Elongation of plasma channel for electron acceleration

Liming Chen[1], Kazuhisa Nakajima[1,2,3,4], Wei Hong (洪 伟)[5], Jianfei Hua (华剑飞)[6], Takashi Kameshima[2], Hideyuki Kotaki[1], K. Sugiyama[3], Xianlun Wen (温贤伦)[5], Yuchi Wu (吴玉迟)[5], Chuanming Tang (唐传铭)[5], Yuqiu Gu (古渝秋)[5], Hansheng Peng (彭汉生)[5], Shinichi Kurokawa[2,4], James Koga[1], Sergey V. Bulanov[1], and Toshiki Tajima[1]

[1] *Advanced Photon Research Center, Japan Atomic Energy Agency, Kyoto 619-0215, Japan*

[2] *Department of Accelerator Science, The Graduate University for Advanced Studies, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*

[3] *Department of Advanced Sciences, The Graduate University for Advanced Studies, Shonan Village, Hayama, Kanagawa 240-0193, Japan*

[4] *High Energy Accelerator Research Organization, 1-1 Oho, Ibaraki 305-0801, Japan*

[5] *Laser Fusion Research Center, China Academy of Engineering Physics, Mianyang 621900*

[6] *Accelerator Laboratory, Tsinghua University, Beijing 100080*

Experiments for the laser guiding have been carried out with the 30-fs, 100-TW Ti:sapphier laser pulse interaction with a long slab (1.2×10 (mm)) and discharged capillary of underdense plasma. Formation of an extremely long plasma channel with its length ($\sim$ 10 mm) 10 times above the Rayleigh length is observed when the laser pulse power is much higher than the critical power for relativistic self-focusing. The long self-guiding channel formation is accompanied by the quasi-monoenergetic electron acceleration with a low transverse emittance ($< 0.8\pi$ mm·mrad) and high electric current (up to $\sim$ 10 nC/shot). In order to continuously elongate the plasma channel, a 4-cm-scale discharged capillary was used. We successfully demonstrated the laser-plasma acceleration of high-quality electron beams up to near GeV. Our results exactly verify the prediction of laser-wakefield acceleration through a centimeter-scale plasma channel in the "blowout bubble" regime, where a micro-scale plasma cavity produced through the ultra-relativistic laser-plasma interactions plays an essential role in the self-injection and acceleration of electrons.

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Propagation of ultra-high intensity laser beams in plasmas has recently received much attention in connection with their potential applications for the development of X-ray lasers[1], plasma-based accelerators[2−4], and fast ignition[5]. For all of these applications, it is necessary for the high-intensity laser beam to propagate controllably over a long distance with high directionality. If the laser peak power is high enough, a laser beam can overcome the diffraction limit and self-focusing in the plasma due to nonlinear self-interaction[6,7]. The balance between the self-focusing and diffraction can provide a condition for the long-distance propagation of the beam[7]. However, the self-guiding of a single laser pulse in plasma is known to be unstable and for ultrashort (< 100 fs) pulses used for quasi-monoenergetic electron acceleration[4] the propagation length is typically limited to the diffraction distance.

In this letter, we present the experimental investigation of relativistically self-guided high-power ultra-short pulse laser evolution over a very long distance in underdense plasma, accompanied by ultrarelativistic electron generation. In order to continually elongate the channel length, we introduced a discharged capillary. GeV electron bunch is also observed by using a 4-cm-scale plasma channel.

