“Electron acceleration and polaritonic transport for laser-plasma acceleration in novel capillary configurations ”

Synthetic final report

period October 2011 – September 2016

Introduction

The main objective of the project consisted in achieving a theoretical and experimental validation of a conceptually new theory, that was recently conceived [M. Apostol and M. Ganciu, **“Polaritonic pulse and coherent X- and gamma rays from Compton (Thomson) backscattering”**, Journal of Applied Physics, 109 (2011) 013307 selected as Research Highlight by JAP]. The theory assumes that the laser-plasma acceleration mechanism results in achieving a propagation regime of the overall system, consisting of a bunch of laser-plasma accelerated relativistic electrons and the laser pulse responsible for such mechanism, as a stable polariton with its speed defined by the group speed of the laser pulse within the propagation media. The basic aspects investigated within the period of time covered by the project were both experimental and theoretical, in connection with recent results in the field, and in particular with respect to late advances related to the „bubble” acceleration regime [S. M. Hooker, Developments in laser-driven plasma accelerators, Nature Photonics 7, 775 (2013)], which leads to quasi-monoenergetic electron beams. For example, Ref. [Geddes, CGR *et al.* High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding. Nature 431, 538–541 (2004)] reports an energy peak near 86 MeV, and a full width at half-maximum (FWHM) of around 2 %. Similar results were obtained by the group from LOA [Faure, J et al. A laser-plasma accelerator producing monoenergetic electron beams. Nature 431, 541–544 (2004)], using a Ti:sapphire laser collimated on a He jet, for a 30 fs pulse duration and 1 J of pulse energy, which generates an electron plasma with a density of around $2\cdot10^{19}$ cm^{-3}. For a 3 mm length acceleration region (relativistic filamentation), a beam of electrons with energies around 170 MeV (FWHM ~ 24%) resulted, with a total electric charge of around 0.5 nC. These remarkable results determined us to focus on such issue of large interest, with an aim to prove the existence of a polaritonic propagation regime, which implies a bunch of monoenergetic accelerated electrons, owing to a physical mechanism that does not contradict the „bubble” model. Probing the existence of such acceleration regime requires implementing specific techniques at CETAL intended for characterizing, aligning and focusing the laser beam on different types of targets, and in particular it implies identifying conceptually new capillary discharge geometries, with an aim to increase the reproducibility, energy and quality of the accelerated electron beams. With such objectives in view, different methods and techniques for generating pulsed filamentary plasmas were investigated, under adequate pre-ionization conditions.

Theoretical aspects

A phenomenological interpretation of the polaritonic transport mechanism can be performed by considering that in the stationary propagation regime, the bunch of accelerated electrons reaches a speed equal to the group speed of the laser pulse which propagates simultaneously. In the “bubble” acceleration regime, the laser pulse generates a powerful shock wave owing to the very large ponderomotive force which becomes sufficiently high as to expel all electrons, which results in a roughly spherical zone populated with positive ions. Plasma electrons are driven away from this spherical zone by the ponderomotive force. As the plasma ions are massive compared to the electrons, they are assumed to be stationary at the time-scales of plasma electron response to the exciting fields. An extremely high longitudinal electric field results between the bubble consisting of positively charged ions and the trailing edge of the wake, where accelerated electrons are located. It was experimentally established that the focalization and acceleration length for electrons is much larger than the Rayleigh range, owing to the relativistic focusing effect generated by an electron effective mass which is larger for higher intensities of the laser pulse, corresponding to a normalized vector potential $a_0 > 1$. Under such conditions the plasma behaves as a waveguide, where the refraction index is larger corresponding to the maximum of the intensity, for a Gaussian profile of the collimated laser beam.

As the laser pulse energy dissipates, the a_0 value decreases, and so does the value of the electron mass and the group speed associated to the laser pulse. Thus, the "bubble" regime is degraded and the bunch of accelerated electrons tends to overlap with the laser pulse. At some point, the condition of spatio-temporal synchronism between the laser pulse and the accelerated electrons can be achieved. Hence, the resonance condition similar to the interaction between a laser pulse and a plasma of characteristic frequency equal to the pulse frequency can be satisfied, an issue which we have described extensively in previous research reports.

