Production of ultracollimated bunches of multi-MeV electrons by 35 fs laser pulses propagating in exploding-foil plasmas

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Very collimated bunches of high energy electrons have been produced by focusing super-intense femtosecond laser pulses in submillimeter under-dense plasmas. The density of the plasma, preformed with the laser exploding-foil technique, was mapped using Nomarski interferometry. The electron beam was fully characterized: up to 10^9 electrons per shot were accelerated, most of which in a beam of aperture below 10^{-3} sterad, with energies up to 40 MeV. These measurements, which are well modeled by three-dimensional numerical simulations, validate a reliable method to generate ultrashort and ultracollimated electron bunches. © *2002 American Institute of Physics.*
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The advent of extremely powerful femtosecond lasers based on the chirped pulse amplification (CPA) technique[1] has opened new horizons in laser-matter interaction studies at ultrarelativistic intensities.[2] In this interaction regime several new phenomena have been discovered and promising applications foreseen.[3] As originally proposed by Tajima and Dawson,[4] electrons can be accelerated by the very strong longitudinal electric fields associated with plasma waves generated, for example, by the beating wave process or by a wake-field. The latter requires a suitable matching between the plasma density and the laser pulse duration. However, even when matching is not satisfied, self-modulation of the pulse can provide useful conditions for acceleration. In fact, the self-modulated laser wake-field (SMLW) has been demonstrated experimentally as a scheme suitable for the acceleration of electrons trapped from the plasma itself.[5,6] More recently, an additional mechanism has been proposed in which electrons are accelerated directly by the super-intense laser electric fields in the presence of autogenerated quasistatic magnetic fields (direct laser acceleration).[7] Experimental evidence for such a mechanism has been also reported.[8]

All these acceleration mechanisms can be investigated experimentally with powerful CPA pulses. CPA pulses, however, are accompanied by a low intensity ''pedestal'' of nanosecond duration arising from amplified spontaneous emission (ASE) in the amplifier chain. This pedestal results in a precursor target irradiation which can affect the dynamics of ultrashort laser interactions with matter.[9,10] A special feature of the experiment we present here is that we used the ASE pedestal in order to produce, via the exploding-foil technique, a preformed plasma, providing favorable conditions for electron acceleration with a 35 fs pulse. This technique, already tested and validated in previous experimental works,[11,12] provides a novel method to investigate acceleration schemes in conditions different from the ones using gas-jet targets. In fact, our technique allows interactions to be achieved with preformed plasmas of smaller size (typically a few tens of μm scale length) compared with the size of typical gas-jet plasmas ($\approx$2 mm length) used in recent acceleration experiments.[13]

The control of electron density, size, and homogeneity of the plasma is a basic issue for a reliable acceleration technique. In this experiment, we were able to measure simultaneously the basic properties of accelerated electrons (number, spectrum, and angular distribution) in a plasma of which we also measured density distribution. Consequently, not only have we achieved record values in terms of accelerating field and number of electrons per unit solid angle, but the detailed knowledge of plasma and laser parameters allowed us to perform accurate numerical modeling of our data. As we will see at the end of this paper, the results of three-dimensional (3D) simulations show striking similarities with our experimental data and strongly suggest a possible physical interpretation of our results. The laser-target configuration is basically the same already used in previous experiments.[11,12] The linearly p-polarized beam of the Ti:sapphire laser of Laboratoire d'Optique Appliquée (Salle

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Jaune), 1 J in 35 fs at 815 nm wavelength, was focussed by an off-axis F/5 parabola on 1.0 μm thick, 500 μm wide plastic foil target, at an angle of incidence of 20 degrees. The laser intensity distribution in the focal spot was Gaussian, with 50% of the total laser energy within a circle of $\approx 4\ \mu$m diameter resulting in a laser intensity on target of $I_L \approx 8 \times 10^{19}$ W/cm^2. The CPA/ASE intensity contrast ratio was of the order of 10^6. Part of the main beam (100 mJ), frequency doubled using a 2 mm thick KDP crystal and timed within a fraction of a picosecond with respect to the main beam, was used as an optical probe beam parallel to the thin foil surface. In this experiment we were able to produce for the first time interferograms in the Nomarski configuration with a femtosecond probe pulse. A detailed description of these femtosecond interferometry measurements will be given in a forthcoming paper.

