State-of-the-art bent silicon crystals for high-energy charged particle beam collimation

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Outline

- Crystals in accelerators
  - Coherent interactions in bent crystals
- Crystals for beam collimation
  - Mandatory issues for collimation
  - Manufacturing techniques
  - Bending and characterization
Channeling

Coherent interactions in straight crystals:
Channeling is the confinement of charged particles traveling through a crystal within atomic planes (planar or axial modes)

Channeling occurs as the trajectory of particles forms an angle lower than the critical angle \( \theta_{\text{max}} \) \[1\]

\[ \theta_c = \sqrt{\frac{2U_0}{p\beta}} \]

\( U_0 \): Potential well depth \( \sim Z \) [22.7 eV for (110) Si]
\( p, \beta \): Particle momentum and velocity
\( \theta_c \approx 20 \mu \text{rad} \) at \( E \sim 100 \text{ GeV} \)

Channeling and volume reflection in a bent crystal

- A channeled particle is deflected by an angle equal to the bending angle of the crystal [1].
- A volume-reflected particle is deflected by the channeling critical angle [2].
- Bent crystals can be used in an accelerator for:
  - collimation and extraction of particles from the circulating particle beam;
  - beam steering;
  - radiation production.
- With short bent crystals (~mm), it is possible to deflect ultra-high-energy particles in CERN (SPS or LHC) with angles (100 µrad – 1 mrad) achievable by 1000 Tesla magnets having a similar size.

UA9 experiment: Crystal assisted collimation of modern hadron colliders (e.g. LHC)

Common collimation scheme

Crystal-assisted collimation
Surface requirements for collimation

- Impact parameter $b$ must be large enough to overcome imperfections (i.e. $b >$ surface roughness $R_A$)
- The effect of miscut was recently studied by the UA9 collaboration: (e.g. Phys. Lett. B 714 (2012) 231)
Miscut precise measurement (x-rays diffraction + autocollimator)
Miscut reduction via Magnetorheological Finishing (MRF)

- Best «pre-selected» wafer had a miscut of $(73 \pm 2) \mu\text{rad}$
- MRF treatment allowed the reduction of miscut down to $(5 \pm 2) \mu\text{rad}$

MRF provided by QED Technologies (USA)
Characterization of MRF-treated Si wafer surface

Flatness improved from 0.39 µm to 0.01 µm (measured with Zygo interferometer by QED)

Surface quality preserved (checked with high-resolution x-rays diffraction and Rutherford back scattering in channeling mode at LNL Legnaro)
Strip crystals fabrication

LPCVD deposition of silicon nitride thin layer

Anisotropic etching:
Etching rate on different silicon planes for KOH 20% at 40 °C

Silicon nitride patterning

Crystalline surfaces

Strip crystals bending

Anticlastic deformation used to deflect particle beam

Mechanical bending holder

Bent strip crystal
Morphological characterization

Veeco NT1100 white light interferometer

FOGALE TMAP 4 Infrared (IR) light interferometer

Thickness measurement

Curvature measurement and torsion reduction
Crystalline planes characterization

Panalytical X’pert Pro x-rays:
- Miscut
- Principal bending
- Anticlastic bending
- Torsion
Strip crystal for the collimation in the LHC (UA9 experiment)

- Channeling plane: (110)
- Titanium holder
- Mirrors installed for laser alignment
- STF75 installed in LHC in February 2014
- Spare crystal STF76 and twin crystals STF105 and STF106 (fabricated in 2015) were then characterized at the extracted lines of CERN-SPS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected</th>
<th>STF75</th>
<th>STF76</th>
<th>STF105</th>
<th>STF106</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness along the beam (mm)</td>
<td>≈ 4</td>
<td>4.10 ± 0.02</td>
<td>4.10 ± 0.02</td>
<td>4.07 ± 0.02</td>
<td>4.08 ± 0.02</td>
</tr>
<tr>
<td>Bending angle (interferometer, µrad)</td>
<td>≈ 50</td>
<td>52 ± 2</td>
<td>52 ± 2</td>
<td>51 ± 5</td>
<td>46 ± 5</td>
</tr>
<tr>
<td>Bending angle (X-rays, µrad)</td>
<td>≈ 50</td>
<td>51 ± 1</td>
<td>53 ± 1</td>
<td>49 ± 3</td>
<td>41.5 ± 1.5</td>
</tr>
<tr>
<td>Miscut (X-rays + autocollimator, µrad)</td>
<td>&lt; 10</td>
<td>6 ± 1</td>
<td>6 ± 1</td>
<td>40 ± 4</td>
<td>40 ± 4</td>
</tr>
<tr>
<td>Torsion (interferometer, µrad/mm)</td>
<td>&lt; 1</td>
<td>6 ± 1</td>
<td>6 ± 1</td>
<td>&lt;2</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Torsion (X-rays, µrad/mm)</td>
<td>&lt; 1</td>
<td>6 ± 1</td>
<td>6 ± 1</td>
<td>&lt;2</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Heating compatibility</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
• 5 pairs of Si microstrip sensors, with an active area of \(3.8 \times 3.8\) cm\(^2\) each
• Long baseline (~10 m for each arm)
• Angular resolution: 2.8 \(\mu\text{rad}\) for the incoming arm, 5.2 \(\mu\text{rad}\) for the difference of the two arms (< critical angle for channeling ~10 \(\mu\text{rad}\) for 400 GeV/c protons)
• Planes 1 and 2 used for measure incoming tracks, while 3, 4 and 5 planes for outgoing tracks
• Events triggered on the signal coincidence with a plastic scintillator placed downstream
Strip crystal for the collimation in the LHC (UA9 experiment)

- STF105 and STF106 crystals tested with 400 GeV/c protons
- Crystals mounted on a high resolution goniometer, and aligned to find channeling
- Protons trajectories tracked with the silicon telescope
- Results are in agreement to characterization performed at SSL Ferrara

<table>
<thead>
<tr>
<th>Parameter</th>
<th>STF105</th>
<th>STF106</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending angle (µrad, 400 GeV/c channeled protons)</td>
<td>49 ± 1</td>
<td>41.5 ± 1.5</td>
</tr>
<tr>
<td>Deflection efficiency (400 GeV/c channeled protons)</td>
<td>(80±1) %</td>
<td>(81±2) %</td>
</tr>
<tr>
<td>Torsion (µrad/mm, 400 GeV/c channeled protons)</td>
<td>&lt;2</td>
<td>&lt;2</td>
</tr>
</tbody>
</table>
Summary and conclusions

- Methods for crystal manufacturing presented
- Crystal-assisted beam collimation:
  - Several prototypes were fabricated and characterized
  - Strip tested with 6.5 TeV protons at CERN-LHC
Thank you for your attention!!!
First crystal-assisted collimation tests in the LHC

Strip crystal STF75 from Ferrara installed in LHC in the horizontal plane of the betatron collimation insertion (IR7) in February 2014 (quasi mosaic crystal from PNPI installed in the vertical plane)

Collimation tests in channeling mode performed in 2015:

- 30/08: both crystals tested at injection energy (450 GeV) with protons (first time in LHC)
- 06/11: horizontal crystal tested at flat top (6.5 TeV) with protons (record)
- 02/12: both crystals tested at injection energy (450 GeV) with Pb ion beam (record for ions)
First evidence of channeling in the LHC

First strong evidence of channeling at LHC top energy (6.5 TeV) !!!