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The laser-matter interaction meets the high energy physics: Laser-plasma accelerators and bright X/γ-ray sources*

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Abstract

Laser matter interaction in the regime of super-intense and ultra-short laser pulses is discovering common interests and goals for plasma and elementary particles physics. Among them, the electron laser wakefield acceleration and the X/γ tunable sources, based on the Thomson scattering (TS) of optical photons on accelerated electrons, represent the most challenging applications. The activity of the Intense Laser Irradiation Laboratory in this field will be presented.

Keywords: Plasma accelerators; Thomson Scattering; X-ray sources

1. INTRODUCTION

The current slowing down of development of the experimental research in high energy particle physics is mainly due to the gigantism of conventional particle accelerators and their cost hardly sustainable, even by international consortia as the CERN.

The size of conventional accelerators producing high energies particles have to be very large in both the cases of linear as well as circular acceleration (Hoffmann *et al.*, 2005). In fact, being the maximum accelerating electric fields, below the material breakdown threshold, of the order of several tens of MV/m, 20 Km would be required to get the energy of 1 TeV, with an accelerating field of 50 MV/m. In the case of circular accelerators, relatively large dimensions are still required, because of the Bremsstrahlung losses.

Plasma does not present the problems connected with the breakdown, and for this reason, it was considered as the ideal medium in which to accelerate charged particles by means of electric fields, which are orders of magnitude higher than the conventional accelerators (Tajima & Dawson, 1979). The experiments on plasma accelerators, started in the early 1980s, had a new impetus with the advent of the ultra-short pulse lasers and the chirped pulse amplification technique that allowed pulses of a few joules in tens of femtoseconds to be produced (Strickland & Mourou, 1985). After that, theoretical and experimental activity was developed achieving more and more encouraging results concerning the energy and the quality of the produced beam (Katsouleas, 2004; Mangles *et al.*, 2004; Geddes *et al.*, 2004; Faure *et al.*, 2004; Malka, 2002; Malka & Fritzler, 2004; Hora *et al.*, 2000; Nakajima, 2000; Dorchies *et al.*, 1999; Tomassini *et al.*, 2004; Reitsma & Jaroszynki, 2004; Breschi *et al.*, 2004).

In fact, huge electric fields can be generated when an intense laser beam is focused inside the plasma and an electron density perturbation (plasma wave) is excited.

The maximum energy that the electrons can gain along a de-phasing length L_{deph}, that is, the distance beyond which the electron starts to be decelerated, is:

$$\Delta U_{\max} \approx 2\gamma_p^2\left(\frac{\delta n_e}{n_e}\right)mc^2,$$

where γ_{p} is the Lorentz factor related to the phase velocity of the plasma wave

$$\gamma_p = \sqrt{\frac{n_c}{n_e}} = \frac{\omega}{\omega_{pe}} \approx \frac{\lambda_p}{\lambda},$$

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n_e the plasma density, δn_e the electron density perturbation, n_c the critical density related to the laser wavelength λ (angular frequency ω), ω_{pe} and λ_p the plasma frequency and wavelength, respectively.

The values of both ΔU_{max} and L_{deph} increase as the electron plasma density decreases. This can be qualitatively understood considering that, as the plasma density decreases, the phase velocity of the plasma wave progressively approaches the speed of light c, allowing the electrons to reach higher values of kinetic energy. On the other hand, at a lower electron density, the longitudinal electric field associated to the plasma waves decreases with the electron density, so longer distances are required to get the same energy gain.

In practice, the actual maximum energy gain ΔU_{max} depends on the plasma density and on the extension of the plasma region in which the plasma wave can be maintained. As an example, for a plasma of density $n_e \approx 10^{18}\text{cm}^{-3}$, in which high amplitude plasma waves can be maintained for distances of the order of a fraction of 1 cm, electrons with an energy as high as 1 GeV can be produced.

To generate a plasma wave, it is necessary to perturb the electron density (so inducing the natural oscillation at the plasma frequency ω_{pe}) with a perturber moving at the appropriate velocity. In fact, the perturber velocity will also be the phase velocity of the wave.

