Extreme power density of hard X-ray free electron laser pulses generated by a two-staged reflective focusing system

The interactions between matter and light transform from linear to nonlinear phenomena as the intensity of light increases. The knowledge of nonlinear optics of visible light are well explored and commonly employed in various optical instruments and devices. Physicists are curious about X-ray nonlinear optics because photons with short wavelengths have substrate dependent responses. This phenomenon has been radical in astrophysics, fusion, and elementary physics. Due to the characteristic of permeability against matter and an insufficiently intensive X-ray source, only theoretical research has progressed. However, this situation has drastically changed from the viewpoints of X-ray sources and optical devices. SACLA produces the shortest-wavelength laser and reaches operations in the 0.6-Å wavelength range.

One of the major advantages of X-rays is the production of a nanometer-sized spot. Diffraction limit theory is a fundamental nature of light in which the wavelength determines the minimum resolution in imaging and focusing. In this decade, various X-ray focusing devices have advanced, reaching the diffraction limit performance. The focal size is continuously decreasing, and is as small as 10 nm [1]. Such focusing optics can enhance the characteristics of XFEL light by further increasing the power density, which is strongly desired to create extreme conditions of matter.

On the other hand, in other XFEL experiments, a focal length distance is necessary because the debris from targets due to radiation of intensive XFEL pulses seriously degrades the optics performance and various equipment must be located around the sample. Although a large aperture is preferable, the extremely short-wavelength lasers propagate while expanding slightly because the expanding angle of the beam is proportional to the wavelength. A very long-beamline is necessary to obtain a large beam size. To overcome these fundamental problems with XFEL light, one more focusing system has been installed to expand the XFEL pulses. Furthermore, the focal beam size is drastically decreased by magnifying the XFEL light before the final focus.

A two-staged focusing system with two Kirkpatrick Baez geometries was designed, developed, and installed at beamline **BL3** of SACLA for focusing XFEL pulses to an extreme tiny size of about 50 nm (Fig. 1) [2]. Total reflection mirrors are employed to tune the wavelength in various analytical methods using XFEL pulses. The four precise mirrors were fabricated by a deterministic fabrication process, consisting of elastic emission machining and interferometric metrology. Figure accuracies are 2 nm (peak-to-valley) and surface roughness is 0.2 nm (root-mean-square). The first pair of focusing mirrors is 120 m downstream from the end of the undulator to focus XFEL pulses to several micrometers with nearly 100% efficiency [3]. Then XFEL pulses propagate with expansion until reaching the downstream focusing system. The second pair of focusing mirrors is located approximately 72 m downstream from the upstream device.

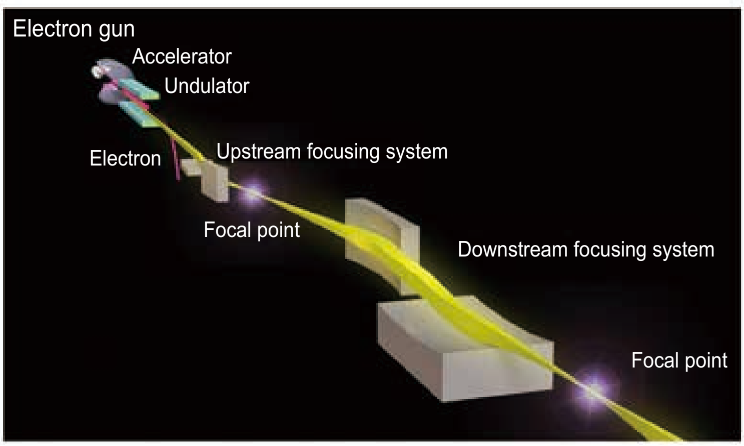

Fig. 1. Two stage reflective focusing system for XFEL focusing.

An XFEL focusing experiment was performed at 9.875 keV. At first, the upstream K-B system was aligned to measure the intensity profile of XFEL pulses at the designed focal point. After that, the downstream K-B system was adjusted to obtain the minimum spot size.

