13 September 22

ECLIM 2022

Book of Abstracts

This book collects the abstracts of the presentations done at the 36th

European Conference on Laser Interaction with Matter (ECLIM). ECLIM is a Conference directed to scientists working with laser-produced plasmas and their applications.

ECLIM 2022 is held in Frascati (Italy) where it had its first edition in 1966 when research on laser-generated plasmas was making its initial steps.

Since then ECLIM has been held almost regularly every two years.

The present edition is one of the exceptions due to a two years delay, caused by the Covid 19 pandemic. Trying to keep the remote participation to a minimum for encouraging personal interchange, it was preferred to delay the Conference to a safer period. Indeed, this is the first time the Conference is held partially in remote mode, even if for a limited number of participants.

Besides the above difficulties, the participation to the Conference appears more than satisfactory with almost 100 contributions.

The contributions are arranged in 9 sessions including invited and oral presentations, while a separate session is dedicated to posters. As in the past, there are no parallel sessions, to allow the full attendance to all the lectures during the days of Conference.

In this edition, the Conference is followed by two satellite meetings. The Workshop on “ElectroMagnetic Pulses (EMPs) generated by laser-matter interaction” on the 26th September and that on “Laser-Plasma Instabilities in Inertial Confinement Fusion (LPI in ICF)” on the 27th September.

An important number of ECLIM contributions deals with inertial fusion research, well representing the renewed interest arisen from recent results on NIF and from the increasing concern on energy and environment.

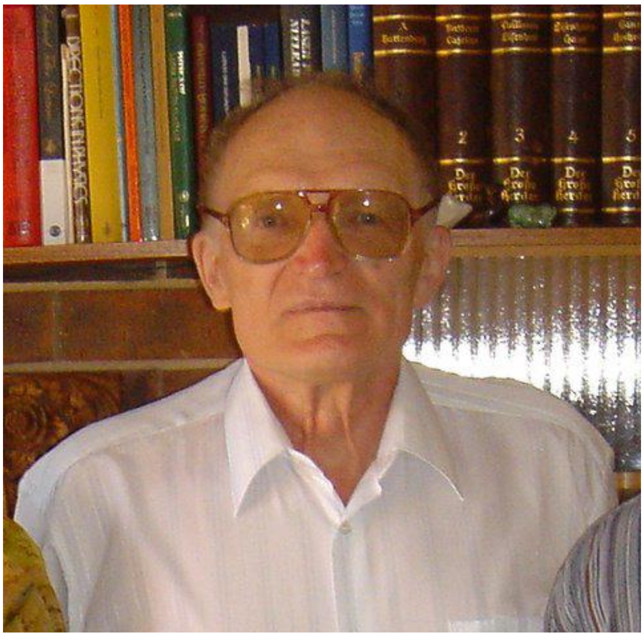
The important implications of laser technology on particle acceleration and advanced radiation sources are witnessed by many contributions and by the development of new dedicated large devices.

Talks on innovative detectors, spectral analysis, production of electromagnetic fields and astrobiology contribute to a full coverage of the Conference topics which, we believe, makes the Conference a good success.

The Conference is dedicated to the memory of outstanding physicists who - with their pioneering work - have significantly contributed to advance in the fields of plasma physics, laser-plasma interactions and inertial confinement fusion.

Vladislav Rozanov

1932 –2019



Vladislav Rozanov, outstanding specialist in the field of nuclear and plasma physics, one of the founders of the theory of inertial confinement fusion passed away on 5 September 2019.

Vladislav Rozanov was born on 11 December 1932 in Moscow. In 1956, he graduated at the Moscow State University and began his scientific activity in the Ural nuclear center (presently Russian Federal Nuclear Center – Zababakhin All-Russian Research Institute of Technical Physics). He worked here from 1956 to 1966 in the field of applied physics and made a significant contribution to the development of the Soviet Atomic Project.

From 1966 until the last days of his life V. Rozanov worked at the Lebedev Physical Institute. He made a significant contribution to the physics of high-power lasers. V. Rozanov is the author of one of the first scheme of an inner-shell photoionization-pumped X-ray laser. His research in the physics of emitting discharges formed the basis for the development of effective pump sources of high-power lasers of various types.

V. Rozanov made a great contribution to the formation and development of research in the theory of inertial confinement fusion. He founded the Department of the Laser-Produced Plasma Theory at the Lebedev Physical Institute, which he headed for 45 years. With his active participation, models of the main physical processes of laser thermonuclear fusion were developed, which have become the basis for the development of numerical codes for simulation of implosion and burning of laser fusion targets. V. Rozanov is one of the authors of the concept of the target in the form of a thin spherical shell designed to achieve spark ignition and high thermonuclear gain. All modern laser fusion target scheme are based on this concept. He is author of the “evolutionary” theory of the development of hydrodynamic instabilities. He made a significant contribution to the development of the physics of a fusion-fission hybrid reactor during controlled initiation of nuclear reaction by thermonuclear neutrons. V. Rozanov is one of the pioneers in this field. He is the author of several promising schemes of reactors of this type.

For 40 years V. Rozanov lectured at the National Research Nuclear University, educating a galaxy of experts in the field of high-temperature plasma and nuclear physics. More than 30 PhD and Professor theses were defended under his scientific supervision.

V. Rozanov was a charming, high intelligent person with encyclopaedic knowledge. His death is a huge loss for science. The bright memory of Vladislav Rozanov, a wonderful man and scientist, will forever remain in the hearts of everyone who knew him.

Milan Kálal

1952 –2020

Professor Milan Kálal, outstanding specialist in the field of optical diagnostics of laser produced plasmas passed away suddenly after very short deadly disease on April 26, 2020 at the age of 68 years.
Milan Kálal was born in Mladějov, Czech Republic. He graduated from the Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague. After obtaining doctoral degree at the same institution, he spent 3 years at the Australian National University, Canberra, Australia, where he started his research in the area of optical interferometry and polaro-interferometry. Professor Milan Kálal is the author of the idea complex interferometry1 and its mathematical foundations. It provides extended capabilities and higher reliability compared to the classical polaro-interferometry. Classical polaro-interferometry independently obtains polarimetric and interferometric images. In contrast, complex interferometry obtains information on magnetic fields in plasmas directly from a phase-amplitude analysis of an image called a complex interferogram, This method avoids errors caused from spatial and temporal shifts between separated channels that
occur in the polaro-interferometry. He implemented this method at the PALS laboratory in Prague in collaboration with professor Tadeusz Pisarczyk. The results of the spontaneous magnetic field (SMF) measurements2 were obtained for the first time using a unique three-frame complex interferometer and confirm the great potential of this method.

Professor Milan Kálal also made an important contribution to the interferometry in the EUV spectral region. In collaboration with prof. Hong Jin Kong he was developing the idea of application of SBSPCM (stimulated Brillouin scattering phase conjugate mirror) in the inertial fusion, both for coherent combination of laser beams, and for self-navigation of a laser beam on the target flying with high velocity in the inertial confinement fusion reactor chamber.

After returning from Australia, Professor Kálal joined his Alma mater and for the rest his life he was reading lectures and educated many Master and Doctoral students. In years 2000-6, he served as a vice-dean for development of the faculty. For a long period, Professor Kálal served as a member of the International Scientific Committee of ECLIM conferences. He was also member of Editorial Board of the journal Laser and Particle Beams.

Professor Kálal was bright and intelligent person with an excellent ability to come with unconventional ideas and non-traditional solutions. His death is a big loss for science, our community and for the Czech Technical University in Prague. The bright memory of Professor Milan Kálal will forever remain in the hearts of everyone who knew him.

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David Neely

1965-2020

Professor David Neely, an internationally renowned scientist in the field of high energy density science, worked at the Central Laser Facility, UK, passed away after a short and sudden illness on August 27th, 2020 at the age of 55 years.

David was born in Londonderry, Northern Ireland in 1965. He studied physics at Queens University Belfast (QUB), graduating in 1987 with a BSc (Hons) degree and a PhD in 1992 on the generation of soft x-ray lasers, under the supervision of Professor Ciaran Lewis. He was a Research Assistant at QUB, teaching and supporting the undergraduate research laboratories, before joining the Central Laser Facility, STFC Rutherford Appleton Laboratory in 1993. David was promoted in 2005 to lead the Central Laser Facility's Experimental Science Group and in 2010 to Head of High Power Laser Science. In 2012, he was awarded a Science and Technology Facilities Council (STFC) Research Fellowship to carry out independent research in high energy density science. Working with his extensive network of colleagues, he was able to carry out experiments on high power laser facilities throughout Europe, Asia and the USA. He held a Visiting Mitsuyuki Abe Chair position at the Proton Medical Research Centre, Japan Atomic Energy Agency, and was awarded the Medal of International Collaboration of the Chinese Academy of Sciences for setting up a government funded UK-China collaboration, giving him an even greater international profile. Appointment to a Visiting Professorship at the University of Strathclyde in 2012 enabled him to co-supervise PhD students and enhance his research portfolio. He formed close and successful working relationships with his students, many of whom went on to take up positions at national and international laser facilities. David also took a very active role on the Editorial Board of *High Power Laser Science and Engineering* (HPLSE).

He pioneered experiments exploring laser driven ion and electron acceleration, fusion studies, high harmonic production, shocks, plasma diagnostics and industrial applications. As short pulse laser power steadily increased over the years attaining PW performance in 2003, which enabled him to carry out experiments fully in the relativistic interaction regime. His interest in pre-plasma free interactions led to utilising plasma mirrors in 2005 to enhance the laser contrast to investigate ion acceleration from ultra-thin (20nm) foils. Recent work utilising multi-pulse and plasma optics have enabled extension into novel plasma environments at intensities of 10^{22} W/cm^2.

David's passing, in August 2020, has been, and will continue to be felt across the high energy density physics community.

Invited contributions

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From Kilojoules to Megajoules
The Journey to Ignition on the NIF

J. Edwards[1] for the ICF Team

[1] Lawrence Livermore National Laboratory, Livermore, California 94550, USA

Abstract

On August 8, 2021, a fusion experiment at the National Ignition Facility (NIF) [1] situated at the Lawrence Livermore National Laboratory in Northern California produced a fusion yield of 1.37 MJ, almost 10X higher than any prior experiment, from an on-target laser energy of 1.9 MJ [2,3,4]. By multiple scientific definitions the capsule ignited [2] (although the overall target gain at 0.7 did not exceed unity), raising the fuel temperature by a factor of ~ 2X and amplifying the yield by ~ 30X. This was the first demonstration of ignition in the laboratory and the culmination of decades of research by thousands of scientists. This included more than a decade of innovation at the NIF that drove tremendous advances in every aspect of fusion science: target physics, diagnostics, probe techniques and analyses, laser science and operations, target fabrication and metrology, and theory and simulation.

The concept of laser fusion was first proposed by Nuckols in 1972 [5]. Since that time researchers have pursued progressively more capable drivers in pursuit of ignition. At LLNL, this ultimately led to the decision to build the NIF. The NIF was sized to achieve ignition with the indirect drive approach [6], but ignition was by no means assured. While significant work was conducted under the Nova Technical Contract [7] that was instrumental in the decision to proceed with the NIF, unchartered territory remained. In particular: the NIF would use targets that were ~ 4X larger than any used before with almost 100X higher energies presenting a new regime for laser plasma instabilities as well as hydrodynamic instabilities and mix; NIF was the first facility to field the cryogenic layered fuel targets that would be needed for ignition; the fuel capsules would need to converge far in excess of any prior experiment placing very stringent control over radiation drive symmetry and pulse shaping. In addition to this, simulation tools were not complete or accurate enough to specify the very large number of parameters that define an ignition experiment with the precision needed for success. The results of the NIF experiments themselves using both layered fuel targets and surrogates would be needed to adjust for this [8,9].

Despite these uncertainties, an initial target design [10] was needed to guide engineering decisions. This design, the “Rev 5” point design performed far from expectations and fell far short of ignition [11]. During the ensuing decade the international ICF team developed a staggering array of surrogate targets, new diagnostics, probe and analysis techniques to understand what was wrong. This was complemented by the exploration of new design ideas supported by impressive advances in theory, models and simulation capability and enabled by impressive advances in target and laser technology. Ultimately, the interplay of these activities led to the “HYBRID-E” target that achieved ignition on August 8th, 2021 with a design that contradicted thinking prior to the onset of experiments at the NIF. Key differences between Rev 5 and HYBRID-E are: low vs. high fill-density hohlraum to largely eliminate LPI induced losses, drive asymmetries and hot electrons; diamond vs. plastic capsule to enable ignition size capsules to be fielded symmetrically in low fill-density hohlraums; a higher adiabat, lower convergence, lower gain implosion that would need more energy.

The higher adiabat implosion of HYBRID-E results in lower pressure (P) in the fuel at stagnation than the original Rev 5 design. Since the energy required to trigger ignition scales as P^2, the design had to find a way to couple more of the laser energy to the fuel. This was a major challenge and was significantly enabled by: the development of data driven hohlraum models [12], cross beam energy transfer [13] and understanding random mode 1 [14] for symmetry control; understanding the origin and impact of hot spot mix and reducing it by improving capsule quality and a smaller, 2µm vs 10µm capsule fill tube [15]; new appreciation and theory of the effects of coasting on pressure generation [16]; improved simulation capability in HYDRA [3,17]; and improved capsule metrology and fabrication techniques. With the exception of the latter, this all relied heavily on the development of many new diagnostics and probe techniques.

Over the last year since the ignition shot N210808, a number of close or near repeats have been conducted. The performance of these has ranged from ~ 300 kJ to ~750 kJ. Recent analysis has shown the performance of all the experiments can be largely explained by the presence of mode 1 asymmetry and hot spot mix with the predominant factor for yield degradation being hot spot mix correlated with capsule imperfections revealed by improved metrology [18].

This talk will illuminate the key developments that led to the target design that achieved ignition, summarize the current understanding and briefly mention the focus of future direction.

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Acknowledgements
*Work performed under the auspices of the U. S. Department of Energy by LLNL under contract DE-AC52-07NA27344
LLNL Document Number: LLNL-ABS-839529

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36th European Conference on Laser Interaction with Matter
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LMJ status at mid-term and full experiments ability

Jean-Luc Miquel[1] on behalf of the laser-plasma experiments team

[1] CEA-DAM, DIF, Bruyères-le-Châtel, F-91297 Arpajon cedex, France
e-mail : jean-luc.miquel@cea.fr

Abstract

The laser mega-joule facility (LMJ) constructed by the CEA/DAM on the CESTA site near Bordeaux (France) has been in the ramp-up phase since 2014. This ramp-up is manifested by an increase in the number of operational beams, and the implementation of more and more plasma diagnostics.

The LMJ will eventually have 176 beams grouped into 44 quadruplets, which are divided into 2 times 2 irradiation cones (at 33.2° and 64° polar angles), comprising 10 quadruplets each, as well as 4 quads for radiography [1]. The LMJ has been coupled since 2017 with the petawatt laser PETAL, an ultra-intense, sub-picosecond and kilojoule-class laser beam, funded in large part by the Nouvelle Aquitaine Region [2].

Up to 2021, from 2 to 16 quadruplets were implemented, and their geometric distribution did not allow a symmetrical irradiation of the targets. Experiments have been carried out mainly in the field of radiative transfer [3], but also in that of hydrodynamic instabilities, and asymmetric capsule implosion. These experiments served as validation tests for the predictive capabilities of the CEA/DAM 3D radiative hydrodynamics code TROLL. Experiments relevant to Astrophysics and Inertial Confinement Fusion (ICF) were also performed as part of the opening of the LMJ facility to the academic community [4, 5].

Since 2022, 20 quadruplets are available and operational, delivering up to 100 TW/300 kJ on target; they will allow a symmetrical irradiation of targets with 5 quadruplets per irradiation cone. With this configuration, and thanks to a complete set of 17 diagnostics, it is now possible to fully address ICF studies. The nominal design of the ICF targets of the LMJ, using a rugby-shaped gas hohlraum, will be validated on a representative scale.

Thanks to a set of high-performance diagnostics dedicated to laser-plasma interaction (LPI), such as the Near Backscattering Imager diagnostic (see Figure 1) [6], the LMJ offers unique possibilities for studying the backscattering of ICF targets. The first experiments dedicated to the characterization of the LPI under the representative conditions of ICF with rugby-shaped hohlraums were carried out in early 2022. Moreover, these capabilities of LPI diagnostics have attracted the attention of the academic community who has proposed experiments in this field.

We will present the current status of the LMJ facility and its performance, as well as some results from the experimental campaigns of the CEA/DAM program and the opening program. Preliminary results on LPI under ICF conditions will also be presented.

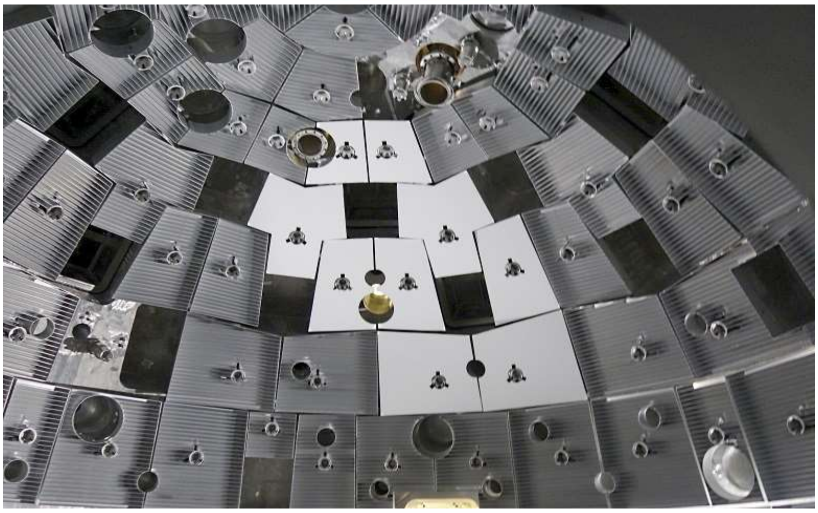

Figure 1. Spectralon reflective panels inside the LMJ chamber for the Near Backscattering Imager diagnostic. The diagnostic analyzes the laser light backscattered by the target over a wide angular range (up to 46° vertically and 64° horizontally), around two beam ports of the quads from the 33.2° and 49° irradiation cones.

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Acknowledgements

The PETAL project has been performed by CEA under the financial auspices of the Conseil Regional d'Aquitaine, of the French Ministry of Research and the European Union, and with the scientific support of Institute Lasers and Plasmas.

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Pathway to high gain laser fusion with fast ignition scheme

M. Murakami, Y. Sentoku, T. Johazaki, H. Nagatomo, S. Fujioka
and FIREX-NEO team

Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan

Abstract

Institute of Laser Engineering (ILE) promote a project "FIREX-NEO" to seek a high gain laser fusion design with fast ignition scheme. In the laser fusion research, there are a several different approach to ignite a compressed core. The NIF, which is an indirect implosion scheme using a gold hohlraum to convert laser light energies to x-rays and implode a cell, had achieved 1.3 MJ neutron yield by imputing 1.9 MJ laser energies in an experiment in August 2021. The NIF's remarkable achievement indicates the laser fusion enters to the burning phase and it encourages us to think how we can make the fusion burn efficient. One of the paths for the efficient laser fusion is the fast ignition scheme which can separate the laser fusion processes, a target compression phase and an ignition phase, thus enable to optimize them separately. We had demonstrated the efficient fast isochoric heating of the imploded core with a kilo-joule petawatt laser, LFEX, and had achieved 2 Peta-Pascal energy density [1]. There, we had introduced a solid ball instead of a shell since a solid ball implosion is less sensitive to the hydrodynamic instabilities thus a stably implosion could be achieved. The energy coupling rate from the heating laser to the imploded core is about 20% with an application of kT external magnetic field. In the FIREX-NEO project, our goal is to propose a design of the high gain laser fusion using the state-of-arts numerical code. The strategy of FIREX-NEO and the physics we tackle will be presented in this talk.

