Generation of a highly collimated, mono-energetic electron beam from laser-driven plasma-based acceleration

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Abstract. An electron acceleration experiment in a self-modulated laser wakefield acceleration regime was carried out using a 45 fs duration Ti:sapphire laser focused to an intensity of $1.8 \times 10^{18}$ W cm$^{-2}$ on helium gas-jet plasma. A highly collimated and mono-energetic electron beam was observed at a plasma electron density of $\sim 8.5 \times 10^{19}$ cm$^{-3}$. The electron beam was produced with a minimum full cone divergence angle of 4 mrad, an energy spread of $\pm 4\%$ and a peak energy up to 21 MeV. The experimental results were explained on the basis of self-modulation of the laser beam and acceleration in the bubble regime.

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1. Introduction

Electron acceleration from the interaction of an ultrashort, intense laser pulse with underdense plasma has been intensively studied to realize compact high-energy accelerators ever since the concept of laser-driven electron acceleration was proposed [1]. In the last few years, the studies have brought significant progress in this field in terms of improvement in electron beam quality, stability, control and maximum energy. For example, after the first results on mono-energetic beam generation [2]–[4] with peak energies up to 170 MeV, many groups have produced low-divergence and mono-energetic beams under various laser and plasma conditions [5]–[11]. Improvement in the stability and control of electron beam energy has been demonstrated through controlled electron injection by the collision of two counter-propagating laser pulses [12] or by using a steady-state-flow gas cell [13]. To achieve higher energies, a high-intensity laser pulse needs to be guided to length of the order of centimeters, which is much longer than the Rayleigh length \( Z_R \). The value of the latter is normally in sub-millimeters. Laser guiding, either by using capillary plasma waveguides [14] or through relativistic self-focusing (RSF) [15], has been used to demonstrate the acceleration of electrons to GeV energy. However, due to the nonlinear nature of RSF and the unstable behavior of capillary waveguides, the reproducibility of the high-energy beam was rather poor. Although active research is continuing to improve the stability of laser beam propagation to produce stable high-energy beams, electron beams from laser-based accelerators are being explored for various applications [16].

For laser guiding through RSF, laser power \( P_L \) should exceed critical power,

\[
P_C(GW) = 17(n_e/n_c)
\]

where \( n_e \) is the electron density and \( n_c \) is the critical density for the laser being used. This condition favors the use of higher density plasmas \( n_e > 10^{19}\text{cm}^{-3} \) for achieving relativistic focusing with laser beams of a few TW power. However, in addition to lowering the dephasing length, the use of high-density plasma also results in the onset of forward Raman scattering (FRS) instability, which can strongly couple with RSF and acquire significant transverse and longitudinal structures [17]. Thus, it is difficult to propagate smooth self-focused laser pulses longer than the Rayleigh length \( Z_R \) [17]. Filamentation instability is also important at higher densities [18], which may influence the acceleration process and thereby produce a poor-quality electron beam. Earlier studies have indicated the importance of the appropriate choice of laser pulse duration or the focal spot [19]–[21]. A non-optimum choice of the laser parameters can lead to laser beam filamentation and large-divergence electron beams with a continuous energy spectrum. At the boundary of stable laser channeling and strong filamentation, the laser channel can split into two channels. Bifurcation of the laser channel was theoretically investigated [22] and has been observed experimentally [23]–[25]. In this paper, we report the production of a highly collimated, mono-energetic electron beam with peak energy up to 21 MeV from double filamentation of a 45 fs duration Ti:sapphire laser beam focused to an intensity of \( 1.8 \times 10^{18} \text{Wcm}^{-2} \) in a relatively high-density \( n_e \sim 8.5 \times 10^{19}\text{cm}^{-3} \) helium gas plasma.

