Compact Laser Accelerators Towards Medical Applications – perspectives for a Brazilian Program

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Abstract— Laser particle acceleration is now in a new trend due to an enormous worldwide effort to increase the peak power of femtosecond lasers, as well as increasing their average power in order to make them useful for applications. The leading example is the Extreme Light Infrastructure in Europe, which has led to the establishment of three large research facilities in the Czech Republic, Romania and Hungary that host some of the most powerful lasers world-wide (above PW peak power). This action is now being followed by the USA LaserNetUS initiative, that comprises all the big laser facilities in US, and similar efforts also happen in Asia. We are starting a program to establish a laser accelerator facility in Brazil, aiming to produce radiation (electrons, protons and X rays) to be used in medical applications, like X ray and electron therapy, nuclear reactions and, eventually, protontherapy.

Keywords—laser particle acceleration, high intensity lasers, Wakefield laser-plasma interaction, radiotherapy

I. Introduction

The peak power of high intensity lasers has evolved over the last few decades more than 10 orders of magnitude, reaching the PW level today, and the achievable intensities are in excess of 10^{22} W/cm^2 [1]. This achievement (that is still in rapid progress) was due to many improvements, like solid state laser materials with high thermal conductivity and good optical and mechanical characteristics (homogeneity, low nonlinear indexes, high damage threshold, among others) allowing good laser optical cycles and broad emission bandwidths. Particularly, diode lasers [2], optical fibers [3] and Ti:Al_2O_3 crystals [4] are the leading laser materials in this trend. Besides, new regimes of laser operation became very reliable like KLM [5], which produces pulses with very short duration, what led to efficient ways of obtaining high peak powers by decreasing the pulse duration at the expenses of the pulse energy. Due to these combined effects, a compactness of new high intensity laser systems came about that included the CPA technique [6] (that avoids the material destruction by surface dielectric breakdown). After the incorporation of these features in the laser systems, the peak power showed a steep growth whose limit is not yet visible.

These lasers can produce extreme conditions that mimic the ones found in stellar cores wherein overdense matter is heated to tens of millions of Kelvin. Besides the basic physics that is being brought to light due to these new regimes, several applications of these systems are very promising, and one of them, the acceleration of charged particles, is the goal of this program. When high intensity laser pulses impinge on a target, the atoms are ionized; the electrons and the parent ions are separated, and a plasma is formed, in which free electrons and protons are accelerated by the light field and/or the plasma field [7]. This technique, in conjunction with PW peak power pulses, has produced 100 MeV proton beams and several GeV electrons in centimeter scale targets [8, 9].

Considering the main current scientific efforts in this area, noteworthy are the programs Extreme Light Infrastructure (ELI) in Europe [10], which has led to the establishment of three large research facilities in the Czech Republic, Romania and Hungary that host some of the most powerful lasers worldwide (above PW peak power) and the USA LaserNetUS [11], that comprises all the big laser facilities in US. The University of Nebraska-Lincoln (UNL) research team is part of this net and has been a pioneer in this area in the last two decades, including the recent demonstration of using laser-driven colliding wakes to produce high energy electron beams [12]. Members of IPEN and ITA have recently joined up efforts with the UNL team to pursue these goals. With the recent advances in proton and electron laser acceleration with medium size lasers with high repetition rates [13], new areas of applications of these new accelerators are emerging. In order to describe the main aspects of the electromagnetic interaction, a brief overview will be given. There are excellent reviews [14, 15] and textbooks [16] that describe the following developments.

The intensity I of a laser is related to the electromagnetic field by:

$$I = \mathrm{Re}\ \{½\ (\mathbf{E}\times\mathbf{H}^*)\}, \quad (1)$$

where **E** and **H** are the complex vector amplitudes for the electric and magnetic fields. In vacuum, the average intensity is reduced to:

$$I = ½\cdot c\cdot \varepsilon_0|E|^2, \quad (2)$$

where c is the speed of light and ε_0 is the permittivity of the vacuum. Therefore, the electric field amplitude can be related to the intensity by:

$$E(\mathrm{V/cm}) = 27.5\ \sqrt{I(\mathrm{W/cm^2})}. \quad (3)$$

For the Bohr atomic model, where the electron in the hydrogen ground state has a binding energy of 13.6 eV and an orbital radius of 0.5 Å, the intensity that corresponds to its electrical field is $1.37\cdot10^{14}$ W/cm^2. Considering that the wavelength of an 800 nm laser is much longer than the atomic dimensions, when an electric field of this intensity interacts with a hydrogen atom there is a suppression of the Coulomb barrier, as shown schematically in Fig. 1 for a defined time. At this moment the Coulomb barrier can be suppressed, and the electron is released.