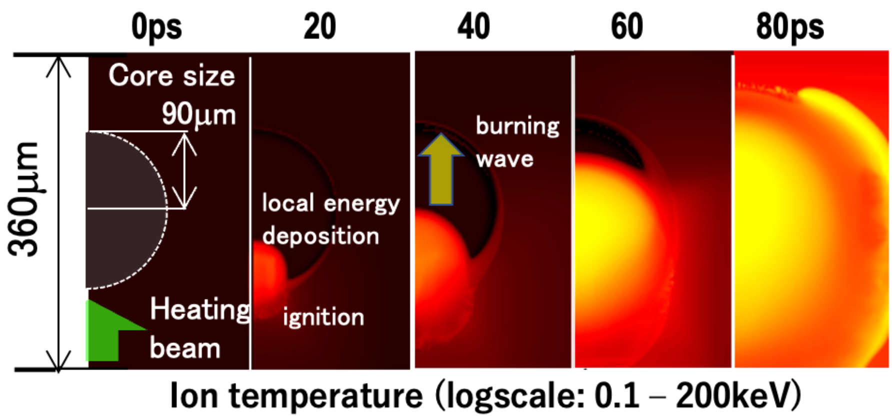

Figure 1. A numerical simulation of ignition/burn for 400kJ implosion / 200kJ heating lasers.

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Theory of extreme plasma conditions

M. Vranic[1]

[1] GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Tecnico - Universidade de Lisboa, 1049-001 Lisbon, Portugal

Abstract

The next generation of lasers will access intensities above 10^23 W/cm^2. When plasmas or relativistic electron beams interact with these lasers, energy loss due to radiation emission, or quantum effects such as electron-positron pair creation become important for their dynamics. Repeated occurrence of pair creation can induce a so-called "QED cascade", that generates an exponentially rising number of particles. This allows for creating exotic plasmas that are a mix of electrons, ions, positrons, energetic photons and intense background fields. Extreme laser-plasma interactions can be explored to form optical traps, create&accelerate particles and produce novel radiation sources. I will introduce a QED module coupled with the particle-in-cell framework OSIRIS that allows studying nonlinear plasma dynamics in the transition from the classical to the quantum-dominated regime of interaction. Studies relevant for (near) future experiments will be discussed.

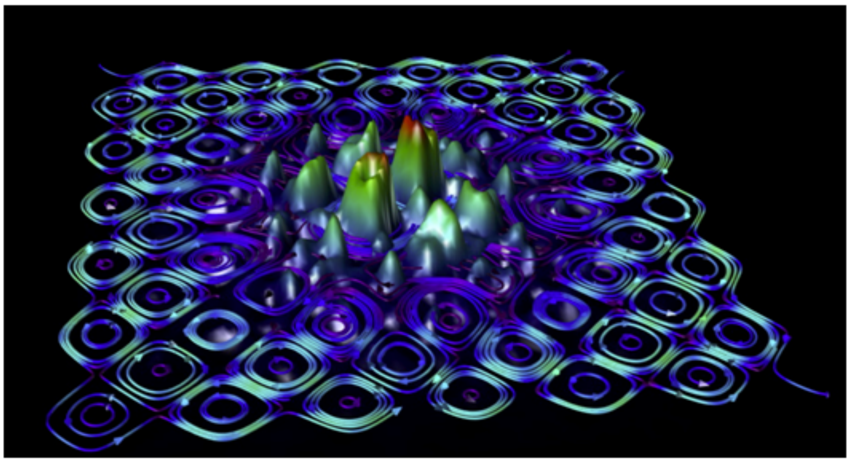

Figure 1. Electron-positron plasma created using a 4-laser optical trap.

Acknowledgements
This work was supported by the European Research Council (ERC2015-AdG Grant 695088), Portuguese Science Foundation (FCT) Grant No. CEECIND/01906/2018 and PTDC/FISPLA/3800/2021. We acknowledge PRACE for awarding access to MareNostrum based in the Barcelona Supercomputing Centre.

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Smilei: an open-source PIC code for laser-plasma interaction

Frederic Perez[1], Olga Abramkina[2], Arnaud Beck[3], Guillaume Bouchard[3], Julien Derouillat[4], Anna Grassi[1], Mickael Grech[1], Ahmed Houebib[4], Matthieu Lobet[4], Etienne Malaboeuf[5], Francesco Massimo[6], Tommaso Vinci[1]

[1] LULI, CNRS, École Polytechnique, 91128 Palaiseau, France
[2] IDRIS-CNRS, Campus universitaire d'Orsay, 91403 Orsay, France
[3] LLR, CNRS, École Polytechnique, 91128 Palaiseau, France
[4] Maison de la Simulation, CEA, CNRS, UVSQ, Université Paris-Saclay, 91191 Gif-Sur-Yvette, France
[5] CINES, 34097 Montpellier, France
[6] LPGP, Université Paris-Sud, 91405 Orsay, France

Abstract

First released in 2015, the particle-in-cell code Smilei [1] has grown into a high-performance, user-friendly, multi-purpose tool for laser-plasma kinetic simulations. Production runs have started in 2018, and are now commonly carried out by tens of teams across the world.

In the past four years, significant improvements have been brought to the code. Additional physics has been introduced: nuclear reactions, QED effects, relativistic beam initialization, and perfectly-matched layers. Performances have been increased with vectorization technology, new domain decomposition schemes, and reduced models such as quasi-cylindrical geometry, particle merging and envelope solvers. Thanks to a growing team of developers, more features will be included in the upcoming year: GPU support, task-based computing, spectral solvers, Bremsstrahlung radiation, betatron radiation.

In this presentation, I will review the capabilities of Smilei and illustrate them with applications in the field of laser-plasma interaction.

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Modeling intense laser-plasma interactions with Exascale systems

R. Fonseca[1,2]

[1] Institute for Plasmas e Nuclear Fusion / IST, Av. Rovisco Pais, 1049-001 Lisboa, Portugal
[2] DCTI / ISCTE-IUL, Av. Forças Armadas, 1649-026 Lisboa, Portugal

Abstract

The development of the field of numerical simulation of plasmas is inextricably connected to the field of high-performance computing (HPC), with the developments in one field driving/supporting the developments of the other, and both having their origins in the early 1950's. Since then, and much like the evolution of laser system power and intensity, the computing power has evolved tremendously, and as done sone following a nearly constant exponential growth, that has led to the deployment of the first HPC exascale system [1], capable of performing over 10^{18} operations per second. This achievement represents a formidable challenge to computational plasma physicists, as it provides the raw computational power for detailed high-fidelity simulations of laser plasma interactions up to QED regimes and extreme propagation lengths, but at the same time requiring that algorithms and simulation codes adapt themselves to the new paradigms and technologies used to support this achievement.

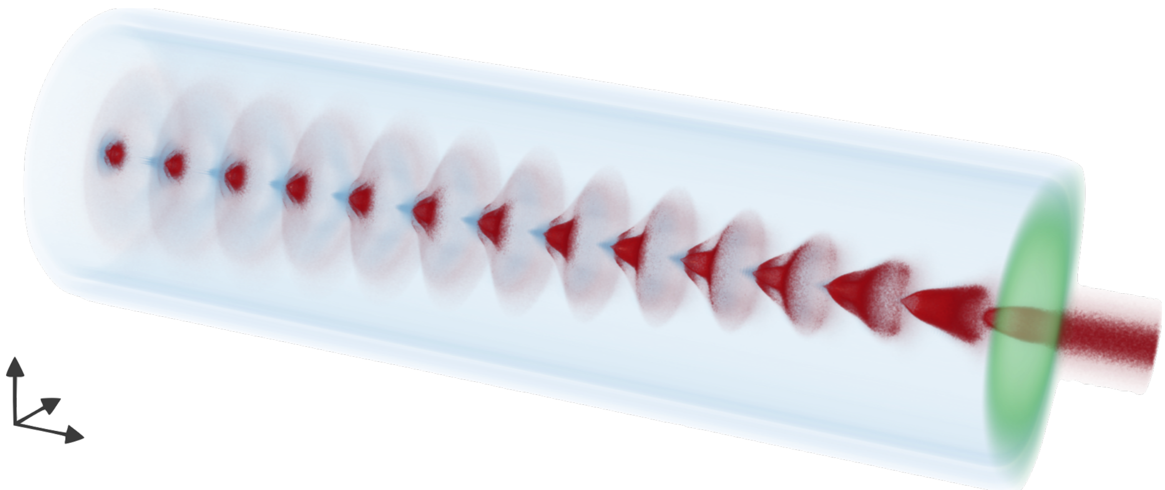

Figure 1. **Full-scale modelling of the AWAKE experiment [Adli 2018] at CERN** using OSIRIS [2]. This simulation combines a proton bunch from the LHC (red) with a high-power laser (green) that ionizes a gas background (light blue).

In this presentation I will address the issues involved in performing full scale numerical experiments of intense laser-plasma interactions using exascale HPC systems. I will focus on the algorithms used for laser-plasma interactions modelling, in terms of extended propagations propagation lengths, high-accuracy laser solid interactions, and the inclusion of QED effects for modeling extreme intensity scenarios. I will also discuss novel diagnostics for short-wavelength (shorter that the simulation cell size) radiation that are currently used to model radiation sources based on laser plasma interaction.

I will then address the issues related with the efficient deployment of these algorithms on modern HPC systems. These systems are generally by a large ($\sim 10^5$) set of independent computing nodes, each one having private memory spaces and processing units, connected through a high-performance computer network; achieving the high-level of performance needed requires efficiently exploiting all the levels of parallelism that this architecture introduces. I will discuss the performance at the computing node level, the strategies used for efficient use of CPU based systems (including vectorization) and of GPU accelerator-based systems, such as the ones powering current exascale machines. I will also discuss performance at system level, enabling parallel scalability to $\sim 10^5$ computer nodes, and the strategies used for maintaining parallel efficiency at large node counts.

The advent of Exascale HPC systems represent an outstanding opportunity for numerical modeling of intense laser-plasma interactions. Addressing the issues involved in the use of these systems for performing large-scale, high-fidelity numerical experiments, allows us to extend the validity of our numerical work to new temporal and spatial scales, as well as to new interaction regimes, and opens new avenues of research between theoretical/ massive computational studies and laboratory experiments in laser-plasma interaction.

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Acknowledgements

The author would like to acknowledge the contribution of the OSIRIS development team.

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Carrier-Envelope Phase Controlled Electron Dynamics in a Laser Wakefield Accelerator

J. Huijts[1,2], Lucas Rovige[1], Joséphine Monzac[1], Igor A. Andriyash[1], Aline Vernier[1], Marie Ouillé[1], Jaismeen Kaur[1], Zhao Cheng[1], Rodrigo Lopez-Martens[1], Jérôme Faure[1]

[1] Laboratoire d'Optique Appliquée, CNRS, Ecole Polytechnique, ENSTA Paris, Institut Polytechnique de Paris, 181 Chemin de la Hunière, 91120 Palaiseau, France
[2] Current affiliation: Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

Abstract

Introduction

Laser wakefield acceleration is a promising way to accelerate electrons to high energies over a very short distance due to the extremely high accelerating fields that can be sustained by non-linear plasma waves. In this process, an intense laser pulse is focused into an underdense plasma to drive a plasma wakefield, in which electrons are trapped and accelerated to relativistic energies [1]. This mechanism, a topic of intensive research since several decades, is typically well described within the framework of the cycle-averaged ponderomotive approximation. However, when using near-single-cycle pulses, this approximation is expected to break down [2]. The plasma response becomes asymmetric, depending no longer only on the pulse envelope, but on the waveform of the electric field itself. In addition, as the laser pulse propagates through the plasma, the carrier-envelope-phase (CEP) slips because the envelope travels at the group velocity v_g which differs from the laser phase velocity v_φ. The length scale over which dispersion changes the CEP by 2π can then be estimated as [2, 3]:

$$L_{2\pi} = \frac{c}{v_\varphi - v_g}\lambda_0$$

The combination of these two effects causes the plasma bubble to oscillate behind the laser pulse during propagation, in the plane of polarization. In the case of self-injection, this can cause the electron beam to be injected off-axis, undergo strong betatron oscillations during acceleration and leave the plasma with an angle that depends on the initial CEP of the laser pulse [4].

Results

We report on the first experimental observation of this effect. In our experiment [5], we drive a laser-wakefield accelerator with near-single-cycle pulses (3.5 fs or 1.3 cycles FWHM in intensity) [6], see panel a) of figure 1. In the gas jet, the laser pulse drives a plasma wake, in which electrons are accelerated to a few MeV. The electron beam charge and distribution are measured with a calibrated CsI(Tl) phosphor screen imaged on a CCD camera. During the experiments, the continuously flowing gas jet allows us to operate the laser-plasma accelerator at the actual repetition rate of 1 kHz.

As we vary the CEP, the pointing of the electron beam varies accordingly, as is clear from panel b) and c) of figure 1. The effect is significant: the amplitude of the oscillation is about 15 mrad, for a beam divergence of around 50 mrad, i.e. a ~ 30% change. The pointing varies in the plane of the laser polarization (y), while in the perpendicular plane (x) the beam pointing is constant except for a slow drift.

Our Particle-in-Cell simulations show that the CEP-driven oscillatory motion of the plasma bubble allows trapping of electrons on the side the bubble has shifted to (as also observed in [4, 7]). This off-axis electron injection takes place in the form of highly localized, sub-fs, ultralow emittance electron bunches. In our simulations, electrons are injected in three consecutive bunches. Each bunch is injected with a transverse momentum opposite to the previous bunch, and also leaves the plasma with a transverse momentum opposite to the previous bunch. The CEP of the laser pulse determines the

relative contributions of the up- and downward injections, causing the observed oscillations of the electron beam with the CEP.

Conclusion

These results imply that we have experimentally observed, for the first time in underdense laser-plasma interaction, the breakdown of the cycle-averaged ponderomotive approximation. They also imply that we can achieve an unprecedentedly high level of control on the injection and subsequent dynamics of the electron bunches through control of the waveform of the laser. This can enable novel injection schemes [7] as well as enhanced betatron X-ray radiation [8,9]. Finally, recent works propose that CEP-locked transverse bubble oscillation can play a role in LWFA driven by initially longer but self-steepened pulses [8,9], indicating the relevance of CEP control is not limited to near-single-cycle pulses.

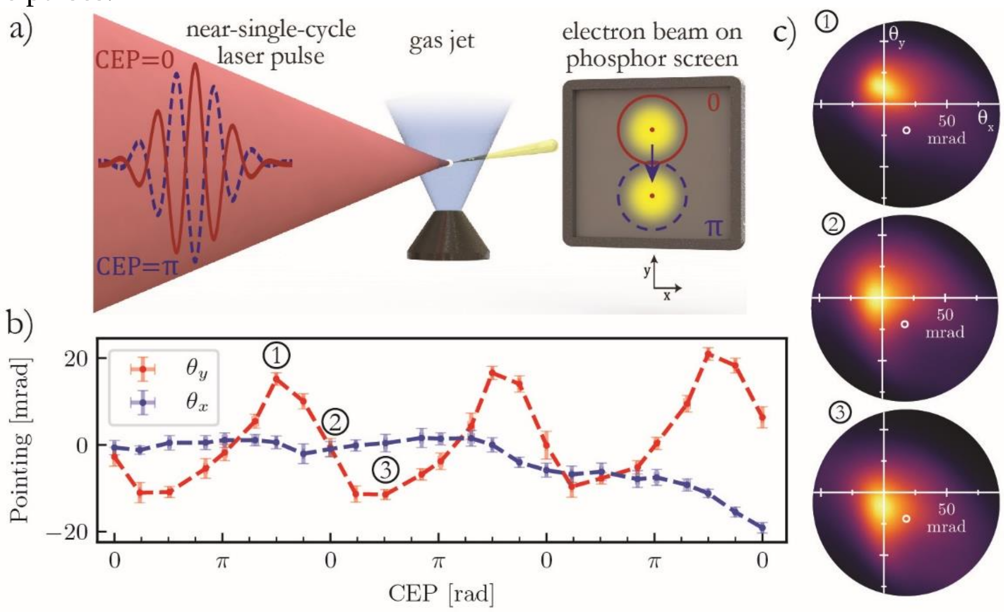

Figure 1. **a): Principle of the experiment**. An intense, near-single-cycle laser pulse is focused into a gas jet, where it ionizes the gas and drives a plasma wake. Through laser wakefield acceleration, electrons are accelerated to relativistic energies. A phosphor screen is used to image the electron beam. The shape of the electric field of the laser pulse is controlled through the carrier-envelope phase (CEP). Varying the CEP in the experiment changes the pointing of the electron beam. **b): The pointing of the electron beam** in the plane of polarization (y, red) and in the perpendicular plane (x, blue). Each data point in a) is the average of 20 acquisitions. The vertical error bars indicate the RMS error of these acquisitions, yielding a sub-2 mrad pointing jitter (RMS). The horizontal error bars indicate the RMS error of the CEP stability, averaged over 200 shots (on the order of 40 mrad). **c): Typical images of the electron beam** (acquired in 200 ms which corresponds to 200 shots) at a high (1), central (2), and low (3) beam pointing.

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This work was funded by the Agence Nationale de la Recherche under Contract No. ANR-20-CE92-0043-01. Financial support from the European Research Council (ERC Starting Grant No. FEMTOELEC 306708, ERC Advanced Grant No. ExCoMet 694596) is gratefully acknowledged. Numerical simulations were performed using HPC resources from GENCI-TGCC (Grand Équipement National de Calcul Intensif) (Grant No. 2020-A0090510062) with the IRENE supercomputer. This project has also received funding from the European Union’s Horizon 2020 Research and Innovation program under Grant Agreement No. 101004730.

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Ultra-bright laser-driven sources of MeV particles and radiation using low density foams

O. N. Rosmej[1,2,3]

[1]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr.1, 64291 Darmstadt, Germany
[2]Goethe University, Frankfurt, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany
[3]Helmholtz Forschungsakademie Hessen für FAIR (HFHF), Campus Frankfurt am Main, Max-von-Laue-Straße 12, 60438 Frankfurt am Main, Germany

Abstract

Experiments on the interaction of relativistic laser pulse with pre-ionized foam targets were carried out at the PHELIX-facility at GSI, Darmstadt. Experiments and simulations demonstrated a strongly enhanced conversion of laser energy into energy of MeV-particles and radiation.