The experiment was carried out in the Laser Fusion Research Center with the SILEX-I laser[8], which is a 100-TW Ti:sapphire laser working at a central wavelength of 800 nm with a laser contrast of 10^7. The pulse with a duration $\tau_0 = 30$ fs was focused with a $f/13$ off-axis parabola onto a focal spot size w_0=16 μm. In the focal region the peak laser intensity is $I = 6 \times 10^{18}$ W/cm^2, about 50% energy concentration in the focal spot. A supersonic pulsed slab He gas jet is produced by a slit nozzle, which is 1.2 mm wide and 10 mm long with a rectangular exit. After the nozzle, a beam charge transformer is introduced to measure the electric charge of the accelerated electrons. A DRZ phosphor screen is used to detect the transverse spatial profile of the electron beam. A bandpass filter, with a 10-nm bandwidth centered at 800 nm, is placed in front of a CCD which is orientated perpendicular to the laser polarization and laser axial direction in order to measure the Thomson scattering of the laser beam. Sometimes, a 4-cm long capillary discharge plasma channel[9] with an axially symmetric electron density profile was used to substitute the gas nozzle to guide the ultra-intense laser pulse that created the wakefield inside the channel. The capillary is made of an acrylic plastic tube with the central hole diameter of 0.5 mm. In our technique for the plasma production, often referred to as the ablative wall capillary, the plasma is initially produced through a breakdown on the inner surface of the capillary, triggered with a Nd:YAG laser pulse of the 40-mJ energy at the wavelength of 1064 nm. An electrical discharge following the laser triggered breakdown heats the capillary plasma that in turn further ablates the capillary walls to increase the plasma density, controlled by the high voltage applied between two electrodes through the capacitor. To form the appropriate density channel in the capillary, the discharge process was well controlled by the applied high voltage of the discharge circuits and injection timing of the laser pulse.

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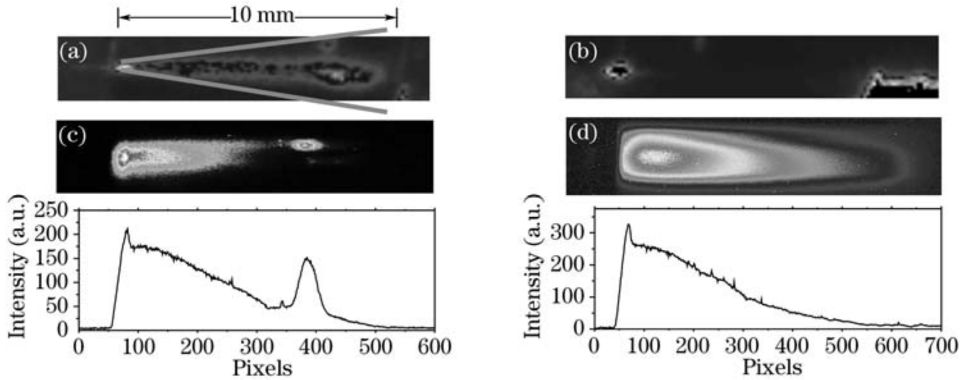

Fig. 1. Top-view Thomson scattering measurement (laser incident from left). (a) Laser energy $E_{\rm L} = 2.5$ J, gas pressure $P = 2$ MPa (long channel formed); (b) $E_{\rm L} = 1.9$ J, $P = 1.5$ MPa (without channel), and the electron spectrum is obtained (c) with long channel or (d) without channel.

Figure 1 represents the Thomson scattering images which are taken for different values of the plasma density when the laser pulse power is about 100 TW. Figure 1(a) shows that for high gas pressure (>2.0 MPa) an extremely long plasma channel with a length about 10 mm is formed. To our knowledge, this is the longest self-guided plasma channel observed till now stimulated by a single relativistic laser pulse propagating in underdense plasmas. The laser diffraction cone is drawn to highlight the formation of long plasma channel whose length is ten times longer than the Rayleigh length $Z_{\rm R} = \pi w_0^2/\lambda$, where w_0 is the laser spot size and λ its wavelength. For relatively low pulse energy and plasma density, as shown in Fig. 1(b), only a short and wide scattering region is seen with a length comparable to $Z_{\rm R}$, giving evidence that a major part of the laser photons is scattered out of that region.

