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Self-Injection and Acceleration of Monoenergetic Electron Beams from Laser Wakefield Accelerators in a Highly Relativistic Regime *

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Self-injection and acceleration of monoenergetic electron beams from laser wakefield accelerators are first investigated in the highly relativistic regime, using 100 TW class, 27 fs laser pulses. Quasi-monoenergetic multi-bunched beams with energies as high as multi-hundred MeV are observed with simultaneous measurements of side-scattering emissions that indicate the formation of self-channelling and self-injection of electrons into a plasma wake, referred to as a 'bubble'. The three-dimensional particle-in-cell simulations confirmed multiple self-injection of electron bunches into the bubble and their beam acceleration with gradient of 1.5 GeV/cm.

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There has been a great deal of interest in investigating laser-plasma acceleration [1] driven by intense lasers that make it possible to generate ultra-high gradient acceleration and high-quality particle beams in a compact size compared with conventional accelerators. Recently many experiments[2−11] have succeeded in producing high-quality electron beams with ultrashort pulse, small energy spread and low emittance. Production of monoenergetic electron beams may take place through the relativistic laser-plasma interaction in the 'bubble' regime proposed by Pukov and Meyer-ter-Vehn.[12] In this regime, the intense laser pulse with duration comparable to or shorter than the plasma wavelength drives away plasma electrons so strongly that a plasma cavity devoid of plasma electrons is formed behind the laser pulse instead of a periodic plasma wave as a result of its self-focusing and longitudinal compression,[13] travelling over a sufficient distance without significant spreading.[14] Part of radially expelled electrons that flow on the cavity wall reaches the rear of the cavity, where the wave breaking occurs and electrons get injected into the first bucket of the wakefield. Beam loading of a dense electron bunch reduces the amplitude of the wakefield below the trapping threshold so that further injection is terminated in the first bucket, resulting in the formation of a monoenergetic electron beam. To date, this theoretical model of monoenergetic electron-beam production predicted by the three-dimensional particle-in-cell simulation has been confirmed phenomenologically by the recent experimental observation of the injection and acceleration processes in the weakly relativistic regime, i.e., $a_0 \simeq 1$, where $a_0 = eA_0/m_e c^2$ is the normalized vector potential. Here we report quasi-monoenergetic electron beams produced by laser wakefield acceleration in the highly relativistic regime, i.e., $a_0 \gg 1$. This is the first experiment to explore self-injection and acceleration of the monoeneregetic electron beams by laser wakefields in the highly relativistic regime, so called 'bubble regime', where three-dimensional nonlinear effects break a naive scaling that predicts the energy gain simply proportional to the laser power as given by the linear laser wakefield theory. A number of our measurements on the monoenergetic electron beams reveal unexpected dependence of the energy gain on the focused power, contrary to the linear prediction.

The experiment used the SILEX-I titanium:sapphire chirped pulse amplification laser[15] at the China Academy of Engineering Physics, delivering ultrashort pulses with the duration of $\tau = 27$ fs at a wavelength of $\lambda = 800$ nm. The laser pulses with energy up to 7.3 J were focused with an F/8.8 off-axis parabolic mirror onto the upstream edge of a 5-mm-long super-sonic He gas jet. A profile of the focused spot was a well defined round shape with spot radius $w_0 = 12\,\mu$m at the $1/e^2$ intensity, containing $\sim 50\%$ of the total laser-pulse energy. This corresponds to

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the peak focused intensity of $6.0 \times 10^{19}\,\mathrm{Wcm}^{-2}$. The accelerated electrons were analysed using a magnetic spectrometer with the field of 0.8 T and the maximum length of 0.33 m, by measuring their energy spectra on a phosphor screen, DRZ (Gd_2O_2S:Tb), placed in the exit of the magnet. The plasma electron density n_e is obtained from a spectral separation between the first and second Stokes peaks ($\omega_p = \omega_{BRS,1} - \omega_{BRS,2}$) of the backward Raman scattering spectrum,[16] where $\omega_p = (4\pi n_e e^2/m_e)^{1/2}$ is the plasma frequency. The plasma density was varied within the range from $n_e = 4 \times 10^{18}\,\mathrm{cm}^{-3}$ to $n_e = 5 \times 10^{18}\,\mathrm{cm}^{-3}$ by adjusting the gas-jet backing pressure. Quasi-monoenergetic dual-beams consisting of two transversely separated

