Energy scaling of monoenergetic electron beams generated by the laser-driven plasma based accelerator

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Monoenergetic electron beams were generated in the self-modulated laser wakefield acceleration regime using a 2–6 TW, 50 fs Ti:sapphire laser system. The monoenergetic electron beams of energies up to 15 MeV and 30 MeV, with a plasma density around $1.5 \times 10^{20}$ cm$^{-3}$ and $3.5 \times 10^{19}$ cm$^{-3}$, respectively, were observed. The monoenergetic energy was found to be inversely proportional to the plasma density. The monoenergetic electron beam was generated at only specific plasma densities for each experimental condition. The plasma density dependence of the electron energy spectrum, the forward scattered light spectrum, and the side scattered light image of the laser pulse was studied in detail. The conditions for monoenergetic electron beam generation are discussed based on the results of the plasma diagnostics. © 2007 American Institute of Physics

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I. INTRODUCTION

Laser-driven plasma based accelerator technology$^1$ such as the laser wakefield accelerator (LWFA),$^{1,2}$ the laser beat wave accelerator (LBWA),$^{1-3}$ and the self-modulated laser wakefield accelerator (SM-LWFA),$^{1,4}$ has been widely studied. Intense ultrashort laser pulses propagating in an underdense plasma excite extremely large amplitude oscillations of the plasma. In the LWFA, when the laser pulse width is about half the plasma wavelength, the plasma wave is resonantly excited. In the LBWA, the beat wave produced by co-propagating two laser pulses with different wavelengths, excites the plasma wave when the beat frequency matches the plasma frequency. In the SM-LWFA, the laser pulse, when longer than the plasma wavelength, decays into a plasma wave and electromagnetic sidebands because of the Raman scattering instability.$^5$ The simple one-dimensional model gives a longitudinal electric field associated with the plasma density oscillation written as $E_p=\frac{(m_e\omega_p)}{\epsilon}e$.

When electrons are injected into the plasma wave they are trapped in the plasma wave potential and move in and out of the acceleration and deceleration phases alternatively. The electrons at the bottom of the plasma wave potential have a maximum energy given by

$$W_{\text{max}}=4mc^2\gamma_p^2\epsilon,$$

where $\gamma_p=\sqrt{1-v_p^2/c^2}=\sqrt{n_p/n_e}$ is the Lorentz factor of the plasma wave with the phase velocity $v_p$, and $n_p$ is the critical plasma density based on the laser frequency. The dephasing length, which is the distance of the electrons in the acceleration or the deceleration phase traveling in the plasma, is a function of the plasma density given by $L_d=(n_p/n_e)\lambda_p$ in the linear regime, where $\lambda_p=2\pi\omega_p/\omega_m$ is the plasma wavelength. The acceleration length is determined from the propagation distance of the laser pulse in the plasma, which depends on the plasma density, the laser power and the focusing optics. The electrons are ejected from the plasma with a maximum energy of $W_{\text{max}}$, when the dephasing length and the acceleration length are equal.

Many experiments have been reported that demonstrate high gradient electron acceleration.$^6-12$ However, in these cases the electrons exhibit a Boltzmann-type distribution or the energy spread was wide. There are significant difficulties in producing a monoenergetic electron beam. The electrons trapped in the appropriate phase of the wakefield are accelerated by the longitudinal field and focused by the transverse field. The phase difference between the acceleration phase and the focusing phase is $\pi/2$. In order to obtain a monoenergetic electron beam, an electron bunch much shorter than $\lambda_p/4$ must be injected into the wakefield. The plasma wave

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period is typically of the order of 10–100 fs. The injection of electrons into a narrow phase range of the wakefield is a significant limitation of the laser-driven plasma based accelerator. Another unphased injection scheme to obtain the monoenergetic electron beam was proposed in Ref. 13. A part of the electrons injected over all phase are focused and phase bunched when the injection energy of the initial electrons is appropriate. The original experiments that employed external electron injection demonstrated high gradient electron acceleration.14 In these experiments, the electrons produced from an aluminum solid target irradiated by a 200 ps laser pulse were injected into the plasma waves. The accelerated electrons exhibit a broad range compared to that of the initial electrons because the bunch length of the injected electrons was much longer than the wavelength of the plasma wave. Utilizing the high quality electron bunch from the conventional accelerator as an external injector is inappropriate in order to obtain an ultracompact accelerator based on the laser-driven plasma accelerator. In the past several electron injection schemes have been proposed. One promising approach is referred to as optical-injection, which utilizes additional laser pulses.15–17 Another approach is the self-injection scheme, where the background plasma electrons are injected into the wakefield because of the wave breaking of the nonlinear plasma wave.18 In recent years, the self-injection scheme has been shown to produce monoenergetic electron beams.19–24 The limitation of the injection bunch length is no longer a significant limitation. The field produced by the injected electrons reduces the plasma wave amplitude and so further injection is terminated.25