In interaction of the sub-ps laser pulses of ~ 10^{19} W/cm^2 intensity with pre-ionized foams, high-current beams of direct laser accelerated (DLA) electrons with an effective temperature up to 10× higher than the ponderomotive potential and a charge of 50-100 nC (> 7.5 MeV) were measured [1, 2]. Using foams combined with µm-thin foils or mm-thick high-Z convertors, we successfully demonstrated the generation of ultra-bright bremsstrahlung with photon energies of up to 50-60 MeV and a record-breaking conversion efficiency of 1.4% for photons > 7.5 MeV (giant dipole resonance) [2, 3]; record efficiency of neutron production in gamma-driven nuclear reactions [3]; super intense betatron radiation [4, 5], and strongly enhanced proton acceleration.

The DLA process proves to be very robust and can be used to generate ultra-bright laser-driven sources of particles and photons with energies of tens of MeV already at moderate relativistic laser intensity, which is typical for large kJ-class PW laser facilities, used in ICF research.

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The UK effort towards a Laser-hybrid accelerator facility for radiobiological studies

E. Boella[1,2]

[1] Department of Physics, Lancaster University, Bailrigg, Lancaster Lancaster LA1 4YW (UK)
[2] The Cockcroft Institute, Sci-Tech Daresbury, Keckwick Lane, Daresbury, Warrington WA4 4AD (UK)

Abstract

Recent radiobiological studies have highlighted how ultra-high doses at rates > 40 Gy/s (the so-called FLASH regime) or spatially fractioned doses from mini-beams could reduce toxicity in heathy tissue, while maintaining clinical efficacy for tumors [1]. Further *in vivo* and *in vitro* studies are necessary to validate these findings. The Laser-hybrid Accelerator for Radiobiological Application (LhARA), an innovative UK project, holds the promise to fill this gap, by delivering proton and ion beams that will enable a complete research programme on these new radiotherapy regimes [2].

In this talk, I will introduce the key technologies of LhARA. Protons and carbon ions will be produced via Target Normal Sheath Acceleration. Particles will be then captured and shaped into a beam by a system of Gabor lenses. The bunches with average energy of 15 MeV will be transported to a low energy *in vitro* station through a beam line designed to deliver uniform dose distribution at the cell layer. In a second phase, protons will be post-accelerated to energies of 127 MeV via a fixed-field alternating gradient accelerator to serve a high-energy *in vitro* or an *in vivo* station.

With the aid of three-dimensional Particle-In-Cell (PIC) simulations performed under realistic LhARA conditions, I will discuss the features of the proton source. By using Monte Carlo particle tracking simulations, which employ the results of PIC simulations as input, I will describe the beam transport from the source to the low energy *in vitro* station. These simulations show that the TNSA divergent protons will be shaped into a well collimated beam with a transverse size < 1 cm (RMS) and 2% energy spread.

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36th European Conference on Laser Interaction with Matter
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Ultra-relativistic spin-polarized plasma driven by high-intensity laser pulses

Zheng Gong[1]

[1] Max Planck Institute for Nuclear Physics, Heidelberg, Germany

Abstract

Interaction of an ultrastrong short laser pulse with non-prepolarized near critical density plasma is investigated in an ultrarelativistic regime, with an emphasis on the radiative spin polarization of ejected electrons. Our particle-in-cell simulations show explicit correlations between the angle resolved electron polarization and the structure and properties of the transient plasma magnetic field. While the magnitude of the spin signal is the indicator of the magnetic field strength created by the longitudinal electron current, the asymmetry of electron polarization is found to gauge the island-like magnetic distribution which emerges due to the transverse current induced by the laser wave front. Our studies demonstrate that the spin degree of freedom of ejected electrons could potentially serve as a tool to identify strong plasma fields.

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Observation of tunable parametric X-ray radiation emitted by laser-plasma electron beams interacting with crystalline structures

Curcio[1], M. Ehret[1], J.A. Perez[1], G. Gatti[1]

1. Centro de Laseres Pulsados (CLPU), Edificio M5. Parque Científico. C/ Adaja, 8. 37185 Villamayor, Salamanca, Spain

Abstract

Parametric X-ray Radiation (PXR) is the quantum mechanism analog to Laue diffraction where a pseudophoton carried by an electron is scattered out of a crystalline structure as a radiation photon. In this work PXR emitted by electron beams generated with a compact laser-plasma accelerator and interacting afterwards with a Si 220 crystal is observed in single-shot operations. The combination of laser wakefield acceleration and PXR is an efficient and table-top way to obtain monochromatic, pulsed, ultrashort, and stable emission of highenergy photons. Unlike other relevant radiation mechanisms, such as betatron radiation or incoherent bremsstrahlung, PXR is insensitive to the beam energy spread. With a long crystal, we demonstrate the stability of the PXR bandwidth toward shot-to-shot variations of the beam energy and divergence.

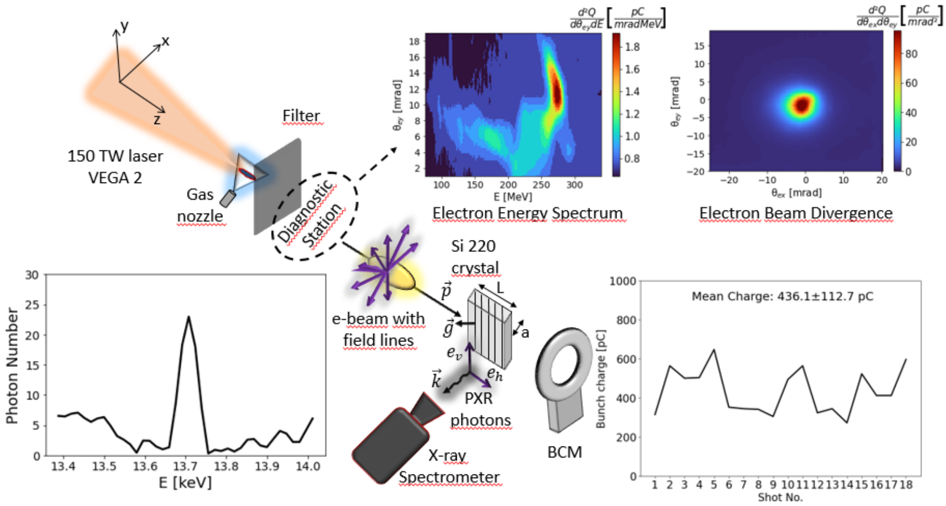

Figure 1. Experimental setup for PXR emission by laser-produced electron beams at VEGA 2.

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High-Performance Implosions on OMEGA and Prospects for Direct-Drive Ignition with Multi-Megajoule Lasers

R. Betti

Laboratory for Laser Energetics, University of Rochester, Rochester NY, USA
2

Abstract

Recent progress in direct-drive inertial confinement fusion has considerably improved the prospects for achieving thermonuclear ignition with megajoule-class lasers. When hydrodynamically scaled to laser energies typical of the National Ignition Facility, recent OMEGA implosions are expected to produce over 800 kJ of fusion yield and 80% of the Lawson triple product required for ignition at 2 MJ of symmetric illumination. Those implosions have benefited from a significant increase in implosion velocity obtained through larger-diameter targets, new laser pulse shapes, and the use of silicon doping to increase laser-energy absorption. A new statistical approach [1,2] used in designing OMEGA targets has demonstrated a considerable predictive capability, thereby enabling the design of targets with improved performance (Fig. 1), leading to recent record neutron yields up to ~3×10^{14} or about 1 kJ of fusion yield [3]. Systematic experiments such as scans of smoothing by spectral dispersion bandwidth, age of the DT fill, and beam-over-target size are used to identify mechanisms of performance degradation and implosion optimization. Pre-shot predictions of the fuel areal density are complicated by low-mode nonuniformities and validating new designs require many shots to acquire statistically meaningful measurements of the average areal density. Ongoing experiments on OMEGA are designed to improve the target convergence and the fuel areal density to achieve the highest value of the Lawson parameter. Implications of these results for direct-drive ignition using multi-megajoule lasers and fourth-generation broadband lasers for suppression of laser–plasma instabilities are discussed.

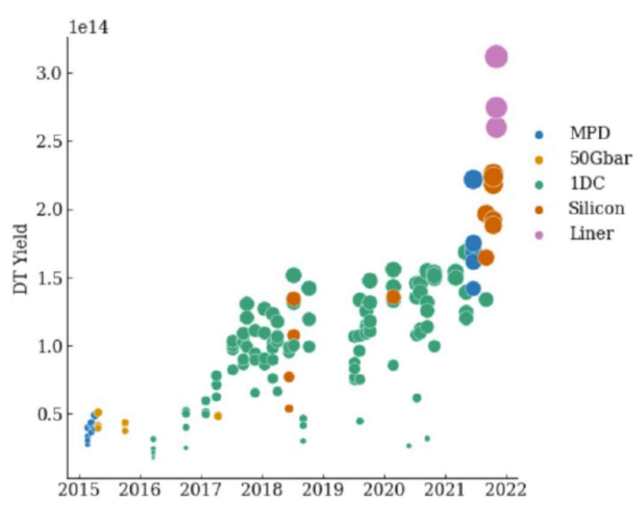

Figure 1: neutron yields (units of 10^{14}) of OMEGA DT-layered implosions since 2015

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Acknowledgements

This work is the result of a large collaborative effort including the Experimental, Theory and Computation, PULSE, Laser and Materials Technology, Administrative and Engineering Divisions, the OMEGA facility crew, the target fabrication group, the cryogenics and tritium facility groups, laser system science and diagnostic development and integration group of the Laboratory for Laser Energetics, the HEDP divsion of the MIT Plasma Science and Fusion Center, and the target fabrication group at General Atomics. This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the Office of Fusion Energy Science award DE-SC0022132, the University of Rochester, and the New York State Energy Research and Development Authority.

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Broadband Lasers will be a Game Changer for ICF—Foundation for this Belief, Plans for Further Validation

D. Turnbull[1], A. Colaitis[2], C. Dorrer[1], D. Edgell[1], R. K. Follett[1], V. N. Goncharov[1], A. M. Hansen[3], P. Michel[4], A. L. Milder[5], K. L. Nguyen[1], J. P. Palastro[1], J. Zuegel[1], & D. H. Froula[1]

[1] University of Rochester Laboratory for Laser Energetics, Rochester, NY, USA
[2] Centre Lasers Intenses et Applications, Bordeaux, France
[3] Sandia National Laboratories, Albuquerque, NM, USA
[4] Lawrence Livermore National Laboratory, Livermore, CA, USA
[5] University of Alberta, Edmonton, Canada

Abstract

Mitigation of crossed-beam energy transfer (CBET) is required to access the region of direct-drive inertial confinement fusion (DD-ICF) design space in which high target gain is feasible, which in turn is needed to make inertial fusion energy practical. Currently, broadband laser technology offers the most promising approach to CBET mitigation. Simulations suggest that O(1%) fractional bandwidth is sufficient to mitigate CBET in implosions [1-3]. Such drivers are now feasible, and a prototype laser—the Fourth-generation Laser for Ultrabroadband eXperiments (FLUX)—is being built at the University of Rochester to facilitate pioneering demonstrations showing the impact of temporal incoherence on laser-plasma instabilities (LPI).

At present, predicting the benefits of CBET mitigation relies heavily on simulations using radiation-hydrodynamics codes that include linear inline models to describe the instability. Confidence in such predictions is undermined by a persistent belief that LPI is not a quantitative field—a sentiment that is exacerbated by the tendency to assign multipliers to CBET models in order to tune the codes [4]. In this talk, we will review a series of experiments that have consistently demonstrated that linear CBET models do quantitatively reproduce the observed energy transfer as long as the plasma conditions are well known [5-7]. Rather than resulting from uncertainty in CBET physics, recent results suggest that the coupling discrepancy that motivated the CBET-model multiplier in DD-ICF simulations was actually caused by an incorrect Coulomb logarithm in the inverse bremsstrahlung computations [8].

Although these experiments have improved confidence in our ability to calculate CBET, broad bandwidth represents a new frontier with potential for new discoveries, so focused single-beam experiments using FLUX will provide further opportunities to validate our models. We have already begun efforts to develop gas-jet and solid-target LPI platforms using narrowband beams. FLUX experiments are expected to commence in early 2024.

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Acknowledgements

This material is based upon work supported by the DOE NNSA under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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Proton Fast Ignition as a path to commercial fusion energy

[1,2]M. Roth. [3]S. Atzeni, [1,2]M. Brönner, [1,4]T. Ditmire, [1]T. Forner, [1,5]P. Gibbon, [1]A. Hannasch, [1]D. Hammond, [1]M. Hesse, [1,6]J. Honrubia, [1]L.C. Jarrott, [1]P. K. Patel, [4]M. Rivers, [1,2]G. Schaumann, [1,2]N. Schott, [1,7]W. Theobald, [1,8]F. Wasser, [1]S. Zähter, [1]M. Zimmer

[1]Focused Energy GmbH, Im Tiefen See 45, Darmstadt, Germany
[2]Technische Universität Darmstadt, Schlossgartenstraße 9, Darmstadt, Germany
[3]La Sapienza Università di Roma, Rome, Italy
[4]University of Texas, Austin, TX, USA
[5]Juelich Supercomputing Centre, Forschungszentrum Juelich, Germany
[6] Department of Applied Physics, Universidad Politecnica de Madrid, Spain
[7]Laboratory for Laser Energetics, Rochester, NY, USA
[8]IU Internationale Hochschule, Frankfurt, Germany

Abstract

Among possible approaches to fusion energy, we regard the Proton Fast Ignition (PFI) as the most credible. PFI as an alternate route to ignition was triggered by the discovery of ultra-bright beams of protons produced by ultra-intense lasers.
Protons are advantageous to other ion species and electrons. Because of their highest ionic charge-to-mass ratio, they are accelerated most efficiently up to the highest energies. They can penetrate deep into a target to reach the high-density region, where the hot spot is to be formed. And they exhibit a characteristic maximum energy deposition at the end of their range, desirable to heat a localized volume. Thus, Focused Energy Inc. has chosen PFI for the primary pathway to fusion energy.

We discuss different ignition scenarios with respect to their applicability for Inertial Fusion Energy (IFE). Focused Energy has chosen the target-normal sheath acceleration (TNSA) ion acceleration mechanism as the most carefully studied one. The required pulse duration of a few ps eases the burden on the driving lasers. TNSA has been demonstrated to exhibit good conversion efficiency and excellent beam focusing capability. The overlap of multiple, ps high energy lasers can further enhance the efficiency and beam quality. We summarize the recent results and discuss the individual aspects that have led us to choose PFI as our path for IFE.

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3D Simulations of OMEGA implosions in presence of low mode asymmetries

A. Colaïtis[1], D. Turnbull[2], I. Igumenshchev[2], D. Edgell[2], R. C. Shah[2], O. M. Mannion[2], C. Stoeckl[2], D. Jacob-Perkins[2], A. Shvydky[2], R. Janezic[2], A. Kalb[2], D. Cao[2], J. Kwiatkowski[2], S. Regan[2], W. Theobald[2], V. Goncharov[2], and D. H. Froula[2]

[1] Centre Lasers Intenses et Applications, Talence, France
[2] Laboratory for Laser Energetics, Rochester, NY, USA

Abstract

Laser-direct-drive implosion experiments conducted on the OMEGA laser system have been found to be prone to a systematic flow anomaly at stagnation [1]. This anomaly persists across warm and cryogenic experiments and after elimination of other perturbation sources such as target offset, vibration, stalk and ice nonuniformity. Recently, a proposed explanation for this anomaly has been the polarized Cross Beam Energy Transfer (CBET) interaction in the particular OMEGA beam configuration of the Polarization Smoothing system, on the basis of post-processing with the BeamletCrosser tool developed at LLE [2].

Here, we present the first polarized CBET model fully coupled to radiative hydrodynamics. The polarized model is implemented in the IFRIIT 3D laser code, coupled to the ASTER 3D radiation hydrodynamics code [3]. The coupled code is used to investigate 4 OMEGA shots considering various sources of low modes: pointing error, balance error, taregt offset, and polarized CBET.

The simulations reproduce bang times and neutron yields - when separately accounting for fuel age and high modes. The magnitude of the flow is well reproduced only when the low mode sources are large, whereas the modeling of stalk is thought to be required to match the flow magnitude in the remaining cases. For the cases explored in more details, polarized CBET - the only known systematic drive asymmetry, brought the results closest to the measured flow vectors, which may help explain the systematic flow orientation evident in the OMEGA implosion database. For typical current levels of beam mispointing, power imbalance, target offset, and asymmetry caused by polarized CBET, low modes degrade the yield by more than 40%. The current strategy of attempting to compensate the mode-1 asymmetry with a preimposed target offset recovers only about 1/3 of the losses caused by the low modes due to the dynamic nature of the multiple asymmetries and the presence of low modes other than l=1. Therefore, addressing the root causes of the drive asymmetries is apt to be more beneficial. To that end, one possible solution to the specific issue of polarized CBET (10 microns DPRs) is shown to work well. Finally, we illustrate how CBET in itself is responsible for a yield drop of 40 to 60%.

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Acknowledgements

This work was granted access to the HPC resources of TGCC under the allocation 2020-A0070506129, 2021-A0090506129 made by GENCI, and PRACE grant number 2021240055. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. The involved teams have operated within the framework of the Enabling Research Project: ENR-IFE.01.CEA “Advancing shock ignition for direct-drive inertial fusion". The software used in this work was developed in part at the University of Rochester’s Laboratory for Laser Energetics. This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award No. DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.

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Development of the Fourth-Generation Laser for Ultrabroadband eXperiments (FLUX)

C. Dorrer

Laboratory for Laser Energetics, University of Rochester, 250 East River Rd, Rochester, NY 14623, United States

Abstract

The coupling of high-energy laser pulses into solid targets is impaired by laser–plasma instabilities (LPI's) such as cross-beam energy transfer, stimulated Raman scattering, and two-plasmon decay. Simulations show that these instabilities can be mitigated using broadband laser pulses having fractional bandwidths (ratio of bandwidth to central frequency) of the order of 1%[1]. Their short coherence time leads to subpicosecond asymptotic smoothing, thereby beneficially reducing the impact of beam imprint. Spectral gain narrowing, which restricts the amplification bandwidth of Nd:glass amplifiers, and phase matching of the nonlinear interactions converting the amplified IR pulses to the UV limit the bandwidth achievable by the current laser facilities.

A novel laser facility, the Fourth-generation Laser for Ultrabroadband eXperiments (FLUX), is being built at the Laboratory for Laser Energetics to generate high-energy UV laser pulses with large fractional bandwidth. Experiments performed with the FLUX system and the 60 narrowband beams of the OMEGA Laser System will support the study of LPI mitigation with large bandwidth, the benchmarking of simulation codes, and the development of technologies for future broadband laser facilities.

In FLUX, spectrally incoherent IR pulses will be amplified in a sequence of optical parametric amplifiers (OPA's) operating near spectral degeneracy. The last OPA will be operated in a collinear geometry with a high-energy pump pulse at 526.5 nm. Its collinear signal and idler will be frequency converted to the UV using sum-frequency generation (SFG) with another pulse at 526.5 nm in a novel scheme based on noncollinearity and angular dispersion. Experiments and simulations show that the OPA and SFG technologies can support the required bandwidth[2,3].

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Acknowledgements
This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, Department of Energy under Award Number DE-SC0021032, the University of Rochester, and the New York State Energy Research and Development Authority.