The degree of novelty which we bring, is connected with the introduction of the Landau damping concept that enables us to consider the polaritonic configuration as stable, for a fully ionized plasma. The Landau damping concept has been coined in 1946 by Lev Davidovich Landau [Landau, L. On the vibration of the electronic plasma. JETP 16 (1946), 574], and it refers to the rapid exponential damping of a perturbation within a fully ionized plasma. For fully ionized plasmas, a perturbation will be redistributed within short time (depending on the electronic density and the volume of the fully ionized plasma) in the oscillation amplitude of the bunch electrons, whose characteristic frequency is equal to the plasma classical frequency. Such effect was found for Tokamak discharges and it represents a great asset in controlling the stability of such plasmas. The issue of Landau damping has recently been solved by Cedric Villani [Mouhot, C., and Villani C. , On Landau damping, Acta Mathematica, September 2011, Volume 207, Issue 1, pp 29–201].

In case of the polariton we have investigated, the remaining energy of the laser pulse (whose frequency and total energy is divided by a 2 gamma factor in the reference system of the accelerated electron bunch) will be rediscovered as plasma oscillations in the reference system of the accelerated electron bunch. In the laboratory system of frame, for transversal observation, this frequency will decrease by yet another gamma factor. A simple numerical estimation performed for gamma = 1000 (~ 500 MeV electron energy) shows a characteristic wavelength of 1.6 m of the observed electron bunch oscillation, in the laboratory reference of frame (for an 800 nm laser wavelength). Such value is much larger than the focalization length. Consequently, the observed polariton is polarized in a single sense (or it changes sense only once) which is in good agreement with the theoretical results we report in the original paper.

A paper focused on this issue and the connection between the Landau damping and plasmas generated by very high power lasers is under current writing, în cooperation with the Embry-Riddle Aeronautical University, Daytona Beach, FL (Prof. A. Ludu). Demonstration of the existence of such stability enables performing Compton backscattering experiments aimed at validating the second hypothesis developed in [M. Apostol and M. Ganciu, "Polaritonic pulse and coherent X- and gamma rays from Compton (Thomson) backscattering", Journal of Applied Physics, 109 (2011) 013307], with respect to obtaining a coherent X-ray source, both for monoenergetic electron scattering as well as by means of the interaction with accelerated ions, for example at LHC, an aspect we have described in the december 2014 report, suggested by us in Ref. [M.Apostol and M. Ganciu, **Coupling of (ultra-) relativistic atomic nuclei with photons,** AIP Advances 3, 112133 (2013)].

Technological and experimental aspects

The technological and technical challenges we have faced during the project duration have been extensively described in previous research reports. Currently, all problems related to the operation of the CETAL PW-class laser within nominal parameters have been identified. We mention that these issues have proven to be considerably more difficult and complex than initially expected. We shall only insist on aspects that were not treated in previous reports, and we will focus especially on a problem of outmost importance, namely the issue of the electromagnetic pulse (EMP) generated as an outcome of the interaction between the laser pulse and different types of targets [A. Poye et al, "Physics of Giant ElectroMagnetic Pulse generation in short pulse laser experiments", Phys. Rev. E 91, 043106 (2015)].

