ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR – ABEN
2019 International Nuclear Atlantic Conference - INAC 2019
Santos, SP, Brazil, October 21-25, 2019

Agência Brasileira do ISBN
ISBN 978-85-99141-08-3

LASER PARTICLE ACCELERATION IN BRAZIL

Nilson D. Vieira Jr.[1], Sudeep Banerjee[2], Edison P. Maldonado[3], Armando V. F. Zuffi[1], Fabio B. D. Tabacow[1] and Ricardo E. Samad[1]

[1]Instituto de Pesquisas Energéticas e Nucleares - IPEN-CNEN/SP
Av. Professor Lineu Prestes 2242
05508-000, São Paulo, SP, Brazil
nilsondv@ipen.br
armandozuffi@gmail.com
fabio.tabacow@gmail.com
resamad@gmail.com

[2]University of Nebraska-Lincoln
1400 R Street
Lincoln, NE 68588
sudeep@unl.edu

[3]Instituto Tecnológico de Aeronáutica - ITA
Pça. Mal. Eduardo Gomes 122
12228-615, São José dos Campos, SP, Brazil
puig@ita.br

ABSTRACT

The fast-growing field of particle acceleration using lasers is now in a new trend due to an enormous worldwide effort to increase the peak power of femtosecond laser systems, as well as increasing the average power of these systems in order to make them useful for applications. The most spectacular example of investment in this area 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). The decade's long progress in this area is being celebrated by the conferment of the 2018 Nobel Prize in Physics to Gerard Mourou and Donna Strickland, who pioneered the technique of Chirped Pulse Amplification, on which all modern-day ultrashort and ultra-intense lasers are based. These lasers can produce extreme conditions that mimic the ones found in stellar cores. 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. Laser particle accelerators are compact and need less radiation shielding, predicting a significant cost reduction with impact in the widespread use, mostly in medicine.

1. 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 now in excess of 10^{22} W/cm^2 [1]. This achievement was due to improvements in solid state laser materials (better homogeneity, lower nonlinearities, higher damage threshold, superior optical and thermal properties, etc.) allowing good laser optical cycles and broad emission bandwidths. Particularly, Ti:Al_2O_3 crystals [2] are the leading laser materials in this trend, presenting an emission bandwidth capable of supporting few fs optical pulses. Regimes of operation became very reliable, like the Kerr Lens Modelocking [3], which produces pulses with very short duration, leading to efficient ways of obtaining high peak powers as a consequence of the pulses short duration instead of an increase of their energy. This capability enabled the advent of the Chirped Pulse Amplification, CPA, technique [4], which stretches the pulse temporally, decreasing its peak power during amplification, and recompresses the pulse to its minimum duration only at the end of the amplification chain. After the incorporation of these features in the laser systems, the peak power showed a steep growth, still in progress, as can be seen in Fig. 1.

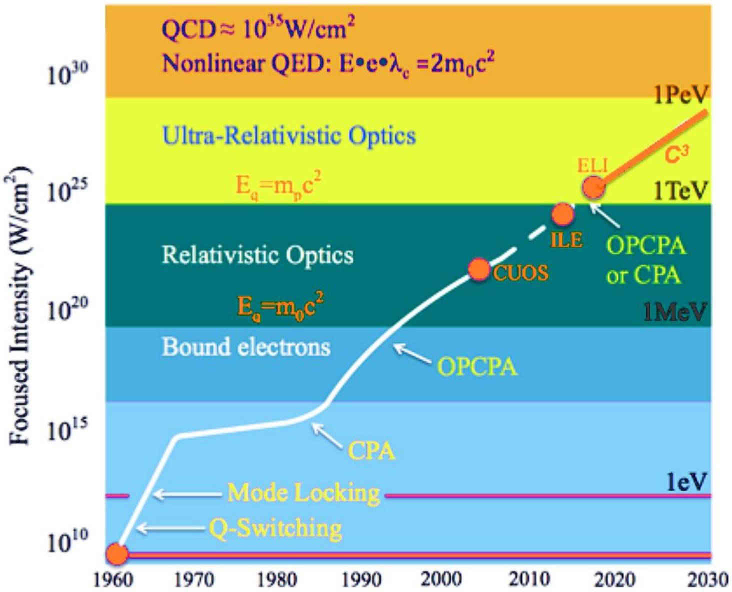

Figure 1: Evolution of the maximum laser focused intensities, with the name of the techniques used, and regions of the most important physical events in the laser-matter interaction, with respective characteristic energies [5].

