Bent crystals for beam extraction from the LHC

Desenzano del Garda
28/09/2016

Andrea Mazzolari
INFN Ferrara and Ferrara University
OUTLINE AND MOTIVATIONS

• Motivations
  • Fixed target experiments @LHC
  • hadron physics

• Crystal specifications

• Crystals manufacturing

• Crystals bending
  • Anticlastic deformation
  • Self standing bent crystals

• Conclusions

"Physics opportunities of a fixed-target experiment using LHC beams”
CRYSTAL SPECIFICATIONS

L → Crystal thickness along the beam
Θ → Deflection angle
R → Bending radius

L = R * Θ

Required deflection angle: ~ 1 mrad

Θ = L / R → Required optimization of both L and R.

L → Limited by dechanneling length (negligible factor)
R → Limited by its influence on the interplanar potential well
CRystal Specifications

- Reasonable channeling efficiency \( \Rightarrow R > \sim 7 \, R_c \)
- At 7 TeV \( R_c \sim 14 \, m \)
  \( R > \sim 100 \, m; \, \Theta \sim 1 \, mrad \)
  \( \Rightarrow L > 100 \, mm \) (\( L= R*\Theta \))

Needed manufacturing, bending and characterization of a crystal with

- (110) or (111) channeling planes
- \( L \sim 100 \, mm \)
- \( R \sim 12 \, m \)
- Uniform bending radius
- \(< 1 \, \text{dislocations/cm}^2\) [2]

---

Crystal manufacturing

-Bulk crystalline quality characterization (Ag x-ray)
Anisotropic etching is a feasible way to realize sub-surface damage free crystals entirely by wet chemical methods. Only for (110) oriented crystals.

Etch rate on different silicon planes for KOH 20% at 40 °C

<table>
<thead>
<tr>
<th></th>
<th>(100)</th>
<th>(110)</th>
<th>(111)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate</td>
<td>7.1 µm/h</td>
<td>10.7 µm/h</td>
<td>Negligible</td>
</tr>
</tbody>
</table>
CRYSTAL MANUFACTURING -DRIE ETCHING-

For crystals of any orientation (also for (111) oriented)
Tests on (111) crystals already performed.

Uses high density plasma to alternatively etch silicon and deposit a etch-resistant polymer on side walls

Unconstrained geometry
90° side walls
High aspect ratio 1:30
Easily masked (PR, SiO2)

Process recipe depends on geometry

For crystals of any orientation (also for (111) oriented)
Tests on (111) crystals already performed.

Uses high density plasma to alternatively etch silicon and deposit a etch-resistant polymer on side walls

Unconstrained geometry
90° side walls
High aspect ratio 1:30
Easily masked (PR, SiO2)

Process recipe depends on geometry
High-quality surfaces achieved via anisotropic chemical etching.

Lateral surface (AFM): Sub-nm roughness achieved (0.2 nm).

Entry surface (High Resolution transmission electron microscopy): Zero nm amorphous layer.
## Crystal Manufacturing - Summary -

<table>
<thead>
<tr>
<th></th>
<th>Anisotropic Etching</th>
<th>DRIE Etching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice damage free</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Crystal orientations</td>
<td>(110)</td>
<td>Any</td>
</tr>
<tr>
<td>Roughness</td>
<td>Sub-nm</td>
<td>Sub-nm</td>
</tr>
<tr>
<td>Possibility to precisely control thickness of crystal along the beam</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Suitable for crystals bent through anticlastic</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Suitable for crystals bent through thick or thin films</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
CRYSTAL BENDING

• Two possible approaches

  • Exploiting anticlastic deformation in «unusual regime»

  • Development of innovative bending schemes (self standing bent crystals)
CRYSTAL BENDING
-ANTICLASTIC DEFORMATION-

Analytical approach
• Fast approach for general guidelines on crystal design.
• Does not take into account influence of crystal clamping.