The change of the initial gas density and laser pulse energy has an expected effect on the self-focusing. The critical power for Gaussian beam self-focusing[10] is $P_{\rm cr}$=16.2($n_{\rm cr}/n_{\rm e}$) (GW), where $n_{\rm e}$ is the initial plasma density and $n_{\rm cr}$=$m_{\rm e}w^2/4\pi e^2$ is the critical density. When the backing pressure is above 2.0 MPa, the average plasma density exceeds 5×10^{18} cm^{-3}. The 100-TW laser power is well above the self-focusing threshold. However, for short laser pulses with a pulse length much shorter than the wake-wave wavelength, the self-focusing does not develop because the summarized plasma collective response is not strong enough to substantially modify the refractive index. In Ref. [11] it is shown that when the laser pulse is too short, self-focusing does not occur, even for powers greater than $P_{\rm cr}$. A roughly estimated threshold for the laser pulse length needed to self-focusing can be written as $l_{\rm las} \geq \lambda_{\rm wf}$, where $\lambda_{\rm wf} \approx 2\pi c/w_{\rm pe}$ is the wake wave wavelength. For the average plasma density 5×10^{18} cm^{-3}, the laser pulse length, $l_{\rm las}$=12.5 μm, is of the order of the Langmuir-wave wavelength ($\lambda_{\rm wf} \approx$ 13.5 μm), i.e. the laser pulse undergoes self-focusing over the length $\approx Z_{\rm R}(P_{\rm cr}/P)^{1/2} \approx 240$ μm. Our experiment demonstrates that the laser pulse is subject to self-focusing when the condition $l_{\rm las} \geq \lambda_{\rm wf}$ is fulfilled. On the other hand, if $l_{\rm las} \ll \lambda_{\rm wf}$, although the laser pulse power is well above the critical power for self-focusing when the backing gas pressure is reduced to 1.5 MPa, the averaged plasma density quickly decreases to 2×10^{18} cm^{-3} and results in $l_{\rm las}/\lambda_{\rm wf}$=0.6. Under this condition laser pulse self-focusing becomes much more difficult due to defocusing caused by the electron-density maximum at the front part of the wake balancing the relativistic focusing.

Accelerated electron charge, emittance and energy distribution have also been studied experimentally in the case of the long plasma channel formation. The measured electric charge of the accelerated electrons ($E > 1$ MeV) is found to be 10 nC per shot. This electron bunch is tightly collimated with an emittance $\approx 0.8\pi$ mm·mrad. In this case, we see quasi-monoenergetic electron bunch generation at 80 MeV with a defined energy spread of 5 MeV in full width at half maximum (FWHM) (Fig. 1(c)). However, for the shorter plasma channel formation, the maximum accelerated electron charge is dramatically reduced to 0.5 nC, in conjunction with generation of a less collimated beam with emittance $\approx 4\pi$ mm·mrad. A typical Maxwellian energy structure is obtained with energy dispersion $\sim$100% (Fig. 1(d)).

In the case of the ablative capillary, significant signals of accelerated electrons were observed for a 100-TW drive pulse. The guided image at 100 TW clearly showed a well-collimated intense spot of 21$-\mu$m FWHM (Fig. 2(a)) giving an intensity of 2.0×10^{19} W/cm^2 on the center of the capillary hole, while the unguided image showed a scattered profile over a hole area with non-collimated spot (Fig. 2(b)). The generation of a nonlinear plasma wave inside the capillary discharge plasma channel was well confirmed by measurement of photon acceleration or deceleration that results from the time-dependent refractive index. In this measurement, the optical spectrum of the transmitted light showed a clear asymmetric shape with respect to the central wavelength. Thus the drive pulse duration was a factor of two shorter than the linear plasma period, that is, in the blowout bubble regime. Therefore trapping of background plasma electrons occurs through the self-injection into the blowout bubble. The accelerated electron beam image was observed on a DRZ phosphor screen and an X-ray film placed in the exit of a magnetic spectrometer, as seen in Figs. 2(c) and (d). Extremely collimated beams with 0.5 mrad divergence were observed at the energy of

