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Ultrashort electron pulses as a four-dimensional diagnosis of plasma dynamics

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We report an ultrafast electron imaging system for real-time examination of ultrafast plasma dynamics in four dimensions. It consists of a femtosecond pulsed electron gun and a two-dimensional single electron detector. The device has an unprecedented capability of acquiring a high-quality shadowgraph image with a single ultrashort electron pulse, thus permitting the measurement of irreversible processes using a single-shot scheme. In a prototype experiment of laser-induced plasma of a metal target under moderate pump intensity, we demonstrated its unique capability of acquiring high-quality shadowgraph images on a micron scale with a few-picosecond time resolution. © 2010 American Institute of Physics. [doi:10.1063/1.3491994]

I. INTRODUCTION

Recently ultrafast real-time diagnosis1–10 of laser-induced plasmas has received great attention due to its unique capability to gain fundamental understanding of the ultrafast dynamics of laser-matter interaction. The in-depth knowledge of these dynamics would lead to optimizing and eventually controlling a wide range of the ultrafast laser-plasma based applications, including laser fusion,11 generation of short-pulsed sources of x-rays,12 electrons, and protons.13 Previously, most time-resolved diagnoses were based on all-optical pump-probe techniques, such as time-resolved optical shadowgraphy2,14 and Faraday rotation effect.15 In general these optical probes are not very sensitive to the electric field and usually only applicable to plasmas with an electron density well below the critical density set by the probe laser wavelength. In contrast, charged particles are inherently sensitive to electric field and charge type. In earlier works, Borghesi et al.4 and Okano et al.5 utilized pulsed proton and electron beams generated by laser-film interaction as probes to investigate the laser plasmas and realized time-resolved investigation of the transient electric field. However the large energy dispersion of the particle beams seriously deteriorates the spatio-temporal resolution.5 Later, Li et al.7 improved the spatial resolution by using monoenergetic proton pulses generated as laser fusion products. However, the time resolutions of all these experiments were limited by the duration of charged particle pulse, to about 60 ps for the best.16

In this paper, we report a four-dimensional (4D) electron diagnostic technique for real-time observation of ultrafast laser-induced plasmas, using 60 keV ultrashort electron pulses generated by a dc electron gun and a two-dimensional single electron detector. By means of this diagnosis, we are able to take snapshots of transient plasma fields on 10 μm length scale and with a picosecond-level time resolution. In particular, for a prototypical experiment of ultrafast laser-induced plasma on a metal target, we demonstrate a unique capability of acquiring such a high-quality image using only one single subpicosecond electron pulse.

II. EXPERIMENTAL SETUP

A. General setup

A sketch of time-resolved electron shadowgraphy is shown in Fig. 1. A 70 fs laser pulse with a central wavelength of 800 nm from an amplified Ti:sapphire laser system running at 10–1000 Hz repetition rate is split into two pulses. The first pulse is guided through an optical delay line and focused on a target to induce transient dynamics of ultrafast laser plasmas. The second beam is first frequency-tripled to a 266 nm ultraviolet (uv) laser beam, and then the uv beam is weakly focused onto a photocathode to generate an ultrashort electron pulse through photoemission. The photoelectron pulse is accelerated to 60 keV and sent through the region of ultrafast laser-plasma generation, producing a shadowgraph on a two-dimensional electron detector. Since the transient electromagnetic field around the plasma would deflect the probe electrons and change the electron beam intensity profile, this shadowgraph taken with an ultrashort electron pulse records a snapshot of the transient field at a particular time point. By taking a series of electron shadow images at different delay times with respect to the pump laser pulses set by the optical delay line, detailed information of the field evolution can be extracted. In a single-shot experiment, the femtosecond laser system is set running at 10 Hz and a mechanical shutter, located in the main laser beam path, is used to allow only one pulse exposure for each image. The open-
measurements. The electron pulse is reshaped by a 100 ns 103505-2 Zhu et al.

