# STABILIZATION OF THE LWFA AND ITS APPLICATION TO SINGLE-SHOT K-EDGE DENSITOMETRY

K. Koyama, H. Madokoro, Y. Matsumura, H. Masuda, M. Uesaka , University of Tokyo, Tokai, Japan
R. Kuroda, K. Yamada, AIST, Tsukuba, Japan
S. Masuda, Osaka University, Suita, Japan

*Abstract*

K-edge densitometry using quasi-monoenergetic X-rays was investigated. X-rays were generated by the inverse Compton scattering process. In order to measure densities with an accuracy of 5% by the two-color method, the energy fluctuation of the electron beam must be smaller than $0.1 - 0.4\%$. The scattering angle dependence of the X-ray energy is capable of measuring densities by taking images of the K-absorption edge. The angle-coded K-edge densitometry requires that the energy width and normalized emittance must be smaller than $2\%$ and $0.1\pi$ mm-mrad, respectively. These restrictions were proved by K-edge densitometry experiments using the laser Compton X-ray source at AIST .

In order to deliver well stabilized electron bunches from a laser wakefield accelerator (LWFA), the slit nozzle for the LWFA experiments was designed and the stability of the density distribution was tested. The interferogram showed that the supersonic flow and the density ramp for electron injection were generated with good reproducibility.

## INTRODUCTION

All optical inverse Compton scattering X-ray sources have the capability for realizing tabletop high-energy X-ray sources, which are based on a laser wakefield accelerator (LWFA) technology. Since an LWFA driven by a 10-TW laser pulse has the ability to accelerate a short bunch of electrons up to 100 MeV in a plasma of a few millimeters, a tunable and quasi-monoenergetic ultra-short X-ray pulse of around 100 keV can be delivered from a compact system via the inverse Compton scattering process[1]. A higher acceleration energy of 1 GeV driven by a 50-TW laser will deliver a 10 MeV mono-energetic $\gamma$-ray pulse. A $\gamma$-ray with an energy of around 1MeV and the X-ray with energy less than 130 keV are applicable to the nondestructive analysis of various materials by nuclear resonance scattering and photo-absorption processes, respectively. K-absorption densitometry is an attractive method for the nondestructive measurement of materials from the view point of nuclear non-proliferation. However, the restriction on energy width and energy fluctuation of X/$\gamma$-rays is more strict when applied to K-edge densitometry than for nuclear resonance scattering, because the difference in X-ray transmission rates at both sides of the K-absorption edge must be precisely determined.

In order to apply inverse Compton X-rays to K-edge densitometry, the required accuracy of the electron beam and LWFA must be made clear. Since the energy fluctuation and transverse emittance of the electron beam have an influence on the accuracy of K-edge densitometry, an analytical and experimental investigation on the accuracy of K-edge densitometry was curried out using an output from a S-band linac, in addition a new supersonic nozzle for stabilizing the LWFA was developed which has a sharp density step followed by a 4-mm-long uniform density flow.

## K-EDGE DENSITOMETRY

The concentration of an element in a material can be measured using K-edge densitometry. From the X-ray transmission ratio $I_2/I_1$ at X-ray energies $E_1$ and $E_2$, which are near both sides of the K-absorption edge, concentration (or density) $\rho$ is calculated using eq. (1),

$$\rho = \frac{1}{(\mu_2 - \mu_1)\, L} \ln \frac{I_2}{I_1}, \tag{1}$$

where $\mu_1$ and $\mu_2$ are the mass attenuation coefficients of the element at X-ray energies $E_1$ and $E_2$, respectively. $L$ is the thickness of the sample.

K-edge densitometry is currently applied to measure the concentration of uranium in a spent fuel reprocessing plant. However, the present system based on an X-ray tube and a Ge-detector takes 20 min to measure the concentration of a sample. A higher throughput is desired from the viewpoint of nuclear nonproliferation by adopting LWFAs.

### *Two-Color K-edge Densitometry*

There is no need to measure the entire spectrum of transmission X-rays around the K-edge, provided that monoenergetic X-rays at both sides of the K-absorption edge are used instead of the continuous spectrum. The problem two-color K-edge densitometry is that the accuracy is quite sensitive to the energy fluctuations of the electron beam $dE_0$ because of the strong dependence of the mass attenuation coefficient on the X-ray energy of $E_x^{-(2.2\sim2.7)}$. The accuracy is expressed by the equation

$$\frac{d\rho}{\rho} \approx \frac{1}{\mu_1 - \mu_2} \left( \frac{p_1 \mu_1}{E_1} + \frac{p_2 \mu_2}{E_2} \right) dE, \tag{2}$$

where $\mu_1$ and $\mu_2$ are approximated by the power law of $\mu_{10} E_1^{-p_1}$ and $\mu_{20} E_2^{-p_2}$, respectively.