FEM assisted approach
• More realistic modelling
• Needed for a fine tuning of the crystal and holder geometry

\[
\left( \frac{\partial^4}{\partial x^4} + 2 \frac{\partial^4}{\partial x^2 \partial y^2} + \frac{\partial^4}{\partial y^4} \right) z(x, y) = 0
\]

(V.I. Kushiriir t, J.P. Quintana and P. Georgopoulos NIMA 328 (1993) 588-591)
Crystal bending -anticlastic deformation-

Plate of lateral sizes $A \times B$
$B$ is kept constant.
$A$ is varied.
Principal curvature along $B$
Anticlastic curvature along $A$

V.I. Kushriir t, J.P. Quintana and P. Georgopoulous
NIMA 328 (1993) 588-591

Ratio between principal and anticlastic curvature in the middle of the crystal
- For aspect ratio $(B/A) > 0.25$ anticlastic deformation start to be suppressed
- Not uniform deformation at large aspect ratio

H8, SPS, LHC crystals

(110) Oriented crystals.
We consider a crystal with thickness along the beam of ~100 mm. Bending angle 1 mrad. We increase aspect ratio—>

- Compact crystal along the vertical direction
- Decrease of deformation uniformity
- Stronger bending

<table>
<thead>
<tr>
<th>Thickness along the beam (m)</th>
<th>Crystal height (m)</th>
<th>Aspect ratio</th>
<th>Bending angle (urad)</th>
<th>Principal radius (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.137</td>
<td>0.137</td>
<td>1</td>
<td>1000</td>
<td>7.79</td>
</tr>
<tr>
<td>0.11</td>
<td>0.22</td>
<td>0.5</td>
<td>1000</td>
<td>14.01</td>
</tr>
<tr>
<td>0.102</td>
<td>2.04</td>
<td>0.05</td>
<td>1000</td>
<td>17.68</td>
</tr>
</tbody>
</table>
FEM assisted design applied to

- design and manufacturing of crystals bending devices
- Crystals dimensions and orientation optimization
Crystal deformational state characterized by HR-XRD

- Crystal bending angle
- Crystal torsion
- Deformation non-uniformities.
CRYSTAL BENDING
-SELF STANDING BENT CRYSTALS-

- Thin/thick films deposited on silicon substrate may induce a deformation of the substrate.
  - Film deposition performed at high temperature.
  - Film and silicon substrate has different thermal expansion coefficients → deformation while cooling to room temperature.
  - Deformation adjustable acting on film thickness and patterning.
- Deformation occurring thanks to surface plasticitazion
Self standing bent crystals
-Thin/thick film deposition-

- Possibility to deposit a wide class of materials
  - Thin films (silicon oxide, silicon nitride, mettals, thickness up to ~400 nm).
  - Thick films (aluminium based alloys, carbon fiber, thickness from a few micron to a few mm).
- Holder needed for a fine adjustment of crystal deformation
### LONG CRYSTALS – ANTICLASTIC DEFORMATION –

<table>
<thead>
<tr>
<th>Feature</th>
<th>PL02</th>
<th>PL03</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal thickness along the beam</td>
<td>23.8±0.1 mm</td>
<td>56.8±0.1 mm</td>
</tr>
<tr>
<td>Crystal transversal thickness</td>
<td>0.52 mm</td>
<td>1 mm</td>
</tr>
<tr>
<td>Channeling plane</td>
<td>(110)</td>
<td>(110)</td>
</tr>
<tr>
<td>Channeling axis</td>
<td>&lt;100&gt;</td>
<td>&lt;110&gt;</td>
</tr>
<tr>
<td>Bending angle (HRXRD)</td>
<td>280 μrad</td>
<td>324 μrad</td>
</tr>
</tbody>
</table>
LONG CRYSTAL «PL02» test with 400 GeV/c protons