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Frascati, 19-23 September 2022

Quantifying the impact of P2 symmetry on burning plasma ICF performance

Joseph. E. Ralph[1]

[1] Lawrence Livermore National Laboratory, Livermore, California 94550, USA

Abstract

The burning plasmas[1] achieved in the HYBRID-E and I-Raum campaigns on the National Ignition Facility in late 2020 and early 2021 led the way to the performance increases reached later in 2021. These campaigns were designed to better optimize the energy coupled to the hot core by increasing the capsule size relative to the smaller scale predecessor experiments. Increasing the scale of the capsule, however, creates challenges for achieving symmetric implosions.

In the experimental data analysis that we will present here, we isolate the yield performance sensitivity to mode-2 symmetry and for the first time quantify the impact. Here mode-2 is the amplitude of the Legendre P_2 along the hohlraum axis and is measured from the time integrated x-ray images of the hot spot. The results of this experimental data analysis indicate that performance leading up to the burning plasmas had been significantly affected by P_2 asymmetry. Neutron yields from more than half of the experiments are found to have been degraded by more than 50% from P_2 alone.

To isolate P_2, the simplified model described in Hurricane et. al.[2] is used to account for performance variations in each experiment resulting from differences in 1D parameters, in-flight ablation pressure, implosion velocity, and capsule scale. In this analysis, the adiabat is assumed constant. We also add correction factors to the 1D performance from the inferred local radiative mix[3], and mode-1 velocity[4] from each experiment to get an expected yield, $Y_{\mathrm{mix},m1}$. The residual yield correction factor (assuming we have all the necessary terms), $\eta_{P2}=Y_{DT}/Y_{\mathrm{mix},m1}$ where Y_{DT} is the measured yield, is then ascribed to a non-zero P_2 drive asymmetry. To compare this analysis with simulations, a series of 2D hydrodynamic simulations were conducted where we scanned implosion symmetry. Simulations were conducted with alpha-heating included and without alpha-heating. The performance sensitivity to P_2 is much greater when including alpha-heating in the simulations. The experimentally inferred P_2 sensitivity is found to be consistent with hydrodynamic simulations that include alpha-heating.

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Acknowledgements
This work was performed under the auspices of the U.S. Department of Energy by LLNS, LLC, under Contract No. DE-AC52- 07NA27344.

ECLIM 2022
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Frascati, 19-23 September 2022

High-power laser-plasma chemistry: laboratory astrophysics, astrochemistry and astrobiology

Libor Juha

The PALS Research Center and the Department of Radiation and Chemical Physics, Institute of Physics, Czech Academy of Sciences, Na Slovance 2, 182 21 Prague 8, Czech Republic; juha@fzu.cz

Abstract

A few years after the invention of lasers, it was found that focusing a pulsed laser beam into a gas causes dielectric breakdown of the gas in a consistent part of the converging beam. The process is called laser-induced dielectric breakdown (LIDB) while the phenomenon is usually called a laser spark. Although the physical nature of laser sparks is the subject of numerous reviews (results of early investigations are summarized in refs [1-3]), their chemical consequences have been reviewed only rarely. A systematic study of chemical reactions initiated by laser sparks was conducted by Ronn’s group at CUNY in the 70s and 80s (see for example [4]; a review of early laser-plasma-chemical experiments is given in refs [5,6]). Their motivation for performing such experiments was the preparation of well-defined fine particles [4]. The research on LIDB-initiated chemical reactions of this kind has been triggered again recently by the advent of nanotechnologies. The systematic part of this contribution describes the laser-plasma-chemical behaviour of simple inorganic gases and their mixtures, metal carbonyls and organometallics, and organic vapours. Laser ignition of fuel mixtures is a deeply investigated branch of laser-plasma chemistry because of numerous commercial and military interests.

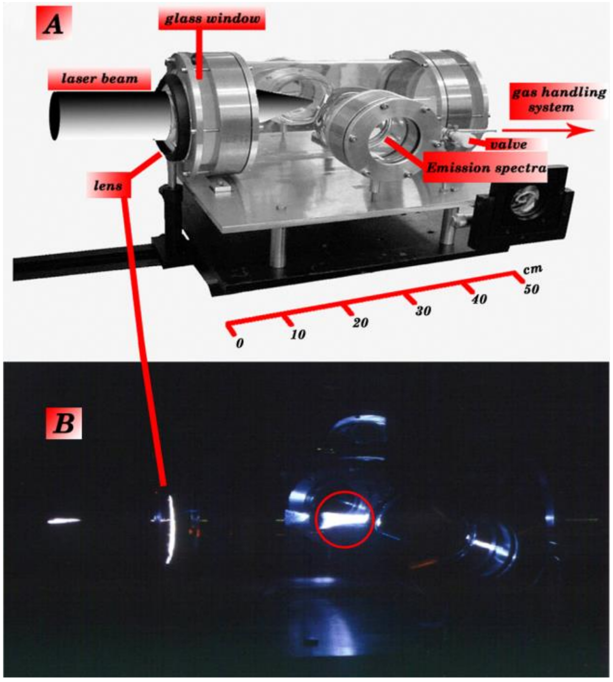

Figure 1. Optical photographs of laser sparks generated at atmospheric pressure by (A,B) high-power iodine photodissociation laser (λ = 1.3152 µm, pulse energy of 85 J behind the entrance window of the cell, τ_{pulse}= 350 ps (FWHM); the NIR laser beam was focused by a glass lens of 25 cm focal length; the LIDB plasma is in the figure B circled) [7].

However, the strongest impulses for studying the laser-plasma chemistry come currently from astrophysics, astrochemistry and astrobiology, where laser sparks have been used as a laboratory model of high-energy-density phenomena (e.g., cometary impact, lightning, meteor flight and related phenomena) in planetary atmospheres and other objects in the Space. Utilization of a single pulse from a high-power laser system for creation of large laser sparks (see Fig. 1 [7]) is discussed. The particular processes responsible for the chemical action of a laser spark are identified and described in detail. Although this contribution is primarily focused on laser-plasma chemistry in homogeneous molecular gases, chemical consequences of LIDB in liquids (laser cavitation) and on liquid-solid and gas-solid interfaces (especially those related to meteor flight phenomena [8]) are reported as well.

Recent results (see for example refs [8-11]) of Space science motivated interaction experiments performed at the PALS (Prague Asterix Laser System) facility are presented and discussed in this talk.

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Acknowledgements

The author and his co-workers greatly appreciate a financial support of the PALS facility operation and development provided by the Czech Ministry of Education, Youth and Sports (CMEYS) and the European Commission (EC) (grant nr. LM2018114). The Czech Science Foundation (GAČR) funded research projects nr. GA19-03314S and GA17-05076S related to the issue reported in this talk.

36th European Conference on Laser Interaction with Matter
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Mirrors and Lenses generated with ultrafast light: the quest for the shortest pulse and charge bunches

Subhendu Kahaly[1]

[1] ELI-ALPS, ELI-HU Non-Profit Ltd., Wolfgang Sandner utca 3., Szeged H-6728, Hungary

Email: subhendu.kahaly@eli-alps.hu

Abstract

Mirrors and lenses are the most fundamental optical elements that are used to enhance our domain of visual observation to render phenomena within the limits of human sense perceptions. The microscopic understanding rests on the physics of how light interacts with charged particles that constitute the matter forming the reflecting (mirrors) or refracting (lenses) material. Light, sufficiently intense and brief, can turn these passive optics into dynamic objects opening the doors to tremendous potentials of nonlinear science. This type of exotic optics can operate at ultra-high intensities making them extremely attractive for applications in attosecond pulse generation and manipulation, laser particle acceleration schemes as well as accessing regimes of laser-matter interaction hitherto impossible.
In this presentation I would review how they can act as tuneable reflective or diffractive elements which can be controlled for surface sharpness, shape, structure; charge particle optics and XUV manipulation. In this context I would discuss the advancements and the relevant opportunities, for further scientific applications, available at ELI-ALPS.

Acknowledgements
ELI-ALPS is supported by the European Union and co-financed by the European Regional Development Fund (ERDF) (GINOP-2.3.6-15-2015-00001). This project has received funding from the European Union Framework Programme for Research and Innovation Horizon 2020 under grant agreement No 871161.

36th European Conference on Laser Interaction with Matter
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Optical generation of transient magnetic fields of high energy density under short laser pulse irradiation

M. Ehret* [1], J. Santos [2], N. Bukharskii [3], Ph. Korneev** [3]

[1] Centro de Láseres Pulsados, Salamanca, Spain
[2] Centre Lasers Intenses et Applications, Talence, France
[3] NRNU MEPhI, Moscow, Russian Federation

* mehret@clpu.es
** korneev@theor.mephi.ru

Abstract

After decades of studies aiming at optical driving of strong magnetic fields in laser laboratories, presently, more and more attention is attracted to use of short ps and fs high-intensity lasers in this context. For interactions with thin solid density targets, it has been found that the target size is one of the most principal parameters, defining generally the whole process from generation to decay. Under interaction of a short laser pulse with a wide target, transient processes may become important under the condition $\tau \ll L/c$, where τ is the pulse duration, L is the target spatial scale, and c is the speed of light.

For quasi-normal incidence of the laser pulse, the excited transient discharge pulse propagates along the target surface with almost the light velocity. For ps laser pulses, the corresponding target scale L should be greater than several hundred microns, while for fs laser pulses, transient processes play an important role already for micron-size targets. In case of intense laser drivers and therefore intense discharge pulses, the latter propagate in a nonlinear regime, forming behind hot expanding plasma carrying magnetic fields. In this case, energy in the discharge pulse gradually decreases and the dispersion may noticeably reduce its group velocity. Using a coil-bent wire as a target allows to create in this regime quasi-stationary magnetised structures, living for hundreds of ps after a very fast interaction stage.

Within certain conditions, the discharge pulse may be visible while propagating for several hundreds of microns. Providing a small dissipation, it may be reflected, divided on several parts and pass along the same surface multiple times. With numerical simulations, this regime is studied for different parameters of interaction in the relativistic intensity domain, for micro-coil targets. Possible applications of the observed phenomena are considered.

A higher efficiency of laser-target interaction was observed in case of grazing incidence. When the direction of the laser pulse coincides with the discharge pulse propagation direction, the latter is feeded by laser energy along its way. One of the schemes based on this property uses a cylindrical hollow where laser pulses may propagate in a whispering gallery regime. A strong quasi-stationary magnetic field is observed in such targets under the action of a relativistically intense picosecond laser pulse; these schemes may yield an efficiency of ~ 10% for conversion of laser light to magnetic field.

Another scheme uses bent wire targets, which allow propagation of a laser-excited discharge pulse for distances of hundreds of micrometres and even more; here we have defined several possibilities. For the quasi-stationary magnetic fields, the discharge current needs to be closed at some point. Without that, the discharge pulse propagates along the wire until fully degraded, performing a transient process.

Experimentally it was evidenced that decay time of plasma structures is on the hundred picoseconds time scale, with the magnetic field strength of the kilotesla scale, when the induced current forms a closed circuit for a coil-shaped wire. We deploy an artificial neural network to detangle the main features of the magnetic field from distortions induced by electric fields. The trained neural network acquires an ability to read the magnetic field values from experimental data, extremely facilitating interpretation of the experimental results.

Without current closure, the quasi-stationary regime can not be achieved. In this domain, we propose to explore a new scheme for the laser-driven generation of intense electromagnetic radiation in the THz domain ─ ranging from 0.3 THz to 10 THz, or in terms of vacuum wavelength from 1 mm to 30 um. Our scheme is based on the emission from a sinusoidal wire antenna which may be geometrically tuned to the spectral range of interest. The potential dynamics on the antenna is driven by relativistic laser induced target-discharge, which enables us to reach high and adjustable power levels.

The all optical generation of strong transient magnetic fields of high energy density paves the ground for platforms to study highly magnetised plasma and the lensing of charged particle beams. The all optical seeding of electromagnetic discharge pulses can become important for new applications, e.g. the controlled generation of ultra-intense electromagnetic pulses.

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Recent progress of experimental campaigns in demonstrating the double-cone ignition scheme

J. Zhang[1,2,3]
[1] Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
[2] Shanghai Jiao Tong University, Shanghai 200240, China
[3] Joint Team for DCI campaigns

Abstract

The double-cone ignition (DCI) scheme consists of four progressive physics processes: quasi-isentropic compression, acceleration inside two head-on gold cones, collision of high-speed plasma jets from the cone tips, and fast heating of the compressed fuel [1], as shown in Figure 1. A series of experiments has been conducted to demonstrate the feasibility of this scheme at a drive irradiance of 8×10^{14}-3×10^{15} W/cm^2 on shell targets inside the cones at the SG-II Upgrade laser facility since 2020. The pulse shapes of the 8 drive laser beams and target configurations are optimized to demonstrate the designed compression and acceleration processes inside the cones and efficient collision process of high-speed plasma jets from the cone tips. The density of the plasma at the tip from a single cone is measured to be 28.3±4.3 g/cm^3 and the velocity of the plasma jets from the cone-tips is about 240 km/s, for a laser energy of 10 kJ from each side. A conversion efficiency of about 90% from kinetic to internal energy is measured during the collision process. The density of the plasma after collision has increased to 62.8±9.2 g/cm^3, corresponding to an areal density of 300 mg/cm^2. An isochoric plasma with an almost uniform density distribution is created for a duration of over 100 ps. An experiment is being carried out since 15 August to demonstrate the heating process of fast electrons generated by a 0.5 kJ TW laser pulse in 10 ps.

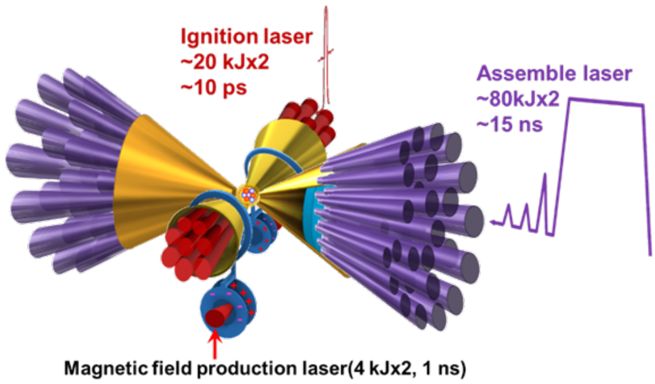

Figure 1. Sketch of the double-cone ignition scheme

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Acknowledgements
This work was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDA25000000).

36th European Conference on Laser Interaction with Matter
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Experimental investigation of Laser-Plasma Interaction in conditions relevant to Shock Ignition scheme to ICF: recent achievements and new challenges

G.Cristoforetti[1], P.Koester[1], L.Antonelli[2], S.Atzeni[3], F.Baffigi[1], C.Baird[4], D.Batani[5], N.Booth[4], M.Galimberti[4], J.Dostal[6], R. Dudzak[6], R.Fedosejev[7], E.Filippov[8], S.Fujioka[9], P.Gajdos[6], K. Glize[10], Y.Hironaka[9], A. Heron[11], S.Huller[11], K.Kawasaki[9], M.Khan[2], R.Kodama[9], M.Krus[6], T.Idesaka[9], P.Loiseau[12], D.Mancelli[5], A.S.Martynenko[8], Ph.Nicolai[3], M.Notley[4], P.Oliveira[4], N.Ozaki[9], S.Pikuz[8], O.Renner[6], A.Schiavi[3], K.Shigemori[9], M.Smid[13], R.Takizawa[9], T.Tamagawa[9], D.Tanaka[9], A.Tentori[5], G.Tran[12], L.Volpe[14], N.C.Woolsey[2], G.Zeraouli[9], A.Yogo[9], L.A.Gizzi[1]

1) INO-CNR, Pisa, Italy
2) University of York, York, UK
3) Università la Sapienza, Roma, Italy
4) STFC Rutherford Appleton Lab, Central Laser Facility, Didcot, UK
5) Université de Bordeaux, CNRS, CEA, CELIA, Talence, France
6) Institute of Plasma Physics & Institute of Physics, CAS, Prague, Czech Republic.
7) University of Alberta, Edmonton, Canada
8) Joint Institute for High Temperatures, RAS, Moscow, Russia
9) Osaka University, Osaka, Japan
10) Key Laboratory for Laser Plasmas, Shanghai Jiao Tong University, Shanghai, China
11) Centre de Physique Théorique CPHT, Ecole Polytechnique, Palaiseau, France
12) CEA, DAM, DIF, Arpajon, France
13) Helmholtz-Zentrum Dresden-Rossendorf, Dresden, Germany
14) Universidad de Salamanca & Centro de Laseres Pulsados (CLPU), Salamanca, Spain

Abstract

Shock ignition (SI) is a promising two-stages scheme for Inertial Confinement Fusion (ICF), where the ignition is driven by a strong converging shock wave, launched at the end of the compression phase by means of an intense laser spike ($I \sim 10^{16}$ W cm^{-2}). One of the main concerns of SI is the relevance of non collisional absorption mechanisms occurring during laser interaction with the precompressed corona, resulting in the growth of parametric instabilities, such as Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS) and Two Plasmon Decay (TPD). Their extent, in fact, can be dramatic, resulting in a significant amount of scattered laser energy and in the generation of large fluxes of suprathermal electrons, with a considerable impact on both the shock pressure and the preheat of the fuel capsule. The non-linear character of these instabilities makes the extrapolation of analytical models quite inaccurate; a more detailed understanding of these processes therefore calls for experiments dedicated at investigating Laser Plasma Interaction (LPI) in conditions as close as possible to those envisaged in SI.

In this presentation, we will try to summarize the state of the art of LPI in SI conditions, reporting recent experimental results obtained in experiments at Gekko XII, PALS and VULCAN laser facilities. Aims of these experiments were understanding the effect of plasma and laser parameters on the growth of SRS and TPD as well as identifying the mechanisms originating suprathermal hot

electrons. In all experiments, Stimulated Raman Scattering and Two Plasmon Decay were accurately spectrally, time-resolved and quantitatively characterized by means of spectroscopic and calorimetric tools, while a full set of diagnostics – including Kα imaging and spectroscopy, Bremsstrahlung cannons and Magnetic Electron Spectrometers - were used for achieving an energy-resolved characterization of hot electrons. The regime of interaction in these experiments is significantly different, with laser intensity ranging from $I\lambda^2 \sim 2 \cdot 10^{14}$ Wμm^2/cm^2 to $\sim 2 \cdot 10^{16}$ Wμm^2/cm^2, plasma density scalelength rising from 50 to 400 μm, laser wavelength going from the UV to the IR range, laser irradiation in single- and multi-beam configuration, allowing a good understanding of the role played by the different experimental parameters.

After critically discussing the experimental results, we will show the future challenges and the new directions of our research in this field, as for example the laser bandwidth effects on LPI, the role of Side-SRS and the onset of collective instabilities.