Such aspect has become an issue of great interest for the PW class lasers, due to the possibility of EMP propagation via the beam line system used to carry the laser pulse. In order to prevent exceeding the threshold that would result in mirror and diffraction grating damage, the laser pulse is expanded up to diameters of tens of cm, which implies inner diameters for the Al transport line of the same order of magnitude. Such pipes behave as a cylindrical waveguide, thus enabling propagation of EMP with frequencies higher than hundreds of MHz. Recent experiments performed at Lawrence Livermore Natl. Lab. -LLNL (USA) and CEA (France) were focused at determining the characteristic frequencies of these EMPs, which depend on the target holder geometry, on the coupling mode with the ground electric potential, as well as on the geometry of the interaction chamber which acts like a resonant cavity. Electric field intensities up to values of 500 KV/m have been measured, for frequencies higher than 1 – 2 GHz (up to tens of GHz). These EMPs are practically one order of magnitude larger than those generated at Earth surface by high altitude nuclear blasts. The solutions to mitigate the destructive effect of these pulses on the control and measurement instrumentation, depend on the particular configuration of every PW class infrastructure, while they represent a niche of high interest for most of the laboratories involved. According to estimations made for the ELI-NP infrastructure, EMPs reaching 50 MV/m could result (http://www.eli-np.ro/2012-3_5-oct/Presentations/Friday/Gugiu121005.pdf). We have developed techniques to simulate and measure such pulses in an attempt to identify and implement the most adequate solutions using shielding and absorber materials, adapted to every experimental configuration. The techniques we have developed are the object of a patent application submitted to OSIM [M. Ganciu, O. Stoican, A. Marcu, B. Butoi, M. Serbanescu, B. Mihalcea, A. Groza, C. Diplasu, P. Dinca, A. Surmeian, **Generator de impulsuri ultrarapide pentru simularea pulsurilor electromagnetice asociate interactiei radiatiei laser de mare putere cu materia**, A00592/23-08-2016] .

Another technological issue that represents a serious challenge is related to the adherence of dielectric layers on holders of large dimensions that must withstand PW pulses. Such limitations have resulted in increasing the diameter of the laser beam to a value of around 15 cm, which resulted in extremely delicate alignment challenges, owing to a long and relatively complicated beam line configuration. These issues have motivated our studies for different techniques intended to increase the adherence of dielectric layers to the substrate, for constant improvement of the alignment techniques by using low power continuous emission lasers and control screens coupled with vacuum compatible web cameras, etc. We currently report ~ 5 J of pulse energy and ~ 40 fs laser pulse duration in the interaction chamber, but the Strehl ratio has to be sensibly improved as it is now limited at 7 – 15 %. The experimental results obtained at the CETAL facility are consistent with the deliverable laser parameters, as they have been described in previous reports. In 2016, progress was recorded with respect to temporal characterization within the interaction chamber area, alignment methods were devised and implemented in order to avoid mirror damage, the laser rods have been replaced at the ATLAS pumping lasers (the cause for modest reliability is not known yet), important advance was made with respect to methods of characterizing the Strehl ratio and mitigation procedures have been implemented to increase its value by use of the built-in laser deformable mirror. In case of most PW class facilities worldwide a deformable mirror is used, located in the close vicinity of the focusing off-axis parabolic mirror (OAP). As a matter of fact, all PW class laser facilities require an yearly budget of at least 10 % of the initial investment, in order to ensure continuous operation at nominal parameters.

Conclusions and future perspectives

The Project PN-II-ID-PCE-2011-3-0958 allowed us to approach problems of large interest with respect to laser-plasma acceleration of charged particles, especially due to the ELI-NP project which is concerned with building two 10 PW lasers (currently considered to be the most powerful PW class lasers în the world), as well as a gamma radiation source that exhibits unique characteristics among other existing facilities worldwide (http://www.eli-np.ro/ro/). Use of these facilities can be handled both separately or using combinations of interest for state of the art and frontier experiments.

