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Express Letter

X-Rays Beam Condensation by Confinement in a Thin Crystal

Tomoe FUKAMACHI*, Riichiro NEGISHI, Masami YOSHIZAWA, Toshio SAKAMAKI[1] and Takaaki KAWAMURA[2]

Saitama Institute of Technology, 1690 Fusaiji, Okabe, Ohsato, Saitama 369-0293, Japan
[1]*JEOL Engineering Co. Ltd., 3-1-2 Musashino Akishima Tokyo 196-8558, Japan*
[2]*Department of Mathematics and Physics, University of Yamanashi, Kofu, Yamanashi 400-8510, Japan*

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We have observed condensation of X-rays emitted from an edge of a thin Ge parallel crystal, using X-rays from synchrotron radiation. When highly parallel X-rays with the energy near an absorption edge of an atom or a nucleus are incident on a thin crystal in the Bragg case, a part of X-rays is confined in the crystal and do not come out either from the top or the bottom surface. The density of confined beam increases as the width of the incident beam is increased. The confined beam can come out from an edge of a thin crystal with higher density than the incident beam. [DOI: 10.1143/JJAP.43.L865]

KEYWORDS: X-ray beam condensation, X-ray beam confinement, X-ray wave-guide, X-ray laser, Borrmann effect, X-ray splitter

According to dynamical theory of X-ray diffraction,[1)] the flux of X-ray photon at a Bragg condition is conserved when no absorption occurs in a crystal. The total flux of the diffracted and transmitted beams in the Bragg case from a thin crystal is the same as the flux of the incident beam. When absorption occurs, the flux is not conserved any more, i.e., X-ray photons are absorbed in a crystal, and the total flux of the diffracted and transmitted beams is smaller than that of the incident beam by the amount proportional to the absorption. In some cases, a part of the fluxes are confined in a film and the total flux of the diffracted beam, the transmitted beams and the confined beam is the same as that of the incident beam. The confined X-rays are repeatedly diffracted in the thin film forming a kind of traveling wave parallel to the surface. The confined X-rays should die away after running a long distance if the thin film is infinitely wide.

In this paper, we report on the observation of the confined X-ray beams emitted from the edge of a thin film. We observe the higher density of the confined beam for the larger width of the irradiated area in the direction perpendicular to the edge. The condensation of X-rays occurs due to the confinement.

The atomic scattering factor is expressed by $f^0 + f' + if''$, where f^0 is the normal scattering factor, f' and f'' are the real and the imaginary parts of anomalous scattering factor. In the following, we study dynamical diffraction when $|f''|/|f^0 + f'| = 0.2$. In this case, the linear absorption coefficient $\mu = 2|k_{0i}|$ has the maximum value when the exact Bragg condition is satisfied and becomes zero at a smaller incident angle away from the Bragg condition.[2)] Here, k_{0i} is the imaginary part of the wave number in a crystal. When $\mu(k_{0i})$ is zero, there is no damping of the wave in the crystal. If X-rays are confined in a thin crystal in this case, X-rays propagate in the direction parallel to the surface and come out from the edge of crystal. The width of the beam coming out of the edge is determined by the crystal thickness and the diffraction angle. It is expected that the flux density of the confined beam should increase when the width of the incident beam is increased. Condensation of X-ray beams is possible.

The experiment was carried out at the beam line 15C, Photon Factory, KEK, Japan. The schematic diagram of the optical system is shown in Fig. 1. The X-rays from synchrotron radiation are monochromated by a Si 111 double crystal monochromator and a Ge 220 monochromator. The parallelty of the X-rays is increased by these monochromators. The beam width is approximately 30–180 μm in the vertical direction and 350–500 μm in the horizontal direction. The crystal thickness is 38 μm. The nuclear plate produced by ILFORD Ltd. with the emulsion layer thickness 25 μm was used to record X-rays. Ge 220 reflection was used so as to suppress the absorption due to thermal diffuse scattering. The measured X-ray energy was 1 eV below the Ge K-absorption edge (11103 eV). In this case, the rate of confinement is estimated to be 2%.