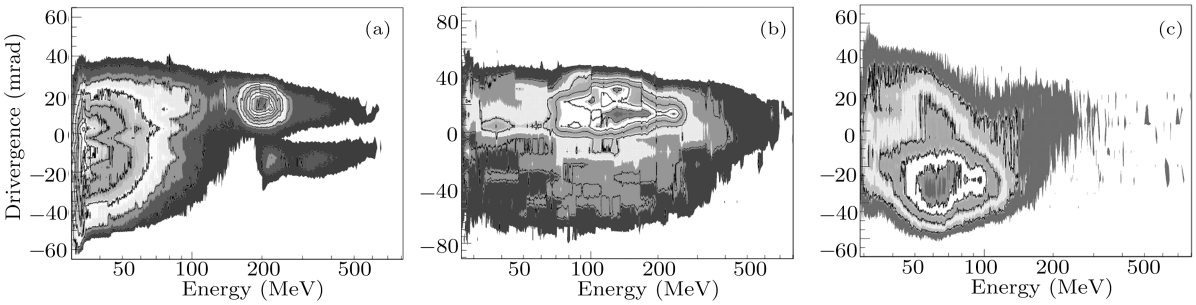

Fig. 1. Energy spectrum and vertical divergence of the electron beam observed on the DRZ phosphor screen at the laser power of (a) $P = 109\,\mathrm{TW}$ ($a_0 = 4.7$), $n_e = 4.3 \times 10^{18}\,\mathrm{cm}^{-3}$, (b) $P = 125\,\mathrm{TW}$ ($a_0 = 5.1$), $n_e = 4.2 \times 10^{18}\,\mathrm{cm}^{-3}$, (c) $P = 135\,\mathrm{TW}$ ($a_0 = 5.3$), $n_e = 4.1 \times 10^{18}\,\mathrm{cm}^{-3}$.

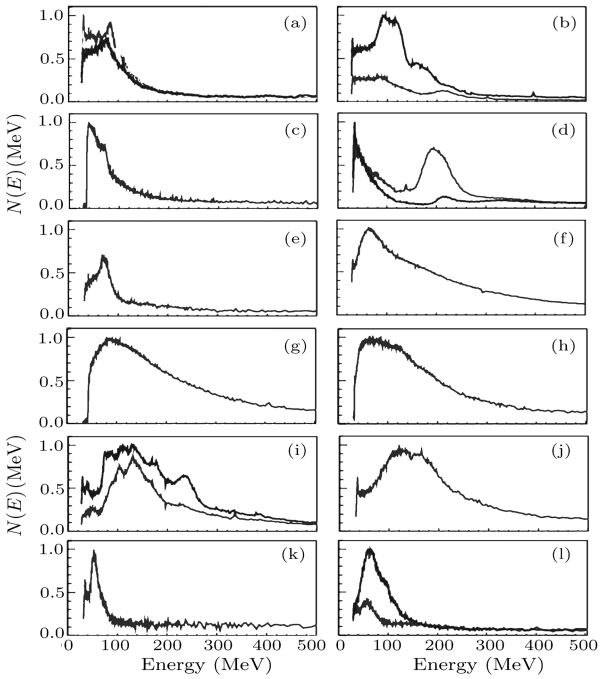

Fig. 2. (Colour online) Energy spectra of electron bunches produced for shots at P [TW], a_0, $n_e[10^{18}\,\mathrm{cm}^{-3}]$; (a) 95, 4.4, 4.8, (b) 101, 4.5, 4.3 (c) 106, 4.7, 4.2, (d) 109, 4.7, 4.3, (e) 110, 4.8, 4.5, (f) 112, 4.8, 4.5, (g) 115, 4.9, 4.9, (h) 125, 5.1, 4.1, (i) 125, 5.1, 4.2, (j) 126, 5.1, 4.7, (k) 132, 5.2, 4.6 and (l) 135, 5.3, 4.1. For each shot, the first bunch spectrum is plotted by the red line, the second bunch one by the blue line and the third bunch one by the green line, respectively.

bunches were often observed for the on-target focused power of more than 100 TW. A dual-beam shown in Fig. 1(a) was obtained from the laser shot at a 5.85 J pulse energy (109 TW peak power on target) and the plasma density of $n_e = 4.3 \times 10^{18}\,\mathrm{cm}^{-3}$. The effective focused intensity is characterized by the normalized vector potential $a_0 = 4.7$. This energy-divergence distribution shows two quasi-monoenergetic peaks of $200 \pm 29\,\mathrm{MeV}$ with 20 mrad divergence in full width at half maximum (FWHM), $220 \pm 19\,\mathrm{MeV}$ with 20 mrad divergence FWHM and a broad peak at $340 \pm 180\,\mathrm{MeV}$.

