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The particle laser-plasma acceleration in Italy

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Abstract. In this paper the beginning activity on Laser Plasma Acceleration in Italy and the recent results obtained in the frame of the INFN Strategic Project PLASMONX will be presented. The project, involving eight groups and two National Laboratory disseminated along Italy, is aimed at the development of an innovative, high-gradient acceleration with super-intense and ultra-short laser pulses, and a tuneable, hard X/ γ -ray source, based upon Thomson scattering of optical photons by energetic electrons. Both experiments require very high power, ultra-short laser pulses in combination with very bright and short electron bunches generated either by conventional acceleration (LINAC) or by laser-driven acceleration in plasmas.

1. Introduction

In a seminal paper [1] Tajima and Dawson proposed in 1979 to accelerate electrons by the very strong longitudinal electric fields associated with plasma waves generated, for example, by the beating wave process or by a wake-field of intense laser pulses. 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 as a scheme suitable for the acceleration of electrons trapped from the plasma itself [2, 3]. More recently additional mechanisms have been proposed as the “forced wake-field” [4] or the “bubble” regimes [5]. All these acceleration physical processes became experimentally accessible with the advent of the powerful CPA (**Chirped Pulse Amplification**) [6] pulses. In fact several groups active in laser-matter interaction at high intensities by the early 90’s of the last century become involved in Laser Plasma Acceleration experiments at the major European and Nord America laser facilities. At that time in Italy the CNR-University Pisa laser group, lead by Antonio and Danilo Giulietti, carried out a successful experimental campaign at Laboratoire d’Optique Appliquée (LOA, École Polytechnique) [7, 8, 9, 10] that induced interest in the National Institute for Nuclear Physics (INFN). After a series of seminars at Laboratori Nazionali di Frascati (LNF) given by Danilo Giulietti on the new acceleration techniques and the results obtained by his group at LOA, INFN launched a Strategic Project: **PLASMONX (PLASma acceleration and MONochromatic X-ray production)** [11]. The facility was built in close interaction with the SPARC (**Sorgente Pulsata Auto-amplificata di Radiazione Coerente**) project [12] based on an advanced 150 MeV LINAC at LNF. The main purpose of the facility consists in R&D activity aimed at the following objectives: 1) demonstration of high-gradient acceleration of electrons injected into electron plasma waves excited by ultra-short, high power laser pulses; 2) development of a monochromatic and tuneable X-ray source in the 20-1000 keV range, based upon Thomson Scattering of laser pulses by

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relativistic electrons; 3) development of secondary sources of particles (protons, ions, positrons, muons, ...) and energetic radiation (Bremsstrahlung, betatron, FEL, ...). All these lines require very bright and short electron bursts together with very high power laser pulses of sub-100fs duration. Studies at the forefront of research in this field consistently indicate that power levels and the focused intensities for a laser system appropriate for these studies are >10 TW and $>10^{19}$ W/cm², respectively. For this reason the PLASMONX facility has been endowed by a Ti:Sapphire laser delivering pulses up to 8J in 20fs at 10Hz, that once focused on target can exceed intensities of 10^{21} W/cm².

2. Exploding-foil technique at ultra-relativistic intensities

At present CPA technique can produce the most powerful laser pulses due to their shortness, however, such pulses 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 ultra-short laser interactions with matter. A special feature of the experiments we performed in the early 2000’s at LOA [8, 9, 10] where we used the ASE pedestal in order to produce, via the exploding-foil technique, a pre-formed plasma, providing favourable conditions for electron acceleration with a 35 fs pulse. This technique, already tested and validated in previous experimental works, 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 (mm length) used in acceleration experiments. The laser-target configuration is basically the same already used in previous experiments. The linearly *p*-polarized beam of the Ti:Sapphire laser of the LOA (Salle 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 deg. The laser intensity distribution in the focal spot was Gaussian, with 50% of the total laser energy within a circle of ≈ 4 μm diameter resulting in a laser intensity on target of $I_L \approx 8 \cdot 10^{19}$ W/cm². 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 the experiment we were able to produce for the first time interferograms in the Nomarski configuration with a femtosecond probe pulse. 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. 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 longitudinal plasma density profile (along the laser path) as obtained from a typical interferogram taken 50 ps before the arrival of the main pulse shows 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/cm³. 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 $\theta_{\text{coil}} \approx 7$ 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. The electron angular distribution is a crucial measurement which was performed using a detector based on radiochromic films (MD55–GAFCHROMICth). 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. The detector was placed 2.6 cm behind the target, with the center of the films aligned with the laser propagation axis. Typical radiochromic film results obtained after a single exposure to the electrons generated by focusing the CPA pulse at an intensity of $\approx 8 \times 10^{19}$ W/cm² in the plasma, show

