STABILIZATION OF LASER ACCELERATED ELECTRON BUNCH BY THE IONIZATION-STAGE CONTROL*

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Abstract

Control of laser-driven quasi-monoenergetic electron bunch via ionization-stage control scheme using nitrogen gas-jet target was conducted. A pointing stability of 1.7 mrad root-mean-square (RMS) was obtained, which is comparable to our previous result using another high-Z (argon) gas-jet target. Further, the peak energy was increased to 40 MeV, which is more than four times larger than that in the argon gas-jet target. These results imply that the ionization-stage control scheme can provide not only stabilization of electron bunch pointing fluctuation but also control of electron energy.

INTRODUCTION

An energetic electron beam source using laser-plasma interaction can generate not only high quality quasi-monoenergetic electron beams [1]-[13] but also ultra-short bunches [14]. In the development of laser-plasma electron accelerator, control of electron bunch is necessary for wide range of applications [15]-[20]. Some experiments using gas-jet target have been conducted for control of the electron bunches. The colliding optical injection [21, 22] and the plasma-density-gradient injection [23] have been proposed and successfully demonstrated [11]-[13]. Moreover, applying an external static magnetic field can produce stable collimated electron bunches [24]. In addition, steady-state flow gas cell target is useful to control of the electron beam precisely [25]. Recently, we found the ionization-stage control can provide stabilization of pointing-fluctuation [26]. A pointing-stabilized (2.4 mrad root-mean-square (RMS)) 8.5 MeV electron bunch from argon gas-jet target was observed. We discussed the long-scale wakefield formation by the preformed plasma and the localized electron injection are important for generating such stable electron bunch.

In this work, control of laser accelerated electron bunch by optimization of the high-Z gas material was performed. A pointing-stabilized 40-MeV range quasi-monoenergetic electron bunch which is close to the maximum energy gain limited by dephasing was observed. This energy is significantly different from the electron energy obtained with another high-Z (argon) gas target. We discuss this energy difference through gas dependence of the ionization potential and the ionization stage. This additional experimental result supports our previous finding [26].

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EXPERIMENT

The experimental setup is shown in Fig. 1. The experimental setup and laser conditions are similar used in previous experiment [26]. We used 4-TW Ti:Sapphire laser system. This laser produces the pulses with the energy of 160 mJ, with the pulse duration of 40 fs full-width-half-maximum (FWHM), and with the wavelength of 800 nm. The amplified spontaneous emission (ASE) pedestal near the main pulse was 2×10^{-6} at <500 ps. Before 500 ps

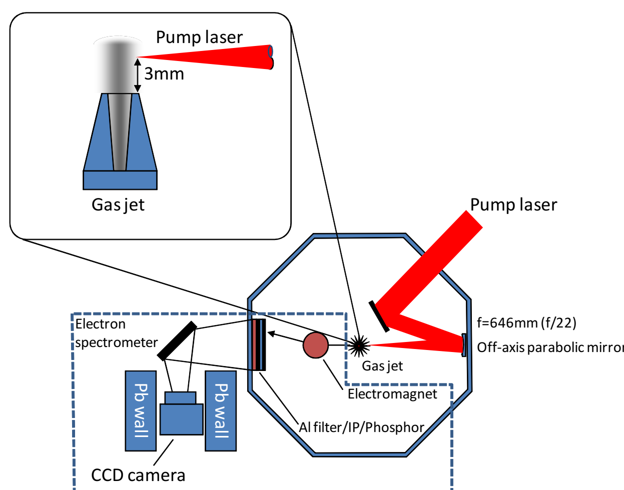

Figure 1: Schematic view of experimental setup.

from the main peak, the ASE pedestal was 3×10^{-8}. The laser beam was focused onto the front edge of the 3-mm-diameter long nitrogen supersonic gas-jet target by using a 15^o, 646 mm focal length, f/22 off-axis parabolic mirror. The peak intensity at the focus in vacuum was 9×10^{17} W/cm^2. In order to detect the spatial profile and the energy distribution of electron bunches, an electron spectrometer (ESM) based on an electromagnet was used.

RESULTS AND DISCUSSION

The pointing fluctuations of electron bunch in nitrogen are shown in Fig. 2. Here, the molecular density was

n_{gas}=3.5×10^{18} cm^{-3}. The data was taken by 50 sequential shots. Each mark corresponds to the data for a single shot. The pointing stability was estimated to be 1.7 mrad RMS. Previously, we observed similar small pointing fluctuations in the argon target [26]. The cascade ionization by ASE pedestal is important to create the long-scale wake-field and this long-scale wake-field can stabilize the electron bunch. In present experiment, threshold intensity of the cascade ionization in nitrogen is smaller than that in argon [27, 28], and preformed plasma could be also generated before arrival of the main pulse. This preformed plasma could guide main laser pulse, and this effect would cause the generation of stable wake-field [29]. Then we have obtained smaller beam pointing fluctuation similarly to the case of argon.