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 the free electrons and protons are accelerated by the light field and by the plasma field. This technique in conjunction with PW peak power pulses has already produced 100 MeV proton beams and near GeV electrons in centimeters scale targets. Among the several efforts that take advantage of these new systems, the research team at University of Nebraska-Lincoln (UNL), which possess one of the most intense lasers in the world, 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 [6]. Considering the main current scientific efforts in this area, noteworthy are the European programs *Extreme Light Infrastructure* (ELI) [7], which has led to the establishment of three large research facilities in the Czech Republic, Romania and Hungary, as well as the USA *LaserNetUS* [8], which comprises all the large laser facilities in US. The University of Nebraska-Lincoln research team is part of this net. The drawback in the case of these high peak power systems is that there is still a challenge in increasing the repetition rate of these large systems, which are of a few hertz at most. In spite of this, due to the impact on basic science and applications, the number of high intensity laser systems is growing worldwide. *The International Committee on Ultra-High Intensity Lasers* [9] provides useful information on the area, such as the map of the Intense Laser Facilities World Wide ($I \geq 10^{19}$ W/cm^2), which is reproduced in figure 2. Also, in the ICUIL website, it is possible to see the evolution of the number of these systems since 2009. There is no such system in the southern hemisphere.

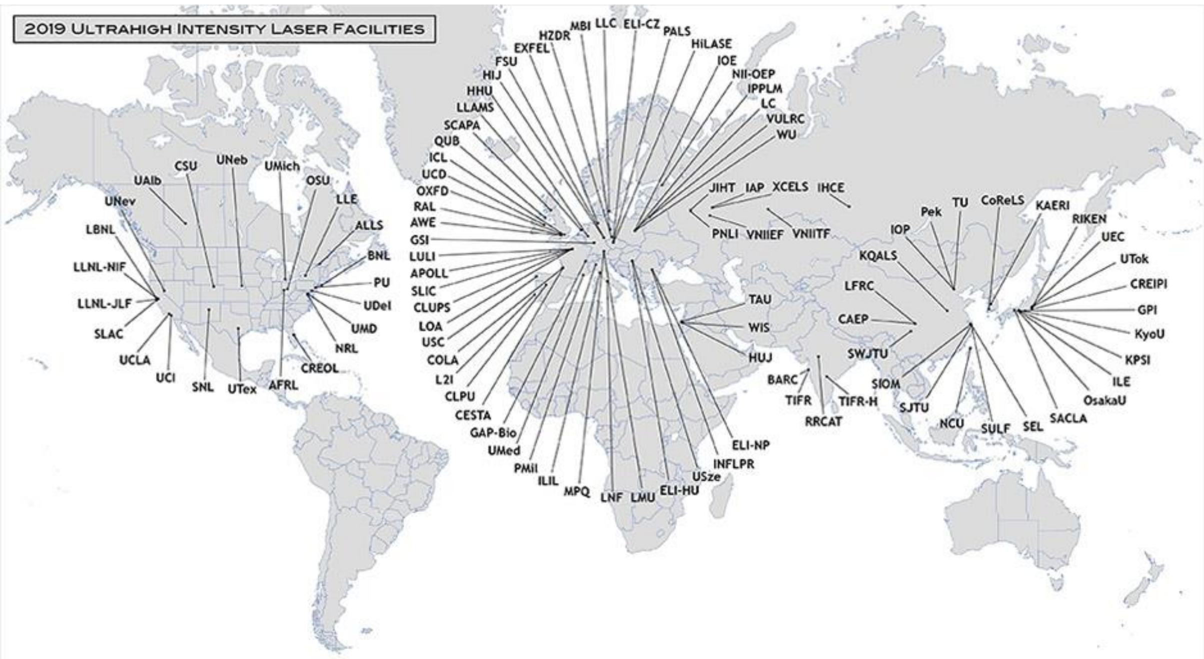

Fig. 2 World map of the High intensity laser Labs (https://www.easymapmaker.com/map/2e8aa0ac172a517adcf031a195ed81e7)

With the recent advances in proton and electron laser acceleration at kHz repetition rates, new areas of applications of these new accelerators are emerging. This class of lasers, not very common yet, are within the scope of medium size research laboratories, like the one we have at IPEN. We are starting this program aiming to produce radiation beams to be used in medical applications like X ray and electron therapy, nuclear reactions and, eventually, protontherapy. With this goal, members of IPEN and ITA have recently joined up efforts with the UNL team. Recently, a collaboration program was also initiated with two theoretical groups from a southern state, Rio Grande do Sul. With the recent advances in proton and electron laser acceleration with medium size laser systems and high repetition rates [10], new areas of applications of these new accelerators are emerging. A brief overview of the main aspects of the electromagnetic interaction in such systems will be given. There are excellent reviews[11, 12] and textbooks[13, 14] that describe the following developments.

