Time-of-flight measurement of ionic species generated during ablation for optimization of focusing condition at free-electron laser beamline

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Abstract. Optimization of focusing conditions is important in free-electron laser applications. A time-of-flight mass analyzer has been designed and constructed for this purpose. The time-of-flight spectra of ionic species evolved from laser ablation of gold were measured. The yields of ionic species showed strong correlations with free-electron-laser intensity. This method conveniently allows for direct estimation of laser intensity on sample and determination of focusing position.

1. Introduction

Free-electron lasers (FELs) with high peak brightness, narrow bandwidth, and perfect coherence have been opening new fields of scientific research. Focusing mirror systems are particularly important for obtaining smaller beam size, which enables ones to observe samples with ultrahigh resolution in space and time, and to create extreme states with high peak fields.

Two FEL facilities are in operation at the SPring-8 site: the SPring-8 Angstrom Compact free electron Laser (SACLÀ) [1] and the SPring-8 Compact SASE Source (SCSS) [2]. SACLÀ is a compact X-ray FEL facility using an 8-GeV linac. Construction of the SACLÀ facility was completed in FY2010, and user operation started in March 2012. SCSS is a prototype machine that was constructed prior to SACLÀ; it employs a 250-MeV linac and provides FEL light in the extreme ultraviolet region. Focusing mirror optics have been utilized to generate small beam spots of ~1×1 µm² at SACLÀ [3] and ~20 × 20 µm² at SCSS [4]. Typical power densities at focusing position of about 10¹⁸ W/cm² and 10¹³ W/cm² have been achieved at SACLÀ and SCSS, respectively.

It is important to optimize focusing conditions for almost experiments using focused beam. For this purpose, we have employed two-dimensional scans of a pinhole or a wire edge under strong attenuation conditions, which avoid unwanted damage of materials. Alternatively, profiles of craters generated by ablation on solid target (such as PMMA and Si) have been measured by scanning probe microscope [4]. These methods have disadvantage because it take a long time to measure one spot size, as a two-dimensional scanning time and as a venting time of the vacuum chamber to access the sample. Consequently, a method to measure the maximum kinetic energy of protons ejected from a sample has been proposed in order to quickly determine the focal position in-situ [5]. It would be useful to measure ions generated during ablation with resolving ionic species, which are highly sensitive to the
focusing condition. In this paper, the development and test results of new compact time-of-flight (TOF) mass analyzers for in-situ optimization of the focusing condition are described.

2. Time-of-flight mass analyzer

Two compact time-of-flight (TOF) mass analyzers—a Wiley-McLaren-type linear TOF [6] mass analyzer (L-TOF) and a reflectron-type TOF [7] mass analyzer (R-TOF)—have been designed and constructed (Figure 1).

The L-TOF consists of double acceleration regions, a 100-mm-long drift region, an electrostatic lens, a 90° deflector, and a micro-channel plate (MCP) detector. The deflector is used to prevent photoluminescence irradiation generated in the ablation process on the MCP. The L-TOF can be used in three operating modes: a normal TOF spectrum and a pulse-extraction TOF spectrum can be obtained by applying static and pulse negative voltages, respectively, to the first extraction electrode; further, by applying a positive voltage to the first electrode (which acts as a high pass filter), ions with initial kinetic energies above a filter level can be detected.

The R-TOF was designed to obtain high mass resolution for ions with high kinetic energies. At the end of the 250-mm-long drift region, ions are deflected into an electrostatic mirror (reflection region), which is 150-mm-long resistive glass tube and defined uniform reflective electric field. Because ions with higher initial kinetic energies pass through the drift region in shorter times, L-TOF achieve relatively low mass resolution. The reflection region in the R-TOF serves to compensate for this time difference; ions with higher kinetic energies can reach deeper into the reflection region (as shown by the dotted line in Figure 1), the shorter time spent in the drift region is compensated for with a longer time spent in the reflection region. The mass resolution (M/ΔM) obtained in the R-TOF for ions with a kinetic energy of 500 eV is estimated to be about 50, which is ten times higher than that obtained in the L-TOF.

