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Charged particle source produced by laser–plasma interaction in the relativistic regime

V. MALKA
Laboratoire d'Optique Appliquée—ENSTA, CNRS UMR 7639, Ecole Polytechnique,
Chemin de la Humiére, 91761 Palaiseau, France

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Abstract

Plasmas irradiated by an intense laser beam have recently been demonstrated to be sources for particles (electrons, ions, positrons). During this interaction, it has been found that these charged particles can be efficiently accelerated. An overview of these results as well as some perspectives are presented here.

Keywords: Particle source; Plasma waves; TW laser; Wave breaking

1. INTRODUCTION

A plasma is an ideal medium for particle acceleration since (1) plasmas can support very high longitudinal electric fields (several hundreds of gigavolts are meter), which are four orders of magnitude higher than presently applied in RF cavities, and (2) plasmas convert the transverse electromagnetic field of the laser into longitudinal space-charged oscillations called "plasma waves" which can trap and accelerate charged particles.

This electric field generated in a very short distance is sufficient to accelerate charged particles from the plasma itself. Therefore plasmas can potentially be a very attractive compact source of energetic particles.

We present in this article an overview of particle sources produced by the interaction of a very intense laser beam with a plasma. In the first section, we present light particle sources (electrons and positrons). The second section is devoted to heavy particle sources (protons and ions). In the last section, we discuss the potential applications of such short, bright, and energetic sources.

2. LIGHT PARTICLES SOURCE

Light particle sources (mainly electron sources) have been generated during the interaction of a subpicosecond laser, beam with an underdense plasma. In most of the experiments, the dominant mechanisms responsible for such an acceleration are the Raman forward and the self-modulated laser wake-field instabilities. In the self-modulated laser wake-field regime (Andreev *et al.*, 1992; Antonsen & Mora, 1992; Sprangle *et al.*, 1992), an intense laser pulse, longer than a few plasma wavelengths, is focused on a high-density gas jet. The laser pulse is strongly modulated by Raman-type instabilities producing large amplitude plasma waves. These waves can trap electrons and accelerate them along the plasma. Mori *et al.* (1994) discussed the acceleration of electrons to very high energies due to the Raman forward scattering instability (RFS). Experimental observations of RFS have been by Joshi *et al.* (1981) at UCLA and they have measured electrons up to 1.4 MeV.

In 1995, electrons with energies up to 44 MeV were generated at Rutherford Appleton Laboratory (RAL) (Modena *et al.*, 1995) with a 25-J, 1-ps laser beam at 1.054 μm in underdense plasmas. In this experiment, the so-called wave-breaking regime was demonstrated. It was characterized by the sudden increase in both the number and maximum energy of the electrons as well as the loss of coherence of the wave as it has been seen from the broadening of the Raman satellites measured in the forward direction. Electrons (100 MeV) with energies greater than the dephasing length have been produced (Gordon *et al.*, 1998). Numerical simulations have shown that electrons are produced by ultrashort bunches (with a pulse duration of the order of the plasma period). These bunches excite fast relativistic plasma waves providing higher electron energies. The maximum electric field achieved was estimated to be over 100 GV/m. Measurements of the Thomson scattered light on the rela-

Address correspondence and reprint requests to: V. Malka, Laboratoire d'Optique Appliqué–ENSTA, CNRS UMR 7639, Ecole Polytechnique, Chemin de la Humiére, 91761 Palaiseau, France. E-mail: victor.malka@ensta.fr

tivistic plasma waves along the laser axis propagation indicates a self guiding over the whole gas jet in the relativistic regime and a plasma wave amplitude of 40 ± 20% (Clayton *et al.*, 1998). Electrons preaccelerated in slow plasma waves driven by the Raman backscattered instability have been accelerated to higher energy (up to 30 MeV) by fast plasma waves driven by the self-modulated laser wake field (Moore *et al.*, 1997). The angular distribution of the electron beams produced by a laser–plasma accelerator has been measured at RAL by using nuclear activation techniques. Electrons are found to be emitted in a cone along the laser axis. The angular spread increases with the plasma density. The electron yield is observed to increase with the plasma density, and reaches up to 4×10^{11} fast electrons (>10 MeV; Santala *et al.*, 2000). A typical setup for this kind of experiment is presented in Figure 1.