2. THEORETICAL FUNDAMENTALS

The laser intensity is related to the electromagnetic field by the Poynting vector that, in the case of vacuum, is reduced to

$$I = \tfrac{1}{2}\cdot c \cdot \varepsilon_0 |E|^2, \tag{1}$$

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:

$$E(\text{V/cm}) = 27.5\ \sqrt{I}(\text{W/cm}^2). \tag{2}$$

For the Bohr atomic model, an intensity of $1.37 \cdot 10^{14}$ W/cm^2 produces an electric field that equals the coulomb attractive field of the atom, suppressing the barrier, as shown schematically in Fig. 3, for a defined time. At this moment the suppressed Coulomb barrier releases the electron.

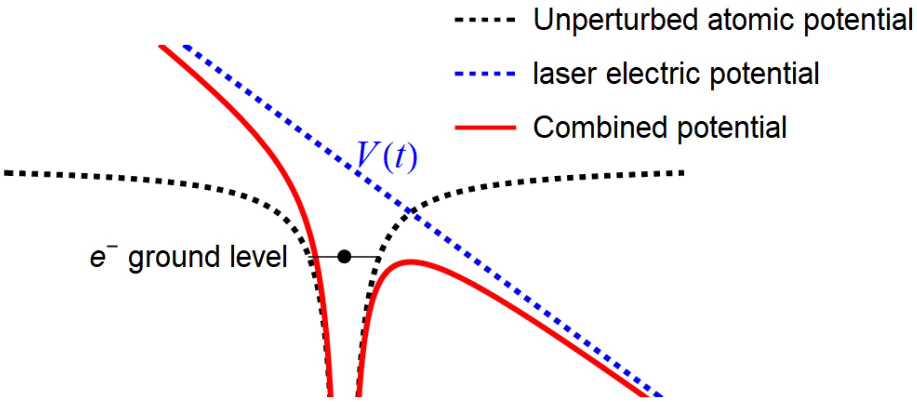

Fig.3 Schematic of the electrical potential of an atom submitted to an intense laser electric field [15].

This critical electric field is the threshold for the ionization above the Coulomb barrier [16, 17], also known as suppression of the barrier regime[18, 19], and above this value, most probably all the atoms are ionized. Another important quantity in the high intensity field interaction with the atoms is the time averaged kinetic energy that the electrons gain in the transverse quivering movement due to the laser electrical field, which is called the ponderomotive energy, U_P, given by:

$$U_P = (E^2 e^2)/(4\omega^2 m_e) = 9.3 \cdot 10^{-20} (I \cdot \lambda^2), \qquad (3)$$

where e and m_e are the electron charge and mass, respectively, and ω is the laser central (carrier) frequency [20], 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 $\sim 9 \cdot 10^{18}$ W/cm^2 at the peak emission of the Ti:Sapphire laser (800 nm).

2.1. Electron Acceleration by the Laser-Plasma Interaction

From the previous considerations, it is possible to accelerate electrons to relativistic energies, in the quivering motion, for high laser intensities ($> 9 \cdot 10^{18}$ W/cm^2@ 800 nm) [21]. At this point the Lorentz force, F_L, is enhanced by the magnetic effect:

$$\mathbf{F}_L = e \cdot (\mathbf{E} + \mathbf{v} \times \mathbf{B}), \qquad (4)$$

where **E** and **B** are the mutually orthogonal electric and magnetic vector fields, respectively, and the electron velocity **v** can be assumed to be initially parallel to **E.** Therefore, a component of the force is now towards along the propagation direction of the laser beam (forward direction, in a lobule following the laser beam). This is a form of *Laser Direct Acceleration* (LDA). With this initial condition that the medium is ionized and continues to get ionized as the laser pulse 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* will separate the electrons and ions of the medium [22]. For under dense plasmas, the medium then responds with its own eigenvalue, the classical plasma frequency ω_p, given by:

$$\omega_p = [(n_e \cdot e^2)/(m_e \cdot \varepsilon_0)]^{1/2}, \tag{5}$$

which is only a function of the density of free electrons, n_e. The plasma group velocity, v_G, for the laser pulse is:

$$v_G = c \cdot [1 - (\omega_p / \omega)^2]^{1/2}. \tag{6}$$

Therefore, the maximum critical plasma frequency defines a critical electron density, given by:

$$n_C = (\varepsilon_0 \cdot m_e \cdot \omega_c^2)/e^2, \tag{7}$$

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 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 [23].

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 three orders of magnitude greater than in conventional accelerators, drastically reducing their size.

2.2. 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 beam 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 [24, 25]. In 2004 three different groups [26-28] almost simultaneously generated for the first time high energy monoenergetic electrons and collimated beams, using the resonant regime. This idea allowed the acceleration of electrons to several GeV in a few cm of plasma [29, 30].