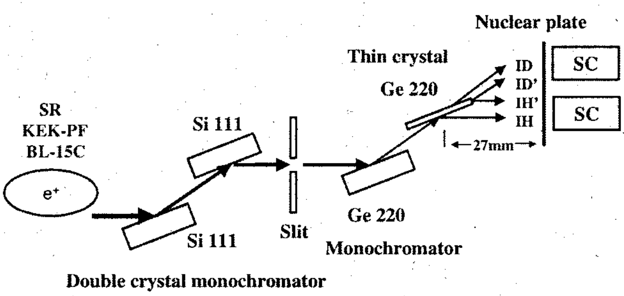


Fig. 1. Schematic diagram of the measuring system.

The measured rocking curves of the diffracted and the transmitted beams are shown in Fig. 2. At the angle A in Fig. 2, the diffracted intensity is high but the transmitted intensity is nearly equal to zero, which is due to the extinction effect.[2)] On the other hand, at the angle B, the diffracted intensity is lowered but the transmitted intensity shows the maximum, which is mostly due to the Borrmann effect.[2)] Photographs at the angle A and B are shown in Figs. 3(a) and 3(b), respectively. The darker contrast corresponds to the higher intensity of X-rays. In Fig. 3(a), the dark contrasts are shown in the reflected beam but no clear contrasts are shown in the transmitted beam, which corresponds to the intensity difference between the diffracted and transmitted beams at the angle A in Fig. 2. In Fig. 3(b), the dark contrasts are observed both in the diffracted and transmitted beams. In addition, the dark contrast in the lower part of the transmitted beam shows emission of the confined beam from the edge into the transmitted beam direction. The dark contrast in the upper part of the

*E-mail address: tomoe@sit.ac.jp

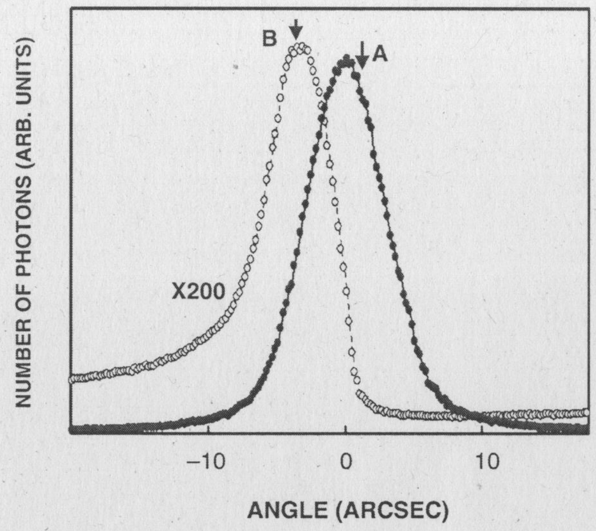


Fig. 2. Measured rocking curves. Closed circles show the diffracted beam intensities and the open circles transmitted beam intensities. The intensity of the diffracted beam is about 200 times larger than that of the transmitted beam.

diffracted beam shows emission of the confined beam into the diffracted beam direction. In the emitted beam, the interference fringe is observed as shown in Fig. 4. The fringe is caused by a sequence of reflections both at the top and the bottom surfaces, which should be expressed by Bragg-(Bragg)^m-Laue ($m > 0$) reflections.

When we increase the width of the incident X-rays, the emission intensity (darkness) of the confined beam increases. In Fig. 3(c), 3(d) and 3(e) are shown the emitted X-ray intensities when we increase the width of the beam as 60 μm, 120 μm and 180 μm, respectively. The incident angle is the same as in Fig. 3(b). We can clearly observe that the emission intensities increase as the width of the incident beam increases. The emission intensity of the confined X-ray beams is proportional to $\eta n|\boldsymbol{E}_0|^2$, where $\boldsymbol{E}_0$ is the electric field of the incident X-rays, η the rate of confinement and n the increase in the beam width. In the present experiment, η is estimated to be approximately 2% by a resonant dynamical theory[2,3] and n varies from 0.8 to 4.7. If we use a thin crystal with sH being approximately 1 for Ge 220 reflection, η becomes 15 to 20%. Here s is a quantity proportional to the atomic scattering factor[3] and H is thickness of the crystal. As n can be expected to be 100 in an optimum condition, ηn can be 20. About twenty times higher intensity can be expected. In the third generation synchrotron radiation using an undulater, the emission intensity of the confined X-ray beams may be proportional to ηn^2.[4] We can expect much higher density of the beam.