The angular separation between two beams is 28 mrad on the vertical direction. The highest energy tail stretches over 600 MeV. Figure 1(b) shows a dual beam with three major quasi-monoenergetic peaks obtained from the laser shot at a 6.7 J pulse energy (a 125 TW peak power, $a_0 = 5.1$) and the plasma density of $n_e = 4.2 \times 10^{18}\,\mathrm{cm}^{-3}$. The highest energy peak is located at $233 \pm 23\,\mathrm{MeV}$. The angular separation between two beams is 15 mrad on the vertical direction. Figure 1(c) was obtained from the laser shot at a 7.3 J pulse energy (a 135 TW peak power, $a_0 = 5.3$) and the plasma density of $n_e = 4.1 \times 10^{18}\,\mathrm{cm}^{-3}$. The highest energy peak is located at $93 \pm 16\,\mathrm{MeV}$. The angular separation between two beams is 30 mrad on the vertical direction.

It is noticed that the energy gain of the accelerated electron beam is not proportional to a_0^2, as predicted by the linear wakefield theory. It seems that the higher laser power produces the lower energy gain and the larger energy spread. In order to investigate these effects in the highly relativistic regime, the energy spectra of all shots that produced quasi-monoenergetic beams are plotted in Fig. 2.

An image of Thomson scattering shows that self-channelling starts before the focus and stretches over 2.8 mm long, as shown in Fig. 3(b), corresponding to 5 times Rayleigh lengths at the peak power of 109 TW that is 16 times larger than the self-focusing critical power of $P_c \approx 0.017 n_c/n_e \simeq 7\,\mathrm{TW}$ at the plasma density of $n_e = 4.3 \times 10^{18}\,\mathrm{cm}^{-3}$, where the critical density $n_c = m_e\,\omega_0^2/(4\,\pi\,e^2)$. The self-channelling length is

limited by the energy loss of the laser pulse due to diffraction and excitation of wakefields, i.e., the pump depletion. The pump depletion length of the drive pulse energy is approximately given by $L_{pd} \approx (a_0/\varepsilon_{\max})^2 c\tau(n_c/n_e)$, where $\varepsilon_{\max} \equiv (eE_z)_{\max}/(mc\omega_p)$ is the peak normalized wake field. Hence assuming that the self-channelling length is as long as the pump depletion length, the peak amplitude of the wakefield is given by $\varepsilon_{\max} \approx a_0(L_{pd}/(c\tau n_c/n_e))^{-1/2}$. The measured pump depletion length is shown in terms of the ratio of $L_{pd}/(c\tau n_c/n_e)$ as a function of a_0 in Fig. 3(a).

This indicates $\varepsilon_{\max} \sim a_0$, as deduced from the one-dimensional nonlinear laser wakefield theory.[17] Accordingly the pump depletion length results in $L_{pd} \approx c\tau(n_c/n_e)$, independent of a_0. This means that the pump depletion of the laser pulse happens due to the front erosion of the pulse length at its velocity given by $v_{\text{erosion}}/c = n_e/n_c$. In the side scattering image of the plasma observed through the bandpass filter at 400 nm, transverse radiation emission formed a series of strung bright spots or isolated bright spots inside the plasma density channel that was clearly observable as a narrow dark region with a ~ 4 mm length over a bright ambient plasma column, as shown in Fig. 4(b).

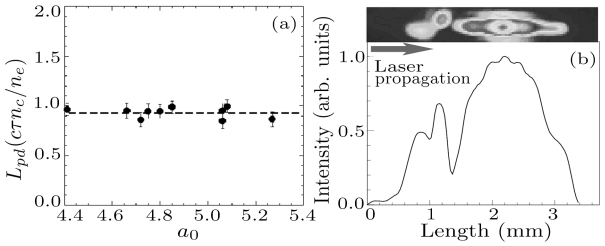

Fig. 3. (a) Pump depletion length L_{pd} measured in terms of $c\tau(n_c/n_e)$ as a function of a_0. The dashed line shows the average ratio of 0.93. (b) The Thomson scattering image and one-dimensional intensity distribution. The laser pulse travels from left to right.

