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Interaction of terawatt laser with plasma

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Abstract

Experimental investigations on interactions of a terawatt laser (0.5–2.5 TW) with an underdense plasma are reported. Formation of self-channeling longer than the vacuum Rayleigh length is observed when ultrashort (100 fs in FWHM) high power (~ 2 TW) laser pulses are focused into a gas (He, Ar, N_2) filled chamber. In addition to the formation of self-channeling along the laser axis, a bright radiation in the transverse direction of the channel was observed for the highly excited dense gases. This sideway radiation was observed for all three gases and especially for N_2, sideway jet-like radiation (we call it electron sideway-jet) was monitored. The energy of the emitted electrons were estimated to be ~ 10 keV from the range of electron trajectories in N_2. © 1997 Elsevier Science B.V.

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1. Introduction

Self-focusing and self-channeling of intense laser pulses through a plasma have attracted a great deal of interest for laser-plasma-based accelerators [1–3] and laser-pumped X-ray lasers [4]. In particular laser wakefield accelerator (LWFA), one of laser-plasma-based particle accelerators, recently made great progress in generation of ultrahigh accelerating field [5,6]. However their energy gains are still below 100 MeV, because their acceleration length is limited around the vacuum Rayleigh length. This effect deducts the advantage of ultrahigh gradient acceleration from laser-plasma accelerators. Therefore it is essential for LWFA to cause a long distance interaction of an intense ultrashort laser pulse with an underdense plasma in order to jump the energy gain from tens of MeV to the order of GeV.

If the refractive index of a plasma along the optical axis is sufficiently high, a laser pulse may be guided without suffering from the diffraction. There are two mechanisms to cause refractive guiding of intense laser pulses. For low focused laser intensities below relativistic regime, a preformed plasma channel with density minima on axis guides a laser pulse in a linear propagation regime similar to that in solid optical fibers. A plasma waveguide with radially increasing density may be formed due to a shock wave created by a first pulse to guide a second pulse after some delay [7]. In relativistic regimes self-focusing and self-channeling in a homogeneous plasma have been predicted to occur above the critical power, given by $P_c = 17(\omega^2/\omega_p^2)$ [GW] where ω is the laser frequency and ω_p is the plasma frequency. Relativistic self-focusing arises from increase of electron mass in a plasma due to relativistic effects because the refractive index of the plasma is peaked on the axis where the intensity of the laser has a maximum. For the ultrashort pulses shorter than the plasma wavelength, however, it is believed that relativistic self-channeling is substantially reduced [8]. In case a pulse length and width are comparable with the plasma wavelength, a strong wakefield excited by a ponderomotive force may cause channel guiding of ultrashort laser pulses. The 2D simulation shows the pulse is trapped in a pocket of the electron density depletion travelling with the laser pulse. As increasing the pulse length to be longer than the plasma wavelength, wakefields excited stimulated Raman scattering instability affect focusing properties of the pulse

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to lead to its self-modulation [9]. These effects are the third mechanism to raise the self-channeling of the laser pulse induced by wakefields. This mechanism implies that the relativistic self-focusing can occur at a lower laser power than the critical power.

2. Laser-plasma experiment

2.1. T^3 laser system

We have constructed the table-top terawatt (T^3) laser system on a 2×4 m^2 table based on the chirped-pulse amplification (CPA) technique at 790 nm. The oscillator is a mode-locked Ti:sapphire laser pumped by a cw-argon-ion laser at a power of 6 W. It produces pulses of 70 fs duration at a repetition rate of 80 MHz to deliver an output power of 0.75 W at 790 nm. The seed pulse from the oscillator is stretched to 320 ps in a four-pass grating arrangement with a reflective telescope. A stretched pulse is amplified to ~ 5 mJ in the Ti:sapphire regenerative amplifier (RGA) pumped at 10 Hz by 35 mJ, 6 ns pulses of a Q-switched Nd:YAG laser at 532 nm.