The remaining important part is also the injection of electrons into the wakefield [12], which 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 [31] regime, which happens above a critical power, P_c, given by:

$$P_c = 17(\omega/\omega_p)^2 \text{ GW} = 17\ (n_c/n_e) \text{ GW}. \qquad (8)$$

2.3. 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 resonance bubble regime 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 (few Hz or lower), what is inadequate for practical applications. Recently, with the increased demand of these high intensity systems with higher repetition rates, TW systems with kHz repetition rates are becoming available. Also, recent promising results demonstrate kHz electron acceleration with a 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 [32-35]. 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 expression (8) [11]. As close the electron density is to $n_c = 1.8{\cdot}10^{21}$ 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, but relativistic energies were already reported [33]. Besides, the main drawback is that the high-density plasma reduces the acceleration length to a few hundred μm.

2.4. Proton Laser Acceleration

The usual laser acceleration of protons is done by PW-class lasers. One of the most accepted models to explain the process is the *target normal sheath acceleration* mechanism, TNSA [36], in which a thin foil of solid material is exposed to very high intensities (typically 10^{21} W/cm^2). The electrons suffer the LDA, acquiring kinetic energies much higher than their rest mass in a few μm of acceleration length, in the fs time scale. 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 proton kinetic energy [37]. Figure 4 depicts the physical picture of this mechanism [38].

Recently, it has been demonstrated that laser systems in the TW level can accelerate protons up to 2 MeV in high density liquids [39], as well as in critical density gas targets [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 boundary targets for the interaction, with very large density gradients in order to create high-contrast electric charge distributions.

It must be pointed out that protons with few MeV (>5 MeV) make feasible table top nuclear reactions, already capable of producing radioisotopes [41, 42], as can be seen in figure 5 that shows the reaction cross section energy dependence for the production of several of the short-lived radioisotopes of medical interest, and among them, ^{18}F that is necessary for the most used radiopharmaceutical, the ^{18}F-FDA (marked fludeoxyglucose molecule).

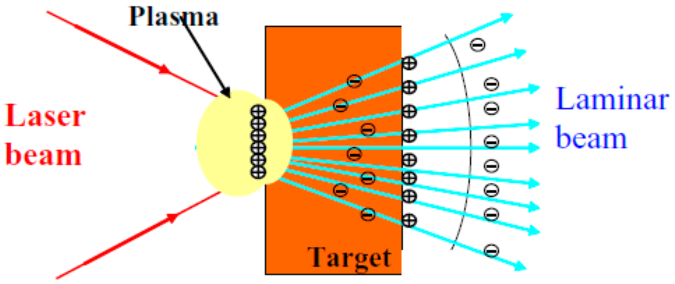

Figure 4. Plasma scheme formed by a high-intensity laser pulse producing relativistic electron beams and ion beams, including protons [38].

Therefore, in the search for practical systems to accelerate particles it is indispensable to do it with TW or sub TW lasers that will require compact flowing targets in the solid or liquid state, with a precise spatial profile to match the plasma acceleration conditions. Supersonic jet nozzle technology became a crucial development in these laser acceleration schemes.