2. Experimental set-up

The experimental set-up used for electron acceleration is shown in figure 1. The experiment was performed with a Ti:sapphire laser system, which delivers laser pulses of 45 fs (full-width at half-maximum (FWHM)) duration with a peak power of about 9 TW at a peak wavelength \( \lambda_0 = 790\text{nm} \) and with a spectral width \( \Delta \lambda = 20\text{nm} \). A supersonic pulsed helium
gas jet was set up in an octagonal interaction chamber evacuated to a background pressure of $\sim 10^{-5}$ mbar. A pulsed gas jet was generated by a shock-wave-free rectangular slit nozzle and a fast pulse solenoid valve. The supersonic slit nozzle had a rectangular orifice of 1.2 mm width and 10 mm length. The pulse valve was opened for 2 ms at a repetition rate of once in 30 s. The backing pressure of the valve was varied up to 70 bar to adjust the neutral gas density in the range of $1–5 \times 10^{19}$ cm$^{-3}$. The gas jet was well characterized by Hosokai et al [26] using interferometry, which showed uniform density distribution with sharp entrance and exit boundaries. The laser beam with an energy of about 400 mJ was focused along the width of the slit nozzle using an $f/10$ gold-coated off-axis parabolic mirror (OAPM). The measured vacuum focal spot had FWHM diameter $d_0 = 18 \mu$m and it was positioned 1 mm above and at the front edge of the nozzle orifice. Considering the $M^2$ parameter, the Rayleigh range of the focused laser beam was $Z_R = \pi d_0^2 / (2M^2\lambda \ln 2) \approx 300 \mu$m and the peak intensity at the waist was $I_L = 4P_0 \ln 2 / \pi d_0^2 = 1.8 \times 10^{18}$ W cm$^{-2}$ (laser strength parameter: $a_0 = 0.9$), considering 50% of energy contained in the focal spot. The contrast ratio of the main pulse to the pre-pulse before 8 ns was measured as $\sim 10^6$. An integrating current transformer (Bergoz: ICT-082–070-5:1) with a 4 mm thick annular aluminum disc in front was kept after the gas jet to measure the electron beam charge. The aluminum disc has a hole of 50 mm diameter to allow electrons emitted within a full cone angle of approximately 20$^\circ$ to pass through the ICT. A 12-bit CCD camera and a DRZ-phosphor screen (covered on the front side with a 10 mm thick aluminum plate) were used to record the spatial profile of the high-energy ($> 5$ MeV) electron beam. The energy spectrum of electrons was measured with a single-shot electron spectrograph. The spectrograph had two circular permanent magnets of 50 mm diameter, separated by a 9 mm pole gap. The magnetic field profile between the pole pieces had a flat top with an effective magnetic field $B_{\text{eff}} = 0.46$ T. The magnetic field disperses the electrons in the horizontal plane. A rectangular slit (5 mm $\times$ 9 mm) made in a combination of 12 mm thick aluminum and 6 mm thick lead was placed at the entrance of the magnet. The angular dimensions of the slit in the horizontal and vertical directions are 33 and 60 mrad, respectively. The laser–plasma interaction was observed through side imaging of the incoherent Thomson side-scattering of laser radiation, with 5× magnification. A narrow band-pass filter was placed in front of the side imaging 12-bit
Figure 2. (a) Forward Raman spectra at different gas pressures. (b) Side image of laser–plasma interaction showing bifurcation of the laser beam into two filaments, as indicated by the arrows on the right. The vertical dotted line shows the location of the top of the gas jet density ramp. (c) Spatial profile of the high-energy (>5 MeV) electron beam.

CCD camera to allow only scattered radiation from the plasma, within the wavelength range of 800 ± 20 nm, to pass through. To understand the electron acceleration mechanism, forward scattered light was collected at an angle of 6° w.r.t. the laser axis and was imaged on the entrance slit of an optical spectrograph.

3. Results and discussion

The electron acceleration experiment was carried out in the regime of self-modulated laser wake-field acceleration (SM-LWFA). An accelerated electron beam was produced for plasma electron density above $5 \times 10^{19}$ cm$^{-3}$ in every laser shot with energy integrated total charge in excess of 2 nC. Since the ICT collects electrons within a cone angle of 20°, the total charge includes large-divergence, low-energy electrons also. The total charge increased exponentially with an increase in plasma electron density, which is similar to the observation in our initial experiments [27]. When the density is below $5 \times 10^{19}$ cm$^{-3}$, the amplitude of the plasma wave was not high enough for self-injection of electrons for acceleration. For plasma electron density in the range of $5 \times 10^{19} - 1 \times 10^{20}$ cm$^{-3}$, the plasma wavelength ($\lambda_p$) varies from 4.7 to 3.3 μm. This implies that the laser pulse length ($c\tau_L = 13.5 \mu$m) is about 3–4 times $\lambda_p$. Also for the above density range, the laser power ($P_L \approx 9$ TW) is about 15–30 times higher than the critical power $P_c$ for RSF. Therefore, the laser pulse can undergo strong self-modulation through FRS instability. The occurrence of self-modulation was confirmed from the observation of the Stokes satellite in the FRS spectrum. Figure 2(a) shows the observed variation of Raman shift with background pressure (i.e. gas density). Since a high-pass filter (RG-850), which strongly attenuates the spectrum below 850 nm, was used to attenuate the transmitted laser light, the anti-Stokes satellite line in the Raman spectrum was not seen. It is seen from figure 2(a) that the amplitude of Raman satellites increased with gas pressure (plasma electron density), which shows that the self-modulation of the laser pulse becomes stronger at higher plasma density.