Figures 2 show the intensity profiles on the focal plane, which are estimated by a grating interferometer [4]. The focused beam sizes are 55 nm × 30 nm in the horizontal and vertical directions, respectively. The intensity profiles are almost the same as those under the diffraction limited conditions [2].

The power density is one of the crucial parameter of the focused XFEL pulse. The power of each XFEL pulse can be precisely measured at SACLA. In an experiment using a photon energy of 9.875 eV and a pulse duration of 7 fs, the average power at each pulse is confirmed to be 42 μJ/pulse at the downstream focusing system. In this experiment, at least 30% of the photons in the focused beam pass through a 50-nm square area on the focal plane. From the experimental outcomes, we can declare that the maximum power density exceeds at least 10^{20} W/cm^2.

Recently, XFEL has activated the X-ray nonlinear optics field. At SACLA, this extremely strong X-ray laser has just opened the next phases for some experiments. For example, a nonlinear phenomenon called "saturable absorption of intense hard X-rays" has been released [5], which clearly shows a signal due to nonlinear interaction between X-rays and matter.

Now, not only XFEL facilities but also various types of next-generation synchrotron radiation facilities are being planned or constructed. These facilities will provide laser-like hard X-ray beams because high quality X-ray beams with extremely short wavelengths have a straight propagation. A two-staged focusing with long mirrors can control the beam size and allow freedom in the optical design, which will create unique X-ray experiment. In addition, single-nanometer XFEL focusing also requires this system. Thus, a power density of 10^{22} W/cm^2 has been achieved. The competition to realize extremely intensive photon beams will be more activate by the birth of XFEL nanobeam. It is believed that the two-staged focusing system will play a crucial role in driving X-ray lasers and lead to unprecedented outcomes in X-ray physics.

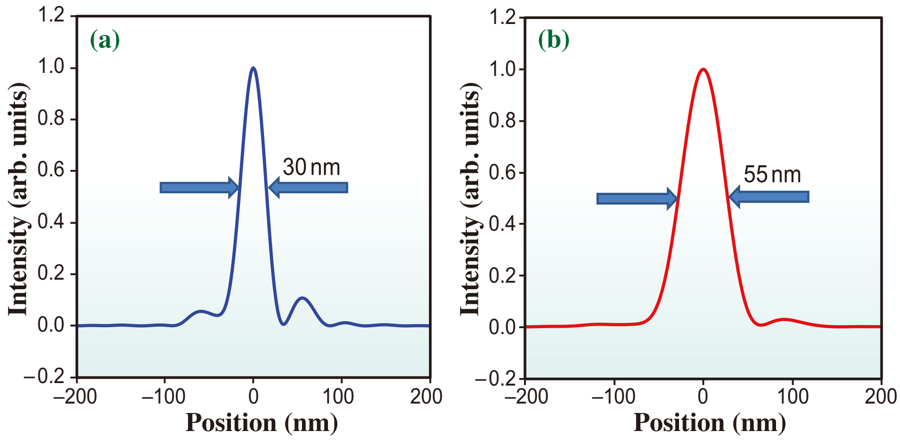

Fig. 2. Intensity profiles of XFEL focused beam in the **(a)** vertical direction **(b)** horizontal direction.

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References

[1] H. Mimura *et al.*: Nat. Phys. **6** (2010) 122.
[2] *H. Mimura, H. Yumoto, S. Matsuyama, T. Koyama, K. Tono, Y. Inubushi, T. Togashi, T. Sato, J. Kim, R. Fukui, Y. Sano, M. Yabashi, H. Ohashi, T. Ishikawa and K. Yamauchi: Nat. Commun.* **5** *(2014) 3539.*
[3] H. Yumoto *et al.*: Nat. Photononics **7** (2013) 43.
[4] S. Matsuyama *et al.*: Opt. Exp. **20** (2012) 24977.
[5] H. Yoneda *et al.*: Nat. Commun. **5** (2014) 5080.