Quasi-mosaic Silicon Crystal Deflectors for LHC Beams

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Reflection of Gamma-Rays From Bent Quartz Plates

O. I. Sumbaev

IN INVESTIGATING the coherent reflection of x- and γ-rays from the 1340 planes of quartz plates cut from an α-quartz single crystal so that the 1340 planes were normal to the plane of the plate and the side edges were parallel to the optical axis of the crystal, Lind, West and DuMond found that the dependence of the integrated reflection coefficient on the wavelength for plates elastically bent to a cylinder of 2 meters radius is close to quadratic. Their measurements of the integrated reflection coefficient for the same plate in the unstressed state led to a dependence close to the linear, i.e., the dependence characteristic of ideal crystals. Lind et al. do not attempt to give an explanation of the observed effect noting only that “...the quartz might, however, become mosaic-like in structure in some elastically reversible way not now understood.”

We felt it would be of interest to verify the quadratic dependence of the reflection coefficient on the wavelength discovered by Lind, West and DuMond and to find an explanation of the effect. The measurements were carried out on the two-meter crystal-diffraction spectrometer of the All-Union Scientific

Lind, West and DuMond assumed that the initially flat reflecting planes remain plane when the plate is bent. This in general is not correct. Actually, when a plate of arbitrary cross section is bent by the application of a bending moment $M$, acting in the $xy$ plane (Fig. 2) the displacements in the $z$-direction of the $z$-axis in the case of anisotropy of the general form are determined by the familiar relation

$$W = \frac{M}{2l_1}[a_{35}xy + a_{33}y^2 + a_{33}(2z - l)],$$

where $M_1$ is the effective bending moment, $l_1$ is the...
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moment of inertia about the $x$-axis and the $a_{ij}$'s are strain coefficients. If $a_{34}$ and $a_{35}$ differ from zero, the cross sections are distorted by the bending into second-degree surfaces. With $a_{35} = 0$ the planes bend along the parabolas:

$$z = k_1 y^2, \quad k_1 = M_1 a_{34} / 2 I_1.$$

If $a_{33} \neq 0$, Eq. (1) becomes invalid for cases of bending of the crystal plate between cylindrical mirrors or by application of moments by the method of Borovskii-Gil'varg.\(^4\)\(^5\) Actually if $a_{33} \neq 0$, in addition to bending, the plate tends to twist. However, the design of the crystal holder prevents twisting with the result that in addition to the moment $M_1$ (couple $PP$ in Fig. 2) the plate is subjected to a moment $M_2$ opposing the torsion (forces $PP'$ in Fig. 2). The deformation of a plate loaded in this manner is satisfactorily approximated by the following expression

$$W = \frac{1}{2\rho (a_{33} - a_{35}^2 / a_{55})^2} \left( a_{34} - \frac{a_{45} a_{55}}{a_{55}} \right) y^2.$$

which is rigorously valid for a plate of elliptic cross section (in which case $a$ and $b$ are the axes of the ellipse) bent to a cylinder of radius $\rho$. Neglecting the terms with $b^2 / a^2$ (in our case $(b/a)^2 \approx 2.5 \times 10^{-3}$), we obtain

$$W = \frac{1}{2\rho (a_{33} - a_{35}^2 / a_{55})} \left( a_{34} - \frac{a_{45} a_{55}}{a_{55}} \right) y^2.$$

The intensity of reflection from the entire lamina will be proportional to

$$[r_0 \rho (F / v) \Delta y / \cos \theta]^2.$$

The width of the diffraction peak will obviously be

$$\Delta \theta = 2k_2 T,$$

where $T$ is the thickness of the plate and the integrated reflection coefficient

$$R_\theta \sim 2k_2 T \left[ r_0 \rho \left( \frac{F}{v} \right) \Delta y / \cos \theta \right]^2 \sim \frac{p^2}{\cos^2 \theta} \rho^2 \left( \frac{F}{v} \right)^2 dT^2.$$

This relation is identical with the expression for the integrated reflection coefficient for a mosaic crystal. Computing $\Delta y$ from (7) with $k_2 = 0.226 \times 10^{-1}$
Thus we see that the quadratic dependence of the reflection coefficient of an elastically bent quartz plate on the wavelength can be explained naturally without recourse to any additional hypotheses. The bent plate actually does become similar to a mosaic crystal in consequence of bending of the reflecting planes.
EXPERIMENTAL INVESTIGATION OF THE ELASTIC QUASI-MOSAIC EFFECT

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Submitted December 14, 1967

ent orientations (the indices of the planes coinciding with the normal cross sections are indicated on the curves)\(^{(9)}\).

The purpose of the present paper is to present a comparison of the experimental and calculated parameters of the diffraction process for different values of the flexure coefficient \(k(\phi)\), and particularly a verifica-

FIG. 4. Position of compared plates in the single-crystal quartz block.

FIG. 5. \(K_{\alpha_1}\) Sn x-ray line obtained with a two-meter Cauchois spectrometer using compared plates of 1 mm thickness. Receiving slit \(\approx 250\mu\); \(N\) – number of \(\gamma\) quanta registered in 30 sec; \(l_{CT}\) – linear displacement of the end of the one-meter arm of the crystal drive. The vertical scale is doubled for the \(= 11^\circ\) line.
Quasimosaic effect in silicon

- Calculations of deformed crystal plate done by V.M. Samsonov (Preprint No. 278, LIYaF AN SSSR, 1976).
  - Resulted in predictions of elastic quasimosaic effect for some other quartz and silicon plate orientations
  - Large elastic quasimosaicity for (011) plane of silicon predicted
- Zero result in the first experiments in 1999
- New calculations using Samsonov approach and new measurements:
  - (111) plane, not (011)
  - Published in JETP Letters 81, 99, 2005