As $P_L \gg P_c$, a single, long interaction channel/filament extending to several $Z_R$ through RSF was expected. However, as seen in figure 2(b), a double filament-like structure was
observed. Each of these filaments has a diameter around 9 \( \mu \text{m} \) and length around 400 \( \mu \text{m} \), which was about 1.3 times the \( Z_R \). The filaments appear at the beginning of the flat-topped portion of the gas jet profile, as indicated in figure 2(b). They were observed in almost all the laser shots, within density range of the experiment. In some shots at higher densities, multiple (scattered) filaments were observed. We did not observe any significant change in length or position of the filaments with change in plasma density. There were shot-to-shot variations in the observed intensity and length of the filaments (from about 400–500 \( \mu \text{m} \)), which may be attributed to shot-to-shot variations in laser–plasma interaction parameters. The separation between the filaments remains constant within the resolution of our measurement.

Along with laser filamentation, we also observed a highly collimated (divergence < 10 mrad) electron beam at a plasma density of around \( 8.5 \times 10^{19} \text{cm}^{-3} \), in the background of diffused electrons with larger divergence (figure 2(c)). The pointing of the collimated beam varied from shot to shot within an angle of about ±25 mrad. Since the pointing variation is larger than the half width of the slit (16.6 mrad) of the magnet spectrometer, the collimated electron beam missed the slit in some of the shots. The energy spectrum of the electron beam was measured at various plasma densities ranging from about \( 5 \times 10^{19} \text{cm}^{-3} \) to \( 1 \times 10^{20} \text{cm}^{-3} \). The electron energy spectra at three different electron densities (6.5 \( \times 10^{19} \), 7.5 \( \times 10^{19} \) and 8.5 \( \times 10^{19} \text{cm}^{-3} \)) are shown in figure 3(a). The typical spectra are continuous with Boltzmann-like \([\exp(-E/kT_{\text{eff}})]\) distribution. The effective temperature \((T_{\text{eff}})\) of the electron beam was observed to increase from 2.7 MeV at \( 6.5 \times 10^{19} \text{cm}^{-3} \) to 11.2 MeV at \( 8.5 \times 10^{19} \text{cm}^{-3} \). Further increase in the electron density to \( 9.5 \times 10^{19} \text{cm}^{-3} \) reduced the temperature to about 6 MeV, which is close to the effective temperature at \( 7.5 \times 10^{19} \text{cm}^{-3} \). At an electron density around \( 8.5 \times 10^{19} \text{cm}^{-3} \), in about 20% of the laser shots, a highly collimated and mono-energetic electron beam with a few tens of picocoulombs of charge was observed. The spectrum of the mono-energetic electron beam, with peak energy at 21 MeV, is shown in figure 3(b). The corresponding image of the energy-dispersed electron beam is shown in figure 3(c). The vertical dimension of the electron beam in figure 3(c) represents the divergence of the electron beam, as the beam size in this direction was not restricted by the slit height (60 mrad) of the magnet spectrograph. The mono-energetic electron beam had divergence angle \((2\theta)\) in the range of 4–7 mrad (less than the slit width = 33 mrad) and an energy spread \((\Delta E/E)\) of ±4–8%. The resolution \((\Delta E/E)\) of the spectrometer at 21 MeV is about 1% and the value becomes lower at
lower energies (0.5% at 10 MeV). Therefore, the estimated energy spread was the upper limit, which arises due to the finite size of the electron beam in the direction of energy dispersion on the DRZ-phosphor screen. Therefore, the actual energy spread may be smaller than the above-stated value. However, as the horizontal width of the slit was much larger than the angular dimension of the well-collimated electron beam, the estimated peak energy, assuming that the electron beam enters the magnetic field through the center of the slit, will have uncertainty. Interestingly, a mono-energetic beam with peak energy in the range of \( \sim 13–15 \text{ MeV} \), because of its pointing variation and large width of the slit, can lead to shot-to-shot variations in the measured energy in the range 10–21 MeV. In such a case, the measured peak energy variation of 10–21 MeV in the present experiment may actually be due to an energy-stable electron beam with its peak energy varying within a very narrow energy interval from about 13 to 15 MeV from shot to shot. The charge of the mono-energetic electron beam was estimated from the calibration of the ICT signal against the intensity of the electron beam image, as recorded using the DRZ-phosphor screen and the CCD camera. Although the total beam charge (energy integrated) was a few nC, the mono-energetic electron beam had a maximum charge of about 60 pC, carrying about 0.5% of the laser energy. The transverse geometric emittance \( \varepsilon_\perp \) of the mono-energetic beam was as low as \( 0.01\pi \text{ mm mrad} \). This was estimated by assuming the upper limit on the electron beam transverse size to be equal to the diameter of each filament.