When a sufficiently intense laser pulse propagates in plasma, it produces a local decrease of the electron density, due to the action of the ponderomotive force (Teychenné, 1994). If the longitudinal size of the pulse is about a half (or less) of the wavelength of the plasma natural oscillation mode (λ_p), a high amplitude plasma wave develops on the wake of the pulse. Since λ_p depends on the plasma density n_e, the condition for the growth of the plasma wave by such a mechanism can be expressed as follows:

$$\tau_{laser}\, c \approx \frac{\lambda_p}{2} \Leftrightarrow \tau_{laser} \approx \frac{T_p}{2} \Leftrightarrow n(cm^{-3}) \approx \frac{3\cdot 10^{-9}}{\tau^2_{laser}(s)}.$$

The laser Wakefield acceleration (LWA) is considered a quasi-resonant process, in the sense that the resonant condition is not so severe.

2. ELECTRON ACCELERATION IN ELECTRON PLASMA WAVES BY SELF-TRAPPING

This is the condition of the majority of the laser plasma acceleration experiments performed up to now. In this case, the energy gain of the electrons depends on the conditions of the injection in the electron plasma wave (that is, electron velocity and the phase of the wave) and those of their expulsion from the wave.

As an example, we reported on a recent experiment (Giulietti *et al.*, 2002) in which collimated bunches of high energy electrons were produced by focusing a super-intense femtosecond laser pulse in sub-millimeter under-dense plasmas. The density of the plasma, pre-formed 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 (3D) numerical simulations, validate a reliable method to generate ultra-short and ultra-collimated electron bunches.

In Figure 1, the experimental apparatus is reported as well as the schematic of the radiochromic film based electron spectrometer (see the inset).

Figure 2 (right) shows a typical radiochromic film result after a single exposure to the electron beam generated by focusing the CPA pulse at an intensity of $\approx 8 \times 10^{19}$ W/cm^2 in the plasma produced by the explosion of a 1 μm thick target. This image shows a small central spot very closely aligned with the laser propagation axis The spectral analysis of the collected electrons suggests that, besides an intense electron flux of lower energy in a ring of $\theta_{ring} \approx 18°$ aperture, there is a bunch of very collimated, high energy electrons accelerated along the laser propagation axis. This electron bunch is confined in a solid angle $< 10^{-3}$ sterad. To our knowledge, this is one of the most collimated electron beams ever observed in laser-plasma acceleration experiments.

It is interesting to compare these experimental results with the predictions of numerical simulations carried out using a 3D particle-in-cell (PIC) code with a plasma density profile and a laser pulse intensity distribution very close to the experimental ones. The angular distribution obtained from the simulations is shown in Figure 2 (left). A comparison with the radiochromic film data of Figure 2 (right) clearly shows that the main feature of the angular distribution observed experimentally, namely the central, collimated electron beam, is well reproduced by the simulations.

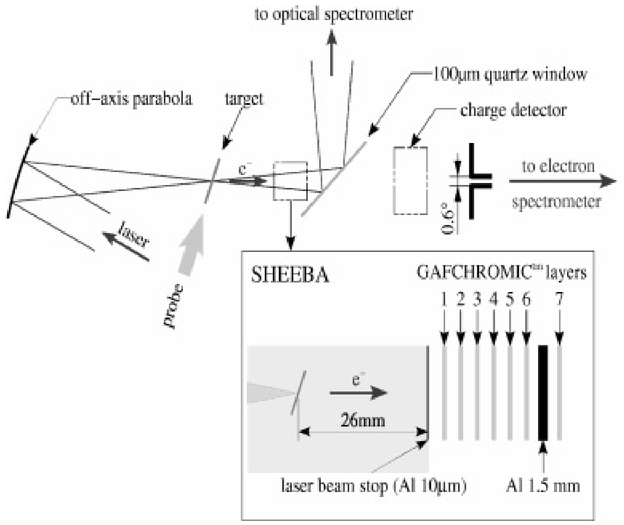

Fig. 1. The experimental apparatus and, in the inset, the schematic of the radiochromic films based electron spectrometer.

