A beam branching method for timing and spectral characterization of hard X-ray free electron lasers

X-ray Free Electron Lasers (XFELs) generate ultra-brilliant, coherent, and femtosecond X-ray pulses. These unique properties allow one to directly probe the electronic and structural dynamics of matter with angstrom and femtosecond spatiotemporal resolution.

Photon diagnostics of XFEL pulses are critical for accurate data analysis, because most of the current XFEL sources show shot-to-shot variations in radiation properties owing to a self-amplified spontaneous emission (SASE) scheme. For example, stochastic fluctuations are observed in the pulse energy, temporal duration, spatial profile, wavefront, and spectrum.

Furthermore, diagnostics on arrival timings between XFEL and optical laser pulses are indispensable to improve the temporal resolution in ultrafast experiments, because the intrinsic temporal resolution, which is determined by the temporal duration of an X-ray or optical pulse, can be significantly deteriorated by a possible timing jitter between these pulses. At XFEL facilities, X-ray/optical cross-correlators have been developed for this purpose. In this scheme, one probes a transient change of optical reflectivity/transmittance accompanied with a rapid increase of free-carrier densities generated in semiconductor materials by intense X-ray irradiation. In the hard X-ray region at LCLS, this method has required XFELs with a large pulse energy on the order of millijoules due to the weak interaction between matter and hard X-rays [1].

At SACLA, Sato *et al.* have developed highly efficient arrival timing diagnostics using a spatial encoding technique [2]. The required pulse energy has been successfully reduced to 12 μJ at 12 keV by combining a one-dimensional focusing mirror and a GaAs target comprising high-Z materials that have high absorption coefficients of X-rays. Also, Inubushi *et al.* have developed a dispersive spectrometer with a high resolution of 14 meV [3]. However, these photon diagnostics cannot be used as shot-to-shot monitoring tools in user experiments owing to their photon-destructive nature.

To perform these photon-destructive diagnostics simultaneously with experiments, we proposed and developed a scheme using a transmission grating to split an X-ray beam into a main branch and several sub-branches [4]. This beam-splitting scheme enables advanced photon-destructive diagnostics to be performed under a quasi-noninvasive condition by using the main branch and sub-branches for experiments and diagnostics, respectively. Here, the +1st-order and –1st-order branches are utilized for measuring the spectrum and the arrival timing jitter, respectively.

The whole optical system is implemented at SACLA **BL3** (Fig. 1). As key optics devices in this scheme, we employ one-dimensional transmission gratings, which diffract a small fraction of the incoming X-ray beam into multiple branches. The +1st-order and –1st-order branches propagate in the vertical plane with the deflection angle given by $\theta_S = a\sin(\lambda/d)$, where λ is the wavelength and d is the period of the grating. The diffraction efficiency can be controlled in the range of 2.1 - 21.6% at 10 keV by tilting the grating along the vertical axis.

For the arrival timing monitor, the –1st-order X-ray beam is reflected by two (flat and elliptical) mirrors located ~8 m from the grating. After the reflection, the –1st-order X-ray beam is irradiated on a GaAs surface with a one-dimensional focused profile. The spatial modulation of the optical transmittance is recorded using a CCD detector with a spatial resolution of 1.1 μm/pixel, which corresponds to 2.6 fs/pixel from

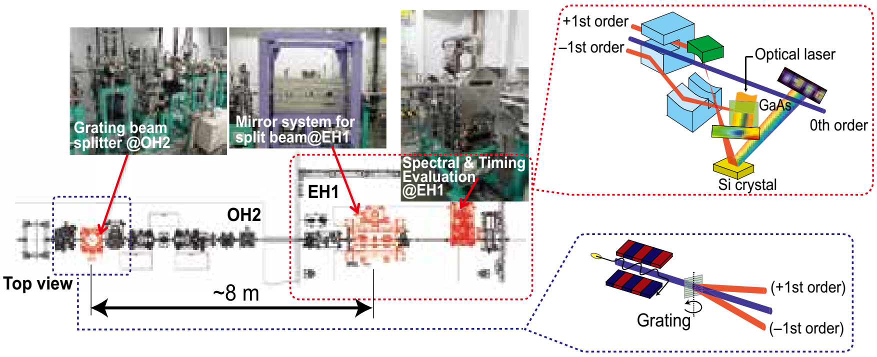

Fig. 1. Whole optical system installed at BL3 of SACLA: the grating beam splitter, the mirror system, and the spectral and timing evaluation chamber are the main components for quasi-noninvasive XFEL characterization in the spectral and timing domains.

the optical geometry. For the dispersive X-ray spectrometer, the elliptical mirror increases the divergence of the +1st-order branch to 2.5 mrad. A silicon analyzer crystal diffracts dispersed X-rays and an MPCCD detector records the spectrum. The spectral resolution and observable range can be tuned by switching the reflecting plane of the analyzer crystal.

