workshop on

2nd GENERATION LASER AND PLASMA ACCELERATORS

Presqu'ile de Giens, France

June 24-29, 2001

MULTI-MeV ELECTRONS PRODUCED BY A FEMTOSECOND LASER PULSE PROPAGATING IN AN EXPLODING-FOIL PLASMA

D. Giulietti[1, 2], M. Galimberti[1, 2], A. Giulietti[2], L.A. Gizzi[2], R. Numico[2], P. Tomassini[2], M. Borghesi[3], V. Malka[4], S. Fritzler[4], M. Pittman[5]

(1)Dipartimento di Fisica Università di Pisa, Unità INFM, Via Buonarroti 2, 56100 Pisa Italy

(2)Intense Laser Irradiation Laboratory, IFAM, Area della Ricerca CNR, Via Moruzzi 1, 56124 Pisa, Italy

(3)Department of Pure and Applied Physics, The Queen's University, Belfast, BT7 1NN, UK

(4)Laboratoire puor l'Utilisation des Lasers Intenses, Palaiseau, Cedex, France

(5)Laboratoire d'Optique Appliquée, ENSTA, Chemin de la Hunière, F-91761, Palaiseau, Cedex, France

danilo.giulietti@df.unipi.it

Abstract. Conditions for efficient electron acceleration in the wake of a 35fs laser pulse propagating in an exploding-foil plasma have been achieved. The density of the plasma, pre-formed by the Amplified Spontaneous Emission preceding the fs pulse, was mapped via Nomarski interferometry. A very collimated bunch of energetic electrons has been detected along the laser axis. The accelerated electrons were characterised both in their angular distribution and energy spectrum. The conditions for electron acceleration were found to depend critically on the experimental parameters.

In the last years, table top laser systems based on the Chirped Pulse Amplification (CPA) technique, delivering relativistic intensity femtosecond pulses have been set-up in several laboratories worldwide, allowing a completely new laser-matter interaction physics to be investigated. At such intensities the laser electric field overcomes by several orders of magnitude the atomic one, so that matter ionisation occurs in a fraction of the impinging wave period (1). In such interaction regime several new phenomena have been discovered (2, 3). In particular the acceleration of particles in plasmas has been demonstrated in many experiments. In the seminal 1979 paper by T.Tajima and J.M. Dawson (4) two physical mechanisms for the electron acceleration in plasmas were suggested. Both mechanisms were based on the enormous longitudinal electric fields of plasma waves excited either by two lasers beating resonantly with the plasma frequency (Plasma Beat Wave Accelerator) or by the propagation of a short pulse in a suitable density plasma (Laser Wakefield Accelerator (LWA)). More recently physical mechanisms have been proposed in which the electrons are directly accelerated by the super-intense laser electric fields in the presence of auto-generated near-static magnetic fields (Direct Laser Acceleration) (5).

The LWA mechanism becomes now possible with powerful CPA pulses. CPA pulses are characterised by a low intensity pedestal due to the Amplified Spontaneous Emission (ASE) in the nanosecond time scale, which affects every laser-matter interaction experiment (6,7). In this work, as in a previous, recent one (8, 9), we used this pedestal to produce, by the exploding foil technique, a pre-formed plasma, suitable for electron acceleration with a 35-fs pulse.

The control of the plasma density, extension and homogeneity is basic for the LWA mechanism. In fact the near-resonant condition for the growth of the plasma wave in the wake of the ultra-short pulse requires $\tau \; c \approx \frac{\lambda_p}{2}$ (4), or $n \approx \frac{3 \cdot 10^{-9}}{\tau^2}$, where τ is pulse duration, λ_p the wavelength of the plasma wave and n the electron density. This simple condition, valid in the framework of the linear theory of LWA, leads, for the laser pulse duration of the present experiment, $\tau \approx 35$fs, to a plasma density $n \approx 2.5 10^{18}$ el/cm^3.

In this paper we report for the first time the detection of a very collimated bunch of energetic electrons generated by LWA in exploding-foil plasma. A detailed plasma density map of the pre-formed plasma was obtained, allowing us to control the required experimental conditions in which high amplitude relativistic plasma waves grow in the wake of a super-intense 35-fs laser pulse. Under these conditions we measured the angular distribution and energy spectrum of the accelerated electrons.

Fig.1 shows the experimental apparatus. The linearly-polarised beam of a Ti:Sapphire laser, 1J in 35fs at 815nm, was focussed by an off-axis F/5 parabola on a ϕ≈5μm FWHM Gaussian function spot, at an intensity of I≈ 10^{20}W/cm^2. The CPA/ASE intensity contrast ratio was 10^6. A second beam (100mJ) of the same Ti:Sapphire laser was frequency doubled by a 2mm thick KDP crystal, allowing an ultra-short blue pulse to be used for plasma interferometry to be achieved. For a detailed presentation of the interferometric technique refer to the forthcoming paper (10). The probe timing was set within a fraction of a ps.