a small central spot aligned with the laser propagation axis. This feature is visible on all seven layers of the stack 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 $\theta_{\text{ring}} \approx 18$ deg 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 $\approx 10^{-3}$ sr. The electron energy spectrum was obtained with a spectrometer based on an electro-magnet coupled with a set of four photodiodes “surface barrier detectors”. The entrance axis of the spectrometer was carefully aligned on the laser propagation axis in order to analyse the spectrum of the electrons in the central bright beam. A typical spectrum is shown in Fig. 1. According to this plot, the electron beam consists of a sizeable number of electrons with energies from a few MeV up to 40 MeV. The experimental results show that the accelerating field in the plasma could approach 1TV/m.

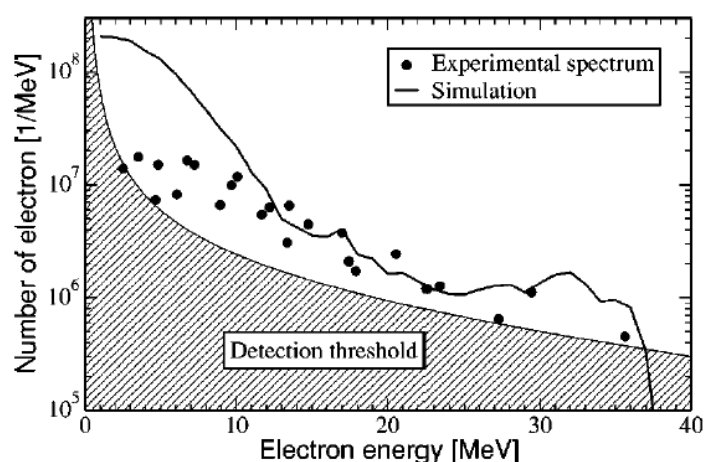


Figure 1. Spectrum of the electrons in the collimated beam obtained by magnetic spectrometer. Black dots represent the experimental data. Also shown is the detection threshold of the electron spectrometer. The solid line is the spectrum of the electrons in the collimated beam (within 3 deg around the axis) as obtained from the PIC simulation.

3. First PLASMONX experimental activity

During the construction of the PLASMONX laboratory and the assembly of the 300TW Ti: Sapphire laser by Amplitude Technologies at LNF the Italian experimental activity on LPA (Laser-Plasma Acceleration) was developed at CNR-Pisa laboratory and other European facilities. The Pisa group devoted its main interest to the study of the propagation of the intense laser pulses in plasmas, taking up the pioneering experiment on laser guiding which was performed in the late 1980s [13]. In that experiment two collinear Q-switching Nd-laser pulses, separated by a few nanoseconds, were focused on an under-dense plasma. While the first pulse was strongly diffracted as a consequence of the self-focusing effects, the second one propagated almost un-attenuated for several Rayleigh lengths in a low density channel formed by the first one. Adapting such studies to the demands of the Laser-Plasma Acceleration techniques the same group conceived an experiment oriented to find the most suitable conditions to improve the electron acceleration length, producing hollow cylindrical plasmas for guiding intense laser pulses [14]. To do so, an experimental arrangement to probe the laser-gas-jet interaction with a fast interferometric technique was setup at INO-CNR (Istituto Nazionale d’Optica of the Consiglio Nazionale delle Ricerche) in Pisa (Italy). The laser system employed to study the plasma evolution driven by an ASE-like laser pulse is a 3.3 GW