This transverse emission was observed simultaneously when the monoenergetic electron bunches were produced. The relative position of the earliest emission is located at a 1 mm distance from the laser focus, where the first electron bunch injection occurs over a $\sim$ 400 μm distance in which the laser pulse travelled. Figure 4(a) shows the distance $\Delta x_{\text{emission}}$ of transverse emission measured in units of the plasma wavelength λ_p from the laser focus as a function of a_0. Each shot produces several bright spots along the plasma density channel, where their positions are roughly grouped into three regions, corresponding to $\Delta x_{\text{emission}} \sim L_{tr}, 2L_{tr}$ and $3L_{tr}$, where L_{tr} is a trapping distance given by

$$L_{\text{tr}} \approx 2\lambda_p(1 + a_0^2/2)^{1/4}(1 + 3a_0^2/16)^2. \qquad (1)$$

Assuming that the observed transverse emission is generated from the self-trapped electrons that undergo the violent acceleration at the injection,[18] it is inferred that the self-injection occurs periodically a couple of times due to the wave-breaking or the injection into successive wake buckets as the drive pulse travels. When the bright emission is observed only in the outlet region, no monoenergetic beam with the energy higher than 30 MeV is produced.

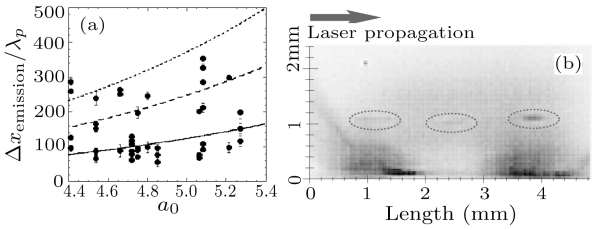

Fig. 4. (a) Distance $\Delta x_{emission}$ of transverse emission measured in units of the plasma wavelength λ_p from the laser focus as a function of a_0. The solid curve shows the trapping distances, L_{tr}, the dashed curve $2L_{tr}$ and the dotted curve $3L_{tr}$. (b) A side scattering image of the plasma viewed with 400 ± 10 nm bandpass filter, taken at $P = 108$ TW and $n_e = 4.3 \times 10^{18}$ cm^{-3}. The laser pulse is focused on the position of 1 mm height above the gas-jet nozzle at its left edge. Circled bright spots are transverse emissions correlated with production of the monoenergetic electron bunches.

The production of quasi-monoenergetic electron bunches was elucidated by the three-dimensional particle-in-cell simulations employing the 3D particle-in-cell code OSIRIS.[19] The size of the 3D moving window is 76.6 μm$\times$96 μm $\times$96 μm, using $3008 \times 160 \times 160$ cells, respectively, with immobile ions and 4 electrons per simulation cell. The spot size of the laser is 12 μm on focus. Longitudinally, the pulse duration of the laser pulse is 27 fs FWHM, with the peak normalized potential of $a_0 = 4.7$. At $t = 0$ in the simulation, the laser pulse is located at the focal spot roughly 0.5 mm distant from the plasma edge. The pulse then propagates into a 1.3-mm-long density ramp, followed by a 2.2-mm-long flat region with the plasma density of $n_e = 4.3 \times 10^{18}$ cm^{-3} and followed by a linearly decreasing density ramp of length 1.8 mm. Figures 5(a) and 5(b) show the evolution of the laser electric field at the propagation distance of $z = 2.48$ and 4.37 mm, respectively. Figures 5(c) and 5(d) show the evolution of the electron density at the propagation distance of $z = 2.98$ and 4.22 mm, respectively. The phase space plot of the accelerated electrons at $z = 2.98$ mm and 4.22 mm is shown in Figs. 5(e) and 5(f), respectively. The self-focused and self-compressed pulse produce an electron density cavity, i.e., a bubble, behind the pulse. The bubble takes the form of a cavity almost free from plasma electrons, surrounded by a high-density sheath of the compressed electron fluids with a few micrometres thickness. The transverse radius of the bubble is initially 12 μm equal to the focal spot size, $w_0 < \lambda_p$, and then increases to $\sim \lambda_p = 14.4\,\mu$m. The longitudinal size of the bubble is initially 18 μm equal to $\sim 2/3\lambda_N$, where $\lambda_N \simeq \lambda_p(1 + a_0^2/2)^{1/4}$ is a nonlinear plasma wavelength. Finally a shape of the bubble is extremely elongated so that its length grows as long as 32 μm and its radius becomes as large as 16 μm. All the electron bunches are injected into the

first period of the plasma wake, as shown in Figs. 5(d) and 5(f).