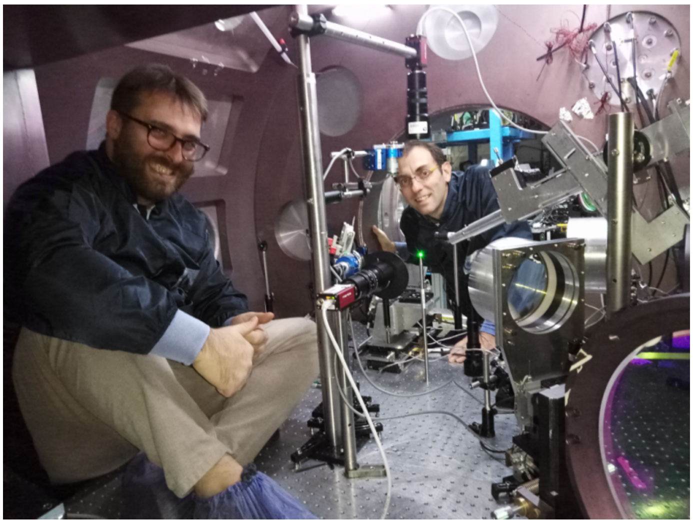

Figure 1. Experimental vacuum chamber at the Target Area West of Vulcan laser facility at Central laser facility (UK).

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. The involved teams have operated within the framework of the Enabling Research Project: ENR-IFE.01.CEA "Advancing shock ignition for direct-drive inertial fusion".

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Direct measurements of DT fuel preheat from hot electrons in direct drive inertial confinement fusion

A. R. Christopherson[1], R. Betti[2], C. J. Forrest[2], J. Howard[2], W. Theobald[2], J. A. Delettrez[2], M. J. Rosenberg[2], A. A. Solodov[2], C. Stoeckl[2], D. Patel[2], V. Gopalaswamy[2], D. Cao[2], J. L. Peebles[2], D. H. Edgell[2], W. Seka[2], R. Epstein[2], M. S. Wei[2], S. P. Regan[2], E. M. Campbell[2], M. Gatu Johnson[3], R. Simpson[3]

[1] Lawrence Livermore National Laboratory, 700 East Avenue, Livermore, California, 94550, U.S.A.
[2] Laboratory for Laser Energetics, 250 East River Rd, Rochester, New York, 14620, U.S.A.
[3] Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts, 02139, U.S.A

Abstract

In laser fusion, a spherical shell of a low-Z ablator (CH, HDC, Be or others) layered with cryogenic DT ice is accelerated inward on a low adiabat to achieve high fusion yields and areal densities with minimal driver energy. Hot electrons generated from laser-plasma instabilities can severely degrade the implosion performance by preheating the DT fuel, resulting in early decompression of the imploding shell and lower fuel areal density. It is shown that, in direct-drive experiments, the hot-electron energy deposited in the DT fuel can be inferred by comparing the hard x-ray signals between a layered DT implosion and its mass-equivalent all-CH implosion irradiated with the same pulse shape[1]. Both implosions have the same source of hot electrons, which means that any difference in the observed hard x-ray signals is proportional to the preheat energy deposited into the DT fuel (Figure 1).

Since a significant fraction of the ice layer is ablated during the implosion, it is also important to assess the spatial distribution of the preheat energy into the fuel, in particular within the unablated fuel which determines the final areal density. The spatial distribution of preheat energy was inferred in two experimental campaigns on OMEGA using warm CH targets with Cu-doped plastic payloads of varying thicknesses. The hard x-rays from the Cu-doped plastic implosions were used to infer the hot electron energy deposited in each layer. A hot electron transport and deposition model was derived to match the hard x-ray spectrum and emission in both warm and cryogenic implosion experiments. The calibrated model was used to assess the areal density degradation due to hot electron preheat. A similar experimental campaign on the NIF using Ge-doped shells has led to the inference of the spatial distribution of preheat energy and provided critical information on the scaling of hot electron preheat at megajoule driver energies[2].

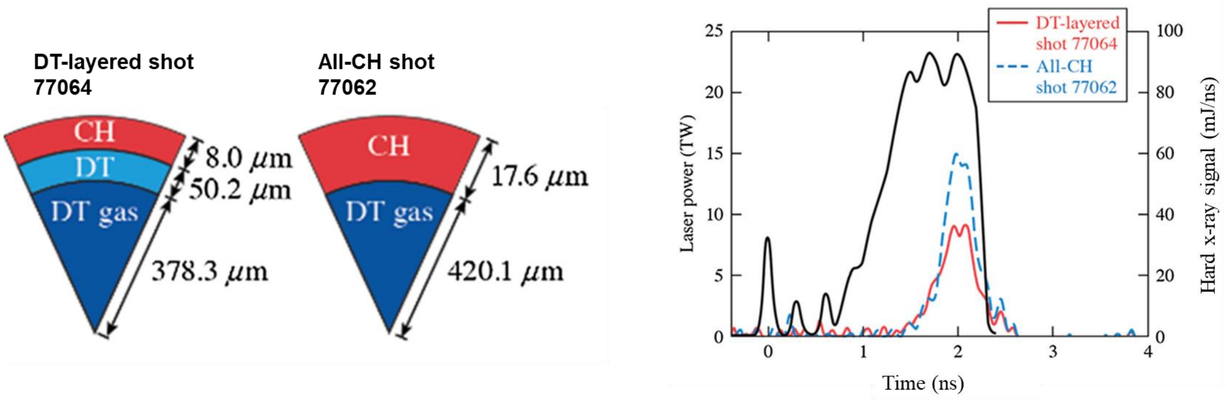

Figure 1. The targets and pulse shape are shown for the DT-layered and all-CH implosions. Both targets are irradiated with the same laser pulse shape leading to similar plasma conditions in the corona and the same hot electron spectrum. The measured difference in hard x-ray signals occurs because some of the electrons are slowing down in DT which is a less efficient emitter of x-rays in comparison to CH.

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Acknowledgements

Work performed under the auspices of the U.S. D.O.E. under Award No. DE-NA0003856 and by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344.

ECLIM 2022
36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Shock Ignited Approaches to Laser Inertial Fusion Energy

R.H.H. Scott[1], D. Barlow[2], W. Trickey[2], A. Ruocco[1], K. Glize[1], L. Antonelli[3], M. Khan,[3] and N. Woolsey[3].

[1] Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Oxford, United Kingdom
[2] Department of Physics, University of Warwick, Coventry, United Kingdom
[3] York Plasma Institute, Department of Physics, University of York, York, United Kingdom

The addition of a strong shock towards the end of the implosion in laser inertial fusion schemes has been shown in numerous studies to be beneficial. The additional strong shock can either increase the gain (fusion energy out/laser energy in) or the probability of ignition.

This talk will begin by discussing shock ignition experiments performed on both the Omega laser facility at the Laboratory for Laser Energetics, and on the National Ignition Facility, Lawrence Livermore National Laboratory. In light of these experiments, and the associated findings, we will discuss the promise and challenges associated with shock ignition.

We will then go on to describe a new shock augmented laser inertial fusion concept. This has the potential to bring the benefits of shock ignition while ameliorating many of the challenges. We find this shock-augmented ignition concept has the potential to expand the viable ignition design-space of laser direct drive inertial fusion. Furthermore, this concept extends to indirect drive implosions, which exhibit substantial yield increases at reduced implosion velocity. Simulations of NIF shot N210808 show substantial yield increases when a shock-augmented ignition pulse shape is used. This talk will also briefly outline 3 upcoming NIF indirect drive shock augmented ignition experiments.

Acknowledgements
This work was funded by EPSRC grant EP/P023460/1.

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Time-Of-Flight detectors and their use as diagnostic for laser-generated plasmas and accelerated particles

M. Salvadori[1, *], P. L. Andreoli[1], M. Cipriani[1], G. Cristofari[1], G. Di Giorgio[1], R. De Angelis[1], M. Scisciò[1], C. Verona[2], F. Consoli[1]

[1] *ENEA, Fusion and Technology for Nuclear Safety and Security Department, C.R. Frascati, Italy*
[2] *Industrial Engineering Department, University of Rome "Tor Vergata", Rome, Italy*

**present address: Intense Laser Irradiation Laboratory, INO-CNR, Pisa, Italy* martina.salvadori@ino.cnr.it

Abstract

The interaction of an intense (> 10^9 Wcm^{-2}) laser pulse with matter leads to the production of a plasma and subsequent emission of charged particles. According to the specific interaction regime, determined by the laser characteristics (energy, intensity, pulse duration) and target type (solid, gaseous, liquid, cryogenic…), the produced ions can be characterized by low energies (tens-hundreds of keV) up to hundreds of MeV[1].

Because of the impact that a well characterized laser-accelerated ion beam can have on a variety of different applications, several diagnostic systems were developed[2] aiming for the accurate measurement of the main features of the so-accelerated particles. These latter usually present high currents and a large energy spread. A suitable detector for them should be able to provide fast acquisition time, real-time operation, high dynamic range, high sensitivity, high energy resolution and angular resolved characterization.

The Time of Flight (TOF) technique can be effectively used to satisfy the most of the mentioned requirements. In TOF, a time-resolved particle detector (e.g. a semiconductor based detector or a scintillator) is placed at a known distance from the source. The signal produced by the detector is recorded by using an oscilloscope. Since particles with different velocities take different times to travel to the detector, there is a direct correspondence between the time of detection and the particle energy. Due to its ease of use and versatility TOF has been used since the very first observations of laser-driven particles[3]. Nevertheless, with growing laser energies and intensities, a sensible growth in the electromagnetic pulses (EMP) generated during the laser-matter interaction was also experienced[4]. These electromagnetic fields may hinder the operation and safety of any electronic device placed in proximity of the target, compromising the signal-to-noise ratio of the acquired signal (thus affecting both sensitivity and energy resolution of the measurement) and in some cases preventing the real-time characterization of produced ions.

Even in this frame, TOF technique can still be effectively used if proper cautions and upgrades are made. Here we show an optimized TOF methodology based on semiconductor detectors that meet the aforementioned requirements and enable the measurement of a calibrated proton spectrum up to a few tens of MeV allowing real-time operation[5,6,7]. We

provide a description of the developed methodology, outlining its advantages over traditional TOF while emphasizing the key outcomes.

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Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 - EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. The involved teams have operated within the framework of the Enabling Research Project: ENR-IFE.01.CEA "Advancing shock ignition for direct-drive inertial fusion"

Oral contributions

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The Vulcan facility development projects

M. Galimberti, P Oliveira, G. Archipovaite, M. Galletti[1], N. Stuart, I. Musgrave, C. Hernandez-Gomez

Central Laser Facility, STFC, UKRI, Rutherford Appleton Laboratory, Chilton, Didcot, Oxon. OX11 0QX, UK
[1] University of Tor Vergata and LNF INFN, Roma, Italy

Abstract

Vulcan is a well-known large scale high energy laser facility, with the aim to support the user community to delivery world research. Over the years it has been upgraded different time. In the last few years, a reduction on the demand of the Target Area Petawatt indicated the needs to improve his capabilities. A new petawatt beamline was decided to be added, to allows betatron imaging, QED experiments, etc. In addition to the main upgrade, small upgrade is on going on the long pulse capability.

VOPEL: Vulcan OPCPA petawatt for electron

The main objective for this project is to provide better imaging capability to the existing Petawatt at Vulcan, adding a laser driven betatron source. The design specifications for the new beamline are:

- Pulse length: < 30fs
- Energy: ~30J
- Repetition rate: 1 shot every 5min.

All the new amplification chain is based on OPCPA, by using the expertise in the Central Laser Facility, to provide high contrast and large bandwidth.

While the large bandwidth (>160nm) is not important for betatron radiation, it will open a new set of experiments for study QED effect.

The laser system is based to the dual CPA scheme. The first four OPCPA stages are pumped by few picosecond pump lasers to provide high contrast. Preliminary work on the ps front end (fig. 1 - left) is encouraging, showing good compressibility, down to 22fs FWHM, and good stability (fig. 1 - right).

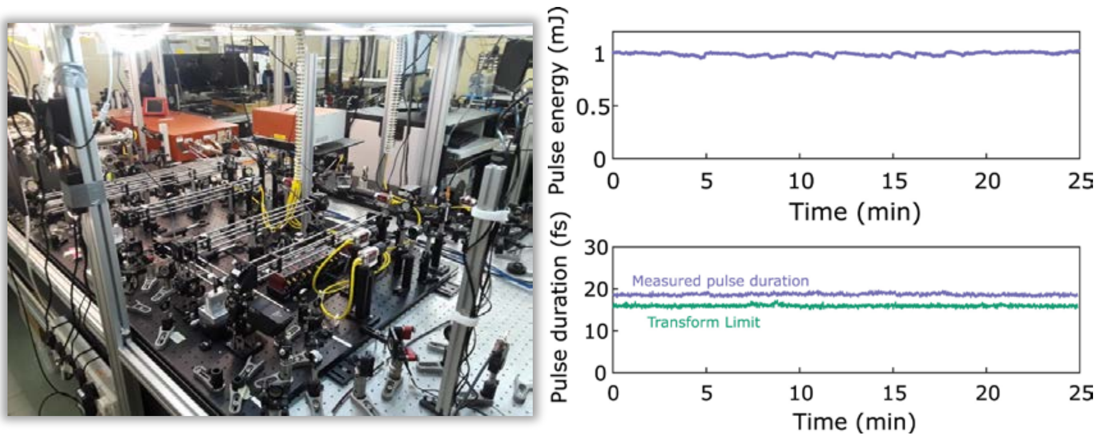

Figure 1: The new ps front end of VOPEL: left – stage 1 & 2; right – energy and pulse length stability.

The pulse is then stretched to 3ns and amplified by further 4 OPCPA stages up to 50J. It will be compressed down to less than 30fs by an off plane grating compressor, using the same geometry as the Gemini laser facility compressor (fig. 2).

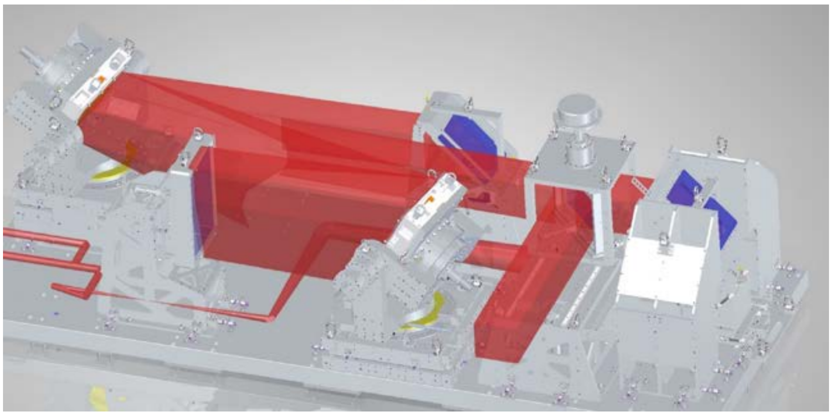

Figure 2: Layout of the compressor

In addition to the new beamline, the long pulse capability for the Petawatt target is planned to the improved, increasing the available energy to the kJ scale.
Unfortunately, different problems are affecting the delivery of this project, like COVID 19, delaying the progress. Nevertheless, the work is progressing, and we are aiming to deliver a short pulse on target in the first half of 2023.

Improving long pulse capability

Over the last few years, the requirements for the long pulses increased. To follow the request, we improved nanosecond shaped capability, and we have now demonstrated 10 nanosecond square pulses at 1.5kJ level (in 6 beams).
A new front end has also been commissioned with a 12 ns capability and 10 times more energy. It is using a new fibre amplifier and a regenerative amplifier cavity with a Harriott cell inside. In this way we can increase the available pulse length.
Within the pulse shaping capability, the requirement of relative broadband (few nm) long pulse has been requested to suppress instabilities in laser plasma interaction. We have exploring different configurations where we could have a nanosecond long pulse with different bandwidths. Simulations have been on the possible scenarios and the consequences this would have on the second harmonic process.

Conclusions

Different upgrading project are on going in Vulcan and, more in general, at the Central Laser Facility. A new petawatt class beamline is under construction to improve the imaging capability at the Petawatt Target Area and, more in general, to increase the flexibility of the facility.
Also the long pulse capability of the Vulcan is on constant improvement, following the requirement from the user community.

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Advance Research on Materials for Inertial Fusion

R. Gonzalez-Arrabal, O. Peña, A. Rivera, D. Garoz, J. Kohanoff, F. Sanchez, J.M. Perlado

[1] Instituto Fusión Nuclear "Guillermo Velarde" – Universidad Politecnica de Madrid
ETSII / José Gutierrez Abascal, 2; 28006 Madrid (Spain)
josemanuel.perlado@upm.es

Abstract

A large effort has been done for study some critical point in material and systems assessment for IFE future reactors: i) Fabricate and test new advanced materials with enhanced properties to withstand the harsh conditions considering combined effects of thermal loads and atomistic damage; ii) extend, improve and validate computational models presently used for studies of radiation-induced damage in diverse materials; iii) fabricate advanced materials to work as permeation and corrosion barriers; iv) contribute to identify and use experimental facilities which allows mimicking, as much as possible, radiation environments in inertial nuclear fusion reactors; v) contribute to reactor technologies by proposing engineering solution to improve reactor operation and safety.

i) Hollow nanospheres of W (hsW) has been studied by Molecular Dynamic and Kinetic MonteCarlo to define their properties under irradiation; not only the structural behaviour but also acting as receptor of gases (He irradiation) generated in the first wall. It has been demonstrated that they will allow temperatures up to 3000 K and pressures of < 5 GPa, with the property of breaking under those pressure to release the He located in its interior when irradiation in inertial fusion [1]. Additionally, the influence of the sputtering parameters (oblique angle, argon pressure and deposition power) on the morphology of the W nanocolumns proposed as first wall coating has been studied, including the thermal conductivity in collaboration with the Center of Micro and Nano-electronics (IMM/CSIC), the Atomic Physics group of the Technical University of Vienna and the physics department of the University of Helsinki to study the behaviour of these nanocolumns under irradiation.

ii) Experiments of sequential C and H irradiation of W nanocolumns were performed including permeation of H for different temperatures and pressures. Those experiments have also been computationally study by DFT model including the diffusion of H in the grain boundaries. A new parameterization of the MonteCarlo MMonCa code has been carried out by considering the data calculated by means of DFT, to consider the incorporation of H in the GBs and its migration along them [2]. By using also DFT, the synergistic behaviour (energy, structural, electronic and mobility) of various defects (interstitial, vacant, H and He) coexisting in W GBs and in massive W has been studied [3]. To study the damage by electronic excitation in fusion material a code called Quebec (quantum electronics Boltzmann equation code) has been developed. This code has been developed from cero to solve the Boltzmann equation with various terms in the quantum mechanics formalism: multiphoton photo-ionization (MA), absorption by free carriers (F0, F1, F2 depending on the type of phonon involved, LO, LA, TA), electron-electron scattering (EE), electron-phonon scattering (P0, P1, P2, depending on the type of phonon involved, LO, LA, TA), impact ionization (II), Auger recombination, exciton formation.

iii) In order to design coatings as permeation and corrosion barriers in blanket of fusion reactors, a large program has been conducted with deposition of SiC on Eurofer steel. Adhesion of coatings to steel has been analyzed as a function of deposition and influence of interlayers (Ti). Furthermore, in collaboration with CIEMAT the morphology, microstructure and elemental composition of the deposited coatings have been characterized, and the corrosion resistance of the SiC coatings when being in contact with solid pebbles and their properties as D permeation barriers [4].