A new and very interesting issue is the production of such electron beams with the use of table-top TW lasers with higher repetition rates (10 Hz). Electrons with energies of up to 10 MeV were first obtained by Gahn *et al.* (1999). Recently electrons with energies of up to 70 MeV have been generated in well-defined homogenous supersonic gas jets (Malka *et al.*, 2001). It was observed that the maximum electron energy increases when the electron density decreases, indicating that faster plasma waves correspond to higher electron energies. Two typical electron spectra obtained at 5×10^{19} cm^{-3} and 1.5×10^{20} cm^{-3} are presented in Figure 2.

The distribution of electrons above 4 MeV are well fitted by an exponential function, characteristic of an effective temperature for the electron beam. These effective temperatures are 8.1 MeV (2.6 MeV) for an electron density of 5×10^{19} cm^{-3} (1.5×10^{20} cm^{-3}). We can also deduce a typical value of 54 MeV (15 MeV) for the maximum electron energy. We observe an important decrease of the effective temperature and the maximum electron energy when the electron density is increased.

We can estimate the maximum electron energy to the one due to acceleration in relativistic plasma waves with a constant amplitude. This energy is equal to the product of

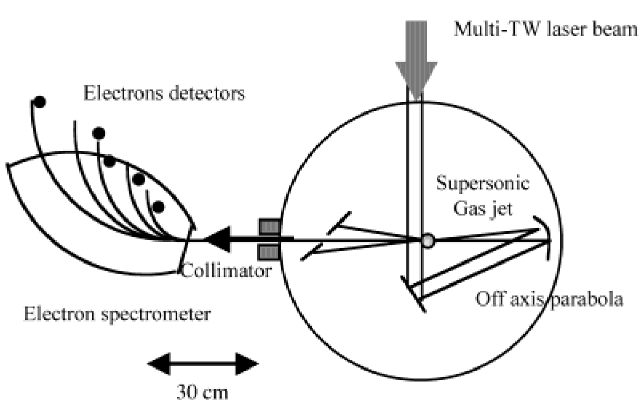

Fig. 1. Typical setup for laser-produced electron beam.

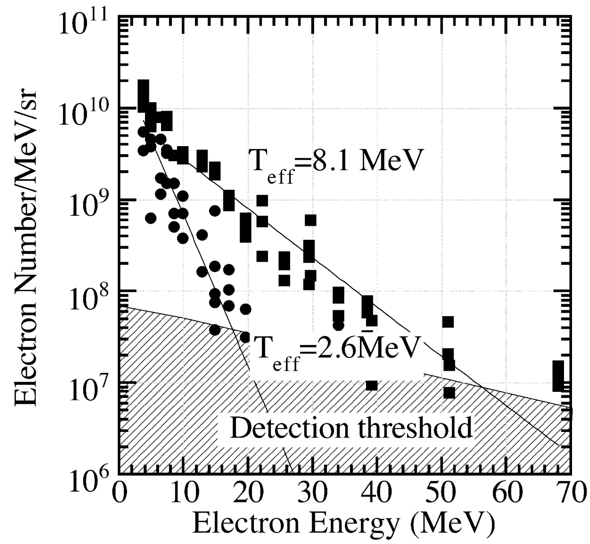

Fig. 2. Electron spectra measured at 1.5×10^{20} cm^{-3} (circles) and 5×10^{19} cm^{-3} (squares). Exponential fit with the deduced effective electron temperature.

the electrostatic field by an optimum length. This length is the dephasing length and corresponds to exactly half a wavelength in the wave frame (Mora & Amiranoff, 1989): $W_{max} \approx 4\gamma_p^2(E_z/E_0)mc^2$, where γ_p is the plasma wave Lorentz factor (which is equal to the square root of the ratio between the critical density and the electron density n_c/n_e) and E_z/E_0 is the electrostatic field normalized to $E_0 = cm\omega_p/e$. For electron densities greater than 1.5×10^{19} cm^{-3}, the measured maximum electron energy varies as: $E_{max}(\text{MeV}) = 0.76\ n_c/n_e$ in reasonable agreement with this model.