No electron bunch is injected before the laser pulse reaches to $z = 1.7\,\mathrm{mm}$. The first bunch of electrons are self-injected over the distance ranging from $z = 1.74\,\mathrm{mm}$ to $z = 3\,\mathrm{mm}$ at the rear of the bubble until the charge of electrons amounts to $\sim 0.2\,\mathrm{nC}$. Afterward the second bunch is injected over the distance ranging from $z = 3.5\,\mathrm{mm}$ to $z = 4.5\,\mathrm{mm}$ until the total charge of electrons amounts to $\sim 0.53\,\mathrm{nC}$. The second bunch forms a quasi-monoenergetic peak at the central energy of 219 MeV with the energy spread of ± 41 MeV ($(\Delta E/E = 37\%$ FWHM). This energy spectrum of the 3D-PIC simulation shows basically good agreement with the experimental result. The injection of the second bunch may be related to a two-pump pulse split as seen in Fig. 5(b). Since the acceleration is limited by the pump depletion at $z = 4.4\,\mathrm{mm}$ before reaching the dephasing length at $z = 6.4\,\mathrm{mm}$, the energy spread has not been compressed due to the phase-space rotation, as shown in Fig. 5(f). It is found that the second monoenergetic peak is accelerated in the average accelerating gradient of $\sim 1.5\,\mathrm{GeV/cm}$, which is approximately equal to an estimate of the average accelerating gradient of $(\pi m_e c^2/\lambda_p)a_0(1 - L_{\mathrm{tr}}/L_{pd}) \approx 1.5\,\mathrm{GeV/cm}$ for the trapping position $L_{\mathrm{tr}}/L_{pd} \approx 0.7$, assuming a linear decrease in the wakefield due to the pump depletion.

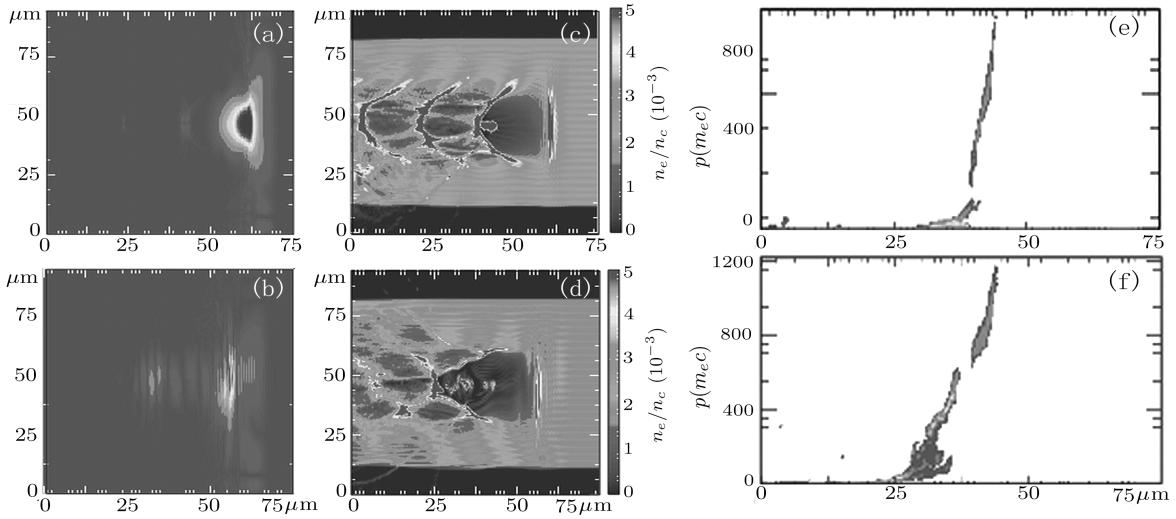

Fig. 5. Three-dimensional particle-in-cell (PIC) simulation results. The evolution of the laser electric field at the propagation distance of (a) $z = 2.48$ and (b) 4.37 mm, the evolution of the electron density at (c) $z = 2.98$ and (d) 4.22 mm, and the phase space plots of the accelerated electrons at (e) $z = 2.98\,\mathrm{mm}$ and (f) 4.22 mm are shown, respectively. The laser pulse travels from left to right.

In conclusion, quasi-monoenergetic beam acceleration of the order of multi-hundred MeV has been first investigated in the highly relativistic regime of $a_0 > 4$. In this regime, multiple self-injection of electron bunches often takes place, turning out to be the production of multi-beams and its broad energy spectra. The acceleration distance is strictly limited by the pump depletion. These effects are directly observed with Thomson scattering and the transverse emission that is produced by violent acceleration of electrons self-injected into the bubble. The 3D-PIC simulation confirmed multiple self-injection of electron bunches into the bubble, where the quasi-monoenergetic beams are accelerated up to the multi-hundred MeV energies. For practical applications such as the injector for x-ray free electron lasers that need GeV-range high quality beams, it will be necessary to control the injection[20] and the acceleration distance, suppressing effects of multiple self-injection and pump depletion in the highly relativistic regime.

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