Generation of high-intensity narrowband X-ray Free Electron Laser through reflection self-seeding

Current X-ray Free Electron Lasers (XFELs) are operated mostly on the basis of self-amplified spontaneous emission (SASE) scheme, where spontaneous radiation originating from density modulations in the electron beam is exponentially amplified along periodic magnetic fields in undulators. Although the SASE scheme is effective in producing intense X-ray beams, the stochastic starting-up processes cause poor temporal coherence and a large fractional bandwidth (~0.3%). To perform specific kinds of experiments, such as wide-angle X-ray scattering and spectroscopy, one must monochromatize XFEL beams at the cost of considerable loss of photon flux. For example, photon flux after the monochromator is only ~3% of that before the monochromator when a silicon (Si) (111) double-crystal monochromator is applied for monochromatization. Narrowing the bandwidth of XFEL beams while retaining the high intensity would boost the throughputs of current XFEL experiments and help open up new field of X-ray sciences.

To realize high-intensity narrowband XFEL beams, a self-seeding scheme using a diamond crystal [1] was proposed and demonstrated at the Linac Coherent Light Source and SACLA. In this scheme, a thin diamond crystal is placed in the middle of the undulators. The SASE radiation from the upstream undulators is monochromatized with the crystal in the Bragg forward diffraction geometry, producing a delayed monochromatic X-ray beam, called the wake pulse, in addition to the transmitted XFEL beam with a broad bandwidth. By achieving a spatiotemporal overlap between the monochromatic wake and the electron bunch in the downstream undulators, one can increase the intensity of the monochromatic component. However, we could not achieve stable operation of this seeding scheme at SACLA, possibly owing to an insufficient signal-to-noise ratio for the seeding intensity as a result of the contamination of the transmitted SASE beam.

As an alternative approach to generating narrowband XFEL pulses, we developed a new self-seeding scheme, called reflection self-seeding, at SACLA **BL3** (Fig. 1) [2]. In this scheme, a Si channel-cut crystal monochromator is used in the reflection geometry for monochromatizing XFEL beams generated by upstream undulators. The X-ray beam injected to the downstream undulators is purely monochromatic in this case. Thus, one could produce a brilliant X-ray beam with a narrow bandwidth by amplifying the seed pulse in the downstream undulator section.

Although reflection self-seeding seems to be a simple approach to producing narrowband XFEL beams, its realization is not straightforward. When we use a conventional Si channel-cut crystal with a gap of ~10 mm, the optical delay caused by the crystal becomes several tens of picoseconds. In this case, a very long (~100 m) magnetic chicane is required to achieve a temporal overlap between the electron bunch and the seed in the downstream undulators. To suppress the optical delay, we developed a Si

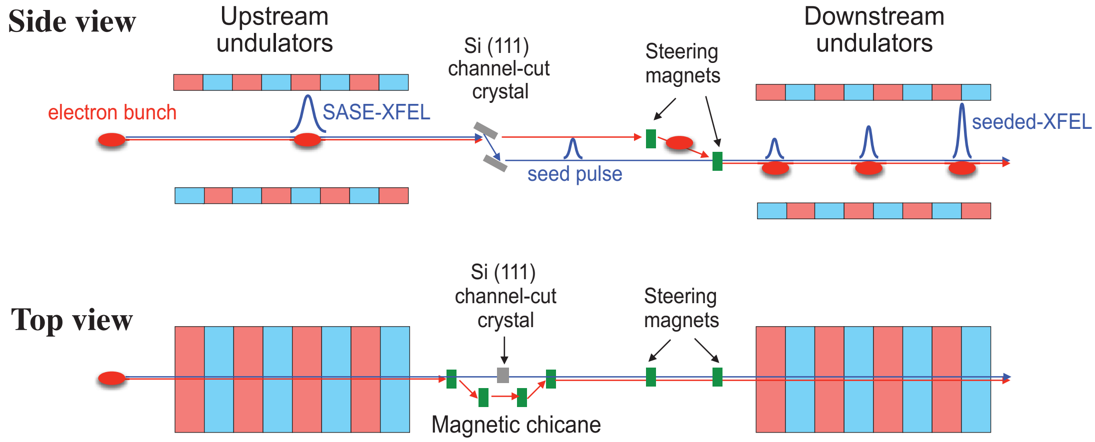

Fig. 1. Schematic illustration of reflection self-seeding at SACLA.

channel-cut crystal with a gap of a few hundred micrometers, which we call a micro-channel-cut crystal [3]. With this new optical device, the optical delay can be reduced to a few hundred femtoseconds, which can be readily compensated by electron beam delay due to the magnetic chicane.

Figure 2 shows the averaged spectra of SASE-XFEL in the normal operating mode and the seeded-XFEL for a central photon energy of 9.85 keV. It is clearly seen that the injection of the seed drastically narrowed the bandwidth of the XFEL beam. The intensity at 9.85 keV of the seeded-XFEL greatly exceeds that of SASE-XFEL, which corresponds to an increase in spectral brightness by a factor of six with respect to the normal SASE mode.

The self-seeded XFEL has been promoted to the normal operation mode of SACLA and used in a wide variety of user experiments. There is, however, still some room to further increase spectral brightness by narrowing the bandwidth of the seeded-XFEL. The use of higher order reflection in the channel-cut crystal is a straightforward approach to achieving higher spectral brightness. In fact, we are currently developing a reflection self-seeding scheme using a Si (220) channel-cut crystal.

The reflection self-seeding is based on a simple and robust principle. So far, our new seeding scheme has been operating stably at SACLA. We anticipate that the seeded-XFEL beam from SACLA will be a strong driving force for opening new frontiers of X-ray sciences, such as the exploration of nonlinear X-ray optical phenomena and the imaging of tiny objects at atomic resolution, as well as for reducing the measurement time in experiments.

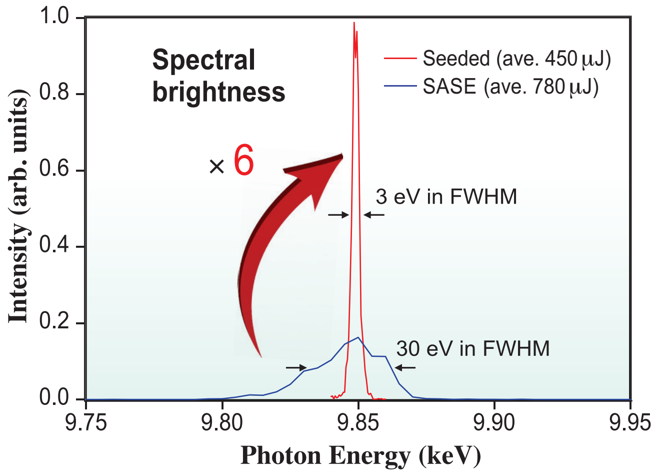

Fig. 2. Averaged spectra of seeded- and SASE-XFEL with central photon energy of 9.85 keV.

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