We have observed condensation of X-rays which are confined in a thin crystal and emitted from the edge of the crystal after a sequence of reflections at the top and the bottom surfaces. In the present experiment, the rate of condensation ηn is not high about 9% of the incident beam. In an optimum condition, however, about 20 times higher condensation is expected. It is an advantage of the above mentioned Bragg-(Bragg)^m-Laue reflections system that it has a function as a resonator of an X-ray laser and the insertion of X-rays is quite easy. Moreover, as it is possible to tune the incident X-ray energy to a resonant energy of an atom or a nucleus, this emission can be applied to the self-emission of X-ray laser.

The authors thank to Prof. M. Tokonami of Saitama Institute of Technology (SIT) for his valuable advice. They also express their thanks to Dr. Hirano (KEK), Dr. Matsumoto, Messrs. He, Tanaka and Ito (SIT) for their

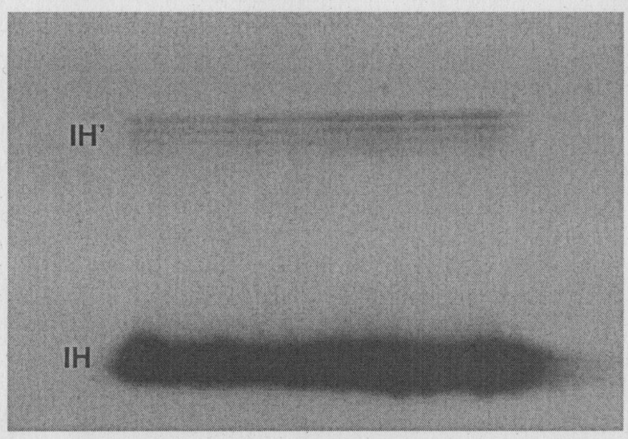


Fig. 4. The interference fringe of the emitted beam into the diffracted beam direction. The incident beam size is 0.35 (W) × 0.035 (H) mm^2.

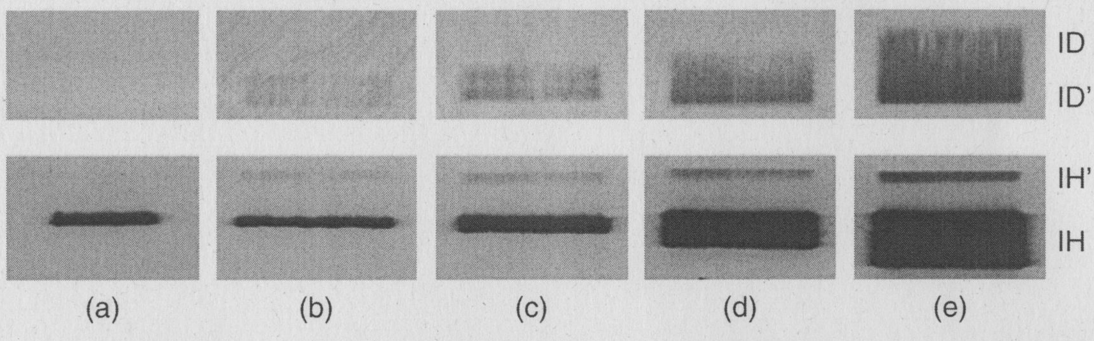
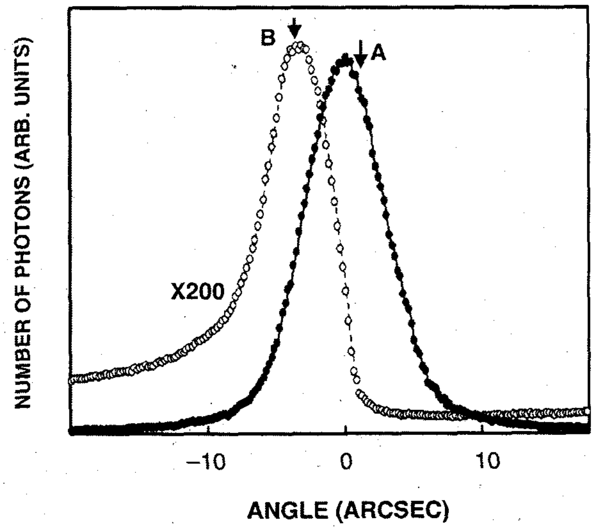