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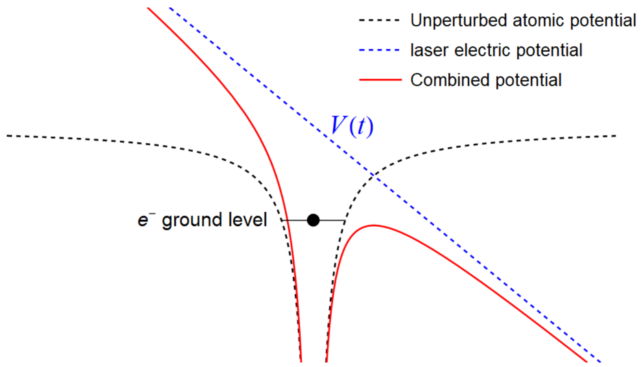

Fig. 1. Electrical potential of an hydrogen atom submitted to an intense laser electric field [17].

This critical electric field is the threshold for the Ionization above the Coulomb Barrier [18, 19], also known as suppression of the barrier regime[20, 21], and above it most probably the atoms are all ionized. Another important quantity in the high intensity field interaction with the atoms is the average kinetic energy that the electrons gain in the quivering movement due to the laser field, which is called the ponderomotive energy, U_p, given by:

$$U_P = (E^2 e^2)/(4\omega^2 m_e), \tag{4}$$

where e and m_e are the electron charge and mass, respectively, and ω is the laser central (carrier) frequency. Alternatively, U_P can be written as [22]:

$$U_P(\text{MeV}) = 9.3\cdot 10^{-20}\,(I\cdot\lambda^2), \tag{5}$$

where I is given in W/cm^2 and λ in µm. The reference energy is the electron rest mass, 0.511 MeV, which corresponds to an intensity of ~$9\cdot 10^{18}$ W/cm^2 at the peak emission of the Ti:Sapphire laser (800 nm).

II. Electron Acceleration by the Laser-Plasma Interaction

From the previous considerations, it is possible to accelerate electrons to relativistic energies, in the quivering movement, for high laser intensities. (> $9\cdot 10^{18}$ W/cm^2@ 800 nm) [23]. At this point the Lorentz force, F_L, must be considered:

$$\mathbf{F}_L = e\cdot(\mathbf{E} + \mathbf{v}\times\mathbf{B}), \tag{6}$$

where **E** and **B** (**B**=μ_0**H**, and μ_0 is the magnetic permeability) are perpendicular, and the electron velocity **v** is initially parallel to **E.** Therefore, a component of the force is now towards the longitudinal direction, along the propagation direction of the laser beam. For these high intensities, the electron beam starts to propagate in a lobule aiming to follow the laser beam. This is the *Laser Direct Acceleration* (LDA) and it occurs much after the whole medium is ionized. With this initial condition that the medium is ionized and continues to get ionized as the laser beam passes through it, a moving plasma is formed that will be propagated with the group velocity of the pulse in this medium. In this condition, besides the electrical field of the laser, a new dynamical electrical force appears due to the action of the laser field ionization and the ponderomotive force that will separate the electrons and ions of the medium [24]. For an overdense medium, the ionization can increase and reach the critical density, at which the laser field cannot penetrate the plasma. This is typical in solids. For underdense plasmas, the medium responds with its own eigenvalue, the classical plasma frequency ω_p, given by:

$$\omega_p = [(n_e\cdot e^2)/(m_e\cdot\varepsilon_0)]^{1/2}, \tag{7}$$

which is only a function of the density of free electrons, n_e. Therefore, the maximum critical frequency ($\omega = \omega_p$) defines a critical electron density, given by:

$$n_C = (\varepsilon_0\cdot m_e\cdot\omega_c^2)/e^2, \tag{8}$$

which is $1.8\cdot 10^{21}$ electrons/cm^3 for an 800 nm laser wavelength.