Two-channel formation due to bifurcation of a single channel after some length of interaction has been reported by a few groups. For example, Chen et al \[25\] inferred that such bifurcation of the laser channel can result from the presence of a pre-pulse. Ionization by a pre-pulse splits the laser propagation channel by creating a sharp localized region of a lower index of refraction. Andreev et al \[28\] observed that short pulses \( (c\tau_\text{l} < \lambda_p) \) can undergo filamentation instability seeded by hot spots in the laser beam. Due to a non-ideal near-field radial profile (neither Gaussian nor circular flat top) of practical high-power laser beams \( (M^2 \approx 3 \text{ for our laser beam}) \), the far-field profile may consist of one principal spot with one or more hot spots in its periphery. Since the value of \( a_0 \) required to observe the growth of these hot spots is quite small, it might be possible that one of the intense hot spots grows on the rising edge of the laser pulse over 100 \( \mu \text{m} \) of the gas density ramp and forms a second intense filament, along with the filament caused by the principal spot, by the time the laser reaches the top of the density ramp, as shown in figure 2(b). Further experiments with more diagnostics would be helpful to deeply understand the formation of double filaments in our parameter regime. More recently, the simulation and experimental results of Thomas et al \[19, 20\] have shown that the appropriate choice of focusing optics \( (\omega_0 > \lambda_p) \) would lead to the smooth self-guiding of a laser over a dephasing length and produce mono-energetic electrons in the bubble regime \( (c\tau_\text{l} < \lambda_p) \). They also report that for the case \( \omega_0 < \lambda_p/2 \), multiple filaments of size \( \lambda_p \) are formed and the interaction length becomes much shorter. This laser filamentation was found to produce electron beams with large divergence and a continuous energy spectrum. However, we observe a low-divergence and mono-energetic electron beam from the double-filamented propagation of a laser at much higher plasma densities compared to the results of Thomas et al \[19\].

The occurrence of self-modulated wake-field excitation and the resulting electron acceleration can be understood as follows. The self-modulation process causes the laser pulse \( (c\tau_\text{l} = 13.5 \mu\text{m}) \) to modulate itself into multiple pulselets of spatial length (FWHM) of approximately \( \lambda_p/2 \), separated by \( \lambda_p \) \[9\]. The fact that the length of the filaments remains \( \sim 400–500 \mu\text{m} \), but did not last for the whole 1.2 mm length of the gas jet, suggests the occurrence of strong modulation, within the first 100–300 \( \mu\text{m} \) of the interaction of the laser.
pulse in both the axial and transverse directions, leading to the formation of pulselets of FWHM length $\lambda_p/2$. Both numerical simulations [29] and laboratory experiments [30] show that relativistic self-guiding is greatly weakened for pulses shorter than $\lambda_p$, even if the laser power exceeds the critical power for RSF. Therefore, the pulselets may not be self-guided beyond 500 $\mu$m. Self-guiding may further be inhibited as the self-modulation results in significant laser energy depletion to reduce the laser power to below critical power ($P_c$) for self-focusing. The side images of the plasma showed that the interaction length did not change much with variation of the electron density. This suggests that the laser pulse may be becoming considerably modulated even at lower electron density. Although the interaction length did not change, there was an increase in the Thomson scattering intensity with an increase in the electron density. This is expected because scattering intensity is proportional to electron density. Although laser modulation is detrimental for achieving long interaction lengths, it drives a large-amplitude relativistic plasma wave that traps the background hot electrons produced by the stimulated side Raman scattering process. The trapped electrons can be accelerated by the relativistic plasma wave, excited by FRS, up to the dephasing length $L_d(=\gamma^2_n\lambda_p = (n_c/n_e)\lambda_p)$, which is 160–60 $\mu$m for $n_e = 5 \times 10^{19}–1 \times 10^{20}$ cm$^{-3}$. Therefore, it appears that the acceleration length (and hence the maximum energy of accelerated electrons) was not limited by the interaction length. Over the initial portion (about 100$s\mu$m) of channel length, the laser pulse evolves through self-modulation before it could drive a strong plasma wave. The plasma wave then traps a significant number ($\sim 10^9$) of background electrons and accelerates them. If the electrons exit the plasma after acceleration distance close to the dephasing length, the electrons gain a maximum energy given by

$$W_{\text{max}} = 2(E_c/E_0)(n_c/n_e)m_0c^2,$$

where $E_0$(V cm$^{-1}$) = 0.96$n_e^{1/2}$(cm$^{-3}$). \hspace{1cm} (1)