Fig. 3. The photographs in (a) are taken under a condition at which the extinction effect is dominant. The photographs in (b)–(e) are taken under a condition at which the Borrmann effect is dominant. Each upper photograph shows the transmitted beam (ID) and the emitted beam (ID′) into the transmitted beam direction. Each lower photograph shows the diffracted beam (IH) and the emitted beam (IH′) into the diffracted beam direction. The incident beam size is (a) 0.35 (W) × 0.035 (H) mm^2, (b) 0.5 (W) × 0.03 (H) mm^2, (c) 0.5 (W) × 0.06 (H) mm^2, (d) 0.5 (W) × 0.12 (H) mm^2 and (e) 0.5 (W) × 0.18 (H) mm^2.



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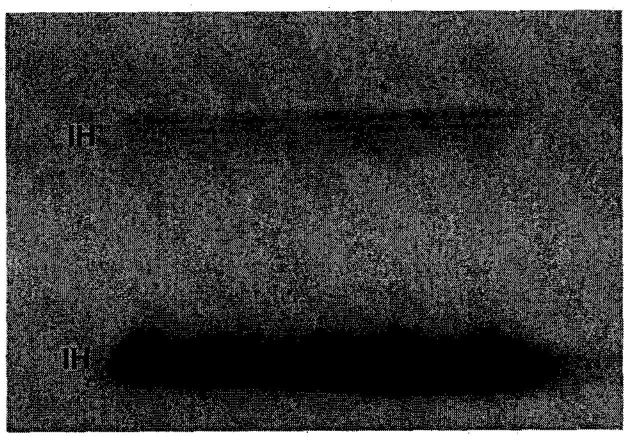

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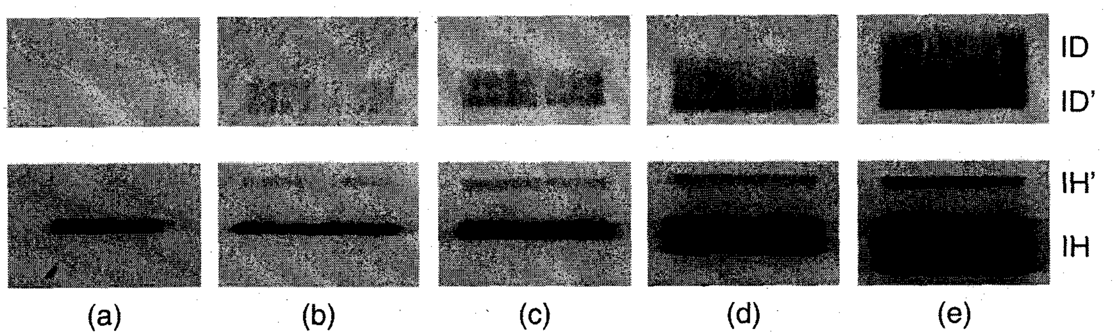

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assistance during the experiment. This work was done under the approval of the Program Advisory Committee of PF (Proposal No. 2002G046 and 2003G211). This work was partly supported by the Advanced Science Research Laboratory of SIT. One of the authors (R.N.) was supported by a Grant-in-Aid (No. 12650018) for Scientific Research of the Ministry of Education, Culture, Sports, Science and Technology.

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