The ionization follows the laser pulse and the ponderomotive force expels the electrons from the peak of the laser pulse. The cations attract the electrons with a restorative force that causes oscillations at the plasma frequency ω_p, and a wake is formed that travels at the speed of the pulse (group velocity). Injected background electrons in this wakefield are pushed forward by the intense longitudinal electric fields. This is the acceleration scheme proposed by Tajima and Dawson four decades ago [25].

In conventional accelerators, the maximum electric field is on the order of 10^9 V/cm (limited by the materials dielectric breakdown), which corresponds to a laser intensity around 10^{14} W/cm^2; nowadays, laser used in particle accelerations are achieving 10^{22} W/cm^2 [1], what corresponds to electric fields at least $10^3\times$ greater than in conventional accelerators, drastically reducing their size.

III. The Resonant Regime – Bubble Regime

The ionization and charge distribution processes are enhanced by a resonant mechanism that matches the pulse length to a semi period of the plasma wave ($\lambda_p/2 = c\cdot\Delta t$) and to the transverse dimension (the radius of the laser beam w_0). In a simple picture, the electron that is pushed away by the ponderomotive force comes back to a place at the end of the laser pulse, oscillating with the same amplitude in both ways ($c\cdot\Delta t = w_0$). This is called the optimized bubble regime [26, 27], and in 2004 three different groups [28-30] immediately generated high energy monoenergetic electrons and collimated beams. This idea allowed the acceleration of electrons to several GeV in few cm of plasma [9, 31].

The remaining important part is also the injection of electrons into the wakefield [15] that is already moving with almost the speed of the light. One of the obvious ways is to use the DLA, what requires very high intensities usually achieved by the self-focusing [32] regime, which has a critical power P_c given by:

$$P_c = 17(\omega/\omega_p)^2\ \text{GW} = 17\ (n_c/n_e). \tag{9}$$

IV. The Laser Electron Acceleration by the Self-Modulated Regime

The requirements to produce the bubble regime demand very high intensity lasers. For laser pulse duration of tens of femtoseconds, the optimized bubble regime resonance requires peak powers in the range of hundreds of TW, and there are few of these systems still now. Besides, they work at low repetition rates, what is inadequate for practical applications. Recently, with the increased demand on these high intensity systems with higher repetition rates, TW systems with kHz rep rates are becoming available. Also, recent promising results demonstrate kHz repetition rate electron acceleration with few mJ and tens of femtoseconds pulses in a regime in which $\lambda_p \ll c{\cdot}\Delta t$ (pulse length much longer than the plasma wavelength), exploring the self-modulation instability of the laser-plasma interaction, requiring very dense plasmas [33-36]. This requirement also helps the electrons injection by the self-focusing mechanism. Thus, the laser system peak power must fulfill the critical power condition stated by (9). As close the electron population is to $n_c = 1.7{\cdot}10^{21}$ e^-/cm^3, systems with peak powers as low as ~20 GW, close to standard amplified laser systems widely available, can be used. Up to now, these electron beams are not as collimated and monoenergetic as the ones obtained in the bubble regime, in spite that relativistic energies were already reported [34]. Besides, the main drawback is that high-density plasma reduces the accelerator length to a few hundred µm.

V. Proton Laser Acceleration

The usual laser acceleration of protons is done by PW class lasers systems. One of the most accepted models to explain the process is the target normal sheath acceleration mechanism, TNSA [37], in which a thin foil of solid material is exposed to very high intensities (typically 10^{21} W/cm^2). At these intensities, the electrons suffer the LDA, acquiring kinetic energies much higher than their rest mass. The electrons leave the target mostly in the longitudinal direction (orthogonal to the target) and leave positively charged particles on the foil. These cations then repel themselves and the lighter ions (H^+ is the first one) are accelerated by the cations and attracted by the electrons. The best result of this process up to now is 100 MeV [38].

