics scan with the Si microstrip, in the range predefined by the fast angular scan ($10^4$ protons per SPS pulse)
Angular beam profile as a function of the crystal orientation

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

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

The particle density decreases from red to blue.

1 - "amorphous" orientation
2 - channeling
3 - de-channeling
4 - volume capture
5 - volume reflection
Angular profile $\mu$rad

Rotation angle ($\mu$rad)

Amorphous
Channeling

Angular profile (μrad)

Rotation angle (μrad)
Identify channeling, reflection and amorphous peaks of the angular profile distribution.

Compute the angular shift -> deflections

(underlying hypothesis: the incoming beam follows a stable direction)
Efficiency

- Integral of the events within $\pm 3\sigma$ around amorphous, channeling and reflected peaks
- Normalize the integrals to the incoming flux
- Ratios of channeling or deflection over amorphous normalized peak integrals -> efficiencies
- (underlying hypothesis: the incoming beam flux is stable)

Example of efficiency estimate

- Channeling: $49.9\%$
- Volume reflection: $93.8\%$
- "amorphous": $95.5\%$

\[
\begin{align*}
\varepsilon_{\text{refl}} &= \frac{P_{\text{refl}}}{P_{\text{amor}}} = \frac{93.8}{95.5} \\
\varepsilon_{\text{ch}} &= \frac{P_{\text{ch}}}{P_{\text{amor}}} = \frac{49.9}{95.5}
\end{align*}
\]
### Typical results

#### QM2 quasimosaic crystal
- $\varepsilon$ (reflection) = 98.2 %
- $\varepsilon$ (channeling) = 52.7 %
- $\Theta_{\text{channeling}}$ = 73 $\mu$rad
- $\Theta_{\text{reflection}}$ = 12 $\mu$rad

#### ST4 strip crystal
- $\varepsilon$ (reflection) = 98.2 %
- $\varepsilon$ (channeling) = 51.2 %
- $\Theta_{\text{channeling}}$ = 163 $\mu$rad
- $\Theta_{\text{reflection}}$ = 14 $\mu$rad
2007 run breaking news

5 heads multicrystal crystal (PNPI)

26 June 2007
Reflection on bent crystals
W. Scandale 18/22
♦ Beam profile in multiple VR condition in the Q5M5 crystal
♦ Active area for best results: 400x800 mm²

Steps to align the five crystals

♦ Volume reflection angle 53 μrad
♦ Efficiency ≥ 90%

High statistics
Conclusion

♦ High efficient reflection (and channeling) observed in single pass interaction of high-energy protons with bent crystals (0.5 to 10 mm long)

♦ Single reflection on a Si bent crystal deflects > 98% of the incoming beam by an angle 12 ÷ 14 μrad

♦ Very promising for application in crystal collimation

♦ Possible development consists in multi-reflections on a sequence of aligned crystals to enhance the reflection angle (successfully tested in the 2007 run).
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**Volume reflection**
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