The compactness of the laser-driven plasma based accelerator is an important feature for potential applications in the medical, industrial, and scientific fields. The high energy electron beam with the energy range from a few MeV to several-hundred MeV is useful for medical and industrial applications. In the scientific field, for instance, the high energy physics at the energy frontier requires the energy over TeV. The wide energy range of the electron beam generated by the compact accelerator is needed for such applications. In addition, accurate control of the energy is required to utilize the laser-driven plasma based accelerator. It is important to investigate the parameter dependence of the energy of the monoenergetic electron beam. Previous experiments19–24 were conducted for a wide range of plasma densities and laser parameters. The energy of the monoenergetic electron beam obtained from the different experiments can be scaled as a function of the plasma density. It was found that the energy increases as the plasma density decreases, as given by Eq. (1). In our previous experiments that employ the self-injection scheme with a 2 TW, 50 fs Ti:sapphire laser, the 7 MeV monoenergetic electron beams were observed at a plasma density of $1.5 \times 10^{20}$ cm$^{-3}$.22 In order to study the energy control of the monoenergetic electron beam, we have conducted new experiments for lower plasma densities. A significant increase in the energy of the monoenergetic electron beam up to 30 MeV for a plasma density around $3.5 \times 10^{19}$ cm$^{-3}$ was observed. These experiments demonstrated that the monoenergetic electron beams could be generated using a relatively small laser system. In the experiments reported here, in order to investigate monoenergetic electron beam generation, the plasma density dependence of forward scattered light spectrum and of side scattered light image of the laser pulse, simultaneously with the electron energy spectrum, was studied. The experimental setup is outlined in the next section. In Sec. III the electron energy spectrum observed in the high and low density experiments is discussed. In Sec. IV the results of the forward scattered light spectrum measurement is discussed. In Sec. V the results of the measurement of the side scattered light image is presented, and the relation between the propagation distance of the plasma wave and the dephasing length is analyzed. In Sec. VI the experimental results of this work are discussed. Finally, a summary of this work is presented in Sec. VII.

II. EXPERIMENTAL SETUP

We used a Ti:sapphire laser system based on chirped pulse amplification that produces 2–6 TW, 50 fs pulses at 800 nm. The laser pulse was focused onto a gas jet target with an off-axis parabolic mirror (OAP). The experiments were conducted for two different density regions. In the high density experiment referred to as case A (previous experiment25), we used an $f/3.3$ OAP (165 mm focal length). The focused laser spot size in vacuum was 5 μm in full width at half maximum (FWHM). The corresponding Rayleigh length was estimated at 70 μm. The laser power was fixed at 2 TW. In case B, the experiment was conducted for lower plasma densities to obtain a higher electron energy. An OAP with the longer focal length of 300 mm ($f/6$) was used to extend the acceleration length, since the dephasing length increases in low density plasma. The focused spot size was 9 μm in FWHM. The Rayleigh length was 230 μm, 3.3 times longer than in case A. To avoid a decrease of the focused intensity due to an increase of the laser spot size, the laser power was increased to 6 TW. A supersonic conical nozzle with a high speed solenoid valve was used to supply the gas jet target. The gas density profile was measured using a Jamin interferometer. The experimental conditions are listed in Table I.

![Table I. Experimental conditions.](image)

Figure 1 is an illustration of the experimental setup. A dipole magnet located behind the gas jet target dispersed the trajectory of the electrons ejected from the plasma with respect to the momentum of electrons. The entrance slit in front of the magnet was 3 mm in width and 7 mm in height. The distance between the slit and the plasma was 65 mm in case A and 120 mm in case B. The electrons deflected by the
magnetic field were detected using an imaging plate (IP). To obtain the electron energy spectrum from the electron image recorded on the IP, the sensitivity curve of the IP, reported in Ref. 26, was used. A spectrum of a forward scattered light from the plasma was measured with a grating spectrometer. A high reflection mirror at 800 nm was placed in front of the spectrometer to attenuate the transmitted laser light. A side scattered light image of the laser pulse was also observed at a normal direction to the laser polarization direction using a charge coupled device (CCD) camera imaging system. A narrow band interference filter at 800 nm was used to eliminate self-emission from the plasma. In addition, a shadowgraph of the plasma using a 50 fs probe pulse was observed to determine the focal position of the laser pulse.