The output from the regenerative amplifier is further amplified to > 400 mJ through a multipass pre-amplifier and a multipass main amplifier. Both faces of a Ti:sapphire crystal are pumped with two frequency-doubled pulses of 100 mJ for a pre-amplifier and 1.3 J for a main amplifier from a Q-switched Nd:YAG laser which produces a total energy of 1.6 J at 532 nm. The amplified pulse is compressed in a two-pass grating configuration to 100 fs with an energy of > 200 mJ, corresponding to a peak power of 2 TW. Since we have succeeded in producing the maximum output energy of 600 mJ at the main amplifier, we can generate the maximum peak power of 3 TW at 10 Hz with the transmission efficiency of 50% in the compressor.

2.2. Plasma production

A plasma is produced through tunnelling ionization when an intense laser pulse is focused into an experimental chamber which is filled with a gas such as helium (He), argon (Ar) and nitrogen (N_2) at pressures of 10^{-3}-760 Torr. For example, the threshold intensities of tunnelling ionization are 2×10^{15} W/cm^2 for He$^+$ and 9×10^{15} W/cm^2 for He^{2+}. In vacuum the laser pulse focuses to a peak intensity of 1.5×10^{18} W/cm^2 for a peak power of 2.4 TW using a $f/10$ off-axis parabolic mirror with a focal length of 480 mm.

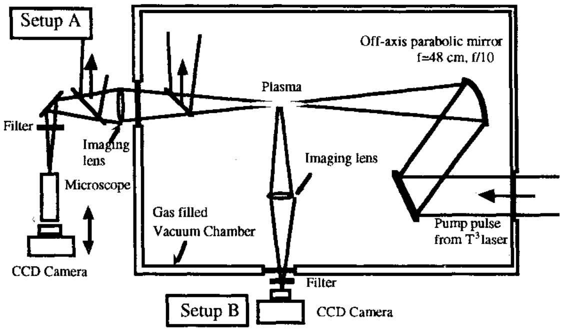

Fig. 1. Setup for the laser-plasma experiments. Setup A is used for the spot size measurement of the laser, while setup B is for the measurement of fluorescence from a plasma.

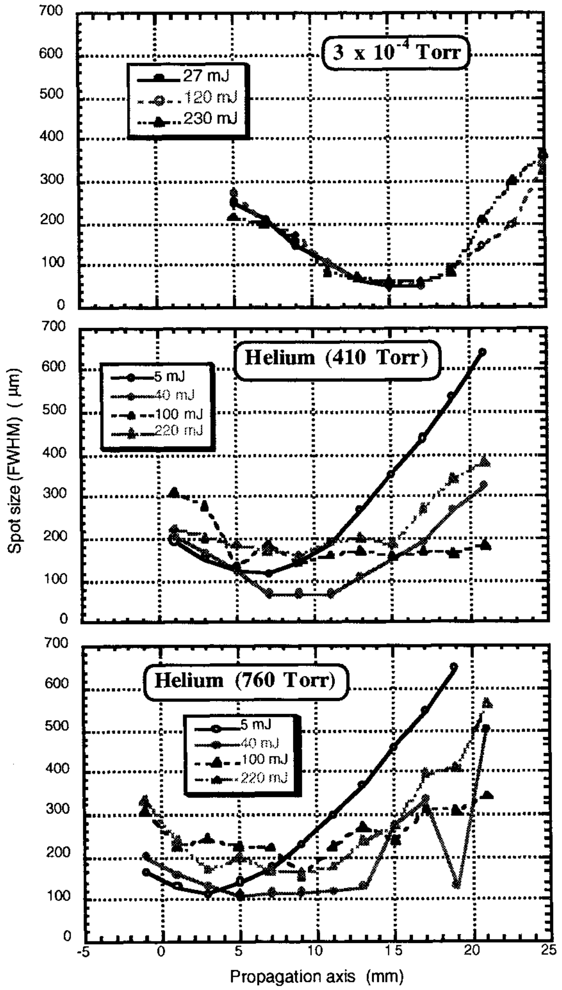

Fig. 2. Measured spot size of the laser along the propagation axis. (a) vacuum (3×10^{-4} Torr), (b) He 110 Torr, (c) He 410 Torr.

