Development of ultrafast pump and probe experimental system at SACLA

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Abstract. We have developed an ultrafast pump and probe experimental system of SACLA combining XFEL and IR-UV lasers. Preliminary tests of pump and probe experiments have been conducted in the autumn of 2011.

1. Introduction
SACLA is the first compact X-ray Free Electron Laser (XFEL) facility, which was built at the SPring-8 site and started user operation in March 2012. Ultrashort pulse duration (~ 10 fs or below) is one of the most important characters of XFEL. This capability to investigate ultrafast phenomena is much enhanced with a pump and probe scheme that combines an XFEL source with ultrafast IR-UV lasers. We have developed an experimental system for ultrafast pump and probe studies at SACLA, and started preliminary tests in the autumn of 2011. In this paper, we report a basic design of the system and commissioning results.

2. Pump and probe experimental station
An XFEL beamline BL3 of SACLA provides intense x-ray pulses (~ 10¹¹ photons) at 10 keV. The photon energy is tunable in a range between 4 keV and 20 keV by changing the electron beam energy and/or the undulator gaps. The detailed specifications and performances of the beamline are written in
references [1, 2]. The IR-UV laser is introduced into an experimental hutch (EH) 2 and 3 from a laser hutch (LH). EH2 is designed for experiments with unfocused XFEL, while EH3 is used for applications with focused XFEL (Fig. 1).

Figure 1 Schematic drawing of experimental hutches and IR-UV laser transportation of SACLA. Solid line indicates the beam line of XFEL and dashed lines indicate the transportation of IR-UV laser. PS means periscope of chicane in transport channel.

2-1 IR – UV laser system
The laser system consists of a mode-locked oscillator, a regenerative amplifier, and wavelength conversion systems, including an Optical Parametric Amplifier (OPA), second harmonic generation (SHG) and third harmonic generation (THG) of Ti: Sapphire laser. The pulse energy of fundamental wavelength (800 nm) at each EHs are 3 mJ (regenerative amplifier) and 100 mJ (booster amplifier). The temporal pulse duration is 30 fs and its spectrum bandwidth is 65 nm. The wavelength range of OPA is from 230 nm to 2 μm. The laser system and OPA are installed in LH. The other wavelength conversions are installed in each EHs. The operation wavelength can be selected by changing the output ports of the laser system and transport mirrors. Laser parameters, such as wavelength, intensity, and temporal profile, can be changed for performing various applications. Components of the IR-UV laser system are written as follows.

Temporal delay control: The temporal delay of the IR-UV laser pulses can be controlled with combination of an optical delay line (up to ~1.5 ns with a resolution of 3 fs) and an electric delay generator (up to ~16 ms with a resolution of 1ps) [3].

Pulse pattern: The Ti: Sapphire laser is operated at 1 kHz for achieving thermal stabilization of the system. For pump and probe experiments, 60-Hz pulses are picked up from 1-kHz pulses by a Pockels cell or a mechanical chopper. For performing single shot or divided frequency measurement, we
developed pulse selectors for both XFEL and IR-UV laser [4], which can be controlled by the integrated DAQ system, which provides high flexibility in designing measurement sequences combined with multiple motorized stages.

Fast photodiode: For confirming temporal overlap between IR-UV laser pulses and XFEL pulses, a fast photodiode (G4176-03, GaAs MSM, Hamamatsu) with a rising time of 30 ps is utilized. The time resolution is estimated to be ±10 ps by edge detection of the signal with an oscilloscope (16 GHz).

IR-UV laser components: EH2 is equipped with optical components on a highly-stabilized experimental table; pulse characterization system (a single shot autocorrelator and a Spectral Phase Interferometry for Direct Electric field Reconstruction (SPIDER)), wavelength conversions (SHG and THG), focusing system (1D and 2D focus, beam expanders and beam reducers), polarization optics (wavelength plates and polarizers), and a mirror chamber for introducing IR-UV lasers collinearly to XFEL in vacuum condition.

2-2 X-ray experimental system
An x-ray experimental system consists of the following experimental tables, motorized stages, and detectors.