III. ENERGY SCALING OF THE MONOENERGETIC ELECTRON BEAM

The monoenergetic electron beam was observed in both cases A and B. The typical electron energy spectra are presented in Fig. 2. In case A, the laser power was 2 TW. The electron energy spectrum was obtained from an average of an accumulation of 90 laser shots. The 7 MeV monoenergetic electron beam was observed at a plasma density of $1.5 \times 10^{20}$ cm$^{-3}$. The number of electrons of the monoenergetic beam was estimated to be $2.7 \times 10^4$ per shot. This value is the lower limit because the average is over all shots that include a shot-by-shot variation. In case B, the energy spectrum with the monoenergetic peak was observed as an average of an accumulation of 8 laser shots, where the laser power was 4 TW. The energy of the monoenergetic electrons increased to 23 MeV when the plasma density was $3.2 \times 10^{19}$ cm$^{-3}$. The number of electrons of the monoenergetic beam was $10^6$ per shot.

The monoenergetic electron beams were observed at only specific plasma densities. Figure 3 shows the dependence of the electron energy spectrum on the plasma density in case A. The laser power was fixed at 2 TW. The monoenergetic electron beam was generated only at a plasma density of $1.5 \times 10^{20}$ cm$^{-3}$. For a plasma density of less than $10^{20}$ cm$^{-3}$, the energy spectrum did not exhibit a high energy component. The number of high energy electrons significantly increased with an increase in the plasma density.

![FIG. 1. Schematic illustration of the experimental setup. Energy resolved electrons were detected using an imaging plate. A forward scattered light spectrum and a side scattered light image were also measured simultaneously. A shadowgraph of the plasma using a 50 fs probe pulse was observed to determine the focal position of the laser pulse.](image1)

![FIG. 2. The electron energy spectrum in both cases A and B. In case A, 7 MeV monoenergetic electrons were observed at a plasma density of $1.5 \times 10^{20}$ cm$^{-3}$. The energy of the monoenergetic electrons increased to 23 MeV in case B for a plasma density of $3.2 \times 10^{19}$ cm$^{-3}$.](image2)
However, the energy spectrum exhibited a Boltzmann-type distribution, and no monoenergetic components were found for a plasma density larger than $2 \times 10^{20} \text{cm}^{-3}$. For denser plasmas at $3.1 \times 10^{20} \text{cm}^{-3}$, the high energy electrons decreased. A detailed discussion of the density dependence of the electron energy spectra was reported in Ref. 27.

The density dependence of the electron energy spectrum in case B is presented in Fig. 4, where the laser power was fixed at 2.7 TW. The plasma density varied from $2.8 \times 10^{19} \text{cm}^{-3}$ to $5.1 \times 10^{19} \text{cm}^{-3}$. The monoenergetic electrons were found at a plasma density of $3.8 \times 10^{19} \text{cm}^{-3}$. The monoenergetic peak was not obtained for a plasma density of less than $2.6 \times 10^{19} \text{cm}^{-3}$. The energetic electrons increased and the monoenergetic component disappeared at a plasma density of $5.1 \times 10^{19} \text{cm}^{-3}$. Similar results to that in case A were obtained for the plasma density dependence of the electron energy spectrum.

The energy of the monoenergetic peak is plotted as a function of the plasma density in Fig. 5. The monoenergetic electron beams were obtained for the plasma density around $1.5 \times 10^{20} \text{cm}^{-3}$ in case A (open squares). In case B, the monoenergetic electron beams were observed at a lower plasma density of around $3.5 \times 10^{19} \text{cm}^{-3}$. The laser power varied from 2 to 6 TW. The open circles denote the monoenergetic electron beams generated using the laser pulses with a power of 2–4 TW. The cross marks denote the monoenergetic electron beams generated using the 5–6 TW laser pulses. The energy of the monoenergetic electron beam and the plasma density were independent of the laser power as seen in Fig. 5.