Energetic electrons emitted forward were the main subject of the experimental investigation. Three distinct diagnostics were used in order to measure (a) the number of electrons, (b) their angular distribution, and (c) their energy spectrum. Further diagnostics included optical imaging and spectroscopy of the transmitted laser light and detection by scintillator detectors of the gamma-rays emitted by bremsstrahlung of the energetic electrons. Optical and gamma-ray diagnostics gave very similar results to those obtained in previous experiments[11,12] and therefore they are not presented in detail in this paper. We only mention that, as observed in those experiments, the transmission of the CPA pulse after the interaction was rather high and its spectrum basically unchanged, suggesting a basically smooth propagation of the pulse through the plasma. As previously observed in gas-jet experiments, these circumstances indicate that (i) the plasma is fully ionized and (ii) SMLW does not play a significant role in our experimental conditions.

The plasma density was measured using interferograms taken at different probing times before and after the arrival of the main pulse in the plasma. The phase-shift maps were obtained from the interferograms using a new method[14] based on Continuous Wavelet Transforms. After a generalized nonaxisymmetric[15] Abel inversion, plasma density maps were obtained. Figure 1 shows the longitudinal plasma density profile (along the laser path) as obtained from a typical interferogram taken 50 ps before the arrival of the main pulse. The laser pulse propagates from the right to the left in this figure. Although the target shadows the fringes close to the peak density region, our interferograms show a well-defined density profile, having an exponential decrease with a scale length typically of a few tens of micrometers starting from a top density that can be reasonably inferred to be approximately 4×10^{19} el/cm^3.

The number of electrons emitted forward (i.e., in the direction of the laser pulse) was measured with a calibrated coil-based charge detector having an acceptance cone of aperture $\theta_{\rm coll} \approx 7$ deg. The detector was placed beyond the target and after a 100 μm thick quartz plate (necessary for optical measurements), which substantially cuts-off electrons of energy below 0.2 MeV. The charge collected in this condition was about 0.2 nC per shot, corresponding to approximately 10^9 electrons.

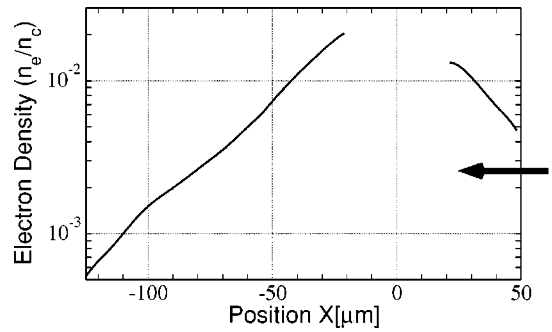

FIG. 1. Longitudinal electron density profile of the plasma as inferred from an interferogram taken 50 ps before the arrival of the 35 fs pulse. The arrow shows the direction of the laser pulse propagation. The $X=0$ position indicates the initial position of the foil target. The critical density n_e refers to $\lambda = 815$ nm.

The electron angular distribution is a crucial measurement which was performed using a detector based on radiochromic films (MD55–GAFCHROMIC$^{\rm th}$).[16,17] Electrons impinging on a radiochromic film release a fraction of their energy to the sensitive layer. This energy results in a change of the optical density of the film which can be read using a densitometer as in the case of a standard photographic film. After calibration, radiochromic films straightforwardly provide the angular distribution of impinging electrons. The detector basically consists of a stack of radiochromic films some of which were separated by aluminum plates of suitable thickness. A 10 μm Al foil was used in front of the first film to prevent direct laser irradiation of the film stack: in fact no film darkening was observed when the laser was fired without target. A 1.5 mm, Al plate was inserted between the sixth and seventh film to increase the sensitivity of the detector to higher energy electrons. The detector was placed 2.6 cm behind the target, with the center of the films aligned with the laser propagation axis.

Figure 2 shows a typical radiochromic film result after a single exposure to the electrons generated by focusing the CPA pulse at an intensity of $\approx 8 \times 10^{19}$ W/cm^2 in the plasma. The plasma was produced by ASE-induced explosion of a 1 μm thick target. These images show a small central spot aligned with the laser propagation axis. This feature is visible on all seven layers while other features surrounding this bright spot are only visible on the first layer. These results suggest that besides an intense electron flux of lower energy in a cone of $\theta_{\rm ring} \approx 18$ deg aperture, there is a bunch of very collimated, high energy electrons accelerated along the laser

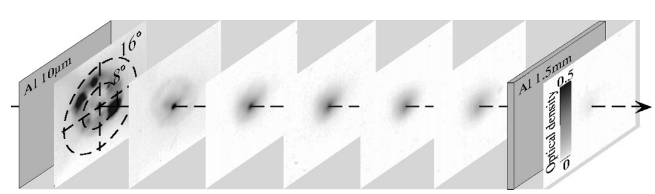

FIG. 2. Densitometer scans of the radiochromic films after exposure to the energetic electron beam produced by interaction of an ultraintense laser pulse with a preformed plasma located at 26 mm on the left. The angular scale is also shown for reference. The arrow indicates the electron beam propagation axis.