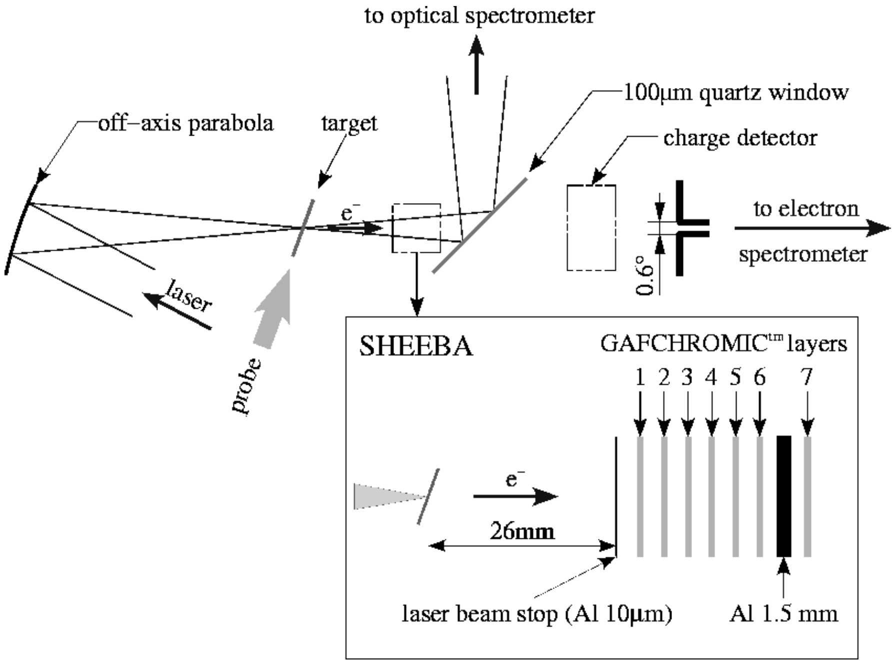
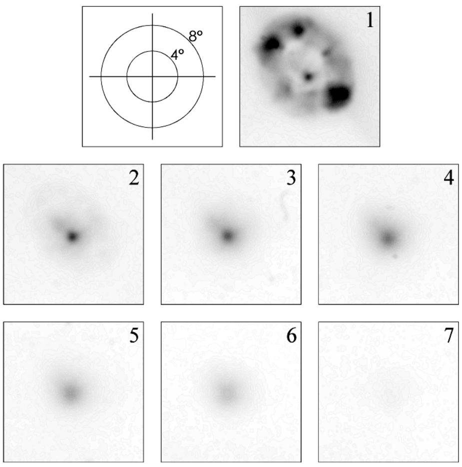


Fig1. Experimental set up. In the insert, schematic of the SHEEBA calorimeter based on a stack of GAFCHROMIC® films with the suitable insertion of metallic filters. A 10μm Aluminium foil is used in front of the first film to prevent direct laser shining on the film stack. Between the 6th and 7th film a 1.5mm Aluminium filter is inserted.

Energetic electrons, being the main subject of this experimental investigation, have been detected by a stack of GAFCHROMIC® films (11) with the suitable insertion of Aluminium filters (see Fig.1). A 10μm Aluminium foil was used in front of the first film to prevent direct laser shining on the film stack; a 1.5mm Aluminium filter was inserted, between the 6th and 7th film to discriminate a possible electron component at very high energy. The films straightforwardly provide the electron angular distribution. Fig.2 shows a set of exposed GAFCHROMIC® films obtained by focussing the CPA pulse at an intensity of ≈10^{20}W/cm^2 on 1μm formvar foil. Foils of such a thickness were expected to give, in our condition, pre-formed plasmas with peak density ranging from 10^{18}el/cm^3 to 5x10^{19}el/cm^3. Notice that only the small central feature propagates up to the 7th layer. All the rest is basically stopped by the first layer. Although a quantitative analysis of such data in terms of electron density and energy characterization is still in progress, it is clear that, beside an intense electron flux of relatively lower energy in a ring of θ_{ring}≈15deg aperture, there is a bunch of much more collimated (divergence θ_{bunch} < 1deg) and energetic electrons inside the ring, close to the laser propagation axis. In our experimental conditions, due to the temporal and radial profile of the short laser pulse, the longitudinal and radial contributions to the electron density perturbation in the wake of the pulse are comparable (12). So a possible explanation of the less energetic electrons in the ring could be the premature escape of them from acceleration region, while a smaller number can take advantage of suitable condition of longitudinal acceleration along the beam axis over a longer region. Different physical mechanisms explaining the origin of the less energetic electron component can be considered. In particular the spotty structure, apparent in the ring, seems to be correlated to the scattered laser light and emitted second harmonic observed in similar experimental conditions (8) and could be attributed to instabilities growing in marginal regions of the pre-formed plasma (13).



Fi2. Exposed GAFCHROMIC® films during the laser-plasma interaction at I≈10^{20}W/cm^2. The first film is at 26mm from the interaction region. The ring divergence is θ_{ring}≈15deg, while that of the central spot is θ_{bunch} ≈ 0.7deg. In the

films, following the 1st, the ring produced by less energetic electrons disappears. The laser focussing angle is $\theta_{foc} \approx 11$deg.

