Experimental observation of dynamic focusing of x rays by a uniformly bent crystal in the Laue case

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The earlier predicted dynamic focusing of x rays by a uniformly bent crystal with a magnification different from unity has been observed experimentally. A diffracted beam can be compressed to a width of $\approx 8\ \mu$m, which is an order of magnitude smaller than the base of a Borrmann triangle.

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Since the refractive index of any material is equal to about 1 (the difference is $\sim 10^{-6}$) for x-rays ($\lambda \sim 1$ Å), it is impossible to construct lenses with ordinary refraction for the x-ray range. At the same time, other optical focusing principles, which are based on diffraction effects (phase lenses, Fresnel zone plates, etc.), are known.[1] A dynamic diffraction focusing of an x-ray wave, whose amplitude and phase are wavefront modulated in a certain way, was theoretically predicted[2] and experimentally realized[3] for the first time several years ago. The diffraction focusing of a spherical wave on a plane crystal plate was investigated subsequently.[4–6] In the first and second cases, however, the magnification of the x-ray optical system was equal to unity. At the same time, the feasibility of diffraction focusing using a uniformly bent crystal with a magnification different from unity was predicted theoretically.[7–8] The aim of this paper, therefore, is to investigate experimentally the dynamic diffraction focusing of x rays by a uniformly bent crystal.

Such focusing can be accomplished in two ways—by using a magnifying or a reducing lens. In the first case, the magnification is 10^1–10^3, the resolution is ~ 1000–100 Å and the focus is $\sim 10\ \mu$m; in the second case, the magnification is $\sim 10^{-1}$–10^{-3}, the resolution is $\sim 10\ \mu$m and the focus is ~ 1000–100 Å. A magnifying lens was initially proposed and investigated theoretically by Petrashen' and Chukhovskiĭ.[7] Of

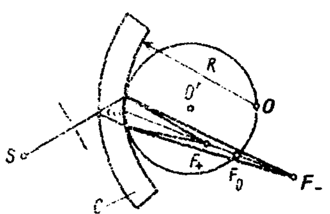

FIG. 1. Schematic of a reducing cylindrical lens. S is the source, C is a crystal bent around a circumference of radius R with the center at the point 0; a circle with the center 0′ represents a set of points F_0 of Cauchois's focusing; F_+ and F_- are two points of dynamic focusing.

the two possible systems, we have selected the reducing lens, since the "point" source in this case is much larger and the image compression increases the density of x-ray radiation, which makes it possible to record it. The focusing system is shown in Fig. 1. In contrast with Cauchois's kinematic focusing,[9] in which incoherent beams corresponding to different Borrmann deltas and having a width $2t\tan\theta$ of about the size of the delta base (t is the crystal thickness) intersect at a distance $L = R\cos\theta$ (R is the bending radius of the crystal and θ is the Bragg angle), the dynamic focusing involves a compression of the beam that emerges from a Borrmann delta and enters a much narrower region than its base. In this case two dynamic foci F_+ and F_- (see Fig. 1), which correspond to two types of Bloch waves in a crystal, appear on the beam axis. The condition for focusing has the form

$$\frac{1}{L_\pm} - \frac{1}{R\cos\theta} = \pm y \frac{\chi_{hr}}{2t\sin^2\theta},$$

where χ_{hr} is the real part of the Fourier component of the crystal's polarizability and y is a coefficient of the order of unity, which takes the cylindrical aberration into account. To eliminate chromatic broadening of the focus, we used a two-lens achromatic scheme illustrated in Fig. 2. The silicon crystals were cut in the shape of plane-parallel plates. After final chemical polishing, their thicknesses were equal to 425 μm and 360 μm and their (448) and (111) reflecting planes were perpendicular to the entrance surfaces and parallel to the bending axes. The photographs were taken using $MoK_{\alpha 1}$ radiation ($y_1 \approx 1$ and $y_2 \approx 1.245$). The crystals were mechanically loaded according to a four-point bending scheme using a device described elsewhere.[10] The bending radii were measured by means of angular displacement of the center of mass of the reflection peak while scanning the sample; a two-crystal system $(n, -n)$ was used for this purpose. By varying the parameters of the setup (Fig. 2), we noticed a focus at the point F_2 with a half-width of $\sim 8\ \mu$m (Fig. 3). The observed broadening of the focus, as

FIG. 2. Two-lens achromatic diagram. S is the source, C_1 and C_2 are the first and second crystals, F_1' and F_1'' are the focusing points of the first crystal for wavelengths λ' and λ'', F_2 is the focusing point of the second crystal, $SA_1' \approx SA \approx 182$ mm, $R_1 \approx 704$ mm, $B_1'F_1' \approx B_1''F_1'' \approx 542$ mm, and $B_2'F_2 \approx B_2''F_2 \approx 232$ mm.

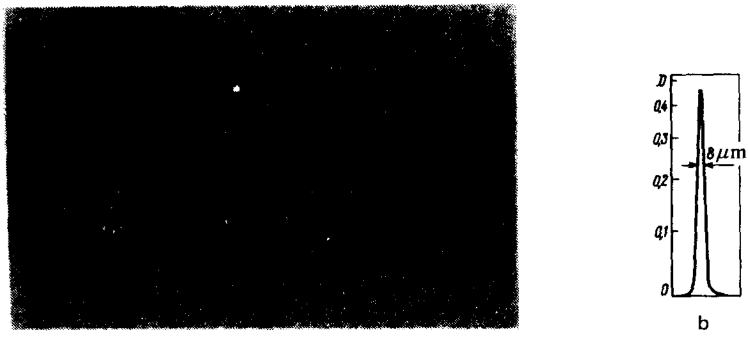

FIG. 3. Intensity distribution of a two-lens system in the focus. (a) Topogram and (b) photometric curve (D is the optical density).

compared with the theoretical values (~ 0.22 μm), can be attributed to a number of reasons. The main reasons are as follows: (a) inaccurate focusing and achromaticity, (b) finite dimensions of the source, (c) distortion of the wave packets in the crystals due to the concentration of strain on irregular surfaces, (d) propeller-like twisting of the reflecting planes (see Ref. 10), and (e) instability of the x-ray optical system with respect to time.

Thus, the width of the observed focus is an order of magnitude smaller than the base of the Borrmann delta (80 μm). This allows us to conclude that the x rays can be dynamically focused by a uniformly bent crystal under the described conditions.

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