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High energy density science using x-ray free electron laser "SACLA"
X線自由電子レーザーSACLAを用いた高エネルギー密度科学研究

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In order to open new high energy density sciences, an x-ray free electron laser source and its beamline containg synchronized intense optical lasers have been developed in SACLA. Brilliant, coherent, femtosecond x-ray pulses are utilized as both probe and pump. In XFEL-probe case, intense optical laser pulses produce high energy density states, and ultrafast dynamics have been investigate by x-ray scattering and diffraction measurements with femtosecond resolution. In XFEL-pump case, novel phenomena related with core-hole atoms generated with an intense XFEL pulse have been observed. In this paper, we report the status of high energy density science performed in SACLA.

1. Introduction

Recently, X-ray Free Electron Lasers (XFELs), such as the Linac Coherent Light Source (LCLS) [1] and SPring-8 Angstrom Compact free electron LAser (SACLA) [2], have successfully generated brilliant, femtosecond x-ray pulses, which have opened frontiers of science ranging in biology, ultrafast material science and chemistry. High energy density (HED) science [3] is also one of the promising scientific fields using XFELs. In SACLA, in order to generate HED states, we have prepared two methods.

One is intense optical lasers synchronized with XFEL pulses. In this scheme, XFEL pulses are utilized to measure characteristics of the HED state as a probe.

The other method is utilization of intense XFEL pulses. By using two types of focusing optics selectively, we can create XFEL intensity of 10^{18} or 10^{20} W/cm^2. These intense XFEL pulses can generate HED states.

2. SACLA status

In SACLA, We have developed two hard x-ray beamlines. BL3 [4] is the first beamline operated from 2011. BL2 is a new beamline, which is now under commissioning. An XFEL pulse of BL3, which ranges from 4 to 19.5 keV, typically contains photons in the order of 10^{11} and has a duration in several fs. Figures 1 show single-shot spectra of XFEL pulses [5], which have a spike structure originating from Self-Amplified Spontaneous Emission (SASE) scheme [6,7]. Spectral width in Full Width at Half Maximum (FWHM) is around 50 eV, as shown in Fig. 1(a) which was measured with spectral resolution of ~1 eV. Figure 1(b) shows spike structures with several-hundred-meV, which are observed in the measurement with high spectral resolution of 14 meV [5].

3. Pumping with optical laser

Intense optical laser pulses are widely used to generate HED state. In SACLA, we have prepared three Ti:sapphire lasers with difference peak powers, i.e., 2.5 TW, 40 TW and 500 TW, and a YAG laser

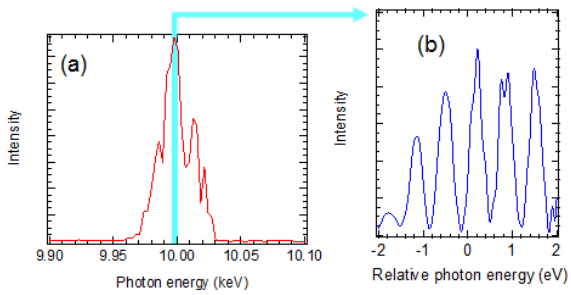

Figure 1. Single-shot spectra of XFEL with 1-eV resolution (a) and 14-meV resolution (b)

with several-ns duration. The 40 TW laser and the YAG laser are being prepared by HERMES project [8]. The 500 TW laser is under commissioning.

By using high pressure states above 100 GPa, which are generated with shock waves driven by these intense lasers, HED experiments related with material science, planetary science and creation of warm dense matters have been performed. Here, phase transitions and lattice dynamics with picosecond time scale are investigated with x-ray scattering and diffraction measurements [9,10].

Focused 2.5 TW laser successfully generated fast electrons. That was confirmed by measurement of Kα line emission from core-hole atoms of a copper foil. Figure 2 shows a picture of typical experimental setup. The 2.5 TW laser is focused with an off-axis parabolic mirror on the solid sample. XFEL pulse irradiates to the same focal spot. Irradiation timing between 2.5 TW laser pulse and XFEL pulse are tunable with accuracy of a few fs by changing its optical path length. This experimental system could contribute to plasma science such as laser-matter interactions and atomic processes

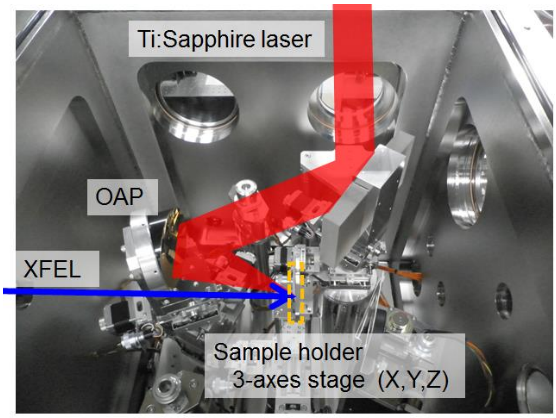

Figure 2. Experimental setup using a 2.5 TW laser.

4. Pumping with XFEL

Pumping with intense x-ray pulses is a new scheme of HED sciences, which started from the birth of XFEL. X-ray photons mainly interact with inner-shell electrons, in contrast to photons from optical laser sources, which interact with valence electrons. A key element of this scheme is core-hole atoms generated via interaction between x-ray photons and inner-shell electrons, since transition energy of bound electrons in core-hole atoms corresponds to a photon energy of XFEL pulses. For example, Cu-Kα line is 8.05 keV. Note that core-hole atoms are quite transient due to their ultrafast lifetime ranging in as – fs.

In order to generate HED states using XFEL pulses, two types of focusing system are selectively utilized. One is a coherent 1-μm focusing system [11] consisting of a Kirkpatrick-Baez (KB) geometry, which produces XFEL intensity of 10^{18} W/cm^2. By using this system, K. Tamasaku, *et al.* created double -core-hole krypton atoms [12].

The other system is a two-stage focusing system [13], which are composed with two sets of KB geometry. A focal spot with 50-nm diameter are produced, and the XFEL intensity reaches to 10^{20} W/cm^2. By using the system, HED experiments pumped with intense XFEL have been performed. H. Yoneda *et al.* measured x-ray saturable absorption originating from a change of K-absorption edge due to creation of core holes [14]. Transmission of XFEL pulses near the K-absorption edge of iron (7.12 keV) became 10 times higher than that in general solid iron. K. Tamasaku *et al.* observed a two-photon absorption of 5-keV x-ray photons, measuring Kα emission from germanium core-hole atoms, which have 10-keV K-absorption edge [15].

5. Summary

HED science is one of promising scientific fields using XFEL. In SACLA, we have two methods to generate HED states. Optical laser systems to generate HED states have been prepared, and high pressure sciences with XFEL probing have been performed. Intense XFEL pulses with intensity above 10^{18} W/cm^2 have opened new HED science using core-hole atoms.

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