Plasma interferograms, obtained 30ps after the arrival of the CPA pulse, confirmed that the laser pulse propagated in a well under-dense plasma. The laser transmission was found to be rather high, with a spectrum of the transmitted light very similar to the laser spectrum. These observations suggest the same interaction scenario as in the previous work (8), indicating that the CPA pulse propagates through the plasma without perturbations close to the propagation axis.

The interferometric measurements show that in the interaction region the plasma density ranges from 10^{18}el/cm^3 to more than 10^{19}el/cm^3.

In order to measure the energy of the electrons accelerated in the forward direction we used a spectrometer based on an electro-magnet coupled with a set of photodiodes (Surface Barrier Detectors). Although the spectrometer allows electrons up to 200MeV to be analysed, due to the photodiode noise, our measurements were limited to 36 MeV (14). The energy spectrum of the forward emitted electrons in an angle of $\theta_{spectro} \approx 0.6$deg along the propagation axis of the laser indicates that a sizeable number of electrons up to energies of tens of MeV is produced. The detected energy distribution is strongly depressed at the lower energies due to electron absorption by the 100μm thick quartz plate used to collect the transmitted laser radiation (see Fig.1).

The maximum energy of the electrons detected by the spectrometer was $U_{exp} \approx 40$MeV. This value can be obtained by simply multiplying the maximum electric field of a plasma wave $E_{max} = \frac{mc\omega_p}{e}$ (15) by the elementary charge e and the actual acceleration length L:

$U_{max} = mc\omega_p L \approx n^{\frac{1}{2}} L \;\; eV$, getting for $n \approx 10^{19}$el/cm^3 and $L \approx 100$μm $U_{max} \approx 35$ MeV. In our experimental conditions L is definitely lower than the "dephasing length" $L_{deph} \approx \gamma_p^2 \lambda_p$, being $\gamma_p = \frac{\omega}{\omega_p}$ the Lorentz factor of the plasma wave (4), so much higher electron energies could be in principle attained if a longer acceleration length could be experimentally carried out.

By means of a charge collector, placed behind the target (and behind the quartz thin plate), the charge of the electrons, forward emitted in a cone of $\theta_{coll}\approx 7$deg aperture along the laser axis, was measured, resulting to be ≈ 0.2nC, corresponding to $\approx 10^9$ electrons. Because the electrons in the ring ($\theta_{ring}\approx 15$deg) were not collected and only the more energetic electrons could cross the thin plate, this number can be considered as representative of the electrons accelerated along the laser axis (θ_{bunch} <1deg).

In conclusion, we have demonstrated experimentally for the first time the efficient forward aceleration to ultra-relativistic energies of an extremely collimated bunch of electrons following the propagation of a 35fs laser pulse in a pre-formed plasma, simply obtained by ASE explosion of a thin foil. The experimental observations consistently suggest that LWA is the leading mechanism for such a process. The method we have used allows experimental conditions to be modified in order to increase both electron energy and electron number in the collimated bunch.

We acknowledge fruitful discussions with F. Amiranoff on the different mechanisms of particle acceleration in plasmas, the electronic and processing data assistance of A. Barbini, the effectiveness of the Laboratoire d'Optique Appliquée laser staff. This experiment has been partially supported by European Commission in the frame of Human Potential Programme, Access to Research Infrastructures.

References

(1) S.Augstet al., Phys.Rev.Lett, **63**, 2212, 1989.

(2) C.J. Joshi and P.B. Corkum, Physics Today, 36, (Jan. 1995).

(3) T. Dimitre et al., Nature, **386**, 54, 1997.

(4) T. Tajima, J.M. Dawson, Phys. Rev. Lett., **43**, 267, 1979.

(5) A. Pukhov et al., Phys. Rev. Lett. **83**, 4772, 1999.

(6) M.I.K. Santala et al.,Phys.Rev.Lett., **84**, 1459, 2000.

(7) D. Giulietti et al. Phys. Rev. Lett., **79**, 3194,1997

(8) M. Galimberti, A. Giulietti, D. Giulietti, L.A. Gizzi et al., Laser Particle Beams, **19**, 47, 2001

(9) D. Giulietti, M. Galimberti, A. Giulietti, L.A. Gizzi et al., Phys. Rev. E, **64**, 015402(R), 2001

(10) M. Borghesi, M.Galimberti, D.Giulietti, A.Giulietti, L.Gizzi, A. Rousse, O. Willi, in preparation.

(11) W.L. McLaughlin, et al., “Radiation Protection Dosimetry”, Nuclear Technology Publishing, Vol.6, Nos. 1-4, pp. 263-268, 1996; Norman V. Klassen and Len Van Der Zwan, Medical Physics, **24**, 1924-34, 1997.

(12) J.R. Marquès et al., Phys. Plasmas, **5**, 1162, 1998; F. Amiranoff et al., Phys.Rev.Lett., **81**, 995, 1998.

(13) S.V Bulanov et al., Plasma Physics Report, **22**, 600 (1995).

(14) V.Malka, Utilisation du spectromètre à électrons à 200 MeV, Note LULI-LOA, 1998.

(15) J.M. Dawson, Phys.Rev., **113**, 383,1959.