The total charge of 8 nC was also measured in this regime with an integrated charge transformer. This charge value is in agreement with recent numerical simulations (Tzeng *et al.*, 1999).

3. HEAVY PARTICLE SOURCES

Focusing a multiterawatt laser onto a thick foil can generate high energies protons (1–50 MeV) and heavy ions (few hundred megaelectron volts; Fews *et al.*, 1994; Clark *et al.*, 2000; Snavely *et al.*, 2000). Protons are also produced by focusing the laser beam on a metallic target. The origin of these protons is the presence of hydrocarbon contaminant on the target surface. As shown experimentally and theoretically, ions are produced from both sides of the target surface. Surface electrons are accelerated into the target by the ponderomotrice force of the laser; the electric field associated to this charge separation will drag ions through the target. Pukhov has estimated the maximum energy of ions produced at the front surface as $E_0 = 2\sqrt{2}aZ\times0.511$ MeV (Pukhov, 2001). Here a is the dimensionless laser amplitude and Z the ion charge.

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Hot electrons pass through the target and escape into the vacuum from the back surface whereas the colder ones stay close to the surface. The corresponding charge separation also creates an electric field which can accelerate ions to high energy.

Uniform or ring structure has been measured in the angular distribution. Angular distribution of ions depends strongly on the propagation of the high current electron beam into the target. In this regime, the electron beam is confined by very intense (greater than 10 MG) self-generated magnetic field. If the target is thin enough, the electron beam is confined through the whole target thickness, producing a ring structure in the ion angular distribution.

A summary of recent results concerning maximum proton energy measurements as a function of the laser intensity is presented in Figure 3. Fitting indicates that the maximum proton energy scales as $E_{max} = 3.5(I(\mathrm{W/cm^2})/10^{18})^{1/2}$. It is important to note the good conversion efficiency (several percent) of the laser energy into ion kinetic energy.

Multi-megaelectron volt ions have been generated in underdense plasma via the "Coulomb explosion" by focusing a terawatt laser beam into a gas jet (Krushelnick *et al.*, 1999). In this case the ponderomotive force pushed electrons radially, creating a charge separation which drags out ions from high-intensity laser region. The maximum energy that these ions can gain is directly related to the ponderomotive laser energy: $U = Zm_e c^2(\gamma - 1)$. Measuring the ion spectra along the laser interaction region provides information concerning the relativistic self-guiding regime and laser intensity along the propagation.

4. APPLICATION OF LASER-PRODUCED PARTICLES

Laser plasma accelerators are now available generating electron beams with energies of to several tens of megaelectron volts and a total charge of few nanocoulombs. The pulse duration of the electron beam at the output of the plasma is less then the laser pulse duration and can therefore be in the order of 30 fs.

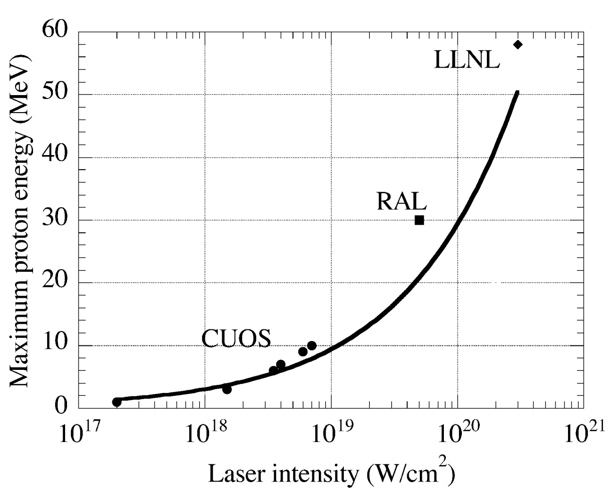

Fig. 3. Maximum proton energy as a function of the laser intensity measured recently at different laboratories