Both theoretical and experimental research using the PW class CETAL infrastructure is mandatory, not only as a preparation stage for the teams that will be responsible for maintaining the ELI-NP infrastructure in operation, but also for performing experiments and preliminary tests that precede and prepare those to be performed at ELI-NP. With respect to such issue, this project has proven to be important, both for elaborating new theories aimed at better characterizing the behaviour of matter under extreme conditions induced by very high power lasers, as well as for identifying and mitigating challenges and problems specific for such complex research infrastructures. PW class infrastructures worldwide require high annual expenses for operation, emergency and unexpected repairs, or specific optimizations. We will supply an example regarding an issue which is characteristic for PW class laser infrastructures, raised especially by our korean partners that host the most powerful laser currently în operation: the high intensity EMP associated with the interaction between the PW laser pulses with solid targets. We have systematically approached such issue and, besides the patent application submitted, our team is also responsible for two research projects that investigate these problems and will yield solutions for ELI-NP and other PW class facilities:

- ***Diagnostica complexă a pulsurilor laser ultraintense şi protecţia la pulsuri electromagnetice extreme, Contract 4N/2016, Proiect PN 16 47 01 01 (Cercetari avansate asupra materiei aflata in conditii extreme)***

- ***Electromagnetic Shielding Structures to assure Biological Safety during target hitting experiments performed on PW Laser Facilities, Proiect IFA- ELI-RO, cod proiect 17 ELI***

As the major issues related to PW class laser operation have been identified during the experiments and tests performed, solutions were advanced by means of a patent application [**Sistem de detectie a radiatiei ionizante in timp real cu protectie la zgomot elec tromagnetic**, OSIM, A/00920, 27/11/2015 autori: L. Tudor, M. Ganciu-Petcu, O. Stoican, I. Barbut, B. Butio, O. Danila, C. Diplasu, A. Groza, B. Mihalcea, A. Surmeian].

Moreover, other issues of interest have been identified for electron acceleration as an outcome of the laser-plasma acceleration. These issues are the object of another project which has been accepted for funding in August 2016, entitled **"Temporally resolved diagnostics of laser produced plasma for electron acceleration forseen to be used at ELI-NP",** Project IFA- ELI-RO, project code: 24 ELI".

Another IFA-ELI-RO project accepted for funding in August 2016 is entitled **"Quasi-classical methods in Laser - Nucleus Interactions",** project code: 04 ELI, based on our paper [M. Apostol and M. Ganciu, Coupling of (ultra-) relativistic atomic nuclei with photons, AIP Advances 3, 112133 (2013)].

Research performed within the frame of the project has resulted in identifying applications of interest for the European Space Agency (ESA), with respect to replicating the aggresive radiation environment characteristic to the cosmic space by use of laser accelerated charged particles, that exhibit the major advantage of an exponential energy distribution, similar to the cosmic space. A national and an international patent application have been submitted [M. Ganciu-Petcu, M. Piso, O. Stoican, B. Mihalcea, C. Diplaşu, O. Marghitu, A. Julea, A. Surmeian, A. Groza, R. Dabu, I. Morjan, **System and method for testing components, circuits and complex systems using syncronized and pulsed laser fluxes consisting of laser accelerated particles**, International Patent Application WO2015030619-A1; RO130134-A2; 26.08.2014], which allowed us to establish a Competence Centre in INFLPR entitled **"Laser-Plasma Acceleration of Particles for Radiation Hardeness Testing – LEOPARD",** ROSA Contract Nr. 53/2013, and in the same time the Contract No. 400011242/NL/CBi June 2014 with the European Space Agency (ESA): **"Feasibility Study for the Use of the Romanian CETAL Infrastructure"** .

To summarize, we emphasize on the fact that, within the period October 2011 – September 2016 the Project objectives have been achieved and we have succeeded în increasing the internaţional visibility by **three international patents granted** (in partnership with Horiba Scientific, France, FR2926161 (B1) 2012-02-10, EP2396645(B1) 2013-01-09, US 8581494 (B2) 2013-11-12), **four national** and **an international patent** applications submitted, as well as a number of **seven papers published în ISI journals**. New national and international partnerships were initiated, especially with ELI-NP and with the Polytechnical University of Bucharest. Our cooperations with partners from France, England and USA have been strengthened, and perspectives for submitting new ESA projects are created. New research directions emerged, în particular related to Landau damping in laser plasmas, an aspect that favourizes the study of polariton stability. Gifted olympic young students are already implied in such direction.

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