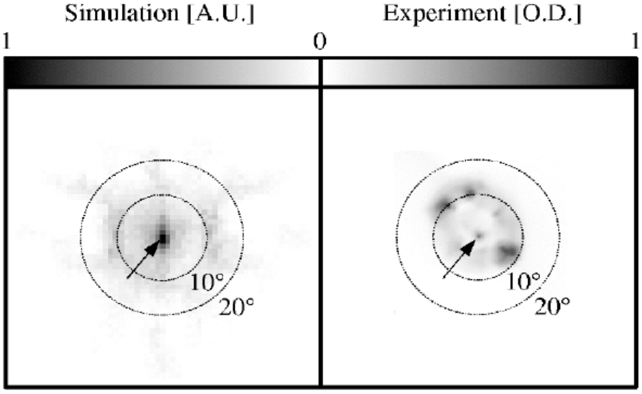

Fig. 2. (**right**) Densitometer scan of a radiochromic film after exposure to the energetic electron beam produced by interaction of an ultraintense laser pulse with preformed plasma located at 26 mm from the first film. The CPA pulse intensity in the plasma is 8×10^{19} W/cm^2. The angular scale is also shown for reference. (**left**) 3D PIC simulation: angular distribution with respect to the laser axis of the electrons emitted forward, to be compared with the radiochromic film data on the rigth. Input conditions of the PIC simulation: the plasma longitudinal density profile had a plateau of 40 μm at density 2×10^{19} cm^{-3} and density decrease both sides with a scale length of 10 μm; the laser maximum intensity is 3.4×10^{19} W/cm^2, wavelength 800 nm, duration 30 fs, spot FWHM 9 μm.

The experimental 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 electro-magnet, electrons from a few MeV up to 200 MeV (Malka, 1998) could be analyzed with an acceptance angle of $\theta_{\text{spec}} \approx 0.6°$. 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. The data from the spectrometer were processed using a Monte Carlo code which also enabled to account for the presence of the quartz plate between the plasma and the spectrometer. The actual electron beam aperture as described above was also taken into account in the Monte Carlo code. A typical spectrum is shown in Figure 3 (black dots). According to this plot, the electron beam consists of a sizeable number of electrons with energies from a few MeVs up to 40 MeV. Also plotted in Figure 3 (solid line) is the calculated spectrum of the electrons obtained from the PIC simulation relative to the electrons in the central feature of Figure 2 (left). There is a very good agreement between the experimental spectrum of the high energy electron beam and the simulated one. Also interesting is the 40 MeV energy cut given by the simulation consistently with the experimental data. This is an indication that a well defined acceleration mechanism is playing a role, whose action is limited by some experimental parameter. We believe that in our experimental conditions the limiting factor is the acceleration length, which is given basically by the plasma length that in our case is much smaller than the dephasing length.

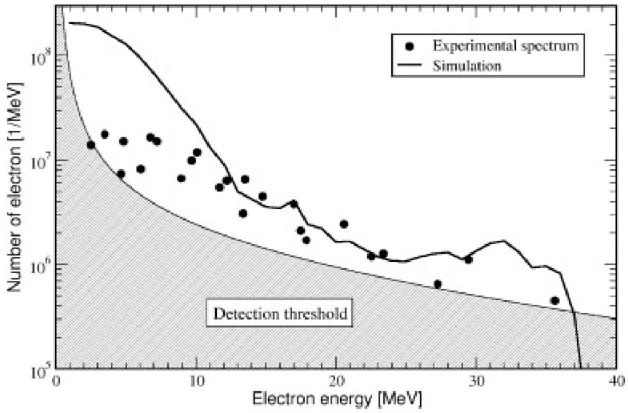

Fig. 3. Spectrum of the electrons in the collimated beam. Filled circles represent the experimental electron spectrum. Also shown is the detection threshold of the electron spectrometer. The solid line is the spectrum of the electrons in the collimated beam (within 3 deg around the axis in Figure 2 (left)) as obtained from the PIC simulation.

3. SUITABLY SHAPED PRE-FORMED PLASMA

Several teams are investigating, by theoretical and experimental approaches, different possibilities of reducing the energy spread of the electrons accelerated by laser plasma techniques.

Bulanov *et al.* (1998) proposed a novel scheme for the production of high-quality electron beams in laser Wakefield acceleration in which a controlled longitudinal nonlinear wave-breaking is induced by electron density depletion. This proposal was supported by both analytical and numerical results in a one-dimensional (1D) configuration. In fact, if the plasma density decreases in the direction of the pulse propagation (z coordinate), the wave number k increases with time. The resulting decrease of the phase velocity v_{ph}, at the interface between two uniform density regions, makes the wave break, even when its initial amplitude is below the wave-breaking threshold. As a result of the break at the interface between the two regions, fast electrons from the wave crest are trapped by the wave and accelerated into the lower density region where the wake field remains regular. An energy balance argument shows that in the weakly inhomogeneous case the relative density of fast electrons is approximately given by the ratio $v_{ph}/\omega_{pe}L$, where L is the scale length of the electron density depletion.