Nd:YLF delivering two beams with a maximum energy of 5 J per beam at a wavelength of 1053 nm and duration of 3 ns FWHM. The system can provide intensities up to 10^{15} W·cm⁻² on a target with a high temporal and spatial quality. The production of quasi-cylindrical plasmas extending over several millimeters and with a hollow density channel on their axis was demonstrated. The mean on-axis electron plasma density was $\approx 4 \times 10^{18}$ cm⁻³. As a speculation, it can be noted that these values of electron density are quasi-resonant in the LWFA (Laser Wake-Field Acceleration) regime with laser pulses of duration $\tau \approx 30$ fs FWHM. For what concerns the transverse density profile, the density minimum has a value in the range of 60 to 70% with respect to the channel walls, while its radius r_{ch} at half of the depth is of the order of 30 to 50 μ m. These values are suitable to optically guide a driving pulse. The density distribution can be described as

$$n(r) = n_0 + \Delta n \cdot \left(\frac{r}{r_{ch}} \right)^2 \quad (1)$$

the values for n_0 and $\Delta n(r_{ch})^{-2}$ being 4.54×10^{18} cm⁻³ and 3.74×10^{22} cm⁻⁵, respectively. With reference to equation

$$w_0 = \frac{r_{ch}^2}{(\pi r_e \Delta n)^{1/4}}, \quad (2)$$

which relates the plasma channel density profile with the laser spot size to match the optical guiding condition [14], the obtained data are consistent with $w_0 = 23$ μ m. It means that pulses focused in spots smaller than w_0 can be refractive-guided in such plasma channels. Plasmas similar to that produced in this experiment are found to be suitable for refractive laser-guiding over many Rayleigh ranges [15, 16], opening to an efficient use in high gain, long-scale acceleration experiments.

The role played by the laser guiding in LPA has been evidenced also in a recent experiment performed in the PLASMONX [17] laboratory at LNF-INFN, where 30 TW, 30 fs pulses from a Ti:Sa laser were focused on a supersonic gas-jet at an intensity of $I \approx 6 \times 10^{18}$ Wcm⁻². The plasma electron density of the ionized N₂ at ≈ 7 –12 bar backing pressure was $n_e \approx 10^{19}$ cm⁻³. Fig 2a shows the image of the electron bunch detected by a LANEX screen after dispersion in the 0.9 T magnetic spectrometer, while Fig. 2b shows the corresponding lineout together with a calibrated energy scale. During the experiment, mainly devoted to individuate the best conditions for LPA, the magnetic spectrometer was operated without the usual entrance slit. So, while the vertical dimension of the electron bunch on the LANEX depends on its divergence (μ s mrad), the horizontal one depends also on its energy spread. The two dimensions being more or less the same (spot almost circular) it evidences that the electron bunch energy spread is less than the one you can deduce from the LANEX image, i.e. $\Delta E/E < 10\%$. In the experiment the activated Thomson scattering (TS) diagnostic evidenced the extension of acceleration length (≈ 2 mm), more than 4 times the Rayleigh length of the employed focusing optics, due to the onset of the relativistic self-focusing, whose threshold power in our experimental conditions was

$$P_c = \frac{2m^2 e^5}{e^2} \frac{n_c}{n_e} \approx 17 \frac{n_c}{n_e} GW \approx 3TW. \quad (3)$$

The Thomson scattering diagnostics together with the direct imaging of the electron bunch on LANEX screen also shows the formation of two acceleration “channels”, due to the splitting of the main laser beam, most probably a consequence of aberrations on the main laser beam.