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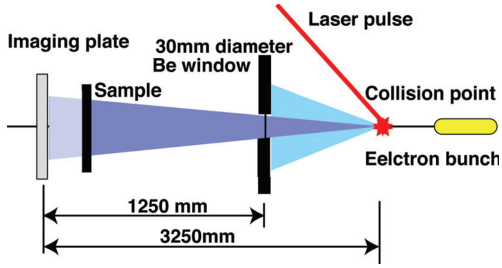


Figure 1: Configuration of the experiment.

The best accuracy is obtained when X-ray energies are close to the K-absorption edge, where the difference of the attenuation coefficients $|\mu_1 - \mu_2|$ is maximum. Equation (2) changes to $d\rho/\rho = CdE_0/E_K$, where $C$ is the numerical constant that depends on element $C = 13$ for uranium, $C = 3.7$ for silver, and so on. In order to measure the concentration of uranium at an accuracy of $5\%$, energy fluctuations of the X-rays and the electron beam must be smaller than $0.4\%$ and $0.2\%$, respectively. The energy stability of the linac satisfies the restriction on fluctuations. However, the energy stability of LWFA is far from satisfying this requirement; output energies from typical LWFAs fluctuate between 2 and 20%. The causes of energy fluctuation in LWFAs is that injection of an electron bunch into the wakefield and the acceleration length are not well controlled. Further investigation of LWFAs is required in order to apply LWFAs to K-edge densitometry.

### *Angle-coded K-edge Densitometry*

Since the X-ray energy of inverse Compton scattering is a monotonic function of the scattering angle with respect to the axis of the electron beam, an imaging technique enables the obtaining of the transmission spectrum around the K-absorption edge without producing two X-ray energies. A sufficiently high X-ray intensity enables single shot measurement. However, the finite energy width and divergence angle of the X-ray blurs the shadow of the absorption edge.

The blurring of the K-absorption edge in the angle-coded image owing to the finite divergence angle of the electron beam, $d\theta_e$, and the fluctuation of the electron energy $dE_0$ are estimated to be $d\theta_x)_{div} \sim 1/\sqrt{2}d\theta_e$ and $d\theta_x)_{egy} \sim (1/2\gamma)\, dE_0/E_0$, respectively, where $\gamma = E_0/mc^2$ is the normalized electron energy. The extent by which the K-absorption edge is blurred must be much smaller than half the apex angle of the X-ray radiation limited by an aperture, which is usually chosen to be approximately $0.1\gamma^{-1}$. Supposing that the permissible blurring is $5\%$ of half of the apex angle, the energy fluctuation and the divergence angle of the electron beam must be smaller than $1\%$ of $E_0$ and $\left(0.007\gamma^{-1}\right)$ rad, respectively. The normalized emittance must be smaller than $\gamma d\theta_e d_f/2 \sim 3.5 d_f\ \pi$ mm-mrad, where $d\theta_e$[mrad] is the half angle of the beam divergence and $d_f$[mm] is the diameter of the electron beam at the collision point.

The experiment on angle-coded K-edge densitometry was performed by using the laser Compton scattering X-ray source (LCS X-ray) at AIST. The collision of the electron bunch ($20 - 40$ MeV, $1$ nC, $3$ ps) delivered by the s-band linac and the short laser pulse (800 nm, 100 mJ, 100 fs) produced a short X-ray pulse. The energy spread of the electron beam was $1.5\%$ for a beam energy of $33.7$ MeV. The normalized transverse emittance of the electron beam was $(1.2 - 1.5)\,\pi\mathrm{mm\text{-}mrad}$. The inverse Compton X-ray energy can be varied in the range of $10 - 40$ keV for a collision angle of $\theta_L = 25°$[2]. Samples made of thin foils of silver (Ag), indium (In) and tin (Sn) were placed at a distance of 3 m from the collision point, as shown in Fig.1. Half the apex angle was 7.5 mrad, which was limited by an aperture of 30-mm diameter at a distance of 2 m from the collision point. X-ray transmission images were taken using the ImagingPlate(IP; FUJIFILM BAS-MS 2025).

The energy spread of the beam was within the permissible range. However, the emittance did not satisfy the requirement of $0.14\ \pi$mm-mrad. Simulation results obtained using parameters of the LCS X-ray show considerable blurring at the K-absorption edges, as shown in Fig. 2. These were calculated by using the laser Compton simulation code CAIN.

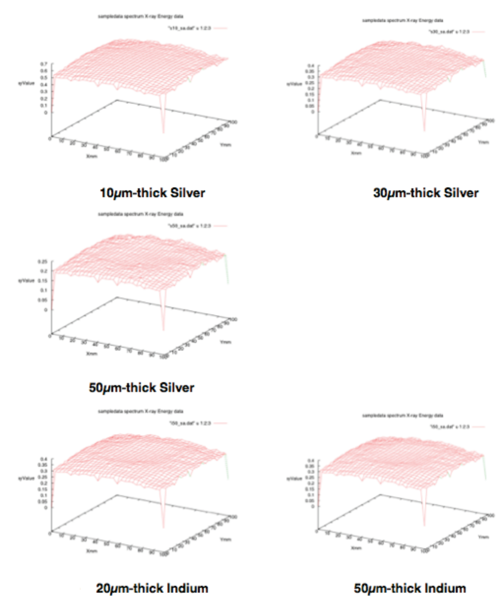


Figure 2: Simulation results of X-ray transmission through Ag and In foils by using "CAIN".