The energy is inversely proportional to the plasma density. The solid lines in Fig. 5 are from Eq. (1) for constant normalized amplitude at $\epsilon=0.3$ and $\epsilon=0.5$. Although the observed energy varies shot by shot, the maximal values are for $\epsilon=0.5$ and $\epsilon=0.3$ for case A and B, respectively. It is presumed that the plasma wave with an amplitude of $\epsilon=0.3$ –0.5 was excited, if the monoenergetic electron beams were accelerated to the energy of $W_{\text{max}}$.

In case A, typical electron numbers within the monoenergetic component were of the order of $10^4$. In case B, the $10^6$ monoenergetic electrons were observed at a laser power of 3 TW. When the laser power was increased to 6 TW, the electron yield increased to $10^7$. The number of electrons contained in the monoenergetic peak depended on the laser power. The number of electrons as a function of the laser power in case B is plotted in Fig. 6. The plasma density was around $3.5 \times 10^{19} \text{cm}^{-3}$. The experimental conditions, except the laser power, was almost constant. The open circles are for the number of electrons as an average of an accumulation of the laser shots. These values are the lower limit because the estimated number of electrons is based on an accumulation of 5–10 shots. The closed circles are for the number of electrons obtained from a single shot measurement. It is seen that the number of electrons increases with an increase in the laser power.
IV. FORWARD SCATTERED LIGHT SPECTRUM

The monoenergetic electron beams were observed for a narrow density range as in Figs. 3 and 4. In order to obtain the condition of the monoenergetic electron beam generation, the plasma density dependence of the forward scattered light spectrum was measured simultaneously with the electron energy spectrum. The first Stokes satellite peak, due to stimulated Raman scattering, was observed in both cases in the forward scattered light spectrum as shown in Figs. 7 and 8. The first Stokes satellite indicates that the self-modulated laser wakefield was excited. The monoenergetic electrons were accelerated by the self-modulated laser wakefield.

Figure 7 is the plasma density dependence of the forward scattered light spectrum in case A. It is noted that the transmitted laser light in the spectrum was not attenuated at the plasma density of $1 \times 10^{20}$ cm$^{-3}$ because the high reflection mirror at 800 nm was not placed in front of the spectrometer. When the monoenergetic electron beam was generated at the plasma density of $1.5 \times 10^{20}$ cm$^{-3}$, a clear signal of the first Stokes satellite around 1000 nm was observed. At a plasma density of $1 \times 10^{20}$ cm$^{-3}$, the signal of the first Stokes satellite at 980 nm was small. For low density plasmas less than $1 \times 10^{20}$ cm$^{-3}$, the signal was not observable. The plasma wave did not grow because the laser power of 2 TW was insufficient for the lower plasma density. The spectrum of the first Stokes peak broadened for the high density plasma of $2 \times 10^{20}$ cm$^{-3}$.

In case B, the forward scattered light spectrum was measured for each laser shot. The typical spectra at various plasma densities are presented in Fig. 8. The first Stokes satellite peak was also observed for each plasma density. Figure 9(a) is the shot-by-shot intensity ratio of the first Stokes satellite to the transmitted laser light, as a function of the plasma density. Although the intensity ratio varied shot-by-shot, it rose with the increase in the plasma density. This value indicates the amplitude of the plasma wave excited because of the Raman instability. The amplitude of the plasma wave increased with an increase in the plasma density due to the increase of the growth rate for the Raman forward scattering. The plasma density dependence of the shot-by-shot spectral width of the first Stokes satellite is also plotted in Fig. 9(b). The broadening of the first Stokes satellite was observed as the plasma density increased. Similar characteristics were observed at a plasma density of $2 \times 10^{20}$ cm$^{-3}$ in case A, as mentioned above. The spectrum of the first Stokes satellite peak was modulated for each plasma density in case B.

V. LASER PROPAGATION

Figure 10(a) is a typical image of the side scattered light at a plasma density of $3.8 \times 10^{19}$ cm$^{-3}$. The dotted circle shows the nozzle exit where the diameter is 0.7 mm, and the 2.7 TW laser pulse propagates from left to right. The bright fish-bone structure with a fine channeling filament was ob-
served along the laser propagation axis. The side scattered light exhibited the same wavelength and the same polarization direction as the laser pulse. This bright region indicates the propagation distance of the laser pulse in the plasma. This is the laser channeling due to the self-focusing effect. Although the region of the plasma wave excitation and the position of the electron injection into the plasma wave remain unknown, it is expected that this length is an upper limit of the acceleration length.