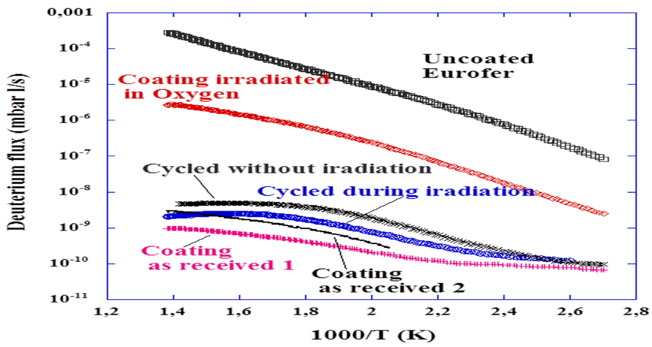

Figure 1. Permeation of D in SiC vs. temperature and type of irradiation

iv) The extremely and peculiar condition of irradiation in inertial fusion conditions with a very high flux short in time and pulsed drove to a very few (if any) experiments in neutron irradiation. The opportunity to, at least, use a Very High Neutron Facility in White Sand (USA) for study a single very intense pulse will be presented.

v) The conceptual design of a ceramic breeding blanket in which it would possible to tune the tritium breeding ratio has been completed. Our design is based on lithium titanate as the breeding material, metallic beryllium as the neutron multiplier, zircaloy as the structural, and heavy water as the neutron reflector. By varying dynamically the filling level of the tank (easy to do), it is possible to modify the TBR between 1.0 and 1.1, which could be real, effective and simple for fusion plants [5].

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Acknowledgements

The authors want to thank two European EUROFUSION Enable Research projects: “Advancing shock ignition for direct-drive inertial fusion” CfP-FSD-AWP21-ENR-01-CEA-02, actually runnig; and “Routes to High Gain for Inertial Fusion Energy”, ENR-IFE19.CCFE-01. They also thanks to the Research Project by Goverment of Madrid Region, “Desarrollo del Programa de actividades de I+d multidisciplinares del Centro de Tecnologías para la Fusión (TechnoFusión)”, S2018/EMT-4437 / TECHNOFUSIÓN(III)CM

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Maximization of Laser Coupling with Cryo-Targets

M. Geissel[1], A. Hansen[1], A. J. Harvey-Thompson[1], D. Ampleford[1], K. Beckwith[1], J. A. Crabtree[1], R. J. Fein[1], M. R. Gomez[1], J. C. Hanson[1], C. Jennings[1], M. W. Kimmel[1], A. J. Maurer[1], J. L. Porter[1], P. Rambo[1], J. E. Shores[1], I. C. Smith[1], C. S. Speas[1], R. J. Speas[1], M. R. Weis[1]

[1] Sandia National Laboratories

Abstract

A major obstacle for depositing laser energy to targets in Magnetized Liner Inertial Fusion (MagLIF) is the need to contain the gas with a laser-entrance-hole window (LEH). Att room temperature, previous experiments used polyimide films of 1.56-2 µm thickness and 2.2 mm diameter which consumed 500-1000 J of laser energy at the maximum plausible beam spot size of 1.1 mm [1,2].
We will discuss the implementation of cryogenic cooling to enable the use of thinner and wider LEH windows along with a larger beam spots size.
As a result (see Fig. 1), we dramatically reduced losses while keeping the laser propagation depth within a useful range for MagLIF, and we comfortably exceeded the previously unobtainable laser deposition of 2kJ.
Figure 1: (Total deposited laser energy (left) and lost laser energy (right) for experiments with room temperature gas fills and 1.6µm thick laser-entrance-window (blue data) compared to cryogenically cooled gas fills and 0.5µm thick laser-entrance-windows (red data).)

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Acknowledgements

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. DOE's National Nuclear Security Administration under contract DE-NA0003525.

Experimental studies of laser interactions with low density porous targets

J. Limpouch[1], O. Renner[2,3,4], Sh. Agarwal[4,5], T. Burian[2,4], J. Dostál[2,4], R. Dudžák[2,4], D. Ettel[4,6], L. Juha[4], M. Krupka[1,2,4], S. K. Singh[2,4], S. Weber[3], W. Nazarov[7], M. Šilhavík[4], J. Červenka[4], T. Laštovička[3], O. Maliuk[8], T. Wiste[3], L. Hudec[1], R. Liska[1], A. Gintrand[3], S. Shekhanov[1,3], V.T. Tikhonchuk[3,9]

[1] FNSPE, Czech Technical University in Prague, 11519 Prague 1, Czech Republic
[2] Institute of Plasma Physics, Czech Academy of Sciences, 182 00 Praha 8, Czech Republic
[3] ELI-Beamlines, Institute of Physics, Czech Acad. Sci., 252 41 Dolní Břežany, Czech Republic
[4] Institute of Physics, Czech Academy of Sciences, 182 21 Prague 8, Czech Republic
[5] FMP, Charles University, 121 16 Prague 2, Czech Republic
[6] INATI, Technical University of Liberec, 461 17 Liberec, Czech Republic
[7] Independent Foam Target Supplier, Carnoustie, DD7 6DP, United Kingdom
[8] Institute of Photonics and Electronics, Czech Academy of Sciences, 182 51 Prague 8, Czech Republic
[9] CELIA, University of Bordeaux-CNRS-CEA, F-33405 Talence, France

Abstract

Low density porous materials are considered in the inertial confinement fusion studies as a promising material for smoothing laser beam intensity modulations and creation of spherical targets filled with a liquid deuterium-tritium fuel. However, the role of intrinsic structural foam inhomogeneities on seeding instabilities is not known. Experimental studies and modelling of the time of foam ionization and homogenization are of prime importance in that context.

We present here the results of a recent experiment on the PALS laser installation dedicated to measurements of foam ionization and plasma characterization. Three types of low-density porous targets were irradiated by intense sub-nanosecond laser pulses on the 3rd and 1st harmonics of iodine laser at laser intensities in the range 10^{14} – 10^{15} W/cm^2: a) plastic TMPTA targets of average density 10 mg/cc doped with 8 weight percent of chlorine, b) 3D graphene targets of average density about 7 mg/cc and c) 3D printed regular porous targets of average density 8 mg/cc composed of plastic wires of radius 2.2 μm (Figure 1). While the pore size of TMPTA and graphene foams is typically 2 μm, the pore size is of order 50 μm for the printed target. The thickness of all targets was in the 600 – 800 μm range and a copper foil was attached to the rear side of all targets for measurements of the hot electron production. All targets were underdense for the 3rd harmonic and overdense for the basic laser frequency.

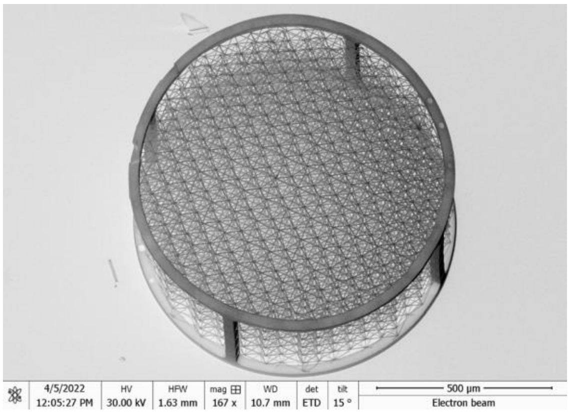

Figure 1. SEM image of 3D printed low average density plastic target.

We measured the speed of ionization wave propagation into the low-density porous matter via X-ray streak. Laser energy transformation into fast electrons was detected via time-integrated spatially resolved absolutely K-α emission from the copper foil. Energy and spectrum of laser radiation scattered back under angle 30° was registered. LYSO scintillators detected a very weak signal of hard X-rays. Chlorine emission spectra (Figure 2) from chlorine doped TMPTA foams were used for measurement of electron and ion temperatures. Electron temperature was estimated from the ratio of Ly-β and He-δ lines. Ion temperature in the ionized material was derived from the Doppler broadening of chlorine He-α_y intercombination line.

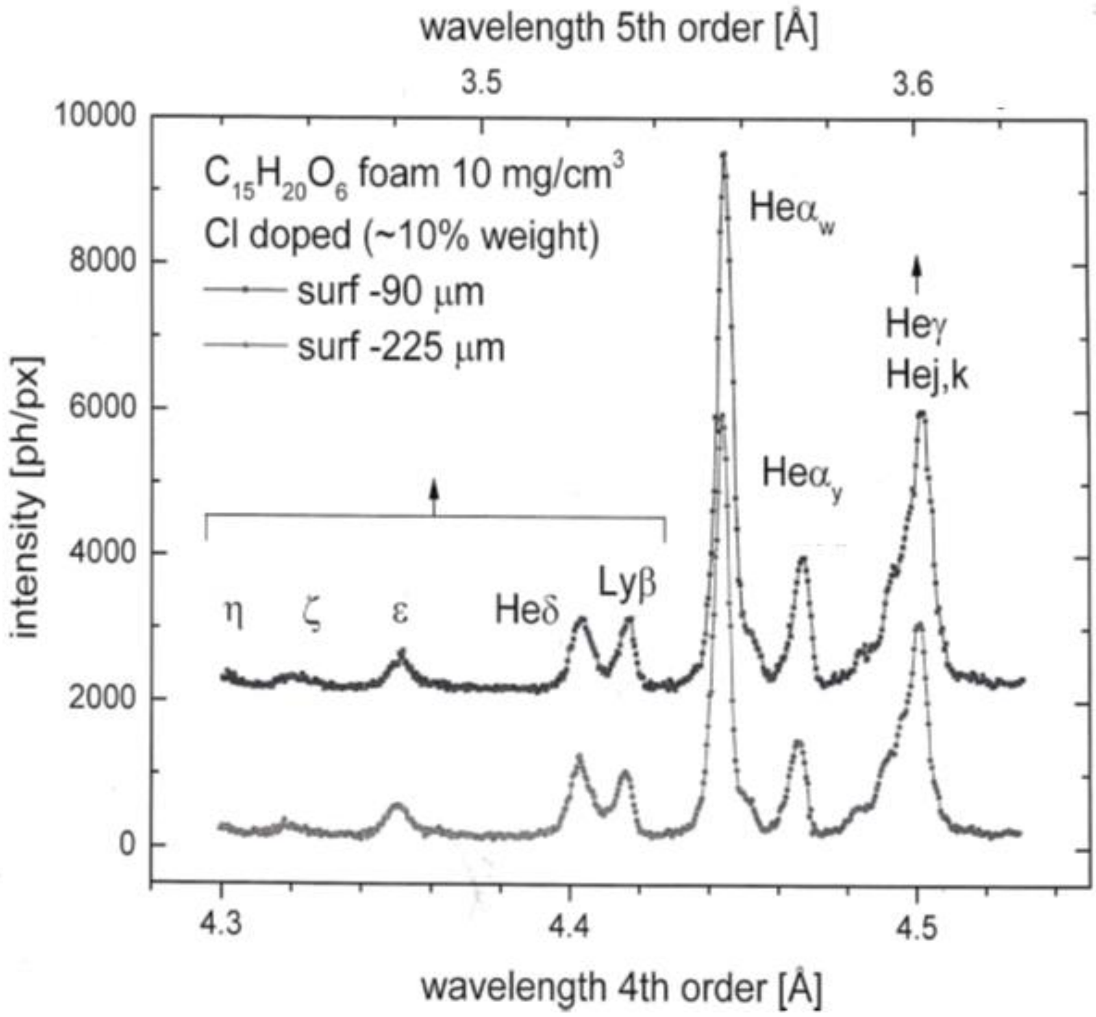

Figure 2. Time-integrated chlorine emission spectra plotted at depths 90 and 225 μm inside chlorinated TMPTA foam. PALS third harmonic of energy 200 J and pulse duration 293 ps was focused on the front surface of the foam

Experimental results are compared with the results of fluid simulations using our novel sub-grid model [1] of laser interaction with low density porous matter incorporated into PALE and FLASH hydrodynamic codes.

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[1] L. Hudec *et al.*, A hybrid (ablation-expansion) model for low-density foams, contribution to ECLIM 2022

Acknowledgements

The authors acknowledge financial support from the European Regional Development Fund through the projects CAAS (CZ.02.1.01/0.0/0.0/16_019/0000778) and ADONIS (CZ.02.1.01/0.0/0.0/16 019/0000789) and from the Ministry of Education, Youth and Sports of the CR via project LM2018114. This work has been partially carried out within the framework of the EUROfusion Consortium and has received funding from EUROfusion project CfP-FSD-AWP21-ENR-01-CEA-02.

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

On the evolution of the hot electron sheath

P. Rączka[1]

[1] Institute of Plasma Physics and Laser Microfusion, 01-497 Warsaw, Poland

Abstract

The laser-target interaction at high laser intensity results in the generation of a population of fast electrons which penetrate through and spread across the target, forming an electron sheath at the target surface. The quasi-static sheath electric field creates a potential barrier close to the target surface that repels hot electrons with energies below the barrier height. The hot electrons with the energies above the barrier escape the target, which results in the electric polarization of the target [1]. The hot electron spot evolution may last for periods orders of magnitude longer than the laser pulse duration [2], [3] and extend to the size orders of magnitude larger than the laser spot [4]. The electric polarization of the target is essential for estimates of the target neutralization currents which are important in the studies of electromagnetic pulse emission, post-acceleration ion guiding and generation of extreme magnetic fields. The hot electron spot evolution is also essential for the studies of x-ray generation relevant for x-ray backlighting at large laser facilities. The first-principles modeling of the hot electron spot evolution is a formidable simulation task [1], hence for estimates in practical situations one must revert to simplified models. An interesting model of the hot electron spot evolution and target charging was proposed in [5], where high computability was achieved at the price of severe simplifications. Nevertheless, the model of [5] proved useful in estimating target charging at the conditions characteristic for the IPPLM 10 TW fs laser facility [6]. However, the model has some shortcomings: the early-phase hot electron spot evolution seems to be oversimplified; it seems that the model overestimates the sensitivity of the target charge to the target material; and it is likely that the model does not account properly for the target charge dependence on the laser pulse duration. In this contribution we take a closer look at this model and propose some improvements.

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Vortex-driven ultrahigh magnetic field generation in microtube implosion

M. Murakami[1], Y. Gu[1], D. Shokov[1], and J. Honrubia[2]

[1] Institute of Laser Engineering, Osaka University, Suita, Osaka 565-0871, Japan
[2] ETSI Aeronautica y del Espacio, Universidad Politecnica de Madrid, 28040 Madrid, Spain

Abstract

Microtube implosion[1-3] is a novel scheme to generate ultrahigh magnetic fields of the megatesla order. The microtube implosion is driven by ultraintense and ultrashort laser pulses. In the original concept of the microtube, however, uniform magnetic fields of the kilotesla order must be pre-seeded along the microtube axis to induce Larmor gyromotion of the imploding ions and electrons. Recently we have found that a structured microtube target can also generate ultrahigh magnetic fields even without seeded magnetic fields. In this case, due to the specific structure made on the inner surface of the microtube, vortex flows of relativistic electrons are collectively formed around the center of the cylindrical target to induce ultrahigh spin current. Two- and three-dimensional particle simulations are performed to clarify the underlying physics of the generation of ultrahigh magnetic fields using the vortex-driven microtube implosions.

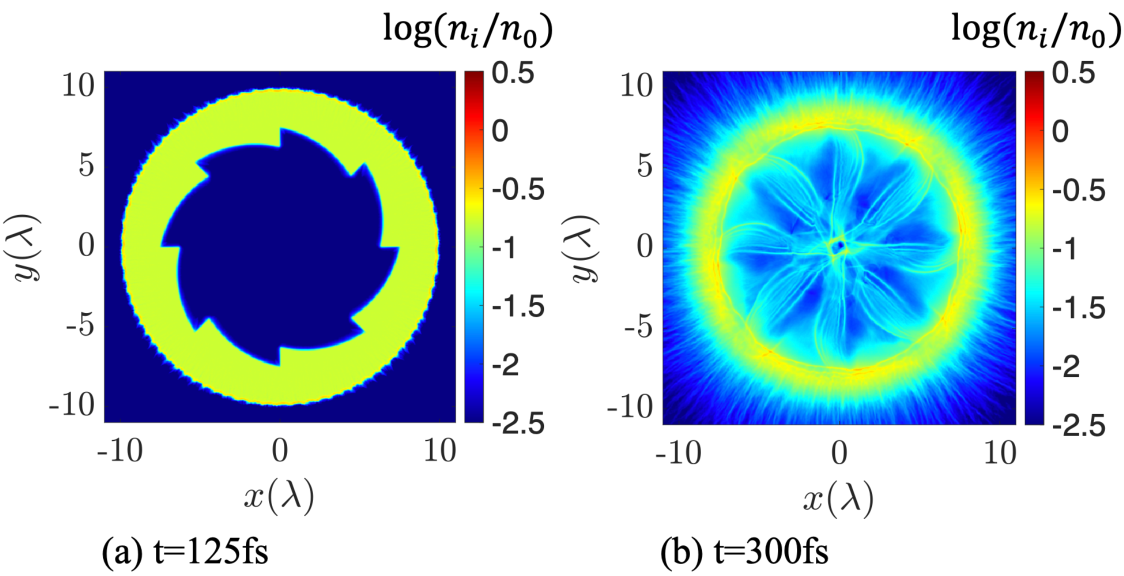

Figure 1. Temporal evolution of the ion density pattern inside the vortex-driven microtube target.

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Kinetic modelling of laser absorption in foams

S. Shekhanov[1], L. Hudec[2], A. Gintrand[1], J. Limpouch[2],
R. Liska[2], S. Weber[1], V. Tikhonchuk[1,3]

[1] ELI-Beamlines Center, Institute of Physics of the ASCR, Dolní Břežany, Czech Republic
[2] FNSPE, Czech Technical University in Prague, Prague, Czech Republic
[3] CELIA, University of Bordeaux, CNRS, CEA, Talence, France

Abstract

Low density foams have interesting properties that make them attractive for fundamental studies of laser plasma interaction and for various applications such as inertial confinement fusion and bright sources of X-ray emission. However, the process of transformation of a cold foam into a hot plasma is complicated and not well-known. Experiments and numerical simulations show that the ionization of foam by laser proceeds slower than ionization of a homogeneous material of the same average density. Qualitatively, it is explained by a delay needed for the foam solid elements to expand and to mix.

The existent numerical models [1, 2, 3] have difficulties in modeling of the propagation of ionization wave in the foam. It is related to the fact that the size of solid elements in the foam is smaller than the laser wavelength. The laser absorption efficiency depends strongly on the shape of the structure and its orientation with respect to the laser polarization. Macroscopic models do not describe accurately how much energy can be absorbed and reflected and how the absorbed energy is distributed between the cold wire and surrounding plasma.

In this work we present an analytical model of laser absorption and scattering in foams and numerical simulations of ablation and expansion of solid elements and plasma formation with a kinetic particle-in-cell code. Since foams are typically composed of randomly distributed wire-like solid elements, we model a single pore with a straight cylindrical wire of a sub-wavelength size in the center. Analytical model and numerical simulations show that the resonance laser absorption in an expanding, radially inhomogeneous wire is the dominant process, which depends weakly of the collisional dissipation. Transformation of a solid wire into a hot plasma is controlled by a competition of expansion and ablation processes which proceed on a 10 ps time scale for laser intensity of $\sim 10^{14}$ W/cm^2. The single-cell microscopic model is implemented in a hydrodynamic code as a sub-grid module describing the foam ionization and homogenization.

