LABORATORY STUDIES ON A SPHERICALLY CURVED BRAGG SPECTROMETER FOR COSMIC X-RAY SPECTROSCOPY

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ABSTRACT

A spherical array of twenty LiF 200 crystals has been built to test the performances of a freestanding, self-focussing spherical crystal cosmic X-ray spectrometer. Measurements presently available show that the size of the image for a point source at infinite distance would be 3mm(FWHM) along the focalisation axis and 2.1 mm (FWHM) along the dispersion axis. The mosaïc spread on individual crystals is less than 0.1 degree. A slightly systematic deviation from the ideal bending (0.1 degree) is observed at the edges of most crystals and this appears to be the major limitation to spectrometer performance.

I. INTRODUCTION

Precise piasma diagnostic on cosmic ray sources can only be obtained from measurements of line strength ratios with Bragg spectrometers. A free-standing Spherical Crystal Imaging Spectrometer (SCIS) similar to the one described by H. Schnopper and P. Taylor (1980) has been chosen for the ESA mission X 80 (L. Culhane, this Workshop). A free-standing spectrometer employs a curved array of crystals to simultaneously collect, focus and diffract the X rays emitted by a distant source. The concave spherical shape provides the minimum loss of spectral and spatial resolution which may result from source extent, spacecraft pointing and alignment errors (R. Griffith, this Workshop).

We began studies on spherically bent lithium fluoride crystals in 1979 to demonstrate the feasibility of the spectrometer we proposed to NASA in collaboration with the Smithsonian and Harvard Astrophysical Observatory (CFA). We describe hereafter the results obtained during this feasibility study. We will see that these results are directly applicable to the Bragg spectrometer of the ESA mission X 80 whose main design goals are :

- spectral resolution $E/\Delta E \simeq 10^3$ at 7 keV
- size (full width at half maximum) of the image of a distant point source : 2.5 mm along the dispersion axis and 4.5 mm along the focalisation axis for a radius of curvature of 2.5 m.

II. TYPES OF CRYSTALS

The following results were obtained with LiF 200 crystals which were proposed in the initial document (ref. ESA.SCL(79)3) for the observation of iron lines between 1.7 and 1.9Å.

These crystals can be provided by cleavage or cut and polished. Cleavage along the 200 plane does not give very flat crystals : impurities produce cleavage steps of a few microns, even tens of microns. Polishing gives surfaces with very good quality which allows optical uses. It is note-worthy that polishing results in a bending of the crystal due to mechanical surface stress. For the tests we used square crystals (5 cm x 5 cm), 0.5 mm thick provided by Quartz et Silice. Other types of crystals (220 LiF, PET, TlAp) for further studies will be provided by the same manufacturer.*

III. TESTS AND SELECTION OF FLAT CRYSTALS

Planimetry

The flatness of each crystal is measured before bending. The required precision on the radius of curvature $\Delta R/R \simeq 5$-10% imposes a severe selection : to understand that we have to remind that a 2.5 m curvature radius produces a sagitta of only 125 microns on a 5 cm length. The surface of each crystal is scanned with a planimeter along several lines parallel to the X and Y axis. The two sides of each crystal are explored with an accuracy of 1 micron. Cleaved crystals with prohibitively

high cleavage steps were excluded. Polished crystals exhibit a strong uniformity and no selection is required for these.

X-Ray tests

They are devoted to estimate the effect of the large scale mosaicity. The test bench consists of a point source, a crystal holder and a radiographic film. Mosaicity means that, at a given point on the crystal, crystalline lattice makes an angle with the upper surface. The different points on the crystal, satisfying the Bragg relation, contribute to the diffraction image on the film which consists in a single regular line for a perfect crystal and several portions of bent lines for actual crystals. The vertical spread ε of the diffraction pattern is proportional to the mosaicity W. Calibration gives $\varepsilon/W = 0.7$ mm/arc.min. The two lines $K\alpha_1$, $K\alpha_2$ of Copper are clearly seen for each scanning position. In most casesthe vertical spread is less than 3 to 4 mm corresponding to a mosaicity less than 0.1°. A few crystals only were rejected after this test.

