Measurement of Stability of Electron Beam Generated by Laser-driven Plasma-based Accelerator

S. Masuda, E. Miura, K. Koyama, S. Kato
National Institute of Advanced Industrial Science and Technology,
Tsukuba Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
E-mail: shi-masuda@aist.go.jp

Abstract. Quasi-monoenergetic electron beams with the energy of 30-80 MeV and large number of electrons more than $10^8$ were produced by focusing a 8 TW, 50 fs Ti:sapphire laser pulse onto $1.6-1.9 \times 10^{19}$ cm$^{-3}$ plasmas. Stability of the quasi-monoenergetic electron beam generation was evaluated using an in-situ observation system for the electron beam diagnostics.

1. Introduction
A laser-driven plasma-based accelerator [1, 2] is expected to be a compact accelerator because the acceleration gradient can be three orders of magnitude larger than the conventional rf linac. A monoenergetic electron beam generation, which was one of the key issues for realization of a practical accelerator, has been demonstrated by many groups [3-6].

We have observed quasi-monoenergetic electron (QME) beams with an energy of 7 MeV at a plasma density around $1.5 \times 10^{20}$ cm$^{-3}$ produced by a 2 TW, 50 fs Ti:sapphire laser pulse [6]. For lower density plasmas around $3.5 \times 10^{19}$ cm$^{-3}$, the energy of the QME beam increased to 30 MeV using a 4 TW laser pulse. However, the number of electrons was limited to the order of $10^7$ [7]. For various applications, more intense beams are necessary. In Sec. 2, we will show the experimental results using a 8 TW laser pulse.

Even though we succeeded in the generation of the QME beams, the probability of the generation of QME beams was a few tens percent [7]. In addition, even though the experimental conditions including the laser energy, the pulse duration, the gas jet density, and so on were fixed, there was the shot-to-shot fluctuation of the peak energy. One of the next issues in the recent laser-driven plasma-based accelerator research is to produce the stable electron beam. The unstable electron beam generation is due to the unstable injection of the electrons into the plasma wave. Faure et al., [8] demonstrated the stabilization of the electron injection controlled by an additional laser pulse. On the other hand, it is important in the self-injection scheme to make clear the experimental condition for the stable injection. As the first step to stabilize the generation of the QME beams, the stability should be evaluated. In Sec. 3, the results of in-situ measurement of the electron beam to evaluate the stability of the QME beam generation will be reported.
2. Generation of quasi-monoenergetic electron beams with higher energy and charge

A 8 TW, 50 fs, 800 nm Ti:sapphire laser pulse was focused onto a He gas jet target by using an \( f = \frac{6}{300} \) (300 mm focal length) off-axis parabolic mirror. The He gas jet was ejected from super sonic conical nozzle with the diameter of the nozzle exit of 0.7 mm. The focal position was set at 1 mm above the nozzle exit. To observe an electron energy spectrum, a dipole magnet was located behind the gas jet target. The electrons deflected by the magnetic field were detected using an imaging plate (IP) [9].

Figure 1 is typical electron energy spectra of the QME beam produced by focusing a 8 TW laser pulse onto plasmas with the plasma density of \( 1.6 \times 10^{19} \) \( \text{cm}^{-3} \). These spectra were obtained by single shot measurements. A clear monoenergetic peak was observed at an energy of 38 MeV. The number of electrons contained in the QME beam reached \( 4 \times 10^8 \). The contrast of the QME beam to the background electrons was higher than the previous results. A QME beam with the energy of 70 MeV was also observed under the almost same conditions. The QME beams were observed only narrow density region as well as the previous results [6, 7].

![Figure 1](image1.png)

**Figure 1.** Typical electron energy spectra of QME beams. The QME beam with the energy of 70 MeV was observed with a 8.3 TW laser pulse focused onto a 1.9 \( \times 10^{19} \) \( \text{cm}^{-3} \) plasma. The QME beam at 38 MeV was observed when the laser power was 8.3 TW and the plasma density was \( 1.6 \times 10^{19} \) \( \text{cm}^{-3} \).

As shown in Fig. 2, the new results is also on the scaling. The energy of the QME beam is inversely proportional to the plasma density. The QME beams in the energy range from 35 to 70 MeV were observed with the laser power of 8 TW at the plasma density of \( 1.6 \times 10^{19} \) \( \text{cm}^{-3} \). Although there were the energy fluctuations, the fluctuation in the present result reduced as seen in Fig. 2.

![Figure 2](image2.png)

**Figure 2.** The energy of the monoenergetic peak as a function of the plasma density. Previous results of the QME beam generation with the laser power \( P_L \) at 2 TW (open squares), 3 TW (open circles) and 5 TW (crosses) are plotted. Closed circles are for the new results obtained with \( P_L = 8 \) TW. Two lines inversely proportional to the plasma density are plotted for reference.