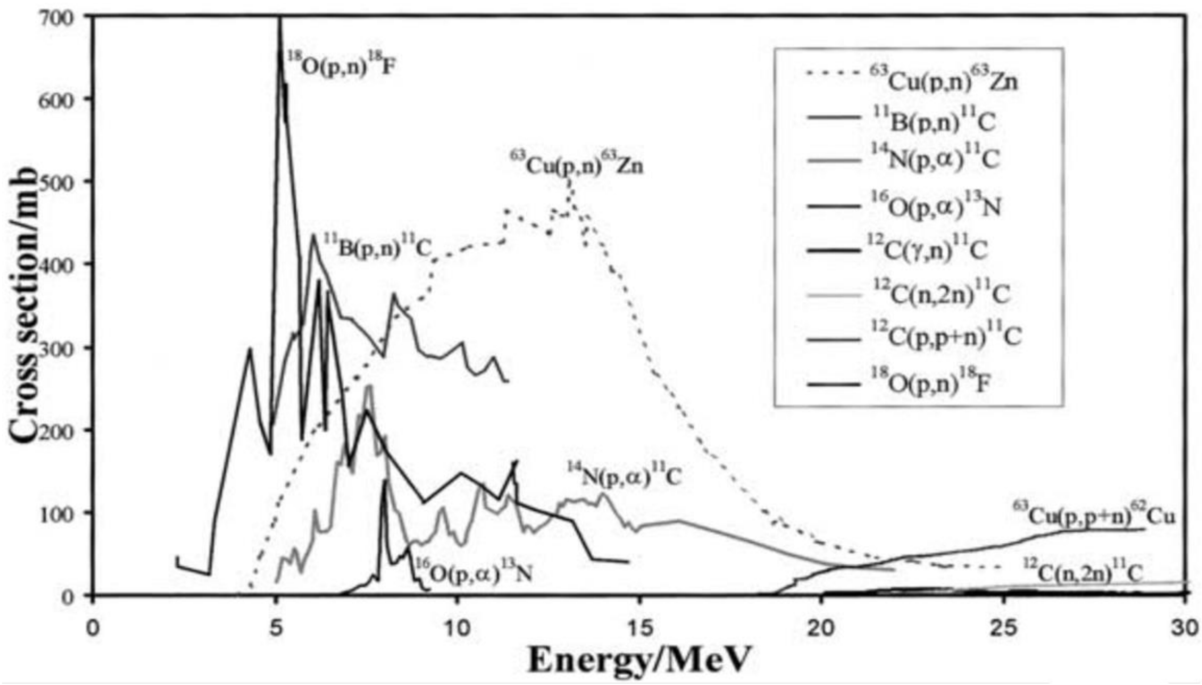

Figure 5. Reaction cross section of several elements as a function of the kinetic energy of the proton [43].

3. STATUS OF THE PROGRAM

The main components of the laser acceleration process are high intensity laser system technology, targetry and particle detection systems, besides modal simulation to define the experimental conditions.

3.1. Experimental developments

Jet nozzles with the de Laval design are adequate to generate homogeneous supersonic gas profiles with sharp edges [44]. 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 electron [45] and proton acceleration [40]. An experimental setup integrating a Mach-Zehnder interferometer and a schlieren shadowgraph imaging system was developed and built [46], shown in Fig. 6, to characterize the shape and the density of the gas target profile; Fig. 7 shows a shadowgram and an interferogram, both obtained in this setup, that indicate a nitrogen supersonic jet with a $M \approx 2.5$ presented near the exit, and a molecular density of 6×10^{19} cm^{-3}. New methods are being implemented to improve this characterization [47, 48], and several nozzles have been designed and fabricated in our laboratory.

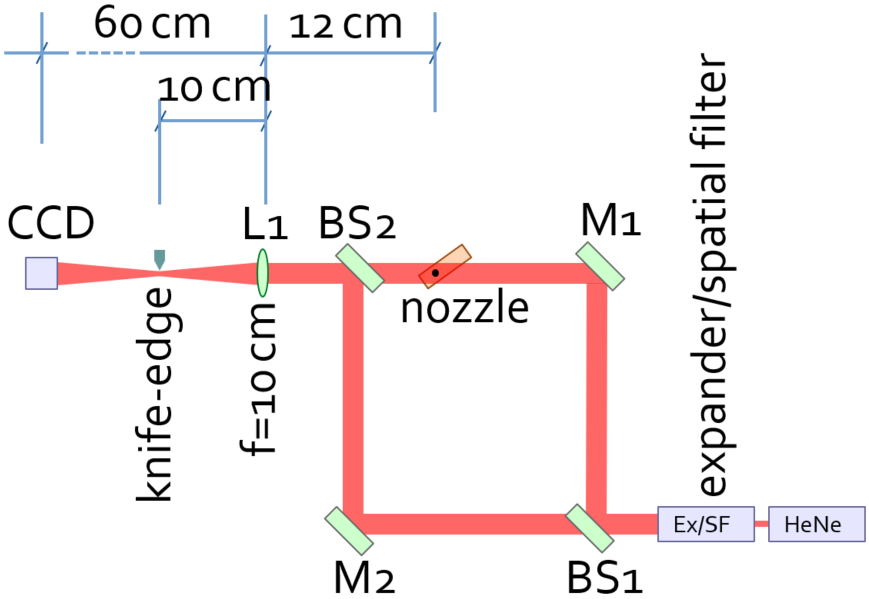

Fig. 6. Setup for the measurement of the gas jet profile and its density through schlieren imaging and Mach–Zehnder interferometry.

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 [49, 50], we are now building a Ti:Sapphire amplification stage and integrating it to a CPA system to reach above 1 TW, 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 is an enhanced c.w. green laser setup to characterize the gas target profiles generated by the homemade de Laval nozzles, and the second is a blue, fs-laser probe setup to synchronously characterize the plasma generated at the focus of a parabolic mirror and monitor the formation

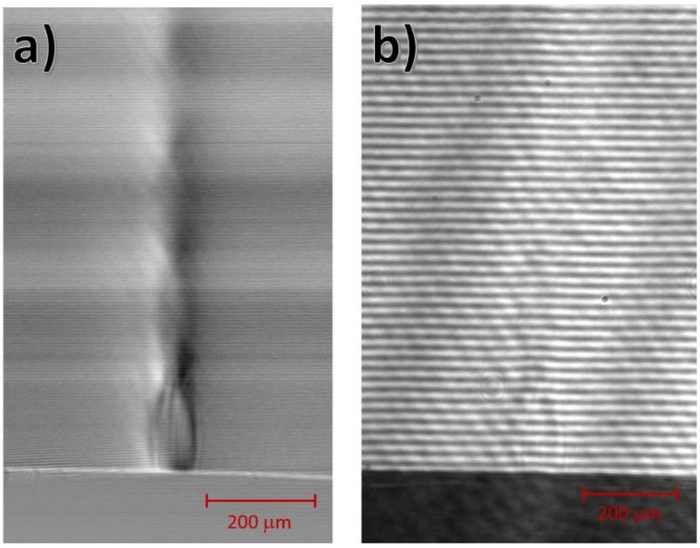

Fig.7 Optical characterization of the gas jet generated by a nozzle in the lower part of the images (not shown) [46]. a) shadowgram of a supersonic gas jet with M≈2. b) Interferogram showing a pressure of 9 atm ~200 µm above the nozzle, corresponding to a ~$4.5 \cdot 10^{20}$ atoms/cm^3 density.