3. Results and discussion

3.1. L-TOF measurements at SCSS

Experiments using the L-TOF were performed at SCSS. An FEL beam with a photon energy of 20 eV was focused down to 15 µm in full width at half maximum (FWHM). The repetition rate and pulse duration were 1 Hz and approximately 100 fs, respectively, at this measurement. The average pulse energy, which was measured shot-by-shot with a photoion yield detector, was 2.0 µJ with a standard deviation of 1.2 µJ. The average power density at the focus position was estimated from the focusing size and pulse duration to be about 1.1 × 10¹³ W/cm². A sample of gold sheet was placed at the focusing position. The L-TOF apparatus was installed at an angle of 45° relative to the incident laser, as shown in Figure 1 (a). Signals from the MCP detector were accumulated by a digital oscilloscope, which was triggered by a signal synchronized to the SCSS master oscillator.

Figure 2 shows a TOF spectrum, averaged over 100 shots. According to the assignment, a singly charged monomer, a dimer, and multiply charged monomers, are observed.
Figure 2. Averaged TOF spectrum measured by L-TOF. The ionic species assignments are indicated.

Figure 3. Averaged pulse-extraction TOF spectrum measured by L-TOF. The ionic species assignments are indicated.

Figure 4. Intensity of peaks (A) and (B) shown in Figure 3 as a function of FEL pulse power density.

Figure 5. Pass energy dependence of total ion yield.

3.2. R-TOF measurements at SACLA
A performance test of the high-mass resolution R-TOF was conducted at the BL3 of SACLA. An FEL beam with a photon energy of 10 keV was focused down to 1 µm in FWHM. The repetition rate and pulse duration were 10 Hz and approximately 10 fs, respectively, at this measurement. TOF spectra

Figure 5 shows the dependence of total ion yield on the voltage at the extraction electrode. Because the sample was grounded, setting a positive voltage at the extraction electrode created a high-pass kinetic energy filter for positively charged ions. Ion yield decreased as the pass energy increased, although ions with kinetic energy higher than 1000 eV were detected. These highly energetic ions caused a broadening in the peaks of the TOF spectra, as can be seen in Figure 2.
were measured at average pulse energies of 63 µJ with a standard deviation of 12 µJ, which were
determined by a thin-foil intensity monitor [8]. The average power density at the focus position was
estimated from the focusing size and pulse duration to be about 8.0 × 10^{17} \text{ W/cm}^2. Spectra were also
measured by inserting a 300-µm-thick Si attenuator, which decreased the average pulse energies to 6.4
µJ with a standard deviation of 1.8 µJ. A sample of gold sheet was placed at the focusing position.
The R-TOF apparatus was installed at an angle of 60° relative to the incident laser, as shown in Figure 1
(b). Signals from the MCP detector were accumulated using a digital oscilloscope, which was
triggered by a signal synchronized to the SACLA master oscillator.

Figure 6 shows a TOF spectrum, averaged over 600 shots. The peaks of this spectrum were clearly
separated, demonstrating the high mass resolution of the R-TOF. These peaks were assigned to Au^{n+} (n = 1 to 5) ions. As shown in Figure 7, the peak intensities of each ionic species were analyzed shot-by-
shot and plotted as a function of the FEL intensity. The ion yields of Au^{+} and Au^{2+} has the maximum at
around 2.5 × 10^{17} and 6 × 10^{17} \text{ W/cm}^2, respectively. Additionally, the ion yields of Au^{3+} and Au^{4+}
increased with an increase in the FEL intensity. Higher FEL intensity increases the yield of higher
charged ionic species. Observation of each ion yield and measurement of FEL pulse energy allow for
determination of focusing position, because FEL intensity depends on the pulse energy and beam size.

4. Conclusion
The TOF mass analyzers described in this paper were designed and constructed for optimization of
focusing conditions by measurement of ionic species generated by ablation. R-TOF was more suitable
for this study than L-TOF, because the maximum kinetic energy of ionic species were higher than
1000 eV. Ion yields obtained through experiments conducted at the SCSS and SACLA showed a
dependence on the FEL intensity. Measurement of TOF spectra with moving a sample along a focused
beam allows for fast and in-situ determination of the focusing position, where shows maximum FEL
intensity.

References
[1] Ishikawa T et al. 2012 Nat. Photon. (doi:10.1038/nphoton.2012.141)
[2] Shintake T et al. 2008 Nat. Photon. 2 555
[3] Yumoto H et al. In this proceedings
[4] Ohashi H et al. 2011 Nucl. Instr. and Meth. A 649 163
[5] Iwan B et al. 2011 High Energy Density Phys. 7 336
[6] Wiley W E and McLaren I H, 1955 Rev. Sci. Instrum. 26 1150
[7] Mamyrin B A et al. 1973 Zh. Eksp. Teor. Fiz. 64 82
[8] Tono K et al. 2011 Rev. Sci. Instrum. 82 023108