Figure from article: V.M. Samsonov and E.G. Lapin, On some possibilities and peculiarities of a curved crystal use in crystal diffraction instruments, Preprint No. 587, LIYaF AN SSSR, 1980
Quasi-Mosaic Effect Applications

- Improvement of efficiency of X-ray focusing crystal-diffraction spectrometers by two orders (chemical shifts of atomic levels)
- Possibility to optimize focusing crystal-diffraction spectrometers according to structure and width of line under investigation (world best measurements of pi-minus, K-minus, and Sigma-minus masses)
- Record resolution of gamma-ray focusing crystal-diffraction spectrometers (~1 microradian)
- Possibility to increase efficiency of X- and gamma-ray double flat crystal spectrometers
New Application of Quasi-Mosaic effect started from Crystal Beam Multi-Turn Extraction Experiments at IHEP (1997-2001)
Crystal beam extraction at U-70

Bending angle \((\sim 0.4 \text{ – } 1.0 \text{ mrad})\)

Small crystal length along beam to provide multi-turn passage of 70 GeV protons
Strip crystals (IHEP)

Sizes $\approx 3 \times 1 \times 60 \text{ mm}^3$
Elastic quasimosaic in dependence on cut angle for Si (111) plane

\[ \Delta \theta = 2 k_9 T, \quad \text{where} \]

- \( T \) – thickness of plate
- \( k_9 \) – deformation coefficient

( formula taken from V.M. Samsonov, E.G. Lapin, Preprint No. 587, LIYaF AN SSSR, 1980 )
Quasimosaic effect in Si with X-rays

Rocking curves for Si plate with quasimosaic before and after bending.

Rocking curves for Si plate without quasimosaic before and after bending.
Shape of bent Si plate with elastic quasimosaic
Bending device
First quasimosaic silicon crystal prepared in 2002 for channeling experiment with 70 GeV protons
Samples 0.3 mm and 2.7 mm with ~0.4 mrad bending angle
Sample 10 mm with \(~100\ \mu\text{rad}\) bending angle
Crystals for experiment on extraction of high intensive proton beam at IHEP

Plane (111)
Length along beam 2.65 mm
Bending angle 400 µrad
Quasi-mosaic crystal installed at gonio
Crystal installation at U-70
Beam extraction from U-70

Number of protons in the ring $5.5 \cdot 10^{12}$ p

Number of extracted protons $4.0 \cdot 10^{12}$ p

Extraction efficiency $\sim 70\%$
Experiment at IHEP with 70 GeV proton beam (2002)

Crystal 1

Magnets

Collimator

70 GeV p-beam

Crystal length along beam 0.7 mm

Crystal 2

S1

S2

S3

Background

Emulsion 1

Emulsion 2

R=3 m

5 m

30 m

35 m

4.6 m

1.3 m

The beam distribution after quasimosaic crystal measured with photoemulsions

Why A и В?
Volume Reflection Effect


and

Volume Reflection of 1-GeV Protons by a Bent Silicon Crystal


Observation of Volume Reflection with 1GeV protons at PNPI using Quasi-Mosaic Crystal of 30 µm Thickness

Crystal angle, step 62.5 µrad

Channel number, step 200 µm

p-beam

channeling

reflection

about 30 min
Results

Deflection angle of reflected protons:

\[ 2\theta_R \sim 240 \, \mu \text{rad} = 1.4 \cdot \theta_c \]

Probability of the volume reflection:

\[ P_R \sim 0.7 \]

Probability of the volume capture:

\[ P_{VC} \sim 0.3 \]
Channeling experiment with 400 GeV protons at SPS CERN (H8-RD22 Collaboration, 2006)
Result of typical angular scan with one of the crystals
Observation of volume reflection effect from 5 quasi-mosaic crystals

Not aligned 5 crystals

Aligned crystals

~55 мкрад
Deflectors QM33 and QM34 for LHC
Materials

**Holder**
- **alloy VT6** (Russian analog of Titanium grade 5)

**Spring**
- **alloy BRB2** (Russian analog of Alloy 25)

**Coating on the mirrors**
- **alloy Ni-Mo (Mo-10%)**, non-magnetic, 2500Å

**Crystalline plate**
- high pure silicon ingot used for QM1-29
<table>
<thead>
<tr>
<th>Technology</th>
<th>Lab Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending device</td>
<td>lab mechanical workshop</td>
</tr>
<tr>
<td>Metal polishing</td>
<td>lab optical workshop</td>
</tr>
<tr>
<td>Coating on the mirrors</td>
<td>lab magnetron sputtering</td>
</tr>
<tr>
<td>Crystalline plate</td>
<td>lab optical workshop and X-ray setup</td>
</tr>
</tbody>
</table>
## Crystal parameters

<table>
<thead>
<tr>
<th>Sample</th>
<th>QM33</th>
<th>QM34</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channeling planes</td>
<td>(111)</td>
<td>(111)</td>
</tr>
<tr>
<td>Length along beam (mm)</td>
<td>4.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Miscut (µrad)</td>
<td>~ 20</td>
<td>~ 20</td>
</tr>
<tr>
<td>Surface layer (nm)</td>
<td>~ 200</td>
<td>~ 200</td>
</tr>
<tr>
<td>Bending angle (µrad)</td>
<td>44 ± 3</td>
<td>47 ± 3</td>
</tr>
<tr>
<td>Torsion in center (µrad/mm)</td>
<td>≤ 1</td>
<td>≤ 1</td>
</tr>
<tr>
<td>Saddle curvature (µrad/mm)</td>
<td>~ 6</td>
<td>~ 6</td>
</tr>
</tbody>
</table>
Future plans

To study installed crystals at SPS and LHC (in the ring and with external beams)