Such bright electron sources offer a potential application in the production of radio-isotopes. To activate targets, a converter can be fixed on the way of the electron beam to produce bremmsstrahlung radiation (Norreys *et al.*, 1999). The γ-flash irradiates and activates the target. Photofission of uranium has already been obtained by (γ, f) reactions. Using a 1-cm-thick uranium target, estimation of 4000 prompt neutrons/pulse has been established by Shkolnikov *et al.* (1997). More recently, (γ, n) activation experiments using laser wakefield accelerators has been performed by the group of Leemans in which several radio-isotope have been identified (Leemans *et al.*, 2001). Positrons have also been produced using a laser plasma accelerator (Gahn *et al.*, 2001). This electron source also can be useful to generate ultrashort X-ray flashes. By focusing a terawatt laser on the electron beam, X-ray pulses can be obtained by Thomson scattering with a pulse duration as short as the laser pulse (Schoenlein *et al.*, 1996). Such short X-ray pulses (30 keV) have been used by the Leemans' group in order to characterize a 50-MeV electron beam produced by a linac (Leemans *et al.*, 1996).

Other applications of such accelerators can be found in chemistry. For example at the University of Michigan, the electron charge of the beam was high enough to conduct time-resolved investigations of radiation-induced chemical events (Saleh *et al.*, 2000). It is important to note that the laser plasma accelerator offers a unique capability to deliver electron beams physically separated from the source (the laser). This can be useful because the region where the electron beam is produced can be very small and the associated radioactivity can be isolated at lower costs. The second main advantage is the presence at the same site of the perfectly synchronized laser and electron beam for pump probe experiments.

The ion source produced by laser–plasma interactions can be useful for different applications. Roth has recently proposed using an ion beam to trigger thermonuclear fusion reaction (Roth *et al.*, 2001) instead of electron beams as proposed several years ago by Tabak *et al.* (1994). This scheme presents the advantage of a better coupling between the ion energy and energy deposited in the fuel. Proton beams emitted from the back surface are well collimated and can be used as a compact heavy ion injection source (Krushelnick *et al.*, 2000). Another attractive application of these sources is the hadrontherapy. Because ions deposit their energy in a well-defined region inside a material at the end of their propagation, they can destroy cells in a tumor region without any damage around and before the region being treated. In Figure 4 we report typical doses deposited by protons, γ-rays, and electrons in human tissue, showing the interest of protons for proton therapy (as well as for fast ignition driven by proton beams). The Bragg peak is also indicated in the figure.

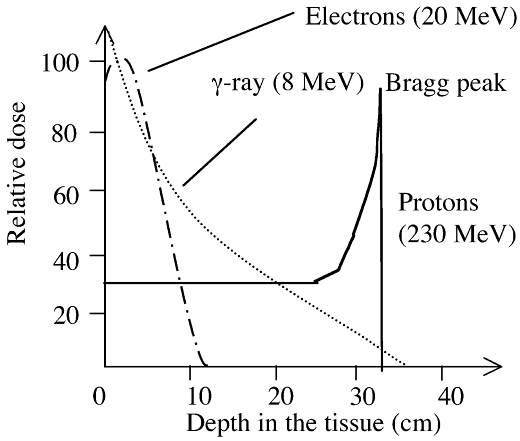

Fig. 4. Depth dose distribution for an 8-MeV γ-ray, 20-MeV electron, and 230-MeV proton.

In medicine, another application of proton source is the production of radio-isotopes. Positron source with an activity of hundreds of megabecquerels can be produced in one hour by irradiating an ^{18}O enriched water with 10-Hz laser-produced proton source (Santala *et al.*, 2001). Finally, proton sources can be useful to radiograph plasmas since the spatial resolution can be of the order of 20 μm (Roth, 2001) with a temporal resolution of the order of a few picoseconds (Borghesi, 2001).

5. CONCLUSION

We have presented a synthesis of experimental results on laser-produced particle beams. As is shown, the emergence of new laser facilities at a moderate cost extend this field of research not only in a few important laboratories but also in many other laboratories with lower budgets. A new and important interest in this field occurs with the appearance of table-top terawatt lasers which can thus provide a compact particle source. This new class of multiterawatt, high-repetition-rate lasers open the door for various applications of these compact, bright, and energetic particle sources.

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