sensitive two-dimensional detector system is constructed. It consists of a linear chain of phosphor screen, image intensifier (II), and electron multiplying charge coupled device (EMCCD), as shown in Fig. 3. High energy probe electrons first hit the fluorescent screen inside the ultrahigh vacuum chamber, forming an optical image replica of the original electron image (or a diffraction pattern). The optical image is then transferred ex situ through a fiber-optic window to an image intensifier that is tightly coupled to the fiber window by a thin layer of optical grease. The intensified images are recorded by a lens-coupled 14-bit EMCCD camera, digitized, and displayed immediately in a desktop computer. The entire detector system can intensify the signal by several orders of magnitude and provides single-electron detection.

The single electron gain of a similar electron detector with an interlined CCD camera was determined in a pulse height counting experiment and its detective quantum efficiency (DQE) of 75% was calibrated by a homemade Faraday cup. The DQE of the current detector with a EMCCD camera should be better than 75%. The overall spatial resolution of the detector system is mostly determined by II and is estimated to be better than 30 μm.

Taking the advantages of the single-electron sensitivity of II and the EMCCD based detector system, high-quality images can be acquired from a single electron pulse containing ~1×10^4 electrons at each delay time point. As shown in the Fig. 4, the position of one single electron is distinguishable. This single-shot imaging capability is a significant step forward as compared with previous experiments. In addition to the multiple-shot mode that have been used in the previous studies to maintain good signal-to-noise ratio for each image, it can also be used in the single-shot mode when necessary. Single-shot imaging avoids the potential complications due to the signal variation related to the surface irretrievable damage caused by repeated laser ablations, particularly in the applications with fragile targets or ultrahigh intense but low-repetition-rate lasers. With a single-shot capability, the intensity of the pump pulse for each corresponding shadowgraph can also be recorded, which eliminates the possible washout of fine features encountered in a multiple-shot measurement when a pulse-to-pulse pump intensity fluctuation is large and unavoidable. This is particularly true for the study under one-shot limited conditions, such as experiments with extremely high power lasers with low-repetition rates. Therefore, a cleaner shot of electron

B. The pulsed electron gun

To make femtosecond electron pulses at a high beam energy up to 60 keV, great care and efforts have been put into the electron gun construction. The schematic of the electron gun is shown in Fig. 2. The photocathode (PC) is made of 35 nm thick silver film deposited on a sapphire disk and carefully connected to a ~60 kV high voltage power supply. The anode, consisting of a 1000 mesh Au grid on an extraction assembly, is grounded and set at 5 mm from the PC. All the electrodes are polished to mirror shine finish to prevent any possible arcing. They are assembled together by ceramic rods. To ensure the smooth operation, the electron gun is put in an ultrahigh vacuum chamber with base pressure less than 1×10^-9 torr and passivated by slowly increasing the extraction field to 12 MV/m. To generate electron pulses, the PC is back-illuminated by femtosecond uv laser pulses. The photoelectrons have very narrow initial energy spread down to 0.5 eV due to the good match of silver PC work function (4.3 eV) (Ref. 18) with the 266 nm excitation photon energy (4.65 eV/photon). After accelerated to 60 keV, the electron pulse is reshaped by a 100 μm pinhole and collimated by a magnetic lens for diffraction and imaging measurements.

C. Single-electron detector

To record the diffraction patterns and images formed by electrons with several tens keV kinetic energy, a highly sensitive two-dimensional detector system is constructed. It consists of a linear chain of phosphor screen, image intensifier

FIG. 1. (Color online) Schematic of the experimental configuration.

FIG. 2. (Color online) Femtosecond pulsed electron gun.

