MONOENERGETIC 200FS (FWHM) ELECTRON BUNCH MEASUREMENT FROM THE LASER PLASMA CATHODE

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Abstract

A measurement of the electron bunch duration from a laser plasma cathode that can generate femtosecond electron bunches has been done.

Since the time-resolution of the fastest streak camera is only 200 fs, we performed the spectrum measurement of coherent transition radiation (CTR) using an IR (infrared) bolometer with different filters and obtained the average spectrum. The bunch duration at 180 mm downstream from the plasma edge is 130±30 fs (FWHM) in a high-monoenergetic case and 250±70 fs (FWHM) in a low-monoenergetic case. Since temporal elongation of high-monoenergetic electron bunch after 180 mm path is about 60 fs, the initial duration of the electron bunch is estimated to be 115 fs (FWHM).

INTRODUCTION

A laser plasma cathode is one of the most promising approach to compact accelerators that can generate ultra-short electron bunches [1-3]. It is expected that the electron bunch duration less than 100 fs can be achieved owing to the high frequency of plasma waves. On the other hand, a conventional linear accelerator can generate the electron bunches of about 240 fs at best. Therefore, a laser plasma cathode has the great advantage of femtosecond time-resolved applications, such as pulseradiolysis and generation of a femtosecond X-ray pulse by relativistic Thomson scattering.

Since the time-resolution of the fastest streak camera that is used widely for a conventional linear accelerator is only 200 fs, we have to use other methods for the bunch duration measurement. While several approaches have been proposed [2], e.g. Michelson Interferometer, E/O (electro-optic) method, and fluctuation method, we use the spectrum measurement of coherent transition radiation (CTR) with an IR (infrared) polychromator [4,5]. It is because this method has possibility to single-shot measurement of the electron bunch duration. As the first step forward it, we have performed a measurement using an IR bolometer with different filters and obtained the average spectrum of CTR.

COHERENT RADIATION

When a charged particle crosses the boundary between the two media with different permittivity, transition radiation is emitted from the boundary [5]. Under the condition that one electron passes from a medium to vacuum, intensity of transition radiation can be written as,

$$I_e = \frac{\alpha\beta^2 \sin^2\theta}{\pi^2\lambda(1-\beta^2\cos^2\theta)} \quad (1)$$

where α is fine structure constant, β the particle velocity expressed in units of c, λ the wavelength of transition radiation, and θ the angle of emission with respect to the direction of the electron velocity.

Radiation from an electron bunch can be expressed by superposition of radiation from each electron in the electron bunch. Total intensity of radiation from an electron bunch is obtained by,

$$I_{total} = NI_e + N(N-1)f(\lambda)I_e \quad (2)$$

where N is the number of electrons in the electron bunch, and f(λ) the bunch form factor. When the wavelength of radiation is longer than the bunch length, radiation becomes coherent; the bunch form factor becomes unity and total intensity of radiation is proportional to the square of N. When the wavelength is shorter than the bunch length, however, radiation becomes incoherent; the bunch form factor becomes zero and total intensity of radiation is proportional to N. Since N is usually on the order of 10^7~10^{10} in a laser plasma cathode and a conventional linear accelerator, intensity of transition radiation is extremely enhanced if radiation is coherent.

On the assumption that the distribution of electrons in the electron bunch is symmetric to some reference angle, and that each electron is independent each other, the bunch form factor can be written as,

$$f(\lambda) = \left| \int_{-\infty}^{\infty} \exp\left(\frac{i2\pi z}{\lambda}\right) S(z)\, dz \right|^2 \quad (3)$$

where z is the direction of electron velocity, S(z) the normalized electron distribution function in the electron bunch. As shown in equation (3), the bunch form factor is given by Fourier transform of the electron distribution function. Hence, the distribution function can be derived from inverse Fourier transform of the bunch form factor, and the bunch duration can be also estimated.

EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The Ti:Sapphire laser system based on the chirped pulse amplification (CPA) technique generates an ultra-short intense laser pulse with the energy up to 600 mJ and the pulse duration of 38 fs at full width half maximum (FWHM). The central wavelength is 790 nm. The laser pulse is focused by f/3.5 off-axis parabolic mirror (OAP) into a helium gas jet. The focal spot size is 6 μm at $1/e^2$ in intensity and therefore the laser intensity is estimated to be 3.5×10^{19} W/cm^2. The properties of the electron beam emitted from the gas jet, such as the spatial distribution, the energy spectrum, and the charge, are evaluated with a fluorescent screen (DRZ), an electron spectrometer and an integrated current transformer (ICT), respectively.