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. A custom-designed, for the expected laser-accelerated electron beams, fast response Faraday cup device is now being developed at ITA. 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. 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 90° off-axis parabolic mirror with 2.54 cm aperture and 5 cm focusing distance, to 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 [46].

4. CONCLUSIONS

The experiments will start with electron acceleration in the self-modulated regime, which requires peak powers achievable in medium size laboratories, like the one at IPEN. The experimental conditions using hydrogen gas were theoretically simulated in the spectral particle-in-cell algorithm FBPIC that showed that a 2 TW laser system will accelerate electrons to the MeV range of energies. This requires gaseous targets properly designed that will be generated by laser machined de Laval nozzles. Besides, experiments with similar conditions will be carried at UNL that will confirm the experimental setup conditions in advance by adjusting their laser parameters to our conditions. The target production control is crucial also for the proton acceleration experiments that will require high densities and sharp boundaries with different types of liquids and/or gases. In this case, new conditions for proton acceleration have not been found to increase the proton energy to several MeV range. In order to use this acceleration mechanisms for protontherapy, energies above 200 MeV will be required to match the proton energy conditions provided by cyclotrons technology. The proton laser plasma acceleration is an area of promising fundamental investigation.

ACKNOWLEDGMENTS

We wish to acknowledge the financial support of FAPESP under grants number 2017/50332-0 and 2018/25961-7. and CNPq for grant 300616/2017-1.

REFERENCES

1. National Academies of Sciences Engineering and Medicine, *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*, The National Academies Press, Washington, DC (2018).
2. D. Yu, Y. He, K. Zhang, Q. Pan, F. Chen, and L. Guo, "A Tunable Mid-Infrared Solid-State Laser with a Compact Thermal Control System," *Appl. Sci.* **8**, pp.878 (2018).
3. U. Keller, "Ultrafast solid-state laser oscillators: a success story for the last 20 years with no end in sight," *Appl. Phys. B-Las. Opt.* **100**, pp.15-28 (2010).
4. D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses," *Opt. Commun.* **56**, pp.219-221 (1985).
5. G. A. Mourou, N. J. Fisch, V. M. Malkin, Z. Toroker, E. A. Khazanov, A. M. Sergeev, T. Tajima, and B. Le Garrec, "Exawatt-Zettawatt pulse generation and applications," *Opt. Commun.* **285**, pp.720-724 (2012).
6. G. Golovin, W. Yan, J. Luo, C. Fruhling, D. Haden, B. Zhao, C. Liu, M. Chen, S. Chen, P. Zhang, S. Banerjee, and D. Umstadter, "Electron Trapping from Interactions between Laser-Driven Relativistic Plasma Waves," *Phys. Rev. Lett.* **121**, pp.104801 (2018).
7. ELI-DC AISBL, "ELI Delivery Consortium | Home" (2019), retrieved June 2019, https://eli-laser.eu/.
8. U.S. Department of Energy, "Welcome to LaserNetUS | LaserNetUS" (2019), retrieved Jun 2019, https://www.lasernetus.org/.
9. "The International Committee on Ultra-High Intensity Lasers" (ICUIL), retrieved Jul 2019, 2019, https://www.icuil.org/.
10. J. Faure, D. Gustas, D. Guénot, A. Vernier, F. Böhle, M. Ouillé, S. Haessler, R. Lopez-Martens, and A. Lifschitz, "A review of recent progress on laser-plasma acceleration at kHz repetition rate," *Plasma Phys. Contr. Fus.* **61**, pp.014012 (2019).
11. T. Tajima, K. Nakajima, and G. Mourou, "Laser acceleration," *Riv. Nuovo Cimento* **40**, pp.33-U102 (2017).
12. V. Malka, "Laser plasma accelerators," *Phys. Plasmas* **19**, pp.055501 (2012).
13. A. Giulietti, "Laser-driven particle acceleration towards radiobiology and medicine," in *Biological and medical physics, biomedical engineering*, (Springer, Switzerland, 2016),Vol. 1 online resource (xviii, 320 pages).
14. J. A. Bittencourt, *Fundamentals of plasma physics*, 3rd ed., Springer, New York (2004).
15. A. S. Kornev and B. A. Zon, "Keldysh theory of tunnel ionization of an atom in a few-cycle laser pulse field," *Phys. Rev. A* **85**, pp.(2012).
16. L. V. Keldysh, "Ionization in the Field of a Strong Electromagnetic Wave," *Sov. Phys. JETP-USSR* **20**, pp.1307-1314 (1965).