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ECLIM 2022
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Frascati, 19-23 September 2022

A hybrid (ablation-expansion) model for low-density foams

L. Hudec[1], A. Gintrand[2], J. Limpouch[1], R. Liska[1], S. Shekhanov[2], V. Tikhonchuk[2,3], S.Weber[2]

[1] FNSPE, Czech Technical University in Prague, Prague, Czech Republic
[2] ELI-Beamlines Center, Institute of Physics of the ASCR, Dolní Břežany, Czech Republic
[3] CELIA, University of Bordeaux, CNRS, CEA, Talence, France

Abstract

Low-density foams have a wide variety of applications in the fields of inertial confinement fusion and high energy density physics. However, direct simulations of laser interaction with foam targets are difficult and computationally expensive due to the necessity to spatially resolve the density differences in the foam microstructure in order to capture the underlying physical phenomena. Unfortunately, low-density foams also cannot be modeled as a uniform material of an equivalent mean density as such results overestimate the propagation speed of the laser-driven ionization wave.

Recent interests in foam simulations led to the development of two-scale models [1,2,3] where a simplified interaction model is computed on the scale of an individual foam pore in addition to the conventional macroscale hydrodynamics. Existing models describe the laser-foam interaction in terms of volumetric heating and expansion of planar/cylindrical foam microstructure. However, further analysis of laser absorption in sub-wavelength objects shows that laser is absorbed mostly at the surface of the overcritical foam elements and that ablation plays an important role in the overall dynamics. The mass ablated from the surface layer rapidly fills the empty space in the pores and creates a high-temperature, low-density plasma background. A significant portion of the absorbed laser energy is converted to an ion kinetic energy due to ion acceleration by the ablation process. The subsequent ion-ion collisions with the ambient plasma contribute to the dissipation of this energy into an ion thermal component, effectively acting as an ion heating.

We present a novel approach to the foam modeling that combines a self-similar expansion of cylindrical elements with a surface ablation by laser. In our microscale model, each foam pore is divided into two regions with separate masses, densities and temperatures - the central cylinder represents the expanding solid element and the outer plasma region acts as the ablated plasma in the pore. The movement of the boundary between these two environments is controlled by the self-similar expansion while the mass transfer between regions is given by a stationary ablation model. Ordinary differential equations for the temporal advancement of the state variables are solved on the microscale and connected to the macroscale hydrodynamics using the conservation of energy. Pores are considered to be homogenized when the cylinder and plasma reach the same density. The cross-section for laser deposition and scattering is calculated according to the Mie theory of electromagnetic scattering on cylindrical particles.
The proposed model is implemented in the PALE and FLASH hydrodynamic codes for laser-plasma interaction and the results are compared to the available experiments. The comparison shows that the model is sufficiently flexible and produces results compatible with observations.

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Particle Acceleration by Twisted Laser Beams: Beat-wave and Wakefield Configurations

J. T. Mendonça[1]

[1] Instituto Superior Técnico, Universidade de Lisboa, Lisboa (Portugal)

Abstract

We consider particle acceleration in plasmas, using twisted laser beams, or beams with orbital angular momentum. We discuss different acceleration processes using two LG laser modes, which include donut wakefield, beat-wave and self-torque acceleration, and compare the respective properties. We show that a self-torque configuration is able to produce azimuthal acceleration and can therefore be considered as an alternative method produce helical electron beams.

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Ion acceleration with four-cycle laser pulses

Sargis Ter-Avetisyan[1], Parvin Varmazyar[1], Prashant K. Singh[1], Joon-Gon Son[1], Miklos Fule[1], Valery Yu. Bychenkov[2, 3], Kwinten Nelissen[4], Sudipta Mondal[4], Daniel Papp[4], Adam Börzsönyi[4], Janos Csontos[4], Zsolt Lécz1,[4], Tamas Somoskői[4], Szabolcs Tóth[4], Gabor Szabó[4], and Karoly Osvay[1,5,]

[1]National Laser-Initiated Transmutation Laboratory, University of Szeged, Szeged, Hungary,
[2]P. N. Lebedev Physics Institute, Russian Academy of Sciences, Moscow, Russia,
[3]Center for Fundamental and Applied Research, VNIIA, ROSATOM, Moscow, Russia,
[4]ELI-ALPS, ELI-HU Non-Profit Ltd., Szeged, Hungary,
[5]Dept. Optics and Quantum Electronics, University of Szeged, Szeged, Hungary

Abstract

Interest in laser driven ion acceleration continues to be strong. Currently, the advances in laser technology have led to the generation of laser pulses with a few optical cycles at kHz repetition rate. These lasers at relativistic intensities can provide a compact and stable source of ions, and, possibly the gamma-rays at high repetition rate which can be highly beneficial for medicine, industry, and science. E.g., high repetition rate ion source can serve as an input beams of diverse accelerator systems, deuterons accelerated to energies above 0.5 MeV at kHz repetition rate can generate large flux of neutrons per second via D(d, n) reaction, production of Radioisotopes with kHz repetition rate is another potential application for nuclear pharmacology.

Ion acceleration resulting from the interaction of 11 fs, ~30 mJ laser pulses with ultrahigh contrast ($<10^{-10}$) focused to a peak intensity of $\sim 10^{19}\ \mathrm{W/cm^2}$ on the target was investigated. Ion yield from various target materials of a thickness ranging from 5 nm up to 9 μm at 0°, 45° and 60° laser incidence was studied in a rear and front surface target normal directions: called forward and backward acceleration, respectivly. The maximum energy of the protons accelerated from the both sides of the target was above 1 MeV. The conversion efficiency of the energy of the laser pulse to the protons of forward direction is estimated to be as high as ~1.4 % at 45° laser incidence on an Al target.

We will be discussing ion acceleration with such short laser pulses, which is not trivial. In forward direction the proton acceleration is understood still as a TNSA-like acceleration scheme. In backward direction the protons are accelerated from a pancake form charged cavity created in a tiny preplasma of neutral origin due to the Gaussian temporal laser pulse shape providing strong Coulomb field with the lifetime mainly determined by the duration of the laser pulse. Despite the strong Coulomb field, the short acceleration time does not allow the protons to gain energy exceeding that of the forward accelerated protons. Experimental results can be a benchmark for further theoretical and computational work. Obviously, the proposed model cannot describe in detail the processes as a whole, which is clearly more complex than our assumptions and it requires very cumbersome 3D simulation with nm-resolution.

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Surface Plasmon-Driven Electron and Proton Acceleration from Solid Foil Without Grating Coupling

J. Sarma[1], A. McIlvenny[1], N. Das[2], M. Borghesi[1] and A. Macchi[3,4]

[1]*Centre for Plasma Physics, Queen's University Belfast, Belfast BT7 1NN, United Kingdom*
[2]*Tezpur University, Tezpur, India*
[3]*National Institute of Optics, National Research Council (CNR/INO)*
[4]*Adriano Gozzini laboratory, Pisa, Italy Enrico Fermi Department of Physics, University of Pisa, Pisa, Italy*

Abstract

Surface plasma wave or Surface Plasmon (SP) excitation following intense laser interaction with solid targets can be exploited for generating high charge and high energy electrons which are accelerated along the target surface by surfing the SP, similar to what happens in a plasma wakefield. Surface Plasmons are electromagnetic modes localized at and propagating along a sharp plasma-vacuum interface with a longitudinal electric field component that can accelerates electrons efficiently along the surface of the solid target [1]. Although usually it is not possible to satisfy the phase matching condition for exciting an SP by an EM wave, some experiments have demonstrated successful excitation of SPs by short pulse lasers, and consequent electron acceleration, by using grating targets which essentially modify the phase matching condition [2]. In this work we show via PIC simulations that efficient SP electron acceleration for currently available short pulse lasers can occur in a flat foil irradiated at parallel or grazing incidence (~5^0 with the target surface) without the need for a surface modulation, which make an easier experimental implementation. We observe acceleration of high energy (~70MeV) and high charge (~780pC) electron bunches accelerated by SP along the target surface when using a laser of intensity $3.4 \times 10^{19} W/cm^2$. The scaling of temperature and charge of the accelerated electrons with intensity are also promising, with temperature well in excess of ponderomotive values. Moreover, for parallel incidence, i.e. with the laser hitting the short edge of the target (similar to the geometry proposed in [3]), we have investigated the effect on the electron acceleration of laser misalignment on a scale of few wavelengths, which is likely to occur due to the limited pointing stability of high-power laser systems. By doing so, we have found that a limited lateral shift of the focal spot makes the electron acceleration more efficient. These electrons which are peeled by the laser and accelerated by the SP create a strong electrostatic field at the rear short edge of the target and accelerate protons present as contaminants on the edge's surface. The total charge of electrons exceeds those of protons at

the accelerating region creating a smooth sheath field which produces a narrow peaked proton spectrum.

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Frascati, 19-23 September 2022

Relaxation of non-thermal electrons in solid density plasmas heated by the European X-ray free electron laser

G. Williams[1], J. Chalupsky[2], P. Estrela[3], M. Hussain[3], M. Mikita[4], T. Preston[4], K. Appel[4], T. Burian, H.K. Chung[5], M. Fajardo[3], V. Hajkova[2], L. Juha[2], J. Kaa[4], J. Koliyadu[4], Z. Konopkova[4], N. Kujala[4], M. Nakatsutsumi[4], H. Scott[6], P. Vagovic[4], P. Velarde[7], V. Vozda[2], U. Zastrau[4]

[1] GoLP, IPFN, IST, Lisbon [2] FZU [3] IST [4]EuXFEL [5]NFRI [6]LLNL [7]IFN

Abstract

We present recent results from an experiment carried out at the European X-ray free electron laser. We harness the unique capabilities of the instrument to create solid density plasmas with tailored non-thermal electron distributions. By heating solids at photon energies above the k-edge, we create non-thermal photo-electrons that relax via collisional pathways. The k-shell fluorescence is measured to quantify the collisions during the XFEL pulse. The short (25 fs) pulse duration provides an ultrafast snapshot of the ionisation state of the plasma in this temporal window. When compared to collisional-radiative models, this data provides quantitative measurements of the multi-body collisional rates in dense, degenerate plasmas which are notoriously difficult to calculate and measure.

36th European Conference on Laser Interaction with Matter
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Towards Bright Gamma-Ray Flash Generation Through Solid Target Irradiated by Multi-Petawatt Laser

P. Hadjisolomou[1], T. M. Jeong[1], P. Valenta[1,2], D. Kolenaty[3], R. Versaci[1], V. Olšovcová1,
C. P. Ridgers[4] and S. V. Bulanov[1,5]

[1] ELI Beamlines Centre, Institute of Physics, Czech Academy of Sciences, Za Radnicí 835, 25241 Dolní Bˇrežany, Czech Republic
[2] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Brehova 7, Prague 11519, Czech Republic
[3] Department of Physics and NTIS - European Centre of Excellence, University of West Bohemia, Univerzitní 8, 306 14 Plzen, Czech Republic
[4] York Plasma Institute, Department of Physics, University of York, Heslington, York, North Yorkshire YO10 5DD, UK
[5] Kansai Photon Science Institute-QST, 8-1-7 Umemidai, Kizugawa, Kyoto 619-0215, Japan

Abstract

The current development of multi-petawatt lasers opens the window to the quantum electrodynamics regime [1, 2, 3], characterised by generation of γ-photons and electron-positron pairs.
In [4, 5] we employ particle-in-cell (PIC) simulations to realise the effect of a tightly focused, single-cycle laser interacting with foil targets. This regime, known as the λ^3 regime [6], has the benefit of providing the maximum intensity possible, in the expense of the least energy, for lasers of the same power. By varying the target thickness in combination with the target electron density, optimal γ-photon generation conditions are estimated. By using a variation of laser polarisations, namely linear, radial and azimuthal, we demonstrate that in the λ^3 regime the use of radially polarised lasers is advantageous due to a strong longitudinal electric field component. For the radially polarised laser, our analysis is extended over an wide laser power range, resulting in a power law for the γ-photon conversion efficiency. Moreover, the properties of the PIC particles are imported into MonteCarlo simulations [7], to simulate the interaction of laser-generated particles with a high-Z material (secondary target). The simulations reveal further electron-positron pair generation and generation of unstable nuclei due to photonuclear interactions.
In [8] we present PIC simulations where a preplasma profile is assumed. The profile is taken from publicly available magnedohydrodynamic simulation results of a background field with solid targets [9]. Extremely high γ-photon conversion efficiency is predicted for few tens of femtosecond, 10 PW lasers with a focal spot of a few micrometers wide. The γ-ray flash occurs in the form of two lobes on the laser oscillation plane, peaking at $\sim \pm 30^o$ with respect to the laser propagation axis. Temporal tracking of the γ-photon emission reveals that the γ-photon generation is directly associated with the laser wavelength.

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Simulation of angle resolved nonlinear light scattering from the surfaces of colloidal particles

Ankur Gogoi[1], Guan-Yu Zhuo[2] and Gazi A. Ahmed[3]

[1]Department of Physics, Jagannath Barooah College, Jorhat 785001, Assam, India
[2]Institute of New Drug Development, China Medical University, Taichung 406040, Taiwan
[3]Department of Physics, Tezpur University, Tezpur 784028, Assam, India

Abstract

Generation of second-harmonic radiation in the interaction of light with nanoparticle surfaces, bio-nanointerfaces, and membranes offer unique opportunities to probe their physical and chemical properties. Although, second harmonic generation (SHG) is usually forbidden in centrosymmetric systems, it is still possible to observe SHG from the surface of centrosymmetric particles due to the absence of inversion symmetry [1]. Generally, such SH signals are too faint to be detected, especially for materials like polystyrene which possess relatively lower values of hyper-polarizability. On the other hand, detectable amount of SHG as well as sum frequency generation (SFG) signals can be generated from a micrometer sized centrosymmetric particle with adsorbed molecules located on the opposite sides of the particle surface in a bulk solution.

A number of experiments on the SH scattering from colloidal particle surfaces/interfaces have been carried out in the recent past to probe the structural and dynamic characteristics of molecular interfaces [2]. Various theoretical models, e.g., nonlinear Rayleigh-Gans-Debye (RGD) approximation [3], nonlinear Wentzel-Kramers-Brillouin approximation [4], nonlinear Mie theory [5,6], etc., were also developed to explain the experimentally observed SH scattering from particle surfaces. Among these theories, nonlinear version of the RGD approximation is popular among the researchers since it is mathematically less complex, applicable to arbitrary shaped optically soft particles, fast and consumes lesser computational resources.

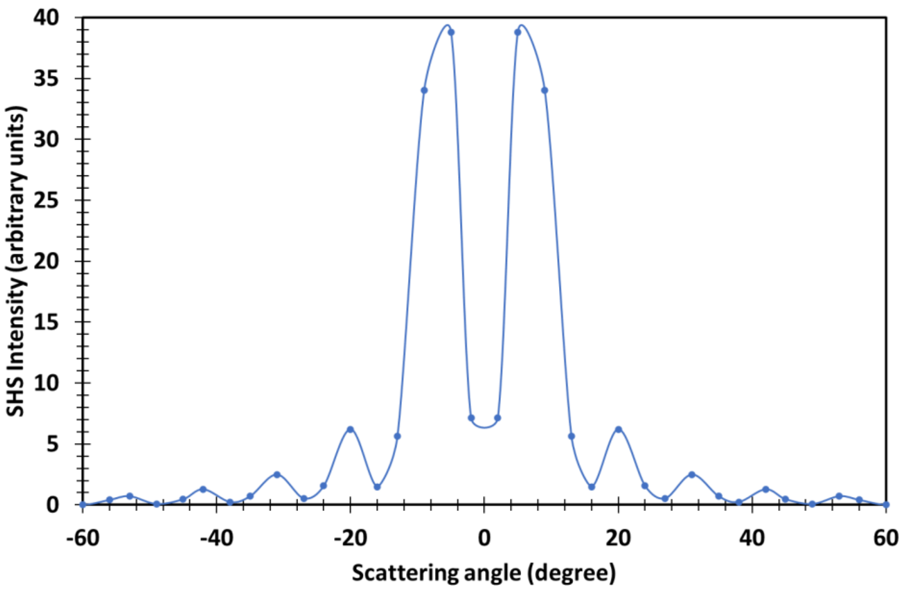

Figure 1. Angle resolved second harmonic scattering (SHS) intensity of water suspended 1100 nm polystyrene (PS) particles for s-in/p-out polarization combination.

In this contribution, the calculation of the nonlinear light scattering properties of optically soft colloidal particle systems by using a model based on nonlinear RGD approximation is reported. Representative calculations for the SH scattering of water suspended 1100 nm PS particles at 800 nm incident wavelength for s-in/p-out polarization combination is shown in Figure 1. Such calculations will be useful in studying the state of surfaces and interfaces, especially surface chirogenesis at the nanoscale.

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36th European Conference on Laser Interaction with Matter
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Experimental investigations of hot electron and X-ray generation by laser-produced tantalum plasma at $10^{14} – 10^{16}$ W·cm^{-2} intensity

S. Singh[1,2], M. Krupka[1,2,3], V. Istokskaia[3,4], J. Krasa[2], L. Giuffrida[4], R. Dudzak[1,2], J. Dostal[1,2], T. Burian[2], R. Versaci[4], D. Margarone[4,5], M. Krus[1], and L. Juha[2]

[1] Institute of Plasma Physics, Czech Academy of Sciences, Prague, Czech Republic
[2] FZU-Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic
[3] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Czech Republic
[4] ELI Beamlines, Institute of Physics, Czech Academy of Sciences, Prague, Czech Republic
[5] Centre for Plasma Physics, School of Mathematics and Physics, Queen's University Belfast, Belfast, United Kingdom

Abstract

Hot electrons generated by laser-matter interaction emit X-rays through bremsstrahlung mechanism. Precise knowledge of the energy distribution and temperature scaling of hot electrons and X-rays is crucial for exploiting laser energy in many applications such as sources of X-rays, radiography of dense plasma, photo-nuclear studies and fast ignition.

The scaling of hot electron and bremsstrahlung radiation from the interaction of sub-nanosecond and kilo-joule class laser pulse with tantalum targets was investigated. The laser intensity delivered by the PALS laser facility was varied in the range of 4×10^{15} to 3×10^{16} W·cm^{-2} at the target focus. The energy distribution functions of electrons were measured by an angular array of magnetic spectrometers indicating the electron temperature in the range of 30 to 70 keV. The bremsstrahlung spectrum was characterized using a scintillator-based calorimeter. The experimental data were compared with Monte Carlo simulation showing a photon energy in the range of 10's of keV to 100 keV. In addition, we experimentally demonstrate the laser energy scaling of the total flux of hot electrons in forward and backward directions with respect to the laser vector as well as the conversion efficiency of the laser energy to the energy carried by hot electrons.

36th European Conference on Laser Interaction with Matter
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Picosecond ramp of ultrashort laser pulse: how it affects laser-driven ion acceleration and plasma shutter?