Preliminary data for PL02

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (±2 µrad)</td>
<td>65±3 %</td>
</tr>
<tr>
<td>Efficiency (±5 µrad)</td>
<td>60 ±3 %</td>
</tr>
<tr>
<td>Efficiency (±10 µrad)</td>
<td>47±3 %</td>
</tr>
<tr>
<td>Mean Deflection (µrad)</td>
<td>280±10 µrad</td>
</tr>
<tr>
<td>Bending Radius (m)</td>
<td>~85</td>
</tr>
</tbody>
</table>

Preliminary data for PL03

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency (±10 µrad)</td>
<td>31±3 %</td>
</tr>
<tr>
<td>Mean Deflection (µrad)</td>
<td>324±10 µrad</td>
</tr>
<tr>
<td>Bending Radius (m)</td>
<td>~175 m</td>
</tr>
</tbody>
</table>
SELF STANDING BENT CRYSTALS  
-THIN FILMS-

- LPCVD Si₃N₄ or SiO₂ on silicon

• \[ \text{SiCl}_2\text{H}_2 + 2 \text{N}_2\text{O} \rightarrow \text{SiO}_2 + 2 \text{N}_2 + 2 \text{HCl} \ (T=950 \, ^{\circ}\text{C}) \]

• \[ 3 \text{SiCl}_2\text{H}_2 + 4 \text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + 6 \text{HCl} + 6 \text{H}_2 \ (T=800 \, ^{\circ}\text{C}) \]
**SELF STANDING BENT CRYSTALS**

**-THIN FILMS-**

Optical profilometry with 1 nm resolution

Measured values of curvature and stress in 300 µm thick Si wafers

<table>
<thead>
<tr>
<th>Si₃N₄ thickness</th>
<th>R (m)</th>
<th>σ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Simulated</td>
</tr>
<tr>
<td>150nm</td>
<td>14.7±0.5</td>
<td>14.4</td>
</tr>
<tr>
<td>200nm</td>
<td>10.5±0.1</td>
<td>10.8</td>
</tr>
<tr>
<td>250nm</td>
<td>9.3±0.1</td>
<td>8.6</td>
</tr>
</tbody>
</table>
**SELF STANDING BENT CRYSTALS -THIN FILMS-**

Deposition of 100 nm thin silicon nitride and patterning

- lines 500 μm wide
- spacing 1000 μm

Perfect agreement between deformed and predicted crystal shape.
LONG CRYSTALS «PL04» - a self-bent crystal

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal thickness along the beam</td>
<td>20±0.1 mm</td>
</tr>
<tr>
<td>Crystal transversal thickness</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Channeling plane</td>
<td>(110)</td>
</tr>
<tr>
<td>Channeling axis</td>
<td>&lt;111&gt;</td>
</tr>
<tr>
<td>Bending angle (HRXRD)</td>
<td>280 μrad</td>
</tr>
</tbody>
</table>

Crystal surface is patterned with a silicon nitride film 100 nm thick.
LONG CRYSTALS «PL05» - a self-bent crystal

<table>
<thead>
<tr>
<th>Characterization</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystal thickness along the beam</td>
<td>55±0.1 mm</td>
</tr>
<tr>
<td>Crystal transversal thickness</td>
<td>1 mm</td>
</tr>
<tr>
<td>Crystal height</td>
<td>55 mm</td>
</tr>
<tr>
<td>Channeling plane</td>
<td>(110)</td>
</tr>
<tr>
<td>Channeling axis</td>
<td>&lt;111&gt;</td>
</tr>
<tr>
<td>Bending angle (HRXRD)</td>
<td>1.6 mrad</td>
</tr>
</tbody>
</table>

- **Self standing crystal**
- Crystal deformation occurs as a consequence of plasticitazion of one of its main surfaces
PRELIMINARY DATA FOR «PL05»

Deflection angle $\sim 1.6$ mrad
(very preliminary)
CONCLUSIONS

- Crystals suitable for LHC extraction are under development
- Bending relies on
  - Anticlastic deformation
  - Self bent crystals
- Characterizations performed with HR-XRD, white light interferometry, 400 GeV proton beam (400 GeV protons, UA9 experiment)