3. Stability of quasi-monoenergetic electron beam generation

To observe the shot-to-shot fluctuation of the QME beam, an in-situ observation system for the electron beam diagnostics was composed. A DRZ fluorescent screen [10] was used instead
of the IP to detect the electrons, and the fluorescence was taken by a CCD camera. The absolute sensitivity of the detection system was calibrated by using an absolutely calibrated IP [9]. Figure 3 shows shot-to-shot energy resolved electron images according to the sequential 20 laser shots. The laser power and the plasma density were fixed at 8.5 TW and \(1.9 \times 10^{19}\) cm\(^{-3}\), respectively.

**Figure 3.** A series of energy resolved electron images on the DRZ fluorescent screen taken shot-to-shot. The laser power was fixed at 8.5 TW and the plasma density was \(1.9 \times 10^{19}\) cm\(^{-3}\).

Figure 4 (a), (b), (c), and (d) show the peak energy, the energy spread, the number of electrons, and the divergence of the QME beams, respectively, for the sequential 20 laser shots. Open circles denote the laser shots when the QME beam was observed. The number of laser shots without the QME beam denoted by closed circles were 4 shots so that the 80 % shots produced the QME beam. The probability of 80 % increased compared with our previous experiments. In addition, the fluctuation of the peak energy was also improved as shown in Fig. 2. The statistics of the parameters of the QME beam of 16 shots is shown in Table 1.

**Table 1.** Statistics of the quasi-monoenergetic electron beam parameter

| Quantity             | Average    | Standard deviation |
|----------------------|------------|--------------------|
| Peak energy [MeV]    | 55         | 16                 |
| Energy spread [%]    | 20         | 11                 |
| Number of electrons  | \(9.5 \times 10^7\) | \(6.3 \times 10^7\) |
| Divergence [mrad]    | 8.2        | 3.8                |
Figure 4. Shot-to-shot fluctuation of the quasi-monoenergetic electron beam evaluated from the measurements in Fig. 3. (a) peak energy, (b) energy spread, (c) number of the electrons, and (d) divergence. Open circles denote the shots in which the QME beam was observed. Closed circles denote the shots when no QME beam was observed.

4. Summary
The experiments of the QME beam generation were conducted with a 8 TW, 50 fs laser pulse. At the plasma density of $1.6-1.9 \times 10^{19} \text{cm}^{-3}$, QME beams with the energy of 30-80 MeV and the number of electrons of $4 \times 10^8$ have been obtained.

The stability of the QME beam generation was also evaluated. The probability of the generation of the QME beam (80%) was improved compared with the previous experiments. The 30% fluctuation of the peak energy was also improved. Although further optimization should be needed, the in-situ observation of the electron beam is powerful tool to search the optimum condition.

References
[1] Tajima T and Dawson J M 1979 Phys. Rev. Lett. 43 267
[2] Esarey E, Sprangle P, Krall J and Ting A 1996 IEEE Trans. Plasma Sci. 24 252
[3] Mangles S P D, Murphy C D, Najmudin Z, Thomas A G R, Collier J L, Dangor A E, Divall E J, Foster P S, Gallacher J G, Hooker C J, Jaroszynski D A, Langley A J, Mori W B, Norreys P A, Tsung F S, Viskup R, Walton B R and Krushelnick K 2004 Nature 431 535
[4] Geddes C G R, Toth C, van Tilborg J, Esarey E, Schroeder C B, Bruhwiler B, Nieter C, Cary J and Leemans W P 2004 Nature 431 538
[5] Faure J, Glinec Y, Pukhov A, Kiselev S, Gordienko S, Lefebvre E, Rousseau J P, Burg F and Malka V 2004 Nature 431 541
[6] Miura E, Koyama K, Kato S, Saito N, Adachi M, Kawada Y, Nakamura T and Tanimoto M 2005 Appl. Phys. Lett. 86 251501
[7] Masuda S, Miura E, Koyama K, Kato S, Adachi M, Watanabe T, Torii K and Tanimoto M 2007 Phys. Plasmas 14 023103
[8] Faure J, Rechatin C, Norlin A, Lifschitz A, Glinec Y and Malka V 2006 Nature 444 737
[9] Tanaka K A, Yabuuchi T, Sato T, Kodama R, Kitagawa Y, Ikeda T, Honda Y and Okuda S 2005 Rev. Sci. Instrum. 76 013507
[10] Kasei optonix http://www.kasei-optonix.co.jp/english/index.html