Recently, laser systems in the TW level could accelerate protons up to 2 MeV in high density liquids [39] and gases [40], with a common characteristic of producing large electrical fields in the interface of the target to the chamber. This requires the production of very sharp overdense targets, with very large density gradients, in order to create high charge densities. It must be pointed out that protons with few MeV (>5 MeV) make feasible nuclear reactions capable of producing radioisotopes [41, 42]. For a review of the state of the art of the ion acceleration see Daido et al [23]. Therefore, in the search for practical systems to accelerate particles it is indispensable to do it with TW or sub TW lasers that will also require compact targets in the solid or liquid state, with a precise spatial profile to match the plasma acceleration conditions. Jet nozzles became a crucial development in these laser acceleration schemes.

VI. Experimental Developments

Jet nozzles with the de Laval design are adequate to generate homogeneous supersonic gas profiles with sharp edges [43]. In order to produce the targets, conical jet nozzles with micrometric dimensions were fabricated in our lab by fs laser machining, which produce supersonic flows with a Mach number, M, dependent on the nozzle geometry. A pressurized backing chamber with adjustable pressure can produce a uniform gas region with high pressure, however, the micrometric dimensions ensure low mass flows. The gas jet generated by this type of nozzle also has steep inlet and outlet gradient regions, which are fundamental for either electron [44] or proton acceleration [40]. An experimental setup integrating a Mach-Zehnder interferometer and a schlieren shadowgraph imaging system was developed [45], shown in Fig. 2, to characterize the shape and the density of the gas target profile; Fig. 3 shows a shadowgram and an interferogram, both obtained in this setup, that indicate a supersonic jet with a $M \approx 2.5$ presented near the exit and a molecular density of $6{\times}10^{19}$ cm^{-3} for the nitrogen gas. New methods are being implemented to improve this characterization [46, 47], and several nozzles were designed and fabricated in our lab.

A Ti:Sapphire CPA laser system (Femtopower Compact Pro HR/HP, from Femtolasers) was used to demonstrate plasma generation in one of those developed supersonic gas targets. This system generates 25 fs (FWHM) pulses centered at 785 nm, with 350 µJ of energy, in a $M^2 \approx 1.2$ beam, at 4 kHz repetition rate. The beam was focused by a parabolic mirror (90° off-axis with 2.54 cm aperture and 5 cm focusing distance) for a 4 µm beam waist (imaged in a CCD with a 10× magnification), comprising 75% of the pulse energy. The intensity reached at the focus was $2.1{\cdot}10^{16}$ W/cm^2. Using a LIBS technique, we could identify the presence of N^{3+} in the created plasma [45].

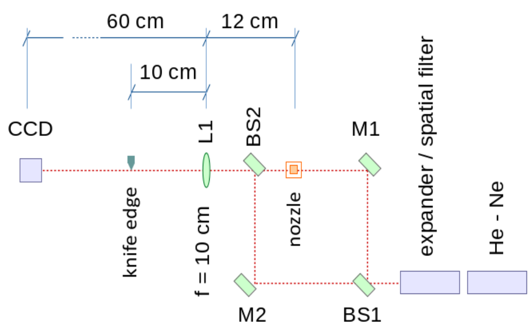

Fig. 2. Setup for the measurement of the gas jet profile and its density through schlieren imaging and Mach–Zehnder interferometry, respectively.

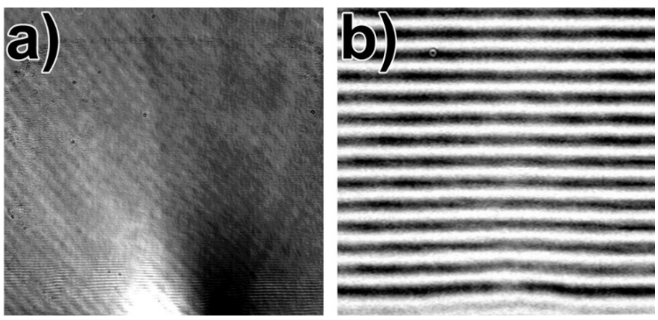

Fig. 3. Optical characterization of the gas jet generated by a nozzle in the lower part of the images (not shown) [45]. a) shadowgram of a supersonic gas jet with $M \approx 2.5$. b) Interferogram showing a pressure of ~2 atm near the nozzle exit, corresponding to a $\sim 1{\cdot}10^{20}$ cm^{-3} density.