17. V. S. Popov, "Tunnel and multiphoton ionization of atoms and ions in a strong laser field (Keldysh theory)," *Physics-Uspekhi* **47**, pp.855-885 (2004).
18. A. Scrinzi, M. Geissler, and T. Brabec, "Ionization Above the Coulomb Barrier," *Phys. Rev. Lett.* **83**, pp.706-709 (1999).
19. T. Topcu and F. Robicheaux, "Dichotomy between tunneling and multiphoton ionization in atomic photoionization: Keldysh parameter γ versus scaled frequency Ω," *Phys. Rev. A* **86**, pp.(2012).
20. Z. Chang, *Fundamentals of attosecond optics*, Taylor & Francis, Boca Raton (2011).
21. H. Daido, M. Nishiuchi, and A. S. Pirozhkov, "Review of laser-driven ion sources and their applications," *Rep. Progr. Phys.* **75**, pp.056401 (2012).
22. D. Umstadter, "Review of physics and applications of relativistic plasmas driven by ultra-intense lasers," *Phys. Plasmas* **8**, pp.1774-1785 (2001).
23. T. Tajima and J. M. Dawson, "Laser electron-accelerator," *Phys. Rev. Lett.* **43**, pp.267-270 (1979).
24. A. Pukhov, S. Gordienko, S. Kiselev, and I. Kostyukov, "The bubble regime of laser–plasma acceleration: monoenergetic electrons and the scalability," *Plasma Phys. Contr. Fus.* **46**, pp.B179-B186 (2004).
25. A. Pukhov and J. Meyer-ter-Vehn, "Laser wake field acceleration: the highly non-linear broken-wave regime," *Appl. Phys. B-Las. Opt.* **74**, pp.355-361 (2002).
26. C. G. R. Geddes, C. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans, "High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding," *Nature* **431**, pp.538-541 (2004).
27. S. P. D. Mangles, C. D. Murphy, Z. Najmudin, A. G. R. Thomas, J. L. Collier, A. E. Dangor, E. J. Divall, P. S. Foster, J. G. Gallacher, C. J. Hooker, D. A. Jaroszynski, A. J. Langley, W. B. Mori, P. A. Norreys, F. S. Tsung, R. Viskup, B. R. Walton, and K. Krushelnick, "Monoenergetic beams of relativistic electrons from intense laser-plasma interactions," *Nature* **431**, pp.535-538 (2004).
28. J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J. P. Rousseau, F. Burgy, and V. Malka, "A laser-plasma accelerator producing monoenergetic electron beams," *Nature* **431**, pp.541-544 (2004).
29. W. Leemans, "High power laser technology for accelerators," in *Beam Dynamics Newsletter*, W. Leemans, W. Chou, M. Uesaka and W. Chou, eds. (International Committee for Future Accelerators, 2011), pp. 10-88.
30. W. P. Leemans, A. J. Gonsalves, H. S. Mao, K. Nakamura, C. Benedetti, C. B. Schroeder, C. Toth, J. Daniels, D. E. Mittelberger, S. S. Bulanov, J. L. Vay, C. G. Geddes, and E. Esarey, "Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime," *Phys. Rev. Lett.* **113**, pp.245002 (2014).
31. S. P. D. Mangles, G. Genoud, M. S. Bloom, M. Burza, Z. Najmudin, A. Persson, K. Svensson, A. G. R. Thomas, and C. G. Wahlström, "Self-injection threshold in self-guided laser wakefield accelerators," *Phys. Rev. ST Accel. Beams* **15**, pp.(2012).
32. A. J. Goers, G. A. Hine, L. Feder, B. Miao, F. Salehi, J. K. Wahlstrand, and H. M. Milchberg, "Multi-MeV Electron Acceleration by Subterawatt Laser Pulses," *Phys. Rev. Lett.* **115**, pp.194802 (2015).
33. F. Salehi, A. J. Goers, G. A. Hine, L. Feder, D. Kuk, B. Miao, D. Woodbury, K. Y. Kim, and H. M. Milchberg, "MeV electron acceleration at 1 kHz with <10 mJ laser pulses," *Opt. Lett.* **42**, pp.215-218 (2017).
34. D. Woodbury, L. Feder, V. Shumakova, C. Gollner, R. Schwartz, B. Miao, F. Salehi, A. Korolov, A. Pugzlys, A. Baltuska, and H. M. Milchberg, "Laser wakefield acceleration with mid-IR laser pulses," *Opt. Lett.* **43**, pp.1131-1134 (2018).