In Figure 4, the results of PIC simulations concerning the energy spectrum of the electrons produced by such an acceleration scheme are reported (Tomassini *et al.*, 2003*a*). The electron density of the pre-formed plasma consists of two regions with a sharp transition. After a smooth vacuum-plasma transition, the longitudinal profile of the electron density reaches a first plateau ($n_{\text{e}} = 2.1\ 10^{19}\text{cm}^{-3}$) and then it decreases abruptly with a scale length of $L = 2$ μm to a second plateau ($n_{\text{e}} = 1.1 \times 10^{19}\text{cm}^{-3}$). The 1 μm wavelength laser pulse, with a Gaussian envelope (waist $w = 20$ μm,

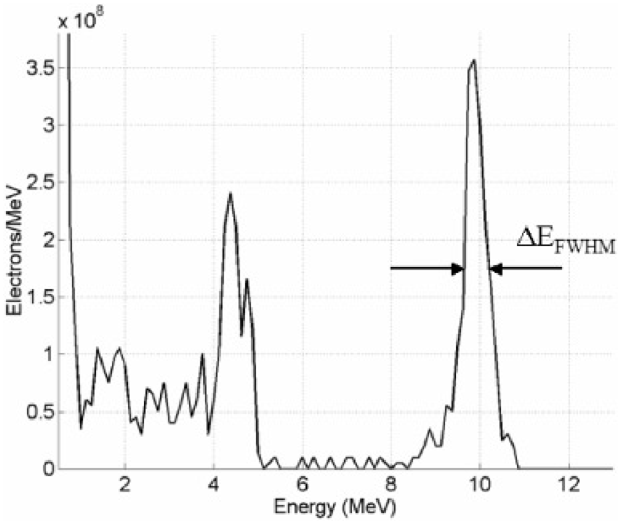

Fig. 4. Energy spectrum of the accelerated electrons in pre-formed plasma with a sharp density depletion

time duration $t_{\mathrm{FWHM}} = 17$ fs) has an intensity of $I = 2.5 \times 10^{18}\mathrm{W/cm^2}$.

We can see that, selecting the electrons with energy exceeding 7MeV, the resulting bunch of $N_e \approx 10^8$ electrons with energy $E \approx 10$ MeV is characterized by a remarkable good quality and has energy spread $\Delta E/E \approx 5\%$, with transverse and longitudinal sizes of $\delta y \approx 1$ μm and $\delta z \approx 5$ μm, respectively, and transverse emittances

$$\varepsilon_{rms}^{tr} \equiv \frac{1}{mc}\sqrt{\langle r^2\rangle\langle p_\perp^2\rangle - \langle rp_\perp\rangle^2} \cong 0.1 \text{ mm}\cdot\text{mrad},$$

$$\varepsilon_{rms}^{lon} \equiv c\sqrt{\langle \Delta z^2\rangle\langle \Delta p_z^2\rangle - \langle \Delta z \Delta p_z\rangle^2} \cong 2 \text{ mm}\cdot\text{KeV},$$

where $\Delta z = z - \bar{z}$ and $\Delta p_z = p_z - \bar{p}_z$, z and r being the longitudinal and the radial coordinates, p_z and $p_\perp$ the longitudinal and transverse momentum respectively.

4. BRIGHT X/γ RAY SOURCES

The linear Thomson scattering (TS) is widely used to diagnose the plasma temperature and density. Recently the TS was used to get the angular distribution of a monochromatic electron bunch (Leemans *et al.*, 1991). Moreover, experimental methods have been proposed to measure the length of a monochromatic electron bunch (Tomassini *et al.*, 2002) and to measure the energy spectrum of a single bunch eventually characterized by a wide energy spread or alternatively to measure the angular distribution of a single bunch with a known energy spectrum (Tomassini *et al.*, 2003*b*). These new experimental methods are based on X-ray detectors having both a good spectral and angular resolution (cooled CCD camera used in the single photon counting regime) (Labate *et al.*, 2002).

