SINGLE-SHOT HIGH-RESOLUTION SPECTROMETRY FOR X-RAY FREE-ELECTRON LASER

X-ray free-electron laser (XFEL) can generate ultrahigh-brilliant femtosecond X-rays with full spatial coherence. New schemes for conditioning and diagnosing the X-ray properties should be developed both for accelerator operation and for user experiments. In particular, the single-shot measurement of the X-ray spectrum is important. The single-shot scheme is essential with the presence of the intrinsic fluctuation of the self-amplified spontaneous emission (SASE) lasing process, which starts from random noises. A high-resolution measurement that resolves a microstructure of the energy spectrum enables the evaluation of a femtosecond pulse width, which is difficult to measure using a conventional time-domain method. Other notable applications are (i) the high-resolution measurement of the acceleration energy of the electron beam and (ii) the precise adjustment of the magnetic strengths of the undulator segments for the efficient amplification of radiation.

Single-shot high-resolution spectrometry can be performed for visible and ultraviolet light using an optical grating. In the X-ray region, however, a resolution better than $\Delta E/E = 1$ eV/10 keV = 10^{-4} has been not realized due to limitation in the availability of optical components. We have developed a new instrument by combining a focusing mirror and a perfect crystal of silicon [1]. With the mirror, the incident parallel X-rays (with a divergence of $\theta_D < 1$ μrad) are focused into a small spot and succeedingly diverged ($\theta_D = 2.3$ mrad). The photon energy of the divergent beam is analyzed with a diffraction of the silicon crystal according to Bragg's law. Since the incident angle on the analyzer crystal varies with the position, the photon energy of the diffracted beam also has a positional dependence. The spatial profile of the diffracted beam, which represents the energy spectrum of the incident X-rays, is measured with an X-ray camera (Fig. 1).

The quality of the X-ray mirror is crucial. Conventional X-ray mirrors which have large figure errors inevitably produce random intensity modulations called speckles. The speckle prevents one from obtaining a spectrum with good accuracy. In the present study, a state-of-the-art mirror with an extremely smooth surface [2], which has been developed in collaboration with Osaka University, was utilized. This mirror is fabricated with a special polishing method called EEM (Elastic Emission

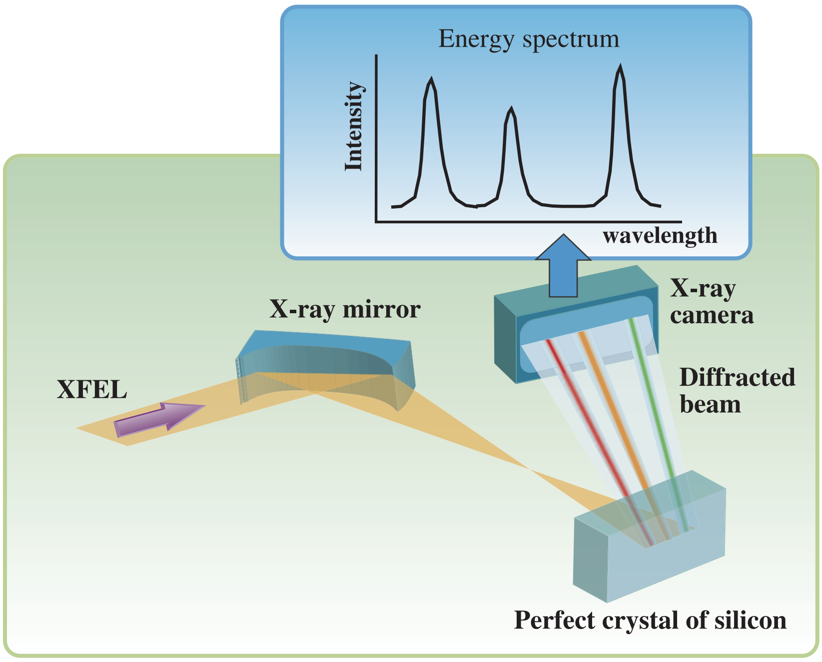

Fig. 1. Principle of spectrometer. The incident beam, which is focused and diverged by the X-ray mirror, is diffracted by the perfect crystal of silicon. The spatial profile of the diffracted beam is recorded using the X-ray camera.

Machining) [3] and a precision metrology technique called MSI (Microstitching Interferometry) [4].

An experiment was performed at the 1-km beamline (**BL29XU**) using the parallel X-ray beam with a photon energy of 10 keV. A monochromator was optionally used to select a narrow bandpath from the incident beam. Silicon 555 diffraction was employed for analyzing the spectrum, where the theoretical resolution is 14.5 meV with a total energy range of 3.5 eV. The profile of the diffracted beam was measured with the X-ray camera (Fig. 2). The beam position linearly depended on the photon energy of the incident monochromatic beam, as designed. From the width of the profile, the energy bandwidth of the optical system was evaluated to be 13.1 ± 1.9 meV (Fig. 3).

The achieved resolution and the uniformity of the intensity distribution of the optical system enable the evaluation of an X-ray pulse width in the range of sub-femtosecond to several picoseconds by choosing an appropriate diffracting plane. This method can contribute to a number of applications related to the FEL short pulse, such as ultrafast diffraction, to resolve atomic/molecular dynamics and high-power experiments for generating nonlinear optical phenomena.

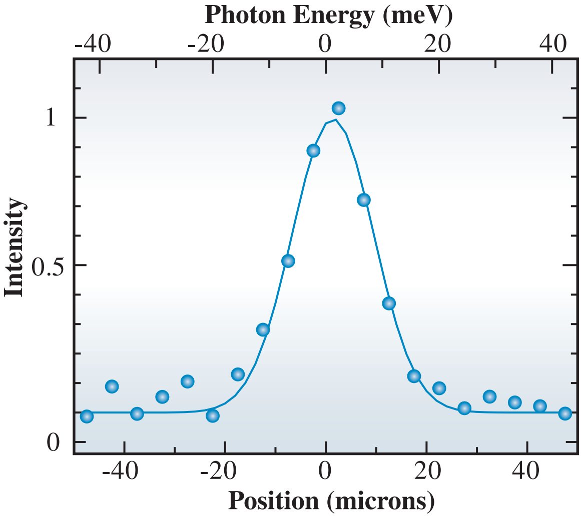

Fig. 3. Energy resolution. Measurement result of energy resolution using monochromatic X-rays as incident beam. A resolution of 13.1 meV was obtained by subtracting the energy spread of the incident beam.

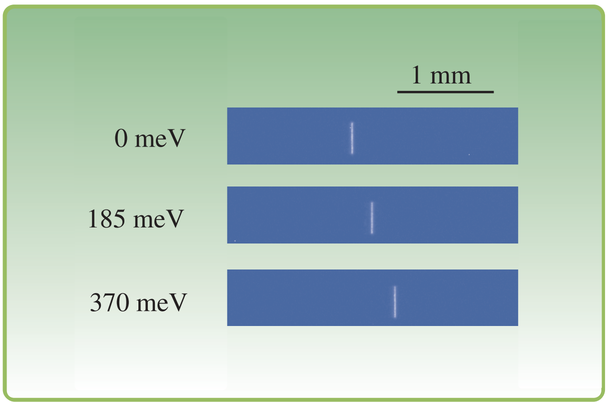

Fig. 2. Profile of diffracted beam. The position of the diffracted beam is shifted as the incident photon energy changes. The numbers on the left indicate deviations of the incident photon energy.

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