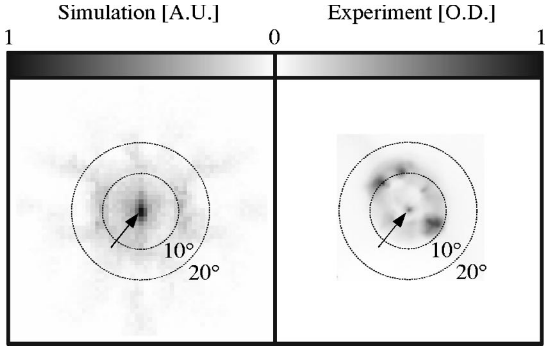

FIG. 3. 3D PIC simulation: angular distribution with respect to the laser axis of the electrons emitted forward (left), to be compared with the radiochromic film data (right). The two arrows indicate the energetic electron beam in the two cases.

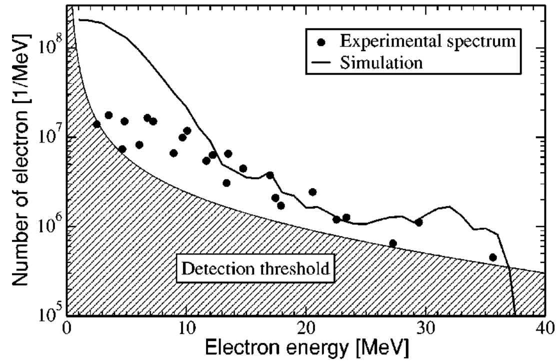

FIG. 4. Spectrum of the electrons in the collimated beam. Black dots represent the experimental data. Also shown is the detection threshold of the electron spectrometer. The solid line is the spectrum of the electrons in the collimated beam (within 3 deg around the axis in Fig. 3) as obtained from the PIC simulation.

propagation axis. This electron bunch is confined in a solid angle $<10^{-3}$ sterad. The solid angle has been evaluated from the central spot size in the first layer and the distance between that layer and the plasma. Multiple scattering of the electrons in the radiochromic films increases appreciably the spot sizes on the other layers. For the first one this effect is negligible. To our knowledge, it is one of the most collimated electron beams ever observed in laser-plasma acceleration experiments.

It is interesting to compare the experimental results with the predictions of numerical simulations carried out using a three-dimensional particle-in-cell code[18] with a plasma density profile and a laser pulse intensity distribution very close to the experimental ones. More precisely, the analytical form for the simulated laser pulse is

$$I=I_0 \cos^2[(\pi/2)\ (t/\tau)]\cos^2[(\pi/2)\ (r/r_0)],$$

where $I_0=3.4\times10^{19}$ W/cm^{-2}, $\tau=30$ fs, and $r_0=9$ μm; the simulated plasma density profile along the laser propagation axis had a plateau of 40 μm at density 4.3×10^{19} cm^{-3} and density decreases both sides with a scale length of 10 μm. The laser wavelength used in the simulation was 800 nm. A comparison of the angular distribution obtained from the simulations with the radiochromic film data, shown in Fig. 3, clearly shows that the main feature of the angular distribution observed experimentally, namely the central, collimated electron beam, is reproduced by the simulations.

The electron energy spectrum was obtained with a spectrometer based on an electro-magnet coupled with a set of four photodiodes (surface barrier detectors). By changing the current of the electromagnet, electrons from a few MeV up to 200 MeV can be analyzed with an acceptance angle of $\theta_{\rm spec}\approx0.6$ deg. The entrance axis of the spectrometer was carefully aligned on the laser propagation axis in order to analyze the spectrum of the electrons in the central bright beam. To study the contribution of the gamma rays on the spectrometer, some zero shots, without the magnetic field, were made, and the photodiodes did not generate a detectable signal. The data were processed using a Monte Carlo code (based on the CERN library GEANT 4) which also enabled us to account for the presence of the quartz plate between the plasma and the spectrometer. A typical spectrum is shown in Fig. 4 (black dots). According to this plot, the electron beam consists of a sizeable number of electrons with energies from a few MeV up to 40 MeV. Also plotted in Fig. 4 (solid line) is the calculated spectrum of the electrons obtained from the PIC (particle-in-cell) simulation relative to the electrons in the central feature of Fig. 3. There is a good agreement between the experimental spectrum of the high energy electron beam and the simulated one, mostly for the higher energy component (above 10 MeV). Also interesting is the 40 MeV energy cut given by the simulation consistently with the experimental data. This is an indication that the acceleration is limited by some experimental parameter. We believe that in our experimental conditions the limiting factor is the acceleration length, which is basically given by the plasma length, that in our case is much smaller than the dephasing length.[4]