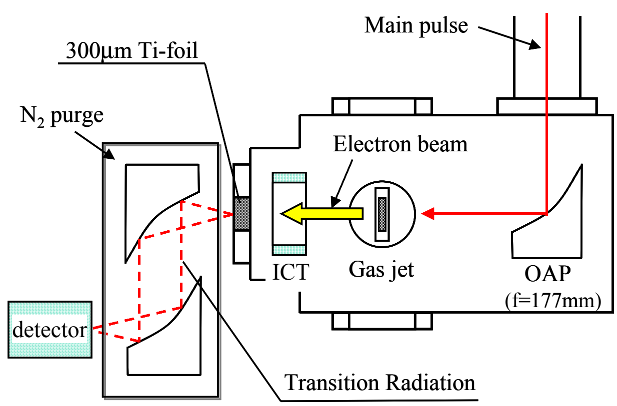

Figure 1: Experimental setup for the spectrum measurement of CTR.

Titanium foil with thickness of 300 μm is placed 180 mm downstream from the gas jet. Transition radiation is emitted from Ti-foil when the electron beam hits, and delivered into the IR bolometer with OAP. In the optical path from Ti-foil to the bolometer water vapour is purged by N_2 to avoid absorption of radiation with wavelength from 50 μm to 200 μm.

RESULTS AND DISCUSSION

Fig. 2 shows the typical energy spectrum of the generated monoenergetic electron beam. In this case, the peak energy is 22 MeV, and the energy spread is less than 23 % at electron density of 6×10^{19} cm^{-3}. However, the energy spread and the peak energy change shot by shot and sometimes energy spectrum become even a Maxwell-like distribution due to instability of laser parameter and plasma. This instability has a bad effect on the spectrum measurement of CTR as discussed later.

Transition radiation emitted from Ti-foil is measured with an IR bolometer and different outer filters. The outer filters are high-pass filters, which cut radiation with wavelength longer than 50 μm and 100 μm. The IR bolometer is equipped with three kinds of inner filters.

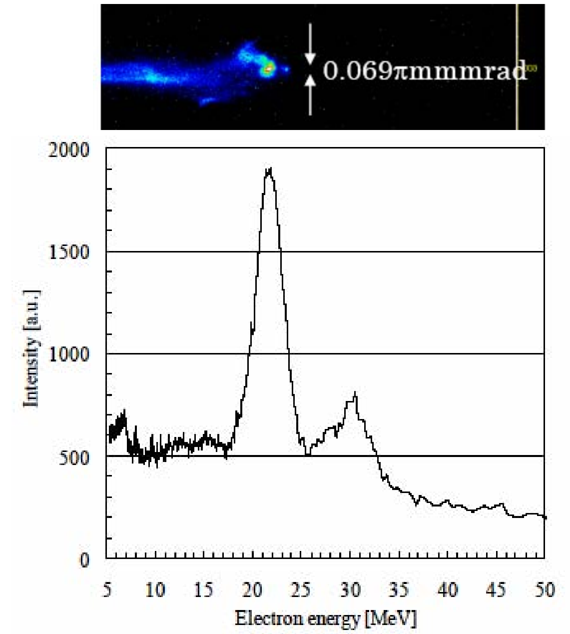

Figure 2: Energy spectrum of the generated monoenergetic electron bunch.

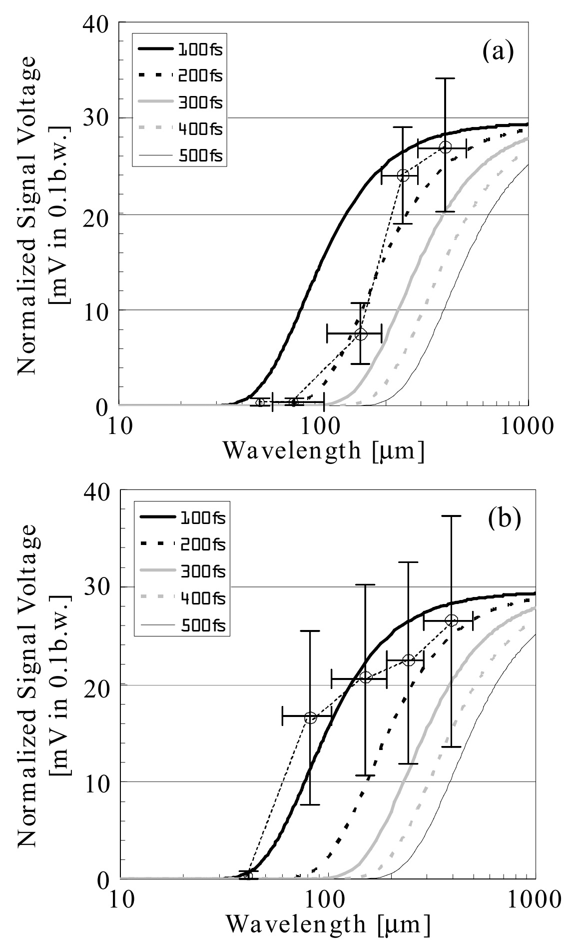

Figure 3: Spectra of CTR from (a) low-monoenergetic electron bunches with peak energy of around 4 MeV, (b) high-monoenergetic electron bunches with energy spectrum like Fig. 2.