To evaluate the performance of the system, we measured a correlation by performing an independent measurement using the main branch (0th-order branch). Figure 2(a) presents the correlation between the arrival timings of the –1st-order and 0th-order branches. We can observe excellent agreement between the two diagnostics. The temporal jitter is obtained from the graphic in Fig. 2(b), where the RMS width is 256 fs. The residual error after the linear fitting of the correlation can be defined as the overall accuracy, as shown in Fig. 2(c). The error graphic in Fig. 2(d) has an RMS width of 7.0 fs. This sub-10-fs accuracy should allow the temporal resolution to be improved down to the femtosecond regime, which is mainly governed by the temporal duration of the optical lasers. We also confirmed the applicability of this method to a wide photon energy range (5-15 keV) to cover the operation of SACLA with a pulse energy of less than 10 μJ.

Figure 3 shows the single-shot spectra of the +1st-order and 0th-order branches. Using a Si (660) reflecting plane, the spike features of SASE radiation were completely resolved (Fig. 3(a)). The spectral range of these two spectrometers was 6.4 eV, while we only show spectra in the overlapping area (~3 eV) between them in Fig. 3(a). We found reasonable agreement in both the energy dispersion (horizontal) and the spatial chirp (vertical) directions between the spectra. The average spike width was determined to be 470 meV. Note that we can easily switch the reflecting plane to a lower index, such as Si (220), in order to cover a wide photon energy range, as shown in Fig. 3(b).

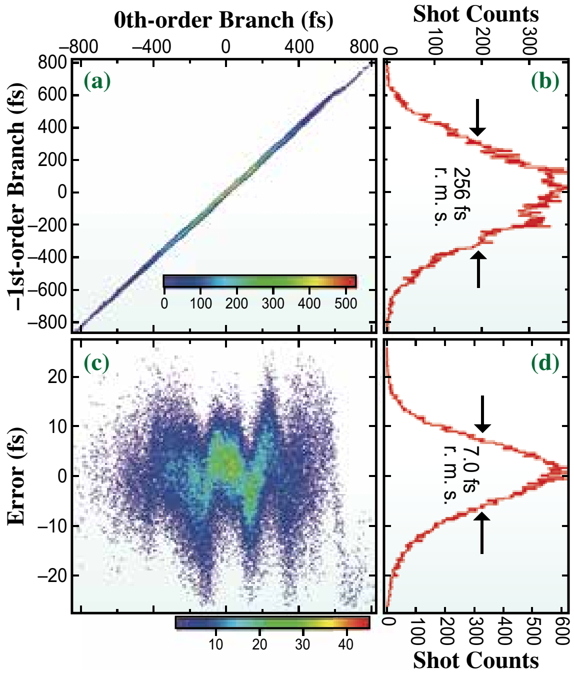

Fig. 2. **(a)** Scatter plot colored by density showing the correlation between the arrival timings of the two branches. **(b)** Graphic showing the temporal jitter. The bin width was 5 fs. **(c)** Residual errors after the linear fitting of the scatter plot. **(d)** Graphic corresponding to (c) with a bin width of 0.2 fs.

In conclusion, we have developed a beam branching method to enable advanced photon diagnostics with small perturbation using a grating splitter. The 0th-order transmission branch, which retains over 90% of the original intensity at 10 keV, is provided for a diverse range of applications.

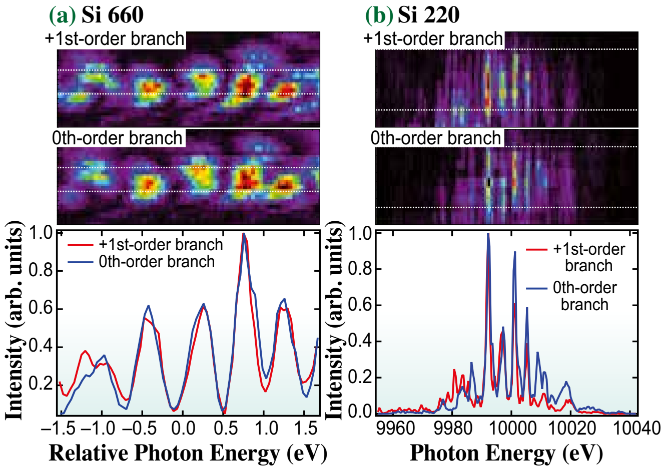

Fig. 3. **(a)** Single-shot spectra measured with Si (660) analyzer crystals using the +1st-order (red line) and 0th-order (blue line) branches. The center of the relative photon energy corresponds to 9999.75 eV. **(b)** Wide-range single-shot spectra measured with Si (220) analyzer crystal. The white dotted lines represent the area of the integration used to extract the spectra.

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