The TS of a laser beam on an ultra-relativistic electron bunch can provide tunable *X* and γ-ray sources. In the case of linear TS on monochromatic and collimated electron bunches, also the scattered radiation comes out to be collimated in the direction of the electron motion, in a cone with $2/\gamma$ aperture; γ being the Lorentz factor of the electrons. The energy of the scattered photons depends on the energy of the impinging photons (E_{L}), the scattering angle θ, the angle between the impinging laser radiation and the electron beam α_{L}, the electron energy (Tomassini *et al.*, 2003*b*):

$$E = E_L \frac{1 - \beta\cos\alpha_L}{1 - \beta\cos\theta}.$$

It is apparent that in the case of counter propagating photon and electron beams ($\alpha = \pi$) and backscattering condition ($\theta = 0$) the energy of the scattered photons is maximum

$$E_{Back} \cong 4\gamma^2 E_L.$$

The number of the scattered photons by the single electron $N_{\mathrm{Sc}}^{\mathrm{1e}}$ in a cone with $2/\gamma$ aperture can be evaluated by using the total Thomson cross section, assuming a full overlap of the electron bunch and the laser pulse:

$$N_{Sc}^{1e} = \frac{\sigma_{Th} N_L}{S} \approx 100\,\frac{E_L[J]\lambda[\mu m]}{w^2[\mu m^2]},$$

where λ and w are the wavelength and the waist of the laser beam. The number of photons scattered by the electron bunch in a cone with $2/\gamma$ aperture is evaluated multiplying the previous equation by the number of the electrons in the bunch N_{e}. The energy distribution of the back-scattered photons by a single electron strongly depends on the angle θ_{M} in which the radiation is collected. It is important to observe that in order to have an energy spread less than 100% the collection angle θ_M must be a fraction of the characteristic emission angle $1/\gamma$.

As an example, let us to consider the linear TS of a laser beam on the electron bunch produced by the LINAC of the SPARC project (Alesini *et al.*, 2004). The bunch energy can vary from 40 MeV up to 250 MeV and the charge is about 1 nC, corresponding to about 10^{10} electrons. The longitudinal dimensions of the bunch can be compressed down to $\sigma_{\mathrm{l}} = 0.3$ mm rms (1 ps duration), while, after focusing, its transversal dimensions can be reduced down to $\sigma_{\mathrm{t}} = 5$ μm *rms*, with a normalized transverse emittance $\varepsilon_n \cong 2$ mm · mrad. An accurate characterization of the scattered radiation in the back scattering configuration should take into account the different Reyleigh lengths of both the electron bunch and the laser pulse, and consequently their partial overlap.

However, by using the previous formulas, we can give a rough estimation of the photons produced in the interaction of a Ti:Sapphire laser ($\lambda = 0.832$ μm, $E_{\mathrm{L}} = 1$ J, pulse duration $T = 1$ ps, focusing waist $w = 10$ μm) with an electron bunch as that of the LINAC of the SPARC project. In the case of a 40 MeV electron beam (maximum energy of scattered photons: 38 KeV) we get 4×10^9 photons in $\theta_M = 1/\gamma$ and 1×10^9 photons in $\theta_M = 0.3/\gamma$.

We observe that the value of the transverse emittance of the electron beam is a crucial parameter for the production of monochromatic radiation. As an example, in the case of a 40 MeV beam, in order to obtain X ray radiation with an energy spread of less than 10% FWHM, the collection angle must be less than $\theta_M = 3.7$ mrad. To make this possible, the electron beam divergence must be much less than the collecting angle: $\Delta\theta \ll \theta_M$. Actually the very low emittance of the electron beam produced by the LINAC of SPARC allows radiation with very low energy spread to be produced. Estimating $\Delta\theta \approx \varepsilon_n/\gamma\sigma_\tau$ and $\theta_M \approx \rho/\gamma$, we get $\rho = \varepsilon_n/\sigma_\tau = 2/\sigma_T\,[\mu\text{m}]$. For a laser beam waist of 7 μm rms we get $\rho = 0.3$, corresponding to a 10% energy spread, while for a laser beam with a waist of 20 μm we get $\rho = 0.1$, corresponding to a 1% energy spread .

In conclusion the linear Thomson back scattering on the electron bunches produced by the LINAC of the SPARC project allows X and γ ray beams to be produced with an energy spread down to 1%. In the case of a Ti:Sapphire laser with 1 J pulse energy, the photon number per shot in an angle of $0.3/\gamma$ and consequently with an energy spread of 10%, is about 10^9.

5. CONCLUSIONS

The laser wake field acceleration technique let us foresee possibilities to overcome the actual limits related to the gigantism of the conventional particle accelerators, even if a viable alternative to conventional accelerators requires a few open questions to be answered, concerning the maximum energy, the energy spread, the quality and the efficiency of the produced electron beam.

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