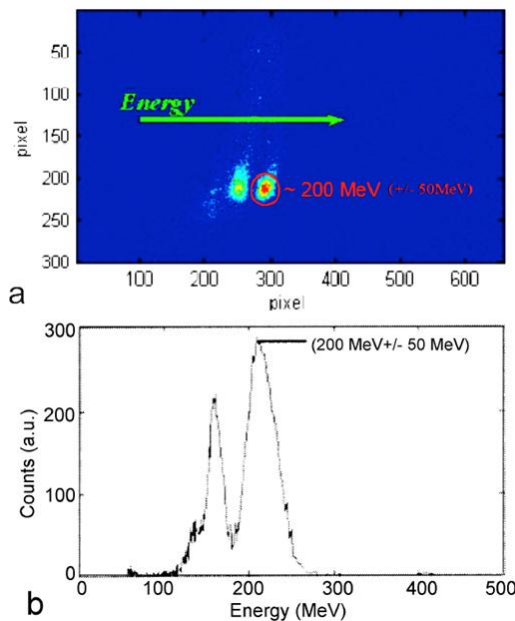


Figure 2. Electron bunch detected on LANEX after deflection in the magnetic spectrometer (a) and corresponding horizontal lineout (b). The uncertainty in the energy measurement is ± 50 MeV.

More recently [18], at LNF electron bunches (≈ 150 pC) were produced in a laser-plasma acceleration experiment using a 10 mm helium gas-jet with backing pressures of 5, 8 and 15 bars. The pulse of Ti:Sapphire laser (duration of $\tau < 30$ fs) was focused with an off-axis parabola F/10 in a 15 μ m diameter (waist) spot. The intensity was $I_0 = 2 \times 10^{19}$ W/cm², which corresponds to a normalized vector potential $a_0 = 3.1$ (see Fig. 3).

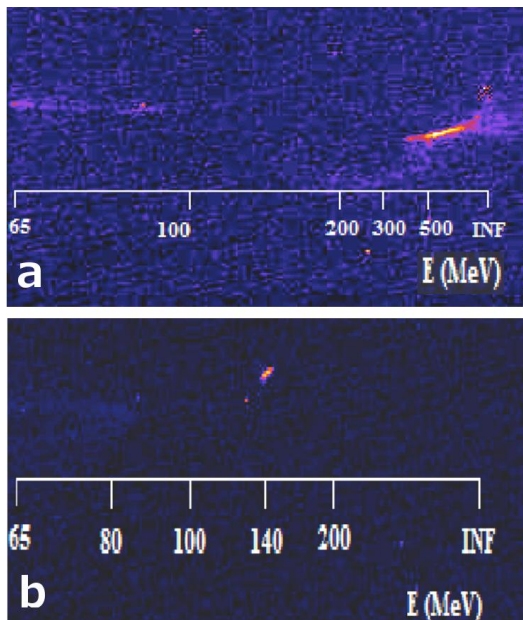


Figure 3. a) Electron spectrum obtained at 8 bars, showing a cutoff energy above 500 MeV. b) Electron spectrum obtained showing the lowest energy spread (4.6 %), obtained again at 8 bars.

4. Conclusions and perspectives

The experimental and theoretical activity in LPA has been in the last fifteen years exceptionally intense and very rich of impressive results. In the next future we expect even more relevant results, as those pursued by the **Berkeley Lab Laser Accelerator (BELLA)** project, under realization at Lawrence

Berkeley National Laboratory by the Wim Leemans group [19]. At present, several regimes for LPA have been successfully investigated, aimed to optimize the maximum energy, the energy spread, the charge and divergence of the accelerated bunches. The extension of the acceleration length, largely overcoming the Rayleigh length, is tempted following different experimental strategies; among them the control of the propagation of the intense laser pulse in the gases or plasmas confined in different ways (cells, capillaries,...). Most probably the next challenge will be the staged injection, in which in a first cell a bunch of energetic and quite monochromatic electrons is created by ionization injection [20] and further accelerated in a second stage, setup to work in the external-injection regime.

Also Italy is intensifying the engagement in this field[21, 22]. In fact the National Institute of Nuclear Physics (INFN) has recently launched the Strategic Project **PLASMONX** in which LPA techniques will be exploited using a 300TW Ti:Sapphire laser, synchronized with an advanced 150 MeV LINAC. First encouraging results are producing at LNF where the INFN, operating the most powerful Italian laser, is greatly contributing to the growth of a National community involved also in the larger European Projects **ELI** (**Extreme Light Infrastructure**) and **HiPER** (**High Power laser Energy Research facility**) [11] since their Preparatory Phase.

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