The numerical simulation also provides the evolution of both the electron density distribution and the electromagnetic field distribution during the propagation of the femtosecond pulse through the plasma. In fact, the temporal evolution of the electron density reveals that a number of electrons are trapped in the wake of the pulse and are efficiently accelerated in a collimated beam up to 40 MeV. The formation, in the wake of the pulse, of an electron wave is clearly visible in Fig. 5 which shows the calculated electron density map (left) and the electromagnetic field map (right), respectively. We observe that the electron wavelength λ_p, as measured from these images, corresponds to the one expected in the background plasma whose density is $n_e=4.3\times10^{19}$ cm^{-3}:

$$\lambda_p=\{(3.34\times10^6)/\sqrt{n_e[\mathrm{cm}^{-3}]}\}[\mathrm{cm}]\approx5.1\times10^{-4}\ \mathrm{cm}.$$

The simulation evidences also the strongly nonlinear wakefield conditions due to the ultrarelativistic intensity in the laser spot.[6]

Later in time, simulation frames show that on the axis of the electron wave an electron beam is created, which then propagates outside the plasma while keeping its strong collimation. The PIC code also predicts that some other electrons are not trapped and are deflected at larger angles due to transverse wave breaking of the laser wake. The spectrum of these less collimated electrons given by the simulation extends up to 10 MeV. This is the only point of disagreement

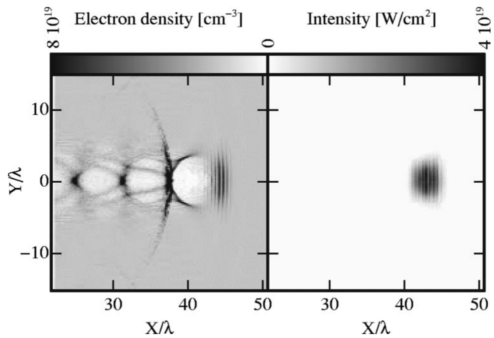

FIG. 5. 3D PIC simulation: electromagnetic field distribution of the laser pulse (right) and electron density distribution (left) at the time when the laser pulse ($\lambda = 800$ nm) is going to leave the plasma. Clearly visible is the formation, in the wake of the pulse, of an electron wave of $\lambda_p = 5.1 \times 10^{-4}$ cm.

between the simulation and the experimental data. In fact, we have observed that the electrons outside of the central spot are stopped by the first radiochromic layer (see Fig. 2). A qualitative evaluation, as well as a more precise Monte Carlo calculation state that the energy of those electrons do not exceed 0.2 MeV. Although the origin of the ''marginal'' electrons observed experimentally has to be further investigated, previous observations[11] suggest that they may also originate from instabilities growing at the boundaries of the laser focal spot, where the plasma has higher density with large gradients.

Summarizing, this method of interacting a femtosecond pulse with a submillimeter plasma preformed by the ASE pedestal, allowed us to obtain, in a reproducible way, ultracollimated bunches of electrons with energy up to 40 MeV. The experimental conditions, including the plasma density profile, were carefully monitored. The high energy electron beam we have produced was fully characterized. The experimental results show that the accelerating field in the plasma could approach 1 TV/m. It is also interesting for many applications, and possible future developments, including laser-plasma beam injectors, that bunches of a few femtoseconds in duration (according to simulation) of 10^9 electrons have been generated, by a source of about 15 μm^2. Considering that in the solid angle (≈ 7 deg aperture) of the charge detector the main contribution is given by the central electron beam (see Fig. 2), it results that a large fraction of the 10^9 electrons are collimated in a solid angle of 10^{-3} sterad. Such a level of collimation was rarely observed in laser acceleration experiments. A comparable level of collimation has been recently reported[19] for a much less intense ($\approx 10^5$ electrons) electron beam of energy up to 4 MeV, produced in conditions of relativistic self-focusing of a 29 fs laser pulse focused at an intensity of 3×10^{18} W/cm^2.

The electron burst duration of a few femtoseconds, if experimentally confirmed, is certainly of great interest for a wide class of studies and applications. It has to be said that femtosecond electron bunches have been predicted in several numerical calculations performed in variety of acceleration schemes. In particular Esarey *et al.*[20] recently showed (both analytically and numerically) the possibility of producing electron bursts of a few femtoseconds by wake-field acceleration of seed electrons in the colliding-pulse laser-injection scheme. This scheme, never implemented so far, could in principle provide quasi-monochromatic electron bursts (a few percent of energy spread is expected). In our case the energy spread is much larger (of the order of 100%), but some 10^7 electrons with an energy spread of a few percent could be extracted using magnetic deflection techniques.

Finally, we note that the exploding foil technique allows us to obtain a higher number of electrons and a more efficient acceleration by optimizing target, laser pulse, and focusing geometry.

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