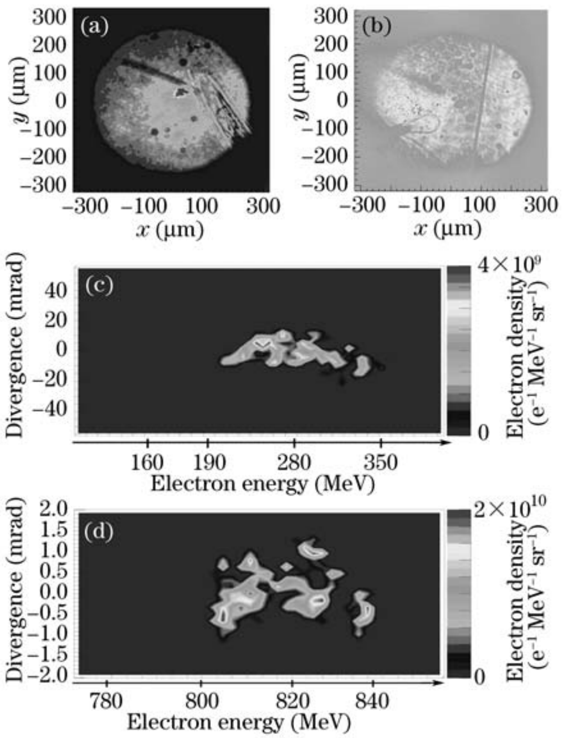

Fig. 2. Output spot images for (a) guided and (b) unguided laser. The profile of the laser spot in the exit of the capillary was viewed with an f/10 lens that imaged the laser spot onto a CCD camera. Energy spectrum and the divergence of electron beams through the capillary are recorded on (c) the DRZ phosphor screen and (d) the X-ray film.

0.83 GeV with the energy spread of ±0.7%, comparable to the spectrometer resolution. The second monoenergetic spectrum was observed at the central energy of 0.26 GeV with the ±10% energy spread and 18 mrad divergence. Noticeable features of the matched channel-guided acceleration are to produce a purely monoenergetic beam free from low-energy background electrons ('dark current') as well as very small emittance and spread. These features have not been obtained from monoenergetic electron acceleration experiments using a gas jet plasma.

These experimental results exactly verified the prediction of the three-dimensional particle-in-cell (PIC) simulations on the laser-wakefield acceleration of self-injected electrons in a centimeter-scale plasma channel, performed by Tsung *et al.*[12] using OSIRIS. The parameters of their simulations are chosen to be essentially the same as those of our experiment for the normalized vector potential $a \equiv e\vec{A}/(mc^2) = 3$ ($\vec{A}$ is the vector potential) and the plasma density at the channel axis $n_e = 3 \times 10^{18}$ cm^{-3}. The simulations predict that the first bunch of self-injected electrons from the channel wall leads to a monoenergetic bunch of the central energy of 0.26 GeV with the ±10% energy spread after dephasing in the wakefield and the second bunch of electrons is accelerated up to the maximum energy of 0.84 GeV at the distance of 1 cm where the laser pulse is significantly depleted of its energy and the acceleration process saturates. The simulation suggests that the first bunch with the lower monoenergetic spectrum is transported, remaining confined within the plasma channel, whereas the second bunch spreads out transversely due to the electric field of the modulated laser pulse, leaving the highest-energy electrons confined within the channel. As a result, after traveling the plasma channel, the highest-energy electrons belonging to the second bunch and the monoenergetically first bunch are experimentally observable in the exit of the 4-cm plasma channel.

In summary, the first experiments aimed at studying laser self-guiding in a long slab underdense plasma have been performed with 30-fs, 100-TW laser pulses. We observed a 10-mm long plasma channel formation. In the case of laser pulse guiding inside the long channel, a quasi-monoenergetic electron bunch is generated with very low emmitance and high electric charge. In the case of the capillary, we demonstrated near GeV-energy electron-beam acceleration with high-quality features, such as the ±0.7% energy spread and 0.5-mrad divergence. The results open the way toward the tabletop GeV-range laser-plasma accelerators as well as a deep understanding of their acceleration mechanism in the ultra-relativistic regime.

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