Experimental tables and stages: To conduct various types of time-resolved experiments including diffractometry, scattering, and spectroscopy, we have prepared three types of experimental tables (1.5 m x 3 m with flat breadboard, 1.2 m x 1.5 m with manual slide tables, and 1.1 m x 1.1 m with a motorized slide table), motorized goniometers and stages, and accessories.

Photodiode (PD): For detection of x-ray signal, photodiodes (S3590-09, Si PIN photodiode, Hamamatsu) are provided. The PD signal data at every shot are collected and updated to the database.

Multi-Port CCD (MPCCD): MPCCDs are utilized for measuring 2D x-ray images. We provide three types of MPCCDs: single sensor (50 mm x 25 mm), dual sensor array (50 mm x 50 mm), and octal sensor array (100 mm x 100 mm). The pixel size of these CCD devices is 50 μm x 50 μm. The fullwell is 2.0 Me- (typical) (= ~1200 photons at 6 keV). System noise is 300 e- (typical) (= ~0.18 photons at 6 keV)

3. Timing synchronization and time resolution
A time resolution is one of the most important parameters for pump and probe experiments. So far, the timing monitors that measures change of optical reflectivity after inducing soft x-ray FEL pulses have been developed [5-7]. In the hard x-ray region, however, a penetration depth is much larger than that in the soft x-rays, which forces to decrease the change of optical reflectivity [8]. Instead, we developed a timing monitor to measure optical transmittance.

We irradiated a GaAs wafer with NIR laser (1.46 eV) and XFEL (12 keV). IR laser with a photon energy higher than the band gap (1.43 eV) of GaAs is absorbed within less than 10 μm. However, intense x-ray irradiation induces direct and/or secondary excitation of electrons in the valence band which rapidly increases the optical transmittance. The typical setup and the result of cross-correlation measurement with ~10 shot average are shown in Fig. 2 and 3, respectively. The NIR laser was introduced on the sample with incident angle of 45 degree. As seen in Fig. 3, fast change of optical transmittance was observed by scanning the delay time of the NIR laser. The rising edge width of the signal intensity indicates that the time resolution is better than 400 fs. For higher resolution measurement, post process techniques combined with a single shot arrival timing monitor are required.
4. Outlook

SACLA started user operation in March, 2012. We have developed and installed the ultrafast pump and probe experimental system. The pump and probe experiments combining SACLA and IR-UV laser have been performed by a number of users. We plan to apply the present arrival timing monitor to the user experiments for improving the time resolution in pump and probe measurements.

Figure 2 Schematic drawing of experimental setup of pump and probe (cross-correlation) measurement between the IR-UV laser and the XFEL.
Figure 3 Optical transmittance as a function of the delay time of femtosecond laser. The edge width includes the information of the timing jitter and the spatial profile of XFEL ($\phi$260 $\mu$m). Error bars indicate the distribution of the standard deviation.

References

[1] Ishikawa T et al. 2012 *Nature Photonics* (London: Nature Publishing Group) in press
[2] Yabashi M and Ishikawa T (eds) 2010 *XFEL/SPring-8 Beamline Technical Design Report ver. 2.0* (Sayo, Hyogo: RIKEN JASRI XFEL Project Head Office) pp 19–35
[3] Tanaka Y, et al. 2010 *AIP Conf. Proc.* 1234 (College Park, Maryland: American Institute of Physics) p951
[4] Kudo T, Hirono T, Nagasono M, and Yabashi M 2009 *Rev. Sci. Instrum.* 80 (College Park, Maryland: American Institute of Physics) p093301.
[5] Gahl C, et al. 2008 *Nature Photonics* 2 (London: Nature Publishing Group) pp165-169
[6] Schorb S, et al. 2012 *Appl. Phys. Lett.* 100 (College Park, Maryland: American Institute of Physics) p121107
[7] Beye M, et al. 2012 *Appl. Phys. Lett.* 100 (College Park, Maryland: American Institute of Physics) p121108
[8] Durbin S. M, Clevenger T, Graber T, and Henning R 2012 *Nature Photonics* 6 (London: Nature Publishing Group) pp111-114