The length of the side-scattered light image is plotted as a function of the plasma density in Fig. 10(b). The side scattered light images were measured with the electron energy spectrum in Figs. 3 and 4. In case A, the length linearly increased with an increase in the plasma density from 1020 to 2020 cm−3. The image length was several-hundred microns in excess of the Rayleigh length. The ratio of the laser power to the critical power \( P_{L}/P_{c} \) was from 6.6 to 13. Here, \( P_{c} = 17.4n_{e}/n_{e} \) (GW) is the power threshold for the relativistic self-focusing effect.\(^{28}\) The laser power was far beyond the critical power for this density region. The laser pulse propagated in the plasma over the Rayleigh length due to the relativistic self-focusing. For a higher density plasma at 3.1×1020 cm−3 the image length decreased. In this case, \( P_{L}/P_{c} \) was about 20. The laser propagation terminated over a short distance because of the breakup of the laser pulse due to the large filamentation instability at the high plasma density. The image length in case B also increased with the increase in the plasma density. The plasma density was from 2.6×1019 to 5.1×1019 cm−3; \( P_{L}/P_{c} \) was from 2.3 to 4.5. The propagation distance of the laser pulse was extended because of the self-focusing as the plasma density increased.

The monoenergetic electron beam was obtained when the image length was about 500 μm for both cases. However, the dephasing lengths in each case were very different due to the difference of the plasma density. For comparison, the plasma density dependence of the dephasing length \( L_{d} \) is plotted in Fig. 10(b). In the nonlinear regime, the dephasing length increases due to the increase in the plasma wavelength. The nonlinear plasma wavelength is given by \( \lambda_{NL} = (2/\pi) \gamma_{L} E(p_{L}) E_{0}^{0.5} \), where \( E(p_{L}) \) is the complete elliptic integral of the second kind, \( p_{L} = (\gamma_{L}^{2} - 1)/\gamma_{L}^{2} \), \( \gamma_{L} = \sqrt{1 + a_{0}^{2}}/2 \), and \( a_{0} \) is the normalized vector potential of the laser field. Taking the relativistic effect of the quivering of the electron into the account, the nonlinear dephasing lengths given by \( L_{d}^{NL} = \gamma_{L}^{2} (n_{e}/n_{e}) \lambda_{NL}^{0.5} \) for \( a_{0} = 1.1 \) and \( a_{0} = 1.5 \) are also plotted in Fig. 10(b). Here, \( a_{0} = 1.1 \) and \( a_{0} = 1.5 \) are estimated from the laser power of 2.7 TW in case
B and 2 TW in case A. The dephasing length is longer than the image length for the plasma density less than $2.6 \times 10^{19} \text{ cm}^{-3}$ in case B. In this case, relatively small amounts of electrons were extracted from the plasma and the electron energy spectrum exhibited no monoenergetic component as seen in Fig. 4. When the monoenergetic electron beam was observed at the plasma density of $3.8 \times 10^{19} \text{ cm}^{-3}$, the image length was about one and one half times longer than the nonlinear dephasing length at $a_0 = 1.1$. The image length is three times as long as the nonlinear dephasing length when the monoenergetic component disappeared at the plasma density of $5.1 \times 10^{19} \text{ cm}^{-3}$. In case A, the image length is much longer than the dephasing length. The image length was about 500 $\mu$m when the monoenergetic electrons were observed at a plasma density of $1.5 \times 10^{19} \text{ cm}^{-3}$, ten times longer than the nonlinear dephasing length at $a_0 = 1.5$.

VI. DISCUSSION

The monoenergetic electron beams were generated only in the narrow plasma density range in both cases A and B. The electron energy spectrum strongly depended on the plasma density. This dependence was similar for both cases. The forward scattered light spectrum also depended on the plasma density and correlated with the electron energy spectrum for both cases. In the density region lower than that in which the monoenergetic electron beam was obtained, the intensity of the first Stokes satellite was small. This indicates that the amplitude of the plasma wave was small, and thus, the high energy electrons were not observed. The amplitude of the plasma wave became large with an increase in the plasma density. The electrons were suitably injected into the plasma wave due to sufficient wave breaking when the monoenergetic electron beam was observed. In contrast, in the higher density region the monoenergetic electron beam disappeared. However, the total number of energetic electrons absolutely increased as shown in Fig. 3. The broadening of the first Stokes satellite was observed as the plasma density increased. The broadening comes from the loss of coherent structure of the plasma wave due to the strong wave breaking of the nonlinear plasma wave. A copious amount of electrons are self-injected, then the total number of accelerated electrons increases. Considering that the condition of the electron injection is extremely limited, it is reasonable to obtain a monoenergetic electron beam only in the narrow plasma density region. In case B, the modulation of the first Stokes satellite was observed. One possible explanation is the relativistic cross phase modulation between the first Stokes satellite and the laser light in the plasma. The broadening of the first Stokes satellite in this case was partly derived from the relativistic cross phase modulation.