Now our group is advancing in different fronts to improve our experimental setup to generate and detect beams of laser-accelerated particles, starting with the acceleration of electrons. Based in our expertise in developing a ½ TW Cr:LiSAF amplifier stage for a hybrid CPA system [48, 49], we are now building a Ti:Sapphire amplification stage and integrating it to a CPA system to reach the 1 TW region, albeit at a low repetition rate (~10 Hz), to obtain conditions to accelerate the electrons. Also, two new interferometers are being developed: the first one using a 543 nm CW HeNe laser to characterize the gas target profiles generated by the homemade de Laval nozzles, and a second one, using the 2nd harmonic of the laser pulses (at 400 nm) to synchronously characterize the plasma generated at the focus of the parabolic mirror and monitor the formation and evolution of the wakefield. New numerical codes are being run to simulate our experimental conditions and to guide us to obtain the electron beams in optimized ways. Electron detection devices are being built based on fluorescent materials that detect the electrons, in experimental setups that allow the determination of their energy. Besides, our collaboration with the University of Nebraska-Lincoln will allow us to also test our ideas in their setups, taking advantage of their expertise in this area.

VII. Discussion

In order to perform electron acceleration with our sub-TW laser system, the experiment must be designed in the self-modulated regime. This requires a high-density electron plasma to achieve the self-modulated wakefield and the electron injection by self-focusing. To reach these conditions, the capability of manufacturing our own jet nozzles is an advantage, and allows us to search for the ideal gas profile for the specific laser-plasma interaction needed to obtain the Laser Wakefield electron Acceleration process, lowering the laser threshold requirements for the self-modulated regime.

We initially obtained a well-defined gaseous target using a homemade de Laval nozzle, which close to its exit presented a high density of atoms in a supersonic flow. Using parabolic mirror focusing, we have then generated a final electron density of $3.6{\cdot}10^{20}$ e^-/cm^3, or ~1/5 of the critical electron population, given by (9). The correspondent plasma wavelength is 1.7 µm and the laser pulse length is $c{\cdot}\Delta t = 7.5$ µm, and this condition is adequate to the self-modulated regime, but the available peak power was still below the critical power for self-focusing.

We have recently obtained 100 µm wide gas jets with atomic densities up to $6{\cdot}10^{20}$ cm^{-3}, which for the N^{3+} case exceeds the critical density. Also, an extra amplifying stage is being built to increase the pulse energy to a few millijoules in order to achieve the conditions for the electrons injection by self-focusing.

Another import limitation of the gas nozzles we can produce is the acceleration length, that will determine the final kinetic energy of the electrons.

The experiments developed in our lab are being simulated by PIC models that can predict the injection conditions of the plasma, the magnitude of the Wakefield and the final energy of the electrons as a function of the gas parameters and laser pulses characteristics. The resultant electron beams geometrical characteristics depend on the electric field that is a function of the charge distribution in the Wakefield, requiring more detailed 3D simulations. These distributions also depend on the laser polarization and are crucial for applications, needing further studies.

Finally, shortening the pulse duration to a few fs will allow us to achieve the resonant conditions in the so called λ^3 regime, because in this case all the dimensions scale with the pulse length. This condition imposes severe requirements on the temporal and spatial conformation of the pulse as well as on the optics, but will allow the increase of the repetition rate for the acceleration process, what favors the practical use of the particle beams generated [13], an important trend to be considered.

This particle acceleration program starts with the electrons, which are already useful to medical applications, mainly in high-resolution x-ray imaging. The target conditions are crucial to these experiments and are very similar to the new possibilities for proton acceleration in high density targets (gases and liquids) that are in the threshold of producing tabletop nuclear reactions, that can be applied to radioisotope production. However, Protontherapy that is the final goal, requires more energetic protons and ions.

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