35. A. Yamazaki, H. Kotaki, I. Daito, M. Kando, S. V. Bulanov, T. Z. Esirkepov, S. Kondo, S. Kanazawa, T. Homma, K. Nakajima, Y. Oishi, T. Nayuki, T. Fujii, and K. Nemoto, "Quasi-monoenergetic electron beam generation during laser pulse interaction with very low density plasmas," *Phys. Plasmas* **12**, pp.093101 (2005).
36. M. Passoni, L. Bertagna, and A. Zani, "Target normal sheath acceleration: theory, comparison with experiments and future perspectives," *New J. Phys.* **12**, pp.045012 (2010).
37. A. Higginson, R. J. Gray, M. King, R. J. Dance, S. D. R. Williamson, N. M. H. Butler, R. Wilson, R. Capdessus, C. Armstrong, J. S. Green, S. J. Hawkes, P. Martin, W. Q. Wei, S. R. Mirfayzi, X. H. Yuan, S. Kar, M. Borghesi, R. J. Clarke, D. Neely, and P. McKenna, "Near-100 MeV protons via a laser-driven transparency-enhanced hybrid acceleration scheme," *Nat. Commun.* **9**, pp.724 (2018).
38. H. Daido, M. Nishiuchi, and A. S. Pirozhkov, "Review of laser-driven ion sources and their applications," *Reports on Progress in Physics* **75**, pp.(2012).
39. J. T. Morrison, S. Feister, K. D. Frische, D. R. Austin, G. K. Ngirmang, N. R. Murphy, C. Orban, E. A. Chowdhury, and W. M. Roquemore, "Corrigendum: MeV proton acceleration at kHz repetition rate from ultra-intense laser liquid interaction," *New J. Phys.* **20**, pp.069501 (2018).
40. P. Puyuelo Valdés, J. L. Henares, F. Hannachi, T. Ceccotti, J. Domange, M. Ehret, E. d'Humieres, L. Lancia, J.-R. Marquès, J. Santos, M. Tarisien, E. Esarey, C. B. Schroeder, and J. Schreiber, "Laser driven ion acceleration in high-density gas jets", Proc. SPIE **11037**, 10 (2019).
41. K. Nemoto, A. Maksimchuk, S. Banerjee, K. Flippo, G. Mourou, D. Umstadter, and V. Y. Bychenkov, "Laser-triggered ion acceleration and table top isotope production," *Appl. Phys. Lett.* **78**, pp.595-597 (2001).
42. K. W. D. Ledingham, P. R. Bolton, N. Shikazono, and C. M. C. Ma, "Towards Laser Driven Hadron Cancer Radiotherapy: A Review of Progress," *Appl. Sci.* **4**, pp.402-443 (2014).
43. "EXFOR: Experimental Nuclear Reaction Data" (2017), retrieved 2017, www-nds.iaea.org/exfor/exfor.htm.
44. S. Semushin and V. Malka, "High density gas jet nozzle design for laser target production," *Rev. Sci. Instrum.* **72**, pp.2961-2965 (2001).
45. K. Schmid and L. Veisz, "Supersonic gas jets for laser-plasma experiments," *Rev. Sci. Instrum.* **83**, pp.053304 (2012).
46. R. E. Samad, A. V. F. Zuffi, E. P. Maldonado, and N. D. Vieira, "Development and Optical Characterization of Supersonic Gas Targets for High-Intensity Laser Plasma Studies," in *2018 SBFoton International Optics and Photonics Conference (SBFoton IOPC)*, Campinas, SP, Brazil, 8-10 Oct. 2018, pp.1-5 (2018).
47. M. V. Petrenko, S. V. Bobashev, and G. K. Tumakaev, "A method for determination of spatial distribution of gas concentration in supersonic jets outflowing into vacuum," *Tech. Phys. Lett.* **43**, pp.428-430 (2017).
48. A. M. Hansen, D. Haberberger, J. Katz, D. Mastrosimone, R. K. Follett, and D. H. Froula, "Supersonic gas-jet characterization with interferometry and Thomson scattering on the OMEGA Laser System," *Rev. Sci. Instrum.* **89**, pp.10C103 (2018).
49. R. E. Samad, G. E. C. Nogueira, S. L. Baldochi, and N. D. Vieira, "Amplification of ultrashort pulses to 0.5 TW at 5 Hz with a flashlamp pumped Cr:LiSAF gain medium", Proc. SPIE **6451**, Solid State Lasers XVI: Technology and Devices, 645112 (2007).
50. R. E. Samad, G. E. C. Nogueira, S. L. Baldochi, and N. D. Vieira Jr, "5 Hz flashlamp pumped Cr:LiSAF multipass amplifier for ultrashort pulses," *J. Opt. A: Pure Appl. Opt.* **10**, pp.104010 (2008).