The matching of the acceleration length and the dephasing length is one of the required conditions for the monoenergetic electron beam generation. The length of the side scattered light image, which is the propagation length of the laser pulse in the plasma, also depended on the plasma density as shown in Fig. 10(b). In case B, the image length was 1.5 times longer than the dephasing length when the monoenergetic electron beam was observed at a plasma density of $3.8 \times 10^{19} \text{ cm}^{-3}$. This result is consistent with the matching condition because the image length is the upper limit of the acceleration length as mentioned in Sec. V. The electron injection occurs after the nonlinear effects shape the laser pulse and increase the plasma wave potential. Thus, the matching condition could be achieved in our result. In the lower plasma density region at $2.6 \times 10^{19} \text{ cm}^{-3}$, the image length was shorter than the dephasing length. No high energy electron was obtained due to the short acceleration length in addition to the small amplitude of the plasma wave. In the higher density region at $5.1 \times 10^{19} \text{ cm}^{-3}$, it is expected that the acceleration length was longer than the dephasing length. The mismatch of the acceleration length to the dephasing length is an possible explanation for the lack of a monoenergetic peak in the high energy region. The image length was much longer than the dephasing length in case A. A monoenergetic electron beam was observed when the image length was ten times longer than the dephasing length at the plasma density of $1.5 \times 10^{20} \text{ cm}^{-3}$. It is possible that the electrons injected into the wakefield repeat the acceleration-deceleration cycle before the electrons are ejected from the interaction region. When the monoenergetic electron beam was observed, the accelerated electrons may have been ejected from a suitable phase.

The improvement of reproducibility of experiments has been a major problem. The number of electrons of the monoenergetic electron beam obtained from the single shot measurement was higher than that obtained by the average of the accumulation of the several shots, as seen in Fig. 6. This means that the shots contained in the averaged value had the shot-by-shot variation and probability of the monoenergetic electron beam generation was not 100%. The probability is roughly estimated by comparing the number of electrons from single shot measurement, $N_s$, and the averaged number of electrons, $N_{\text{ave}}$. The probability $N_{\text{ave}}/N_s$ in case B can be estimated to be 15%–60% based on the results shown in Fig. 6. The number of electrons of the monoenergetic electron beam in case B was substantially larger than that in case A. The probability in case A could not be estimated because all of the obtained number of electrons was the averaged value. Although a quantitative comparison between the two cases is difficult, the increase of the number of electrons in case B is found to be due to the larger spot size of the laser pulse compared to case A. The stability of the monoenergetic electron generation was found to improve for case B. The lack of the reproducibility may be due to the shot-by-shot variation of the laser and/or the gas jet. The shot-by-shot variation was observed in the measurements of the forward scattered light spectrum [see Figs. 9(a) and 9(b)] and the image length of the side scattered light [see Fig. 10(b)]. The next main issue associated with practical accelerator research is the improvement of stability.

VII. SUMMARY

We have conducted laser-driven plasma based accelerator experiments for different plasma densities. For a high density plasma (case A), the monoenergetic electron beam...
with the energy up to 15 MeV at a plasma density around $1.5 \times 10^{20} \text{cm}^{-3}$ was observed. For a low density plasma around $3.5 \times 10^{19} \text{cm}^{-3}$ (case B), the energy increased to 30 MeV. The relation between the energy of the monoenergetic electrons and the plasma density corresponding to $W_{\text{max}} \propto n_p^{-1}$ was observed experimentally. Using the OAP with a longer focal length, the number of electrons of the monoenergetic electron beams were generated in the narrow length to the dephasing length. This is the reason why the electron energy spectrum. The condition of the monoenergetic electron beam generation strongly depended on the plasma wave excitation and the matching of the acceleration length to the dephasing length. This is the reason why the monoenergetic electron beams were generated in the narrow plasma density range.

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