Here $E_c$ is the amplitude of the plasma wave. An electron beam produced from self-modulated laser wake-field acceleration normally has high charge (typically a few nano-Coulombs), large divergence ($\sim 100$ mrad or above) and continuous energy distribution (typically 100% energy spread) [31]. Also, at higher plasma electron densities (as in the present experiment), the relativistic electrons generated initially from the wake-field can gain further higher energy by direct laser acceleration (DLA) and have large divergence [32]. This may be the reason for the diffused background electrons seen in figure 2(c). The same may also account for the observation of a continuous energy spectrum as shown in figure 3(a). If the electrons are accelerated by only SM-LWFA, the maximum energy of the electrons is expected to decrease with electron density, as predicted by equation (1). This is because of the reduced dephasing length at higher densities. However, we have observed that the maximum energy of the electrons as well as $T_{\text{eff}}$ increased as the plasma electron density increased from $6.5 \times 10^{19}$ to $8.5 \times 10^{19}$ cm$^{-3}$ (see figure 3(a)). This could occur if electron acceleration took place due to the cascade of SM-LWFA and DLA. As the laser modulation rate increases with increase in plasma density, trapping of electrons by the relativistic plasma wave would occur earlier for higher electron density. Subsequently, the electrons will be accelerated under the direct laser field for longer length, resulting in an increase in maximum energy or temperature of the accelerated electrons with an increase in plasma electron density. Such an increase in maximum energy and $T_{\text{eff}}$, with electron density, has also been reported by a few groups [32, 33]. At an electron density of around $8.5 \times 10^{19}$ cm$^{-3}$, the laser pulse may be significantly modulated over the first 200–300 $\mu$m of interaction length, leaving one or more pulselets of length $\sim \lambda_p/2$ that can drive wake-fields in the bubble regime [9, 34, 35]. Simulations have shown that this regime is very
well suited for producing high-quality electron beams (mono-energetic and highly collimated electron bunches of ultrashort duration) [33]. However, the location of electron injection into the bubble is sensitive to the history of pulse modulation, which significantly changes with a slight variation in initial laser and plasma parameters. In the case of electrons exiting the plasma after $L_d$, the electron beam exhibits a continuous energy spectrum [3], as seen in figure 3(a). For plasma densities beyond $8.5 \times 10^{19}$ cm$^{-3}$, the growth rate of modulation may become so large that the laser pulse gets self-modulated very early during the interaction. The pulselets drive the wake-field in the bubble regime and produce an accelerated electron beam. Since the injection of electrons into a bubble occurs much earlier in the interaction and the dephasing length is shorter at high plasma densities, the maximum energy of the beam is reduced and the quality becomes poor [3, 36]. Considering the maximum energy of the mono-energetic peak at 15 MeV in equation (1), we estimate the accelerating field $E_z$ of the order of 6.2 GV cm$^{-1}$.

4. Summary

An electron acceleration experiment in the self-modulation regime was carried out using a 45 fs duration Ti:sapphire laser focused to an intensity of $1.8 \times 10^{18}$ W cm$^{-2}$ on helium gas-jet plasma. Although the accelerated electron beam typically had a continuous spectrum, at a plasma electron density $\sim 8.5 \times 10^{19}$ cm$^{-3}$, a low-divergence ($\sim 4$ mrad) and mono-energetic ($\Delta E/E \sim 4\%$) electron beam was detected in about 20% of laser shots, with a peak energy of up to 21 MeV. We infer strong modulation of the laser pulse and excitation of the large-amplitude plasma wave from the FRS measurements. It is observed that although the initial laser pulse length $c\tau_L \gg \lambda_p$, laser interaction with the plasma at high density appears to modify the pulse structure significantly through strong self-modulation of the laser beam. The self-modulation may then be producing radially as well as longitudinally compressed intense pulselets of radial size $\sim \lambda_p$ and FWHM length $\lambda_p/2$. Such pulselets can drive strong wake-fields in the bubble regime, leading to localized self-injection of electrons into the bubble. The electron acceleration in the bubble would lead to the production of a low-divergence and mono-energetic electron beam when the acceleration length in the bubble is close to the dephasing length.

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