IV. METHOD USED TO SPHERICALLY BEND THE LiF CRYSTALS

The LiF crystals are 0.5 mm thick and 50 x 50 mm^2 in area. The nominal radius of curvature is R = 2.50 m. Individual crystal holders 50 x 50 mm and 5 mm thick are made in aluminium alloy. They can be individually aligned by a classical optical method using the rear face. The front face is covered by a spherical deposit of STYCAST resin obtained by molding, the surface being polished against a convex spherical shape to remove any imperfection. Then the crystal is glued on the holder during 72 hours or more at room temperature under pressure of $\sim 7.10^5$ Pascals.

V. TESTS OF BENT CRYSTALS

Mechanical measurements

The same instrument as in sect.III was used to estimate the crystal sphericity. The profiles show slight cleavage steps. The set of tested crystals have radius clustered around the nominal value +5% with a maximum spread of about $\pm$ 8%.

X-ray tests

The equipment is shown in fig.1. It consists of an X-ray generator with a copper anticathode. The size of the X-ray source is 1 x 1 mm^2 ; after a trip of 6.5 meters in a tube filled with helium, X-rays reach the LiF crystal. The part of the radiation impinging the crystal with Bragg incidence is reflected and focussed, after another 6.5 meters trip in helium, on the sensor (film, PM, position sensitive proportional counter). For a perfect crystal, reflection should occur on a vertical line.

Fig.1 Test bench in X rays for spherical crystals.

Two tests were carried out :

(i) for a given position of the crystal the image is scanned along a vertical axis so as to estimate focussing properties. The image brightness is not gaussian in most cases and may exhibit some spikes or bumps. On the average the width with cleaved crystal is smaller than with polished ones, but the shape is not so smooth. This is probably due to small cleavage steps which give rise to different curvature radii.

(ii) The crystal is rotated around the curvature center. The detector is located so as to measure $K\alpha_1$ copper line only. Then the crystal is rotated around a vertical axis going through the theoretical curvature center. A perfectly bent crystal would give a constant reflection for a rotation of $\Theta = 75$ arc minutes. Most of the crystals show an increased reflection at the edges proving that they are not properly curved at those place ($R > R$ nominal). From the width and shape of the curves one can conclude that local angular deviations from a perfectly spherical surface is less than 0.1°. The reflectivity of polished crystals is about twice the reflectivity of cleaved ones.

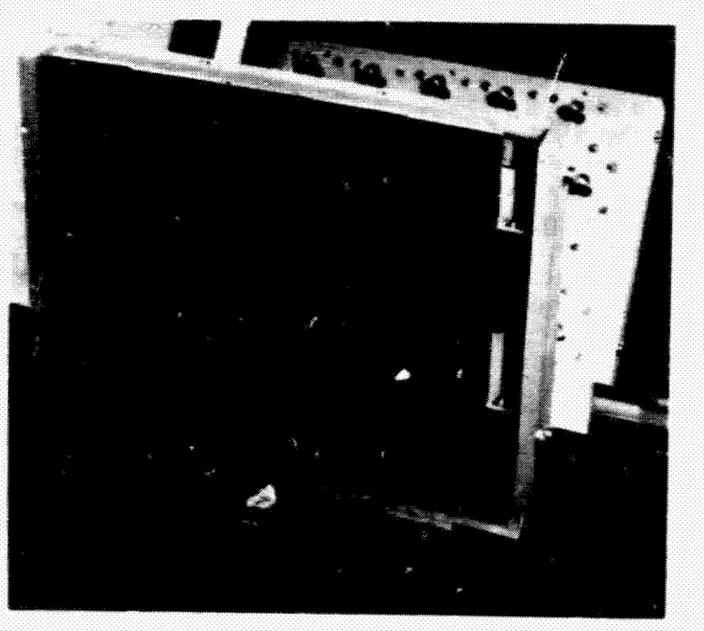

Fig.2 Mosaic array of 20 spherically curved LiF 200 crystals.

Testing of a mosaic array of spherically curved crystals

A mosaic array of 20 individual crystals is shown on fig.2. On this panel 4 crystals are cleaved, the other ones cut and polished.