2.3. Laser propagation experiment

We measured spot sizes of a laser pulse along the propagation axis. Here, the spot size is defined as an FWHM (full width at half maximum) length of the cross-section of the laser profile. The diagnostic system is shown in Fig. 1. The forward scattered laser light was imaged onto a CCD camera coupled to a microscope objective through a 10 nm FWHM interferential filter centered around the laser wavelength. The exposure time of the

CCD camera was 100 ms synchronized with the 10 Hz laser trigger.

The measured spot sizes along the propagation axis in He are shown in Fig. 2. In vacuum the spot size along the axis was in good agreement with the theoretical beam envelope for the Gaussian beam propagation without regard to the laser power. When the gas pressure increases toward more than 100 Torr, the spot size decreases down to the smaller size than the expected Gaussian propagation over the range of a few cm as the laser power increases toward more than 1 TW. The theoretical threshold for relativistic self-focusing is 1 TW (100 mJ) for 410 Torr helium, we can see the self-focusing occurs at 40 mJ in Fig. 2.

2.4. Plasma fluorescence measurement

Plasma fluorescence was taken by a CCD camera through a blue-pass filter. Fig. 3 shows the images of 50 Torr N_2 plasma fluorescence emitted in the process of recombination. In the figure the laser beam came from the right side. Relatively, at a low pressure (< 1 Torr), we can observe long *thin* plasma fluorescence. As a pressure and a laser power increase, the fluorescence become *thick*. In particular, bright radiations in the transverse direction can be seen when a pressure is 50 Torr and a laser power was more than 1 TW. These radiation can be observed for all three gases (He, Ar and N_2) and especially for N_2. Since a shape of this bright radiation was deformed with a magnetic field, it was inferred that high energy plasma electrons were accelerated by wakefields left trajectories due to gas ionization. Therefore we call this bright radiation sideway electron jet. For the lower incident power, these are ejected perpendicularly outward. A length of the jet becomes shorter as the gas pressure increased since the range of electrons is inversely proportional to the gas pressure.

The energy of emitted electrons can be calculated from the range of electron due to ionization energy loss in a gas. We employ the empirical formula for range of electron [10]. For a 50 Torr N_2, the energy is estimated to be ~ 10 KeV (Fig. 4).

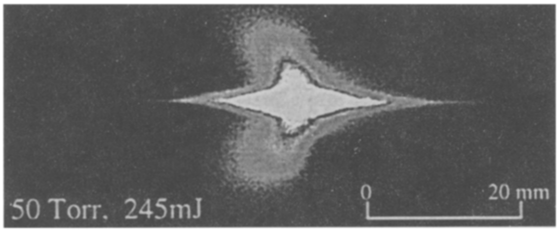

Fig. 3. Plasma fluorescence image taken through a blue-pass filter. The laser beam is going right to left.

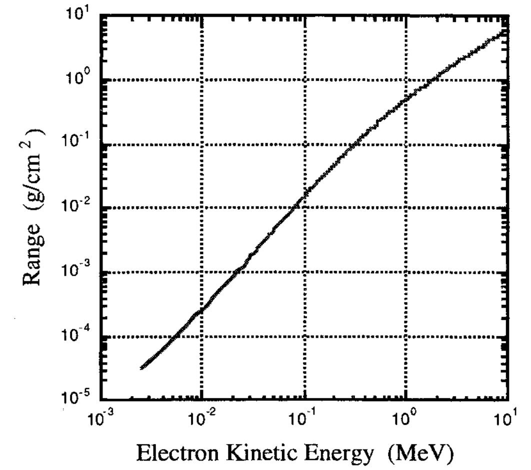

Fig. 4. Range of electron in N_2 calculated with an empirical formula.

3. Conclusion

We have first demonstrated that the self-channeling of ultrashort multi-terawatt laser pulses occur over the order of a few cm in an underdense plasma even if the laser power is below the theoretical threshold of relativistic self-focusing. We have observed that side-way electron jets are formed when the self-focusing occurs. It is inferred that electron jets are induced due to wakefields generated by ultrashort laser pulses.

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