FIG. 3. (Color online) Single electron detector. Each component is rescaled for viewing purpose. In the actual detector, the fiber window and image intensifier are tightly coupled with a thin layer of optical grease to minimize the image blurring due to the spreading of a point source.
attributed to a transient electric field induced by the ejected electrons from the target surface.\textsuperscript{8-10,21} During and after the laser irradiation, the ejected electron charge cloud produces a transient electromagnetic field\textsuperscript{15,22} in the region around the interaction spot, as shown in Fig. 5. Under the laser intensity used in this experiment, the effect of the magnetic field on the probe electrons can be ignored.\textsuperscript{9} To estimate the electric field strength, we model the electron-deflecting process with a mean field approximation, assuming that the probe electrons are deflected by an averaged transverse field $\langle E_\perp \rangle$ along an effective length $l_e$ as the characteristic range of the electric field. Under this approximation, the electron deflection angle\textsuperscript{9,16} can be estimated as

$$
\tan \alpha = \dfrac{v_\perp}{v_\parallel} = \dfrac{e\langle E_\perp \rangle l_e}{m_e v_\parallel^2},
$$

where $v_\parallel$ is the original speed of the probe electrons with 60 keV kinetic energy, $v_\perp$ is the perpendicular speed imposed by the transient electric field, $e$ and $m_e$ are the charge and rest mass of an electron, respectively, $l_e$ is estimated as 100 $\mu$m, twice of the focal laser diameter. Given the maximal deflection angle 5.8 mrad obtained in Fig. 4, we can get the effective maximum plasma field strength $\langle E_\perp \rangle$ on the order of $7.0 \times 10^6$ V/m. We also conduct a simulation on the deflection of a 60 keV electron beam induced by a point-charge field using the \textsc{general particle tracer} code,\textsuperscript{23} and it shows that a point charge with $8.0 \times 10^7$ electrons will generate similar electron-depleted region as those in Fig. 4. For a 4D real-time diagnosis of ultrafast plasma dynamics, the spatiotemporal resolution is a crucial criterion for its potential applications. Its time resolution is determined by the convolution of the probe pulse duration and the flight time of the probe electron across the transient fields. For the current electron gun with 12 MV/m extracted field, the duration of the probe pulse containing $1 \times 10^{10}$ electrons is estimated to be shorter than 1 ps at the target location when the beam is not focused.\textsuperscript{20} It takes 60 keV electrons and about 0.75 ps to propagate 100 $\mu$m. So, the overall time resolution ranges from 1 to 2.5 ps, depending on the dimension of the transient electric field. In the single electron detector reported in this study, the spatial resolution of II corresponds to a $30 \times 30$ $\mu$m$^2$ phosphor area. For a 45 cm camera length, the corresponding angular resolution is better than 0.07 mrad. This angular resolution would enable the detection of a field down to 8 kV/m. By using the optimal geometrical arrangement and conducting more advanced data processing, the field detection limit can be further improved to 1 kV/m.\textsuperscript{9}

![Fig. 4. (Color online) A series of electron shadow images at different delay time. A silver needle with 400 $\mu$m diameter flat top is used as the target. The pump laser (0.4 mJ/pulse) is focused on the tip of the needle. The focal spot is estimated to be 50 $\mu$m in diameter and the corresponding laser intensity is $3.0 \times 10^{14}$ W/cm$^2$.](image1)

![Fig. 5. (Color online) Sketch of the shadowgraph formation. Probe electrons are repelled and deflected by the transient electric field of the laser-induced charge cloud.](image2)
IV. CONCLUSIONS

In this paper, we present a 4D diagnosis for a real-time observation of ultrafast laser-plasma dynamics. The system combines the subpicosecond time resolution of a femtosecond pulsed electron gun with the micron spatial resolution of a state-of-art single electron detector. Using this diagnosis, we are able to record single-shot images of a transient plasma field in real-time and gain new insights into the ultrafast electron and ion dynamics during the first 200 ps of plasma formation induced on a metal target by an ultrashort laser pulse at moderate intensity. These results have demonstrated the potential of ultrashort electron pulses as a picosecond time-resolved diagnosis for laser plasmas.

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23 See http://www.pulsar.nl.net for more information.