First the panel is optically aligned on the test bench described on fig.1, his surface being perpendicular to the line joining the center of the panel to its center or curvature. Then each crystal is individually aligned using the reflection of a laser beam, all centers of curvatures are adjusted to coincide. The final alignment of individual crystals is obtained with the X-ray beam on the test bench : each crystal must focalise the diffracted beam on the line joining the source to the center of curvature of the crystal. When the whole panel is illuminated by X rays we can get the summation of diffracted beams coming from a row of 5 crystals. The figure 3 shows the X-ray intensity at the focus versus distance from the center of the image. The full width of the curve at half-maximum (FWHM) is 6 mm for 5 polished crystals. The composite image has a more gaussian shape for polished crystals.

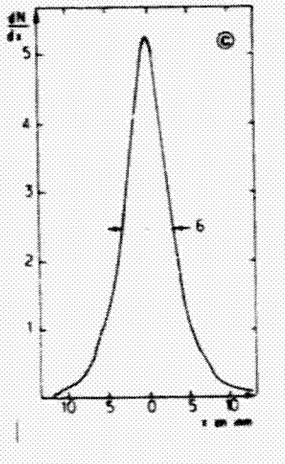

Fig.3 X-ray intensity distribution along the focussing direction versus distance from the center of the image.

Finally the whole panel is rotated around the center of curvature to test the response in the dispersion plane. Fig.4 shows the received intensity versus angle of rotation for the whole panel. The upper curve corresponds to an aperture of 5 x 30 mm in front of the detector, the lower curve to an aperture of 5 mm diameter. The total diffracted intensity corresponds as expected to 4 times the mean intensity given by individual crystals. The imperfections of the curvature at the edges of the crystals explain the irregular shape of the curves. From the ratio of diffracted intensities between the upper and lower curves in fig.4 one deduces the size of the image in the dispersion plane : 4.2 mm (FWHM). During these tests we have monitored the focussing properties of the array which showed acceptable variations.

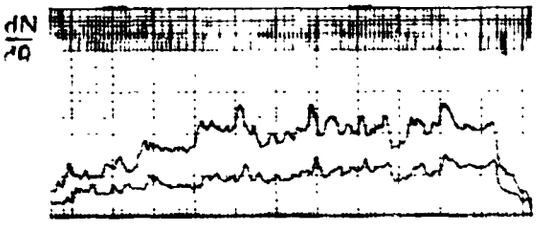

Fig.4 Diffracted X-ray intensity distribution along the dispersion direction versus rotation angle of the crystals around a vertical axis going through the theoretical curvature center.

VI. CONCLUSIONS

The results gathered with a limited size sample of twenty 200 LiF crystals (16 polished and 4 cleaved ones) show that :

- the focussing and dispersion curvatures are slightly better with cleaved crystals than with polished ones but reflection coefficient is increased by a factor two by polishing.

- a slightly systematic deviation from the ideal bending of less than 0.1° observed at the edges of most of the crystals is the major limitation of the spectrometer performance.

This deviation results in :
(i) A slight degradation of the energy resolution and focussing properties (non gaussian distribution, existence of wings).
(ii) A non-uniform energy range coverage.

The presently available measurements show that the size of the image for a point source at infinite distance (flight configuration) along the focussing direction would be 3 mm (FWHM) or 6 mm (FW at 1/8 max.). These figures are better than the estimated ones based on a mosaicity of W = 0.1° (5.4 mm FWHM or 7.8 mm at 1/8 max.). This proves that the mosaicity induced degradation has been, on the average of 5 crystals, overestimated. The effect of badly curved individual crystals does not show when considered in a set of several crystals (4 in the present case). The size of the image for a point source at infinite distance along the dispersion direction would be 2.1 mm (FWHM), better than the design goal. These results indirectly demonstrate that the energy resolution of 1000 at 7 keV is obtained together with a spatial resolution of 2.5 min of arc. This will be confirmed soon by measurements along the dispersion direction in a parallel X-ray beam. In these conditions point 2 appears to be the most severe limitation of the system but it can be overcome if we use staggered or alternative rows of crystals which produce the right overlapping for a nearly uniform energy range coverage.

Future tests will extend measurements to LiF 220, PET and TlAp.

The results obtained so far are surprisingly good and should be still better with an improved bending technique (increased curing time of the glue, optimization of the bending matrix shape).

References

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