Figure 3 shows the measured intensity distributions of X-rays through the In and Ag foils. Vertical and horizontal axes are photo stimulated luminescence (PSL) values which are proportion to X-ray intensities and scattering angles, respectively. The difference in the steepest positions (scattering angles) for the measured curves between Ag and In was 2 mrad, which corresponds to the difference between the K-absorption edges of Ag (25.5 keV) and In (27.9 keV). The width of blurring shown in Fig. 3 was so

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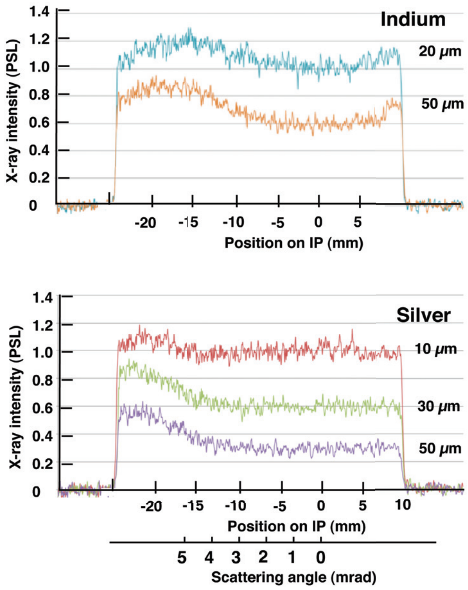


Figure 3: X-ray transmission through In and Ag foils recorded on IP.

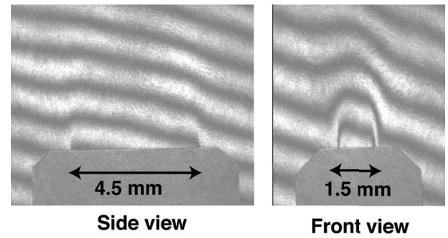


Figure 4: Interferograms of supersonic flow from the slit nozzle.

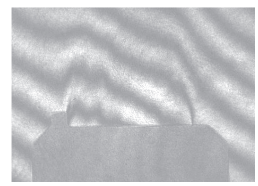

Figure 5: The interferogram of the density jump in the supersonic flow. The second (right) bump was produced by a manufacturing defect on the nozzle wall.

large that it was difficult to determine the X-ray transmission difference across the K-absorption edge by extrapolating the data. In order to obtain an accurate X-ray transmission difference across the K-absorption edge, a larger apex angle for the Compton scattering than $0.1\gamma^{-1}$ must be adopted for reducing the blurring area.

## GAS JET FOR THE LASER WAKEFIELD ACCELERATOR

In order to use the LWFA for K-edge densitometry, the energy stability, energy width, electronic charge, and the emittance of the output beam must be improved by adopting a controlled injection technique for the initial electron bunch and a clearly defined density distribution and length of plasma channel for propagating the intense laser pulse. The production of the density down ramp, produced by an oblique shock wave in a supersonic gas jet of M=5 was reported by the authors in [1].

Although the density down ramp worked as an electron injector, the reproducibility of the monoenergetic electron bunch was poor because of faults in the supersonic nozzle. A newly designed nozzle produced sharply bounded, uniform supersonic flow with a sufficient stability as shown in the interferograms Fig 4. The preliminary test with a flow deflector at an edge of the nozzle showed the density step as shown in Fig. 5. A manufacturing defect in the nozzle caused an unexpected shockwave as shown in the figure.

## SUMMARY

In order to clarify the required parameters of all-optical Compton X-ray sources for the application, K-edge densitometry experiments were performed by using an LCS X-ray source. Angle coded K-edge densitometry has an advantage over two-color K-edge densitometry. However, the energy width and the normalized emittance must be smaller than than 2% of $E_0$ and $d\theta_e\gamma d_f/2$, respectively, for measuring the density at an accuracy of 1%. In order to obtain a sufficiently discontinuous image at the K-absorption edge, the transverse emittance must be decreased to a value lower than $0.14$ $\pi$mm-mrad or the apex angle of the Compton scattering must be extended to a value larger than $2/\gamma$.

Injection of electrons into a laser wakefield accelerator (LWFA) via a wavebreaking process was investigated in order to obtain stable output of electron bunches. The newly designed slit nozzle delivered a stable supersonic jet of a high-Mach number of M = 5, which was sharply bounded from the vacuum. The small flow deflector made the density ramp in the supersonic jet.

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