They are low-pass filters, which cut radiation with wavelength shorter than 10 µm, 100 µm, and 280 µm. We obtain the average spectrum of CTR by combination of these inner and outer filters.

The measured spectra of CTR from electron bunches with (a) low-monoenergetic distribution and (b) high-monoenergetic distribution like Fig. 2 are shown in Fig. 3. The calculated spectra are also inserted in the figures. From the calculated spectra, we can conclude the bunch duration of the electron is 250±70 fs (FWHM) in low-monoenergetic case and 130±30 fs (FWHM) in high-monoenergetic case.

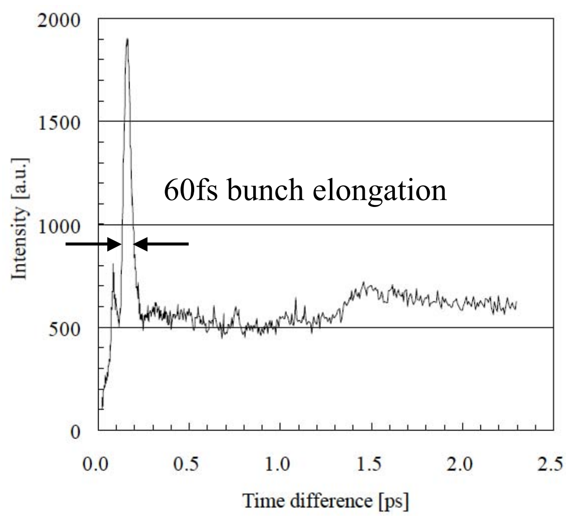

Figure 4: Bunch elongation at Ti-foil that is placed 180 mm downstream from the gas jet.

The reason that the bunch duration extends to 130 or 250 fs and that the obtained bunch duration in two cases are not same is the energy spread of the electron bunch. Since Ti-foil is placed 180 mm downstream from the gas jet, the electron bunch with the energy spread is extended before reaching Ti-foil. Fig. 4 shows the bunch elongation at Ti-foil on the assumption that the longitudinal electron distribution is initially the delta function at the gas jet and that the energy distribution is the monoenergetic distribution like Fig. 2. In this case, the bunch duration is extended for more than 60 fs and therefore initial bunch duration in high-monoenergetic case (corresponding to Fig. 3(b)) is estimated to be 115 fs (FWHM) by the error propagation. Furthermore, the bunch elongation is much more serious when the quality of the electron bunch, such as the peak energy and the energy spread, is poor. In the case of Fig. 3(a), the low quality of the electron bunch leads to the longer bunch duration of 250 fs (FWHM) at Ti-foil.

For the next step of the bunch duration measurement, we plan to perform a single-shot measurement using the 10-channel InSb polychromator in this July. Fig. 5 shows the schematic image of the polychromator. Since the bunch duration at Ti-foil varies shot by shot as already described, a single-shot measurement is required for more detailed evaluation of the bunch duration. In the

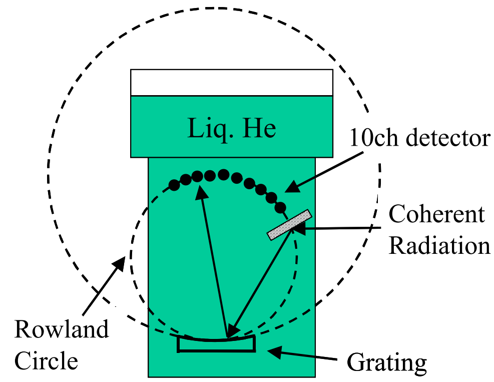

Figure 5: 10ch InSb polychromator.

measurement using the polychromator, however, CTR is separated according to its wavelength by the grating and delivered into each detector. Therefore, CTR cannot be detected if total intensity of CTR is not so strong.

We have carried out the experiment for the electron beam generation with external magnet field [6]. In this experiment, the emittance and the total charge of the electron bunch are significantly enhanced; the transverse geometrical emittance is about 0.02 πmmmrad and the total charge is 1.2 nC. Hence, it is expected that CTR separated by the grating can be detected by the 10-channel polychromator and a single-shot measurement can be performed.

CONCLUSION

We have performed the measurement of the electron bunch duration from a laser plasma cathode by the spectrum measurement of coherent transition radiation. The bunch duration at Ti-foil is 130±30 fs (FWHM) in high-monoenergetic case and the initial bunch duration at the plasma edge is estimated to be 115 fs (FWHM).

Although a single-shot measurement with a 10-channel polychromator is required for more detailed evaluation, this result demonstrates the possibility of a laser plasma cathode to generate ultra-short electron bunches compared to a conventional linear accelerator.

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