In particular, we observed that the electron energy distribution in nitrogen was significantly different from the case of argon target. Typical electron energy distributions are shown in Fig. 3. In the experiment, 40-MeV peak energy was observed. This value is more than 4 times larger than that in argon (E=8.5 MeV) [26].Under the conditions of our experiment, the argon and nitrogen are incompletely ionized at intensity of 9×10^{17} W/cm^2. Since the ionization stage depends on the laser intensity, the electron plasma density changes. The critical power for the relativistic self-focusing [30]-[32] at electron density of n_e∼5×10^{19} cm^{-3} is P_c=0.6 TW and the ratio of pulse length to plasma wavelength $c\tau/\lambda_p$=2.5. As we see it is sufficient to induce that relativistic self-focusing at 4-TW laser power and the laser pulse can be focused more tightly enhancing the focused intensity. Due to the enhancement of the laser intensity, an extra ionization can happen in high-Z target. Assuming in the electron plasma density increases, which results in simple electron injection model[33], the ionization stage in argon and nitrogen are estimated to be Ar^{13+}(I_p= 686 eV) and N^{7+}(I_p= 667 eV) by the barrier suppression ionization model (BSI) [34]. Then, the enhanced electron plasma density in argon is estimated to be n_e=6.5×10^{19} cm^{-3}, which is 1.3 times larger than that in nitrogen (n_e=4.9×10^{19} cm^{-3}). Previously, the energy dynamics of the electron bunch as a function of plasma density using helium target has been discussed in Ref. 10. For the optimum plasma density, the electron energy is maximal at the dephasing limit given by w_{max}=$2m_ec^2n_c/n_e$ (here n_e is the electron density and n_c is the cut-off density of the drive laser). The electron energy is significantly lower for increasing the electron plasma density due to the dephasing effect. Here, the dephasing limit at electron plasma density of n_e=4.9×10^{19} cm^{-3} is estimated to be E∼40 MeV. It is close to the experimentally observed result in nitrogen. Previously, we also observed energetic electron bunch (E=24.8 MeV) at plasma density of n_e=4.4×10^{19} cm^{-3} in helium[26]. These results imply that strong dephasing effect is thought to happens in argon. We may conclude that the ionization-stage control scheme has controllability of electron energy by optimizing the enhanced electron plasma density effect.

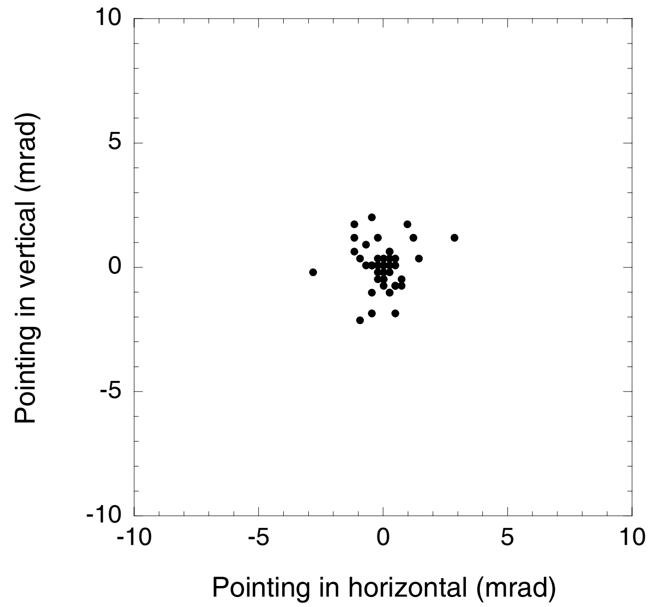

Figure 2: Beam-pointing stability in nitrogen target. The molecular density was 3.5×10^{18} cm^{-3}.

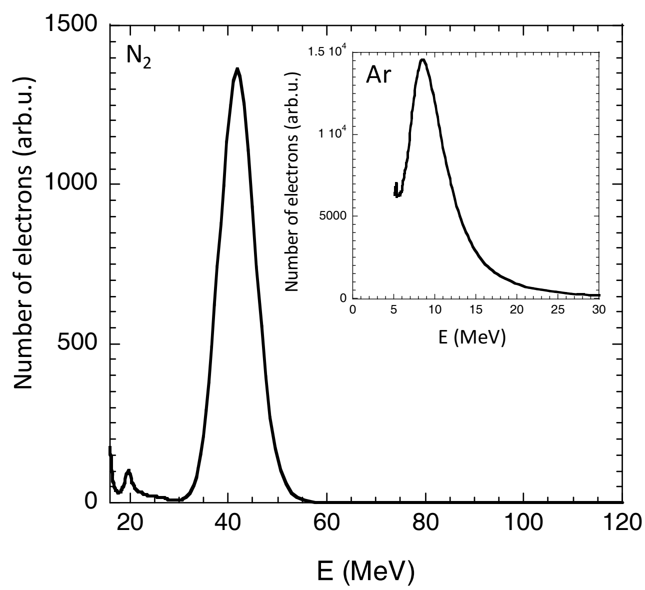

Figure 3: Typical electron energy distributions in N_2 measured in the experiment with the molecular density of 3.5×10^{18} cm^{-3}. Typical electron energy distributions in Ar with the molecular density of 5.0×10^{18} cm^{-3} in previous experiment are shown in the inset.

CONCLUSION

In conclusion, we have studied the stability and energy of quasi-monoenergetic electron generated in the nitrogen gas-jet target. Pointing-stabilized 40-MeV electrons were observed. This experimental result shows that the ionization-stage control scheme can provide not only stabilize the electron beam pointing but also control the electron energy by selecting by enhancing electron plasma density.

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