J. Psikal[1,2]

[1] FNSPE, Czech Technical University in Prague, Brehova 7, 11519 Prague 1, Czechia
[2] ELI-Beamlines Centre, IoP CAS, Za Radnici 835, 25341 Dolni Brezany, Czechia

Abstract

Ultrashort high-power laser pulses are accompanied by ASE pedestal, ultrashort prepulses, and picosecond ramp. The ratio of the peak intensity of the main pulse to the intensity of pedestal and prepulses, the so-called laser pulse contrast, can be substantially enhanced by various methods, such as single or double plasma mirror ((D)PM). However, picosecond ramp (also called shoulder) can be only partially reduced even if (D)PM is applied as shown by experimental measurements [1]. Thus, there is an increased intensity of laser radiation which can affect the state of any irradiated target starting from one or even a few picoseconds before the peak of the main ultrashort pulse [2,3]. Therefore, it is important to assess the impact of realistic temporal profile of laser pulse which includes picosecond ramp on the interaction between ultrashort high-power pulse and the target. In this contribution, we analyze the impact of picosecond ramp on target normal sheath acceleration (TNSA) of ions as well as on the propagation of ultrashort laser pulse through plasma shutter (PS) which is an ultrathin solid foil or a membrane used for the improvement of laser pulse contrast in addition to the techniques like DPM. This study is done with the help of 2D particle-in-cell simulations using the code SMILEI [4].

In this study, three cases of temporal profiles of laser pulse have been assumed. The first case represents ultrashort laser pulse with its picosecond ramp. Time characteristics of the pulse are the same as in Ref. [2] (based on real experimental data): the whole pulse envelope is described by the sum of three Gaussian functions $A_i*\exp(-t^2/(2*\sigma_i^2))$ in laser intensity (where A1=0.5, σ1=15 fs, A2=0.5, σ2=90 fs, A3=0.0001, σ3=350 fs). The second case presents "clean" ultrashort pulse of the same energy as the whole pulse in the first case (thus, the peak intensity has to be reduced in the first case by a factor 3.5 compared with the second studied case in 2D simulation). It means that the whole pulse envelope is described by only $A*\exp(-t^2/(2*\sigma^2))$ with A=1 and σ=15 fs. The third case is introduced with the pulse envelope $A*\exp(-t^2/(2*\sigma^2))$ but reduced peak intensity, thus also with reduced pulse energy compared with previous two cases.

In the study of TNSA, the results of PIC simulations reveal a strong dependence on the intensity of ultrashort laser pulse. At peak intensity 10^{20} W/cm^2 (for clean ultrashort pulse and at reduced value for more realistic pulse including picosecond ramp with the same pulse energy), the energies (and energy spectra) of accelerated protons are very similar, in agreement with Ref. [2]. However, at peak intensity 10^{21} W/cm^2 corresponding to PW laser pulse, TNSA leads to substantially higher maximum energies of accelerated protons (1.5 or twice higher depending on simulation time and target) in the case of the clean pulse. The acceleration is well illustrated by the development of maximum proton energies in Fig. 1. Most of the acceleration happens during short period of the interaction in the case of optimal (clean) ultrashort pulse. When picosecond ramp is present, ions are accelerated earlier to higher energies, but the acceleration is less efficient when the peak intensity of the pulse interacts with the target. Later, the difference between the clean pulse and the pulse including picosecond ramp (shoulder) is reduced as the ramp after the main pulse still interacts with the target. These results can be explained by more rapidly expanding target with increasing laser pulse intensities as the target

expands already during its interaction with picosecond ramp before the main pulse. Target expansion leads to reduced accelerating fields after the interaction with peak pulse intensity, thus to lower energies of accelerated ions when picosecond ramp is present.

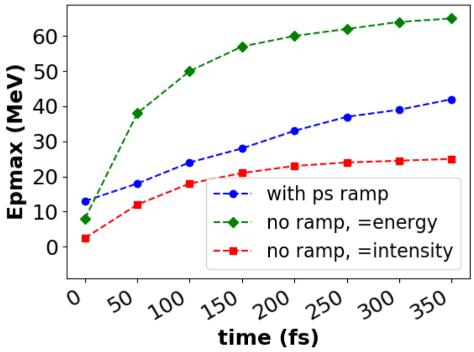

Figure 1. Temporal development of maximum energy of protons accelerated by TNSA mechanism from 1 micron thick fully ionized hydrogen foil of electron density corresponding to its solid state. The foil was irradiated by ultrashort laser pulse with picosecond ramp (blue, circles), by clean ultrashort pulse of length 35 fs (at FWHM) with the same total energy as the pulse with ramp and peak intensity 10^{21} W/cm^2 (green, diamonds), or by clean ultrashort pulse with the same peak intensity as the pulse with ramp (red, squares).

In the study of laser pulse propagation through plasma shutter, the comparison of the interaction between laser pulses with/without picosecond ramp (peak intensity 10^{21} W/cm^2 for the clean pulse) and 12 nm thick Si_3N_4 shutter of realistic density shows substantial difference in terms of laser pulse energy transmitted through the target. In the simulation with clean ultrashort pulse, the amount of transmitted energy was reduced to 41 percent from 63 percent in the case of the pulse preceded by the ramp. Ultrashort laser pulse without any ramp starts to be transmitted roughly at the pulse peak, whereas picosecond ramp starts to be transmitted before the main pulse arrival and the main part of the pulse is fully transmitted. The case of "clean" pulse with reduced energy but the same peak intensity as the pulse with the ramp was also tested. In this case, the pulse transmission through the shutter is not observed as the shutter does not expand sufficiently to reduce its density.

The effect of collisions between charged particles during the interaction between laser pulse with picosecond ramp and targets was also investigated. Any target differs mainly at earlier stage of the interaction when collisional absorption dominates at lower intensities of picosecond ramp. However, any significant difference in the transmission of the pulse through plasma shutter was not observed. In the case of TNSA, sligthly higher maximum energies of accelerated protons (within 10 percent difference) can be observed in collisionless simulations at later stage of ion acceleration whereas larger maximum energies (but low in absolute values) are observed in the beginning of PIC simulation including collisions between charged particles.

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Acknowledgements

This work was supported by European Regional Development Fund – Project CAAS ('Center of Advanced Applied Sciences') No. CZ.02.1.01/0.0/0.0/16_019/0000778. Fruitful discussions with M. Matys, M. Jirka, O. Klimo, S. Bulanov from ELI-Beamlines Centre are appreciated.

ECLIM 2022
36th European Conference on Laser Interaction with Matter
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Formation of ultra-intense electromagnetic radiation focused by relativistic flying mirror and its application to strong field QED

T. M. Jeong[1], S. Bulanov[1], P. Valenta[1], T. Esirkepov[2], G. Korn[1], J. Koga[2], A. Pirozhokov[2], M. Kando[2], S. Bulanov[3]

[1] ELI-Beamlines Center, Institute of Physics of the ASCR, Dolní Břežany, Czech Republic
[2] KPSI QST
[3] Lawrence Livermore National Laboratory

Abstract

An intense femtosecond laser pulse propagating in the plasma medium produces promising plasma optics, such as the relativistic flying mirror (RFM) [1] and relativistic oscillating mirror (ROM) [2] (for details see review [3]). These plasma mirrors generate intense attosecond laser pulses [4,5]. The frequency upshift of the reflected laser pulse and the decrease in the pulse duration are common features originating from the double Doppler effect [4,5]. In particular, a curved RFM can intensify the incident high power laser radiation over the conventional focused intensity through $r(D/\lambda)\gamma^3$ [6], where r is the reflection coefficient of the RFM, D the beam size of the reflected laser on the RFM, λ the wavelength of the laser, and γ the Lorentz factor of the RFM. Due to the intensification capability, the RFM can be applied to the study of strong field quantum electrodynamics (SF-QED). Recent theoretical investigation makes it possible to formulate the analytical expression for the electric field focused by the curved RFM, and to investigate the creation rate of electron-positron pairs under that field [6]. Another interesting application is to collide the intensified laser focus with energetic electrons for the gamma-photon generation via the nonlinear Compton scattering.
In this talk, we present the optical characteristics of a curved RFM, and its application to electron-positron pair production via the Schwinger mechanism and to nonlinear Compton scattering with energetic electrons.

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Non-thermal radiation emission from an X-ray laser-produced plasma

P. Velarde[1], M. Cotelo[1], E. Fernandez-Tello[1]

[1] Instituto de Fusión Nuclear, Universidad Politécnica de Madrid

Abstract

X-ray lasers such as XFEL produce dense plasmas with out-of-equilibrium electron populations during interaction with matter. Once the pulse is over, the system returns to equilibrium in a few tens of fs, but the emission of radiation during the interaction can reveal features of the non-equilibrium electronic population during the interaction. We present numerical simulation results of the interaction of an X-ray laser with matter where the differences in time-integrated emission between a thermal and a non-equilibrium distribution are observed. For these simulations, we use a code that calculates the rate equations for atomic populations as well as the time evolution of the free electron population calculated with the Fokker-Planck equation. The results show a significant difference between the radiation emission assuming a Maxwellian and a non-equilibrium distribution, in energy bands on both sides of the laser frequency. We study these results for different materials as well as the possibility of measuring non-thermal effects.

36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Generation of intense light with high-order modes mediated by a relativistic plasma aperture

M. King[1,2], M. J. Duff[1], E. Bacon[1], T. P. Frazer[1], R. Wilson[1], A. Higginson[1], S. D. R. Williamson[1], Z. E. Davidson[1], R. Capdessus[1], N. Booth[3], S. Hawkes[3], D. Neely[3], R. J. Gray[1] & P. McKenna[1,2]

[1] SUPA Department of Physics, University of Strathclyde, Glasgow, G4 0NG, UK
[2] The Cockcroft Institute, Sci-Tech Daresbury, Warrington WA4 4AD, United Kingdom
[3] Central Laser Facility, STFC Rutherford Appleton Laboratory, Oxfordshire, OX11 0QX, UK

Abstract

An ability to control the spatio-temporal and polarization properties of intense light is of fundamental importance for a wide variety topics involving extreme light-matter interactions. This includes laser-driven particle acceleration, high-field physics, plasma photonics, and laboratory astrophysics. Here, we demonstrate the generation of intense light with higher-order mode spatial structure, at both the fundamental, ω_L, and second harmonic, $2\omega_L$, frequencies, during the interaction of an intense laser pulse ($>10^{18}$ Wcm^{-2} for λ_L=1 µm) with a self-formed *relativistic plasma aperture*[1] produced from an initially opaque ultrathin foil target[2]. We also demonstrate that preformed aperture targets can be used and optimized to produce similar higher-order intense light[3]. An example result from 3D particle-in-cell (PIC) simulations of each of these interactions is shown in figure 1 for the generation of intense $2\omega_L$ light.

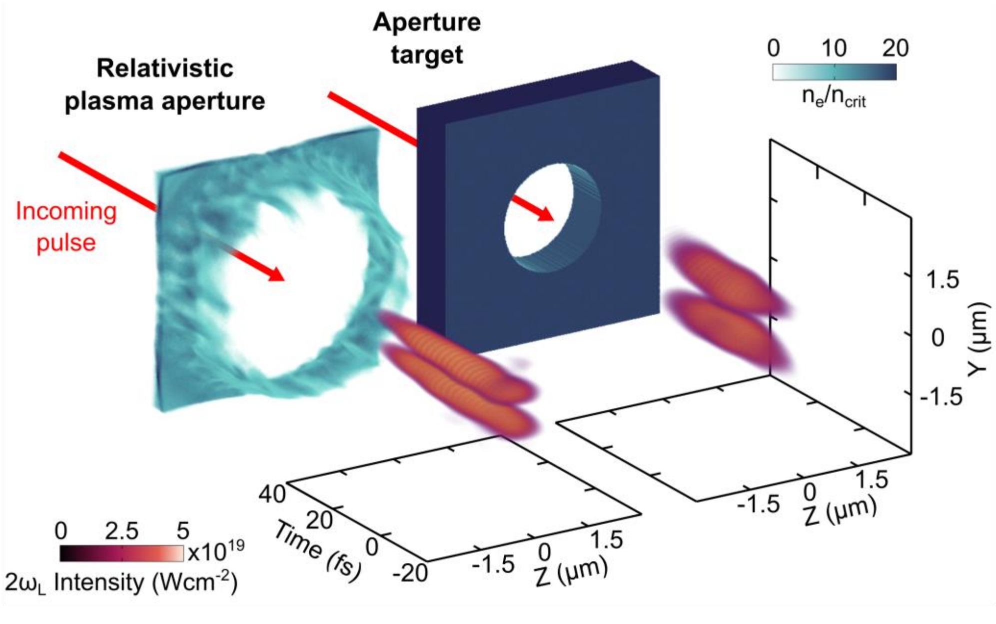

Figure 1. 3D PIC simulation results showing the generation of intense high order spatial modes at $2\omega_L$, produced from the interaction of an intense laser pulse with a fundamental TEM_{00} mode interacting with; (left) a relativistic plasma aperture, formed during the interaction of an intense laser pulse with an initially opaque thin-foil target; (right) similar high order mode generation in the interaction of a laser pulse with the same parameters with a preformed aperture target.

During the interaction of an intense laser pulse with an ultrathin (nanometer-scale) foil, the resultant plasma quickly heats (to relativistic temperatures) and expands, becoming relativistically transparent, enabling the laser light to propagate. Due to the spatial profile of the laser pulse, this occurs within a finite region in the plasma, forming what is termed a *relativistic plasma aperture*[1]. Transmission through this aperture can cause the laser light to diffract, but it can also lead to direct laser acceleration[4] (*DLA*) of the electrons from the aperture edges. For a linearly polarized pulse, as the longitudinal electric field associated with the focused laser pulse aligns with the $\mathbf{j}\times\mathbf{B}$ force at the aperture edge, electron bunches are alternately accelerated from opposite sides of the aperture every half-wave cycle. As the electrons accelerate from the edges and decelerate in the longitudinal electrostatic sheath field at the target rear, they emit and the resultant radiation interferes with that produced from the alternately accelerated bunches to produce coherent light at the fundamental and higher harmonics frequencies of the laser. Due to the asymmetric nature of the electron bunches, the produced radiation interferes to produce a higher order spatial mode, as shown for $2\omega_L$ light on the left of figure 1. The produced light can also have a different polarization state to that of the drive laser pulse. As this process relies on the self-formation and evolution of a relativistic plasma aperture over the course of the laser pulse, this can also lead to intra-pulse changes to the spatial structure of the generated light. This has been demonstrated in 3D PIC simulations and inferred from experimental results on ultrathin foil targets[1,2].

Similarly, intense light can also be generated from the interaction of an intense pulse with a thin, solid density target with a preformed aperture (micron-scale). This can be seen on the right of figure 1. Here, the laser is free to propagate through the aperture, but if the aperture diameter is made such that it is on the order of the laser focal spot, the longitudinal electric field of the focused laser can again directly accelerate electrons from the aperture edge. This has the advantage of allowing the entire laser pulse to interact with the aperture. We have performed a detailed simulation study to investigate and optimize such targets to produce intense $2\omega_L$ light through variation of the target thickness, aperture diameter and laser intensity.

In this presentation, we will demonstrate the generation of intense light with higher order spatial modes from initially opaque targets, due to the formation of a relativistic plasma aperture. We will present 3D PIC simulation and experimental results that show the generation of this light along with a 3D simulation study demonstrating the optimization of preformed aperture targets to efficiently produce intense $2\omega_L$ light.

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Acknowledgements

This work is financially supported by EPSRC (grant numbers EP/R006202/1 and EP/V049232/1) and STFC (grant number ST/V001612/1). It used the ARCHIE-WeSt and ARCHER2 high performance computers, with access to the latter provided via the Plasma Physics HEC Consortia (EP/R029148/1), and the University of Cambridge Research Computing Service (funded by grant number EP/P020259/1). EPOCH was developed under EPSRC grant EP/G054940/1. The research has also received funding from Laserlab-Europe (grant agreement no. 871124, European Union's Horizon 2020 research and innovation programme)

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Towards laser-driven neutron sources capable for nuclear physics and their applications

M. M. Günther[1]

[1] GSI Helmholtzzentrum für Schwerionenforschung, Planckstr.1 64291 Darmstadt, Germany

Abstract

Relativistic laser-plasma driven high energy (MeV) photon and particle generation is an attractive basis for many applications, but still a challenging and not well understood topic within the laser-plasma physics. The relativistic laser-matter interaction was more than two decades investigated in the framework of different aspects of laser-plasma creation. One of these is the generation of photons with MeV energies [1,4,5] as well as the relativistic acceleration of electrons [2] and ions [3]. MeV-gamma radiation can be in general produced by two ways. Laser ion acceleration has been investigated over the last two decades and different acceleration mechanisms identified. These acceleration mechanisms depending on laser pulse parameter and target systems. The most widely investigated mechanism is the target normal sheath acceleration (TNSA), which based on interaction of relativistic laser pulse with µm thick solid target systems [6-8]. Other mechanisms are the radiation pressure concepts [9,10], the acceleration in the relativistic transparency regime [11] as well as the breakout afterburner (BOA) concept [12]. Latter mentioned mechanisms based on ultra-relativistic PW-class laser pulses with ultra-high contrast interacting with several nm thin foil targets.
Such sources provide the basis for the generation of neutrons via nuclear reactions. Furthermore, they open the opportunity of laser based nuclear physics. Optimization and control of such sources are promising to path the way towards compactness and high applicability in multidisciplinary science fields [13]. In the past different concepts are discussed for laser-driven neutron sources and for what they are interesting [14-17]. Besides applications of laser generated fast neutrons, the more sophisticated applications are those using neutrons in the energy range below several hundred of keV. Such applications are based in the whole nuclear physics, which need mostly low energy neutrons (tens of eV up to below of 1 MeV) for capture reactions, fission and elastic/inelastic nuclear reactions. Current conventional neutron sources are based on nuclear fission reactors and accelerators. They provide reliable neutron radiation. Especially in nuclear astrophysics and medical applications it would be more suitable to have spatially compact, ultra-short pulsed and ultra-high flux neutron sources most in the epithermal energy range. Therefore, important values are the angle fluence and the conversion efficiency of primary energy to neutrons. A promising basis for such neutron source properties are laser-driven sources. In the past, records were reached in the laser-driven neutron generation, producing means of fast neutrons above more than 10 MeV energies. Such sources where recently used to demonstrate the applicability in material sciences [18]. However, for applications ultra-fast neutrons must be moderated, which lowers the angle fluence as well as the neutron density and decreases the neutron flux.

Recently we demonstrated that there is an applicable potential to generate high efficiency neutrons with energies needed for the above-mentioned applications in nuclear physics [13]. This reached neutrons are in the energy range, represents a best start point to produce high fluence neutrons in the epithermal energy range.
Therefore, in this presentation, we report on recent results with new record values in efficient laser-driven neutron generation for nuclear physics and their applications. The principal approach based on the interaction of sub-picosecond laser pulses in the moderate relativistic laser intensity range with

homogeneous sub-mm long-scaled near critical electron density plasmas from low-density foam taget systems [19]. We observed for the first time in such laser pulse interaction with foam-foil target systems the acceleration of highly collimated protons with $dN/dE \propto E^{-1}$ power law like spectral properties and strongly enhanced maximum cutoff energies with proton fluences of around 10^{12} (MeV sr)$^{-1}$ protons from above 7 MeV up to maximum proton cutoff energy. Furthermore, using foam-high-Z material target systems, we observed strong directed gamma beams with fluences of more than 10^{12} sr^{-1} and conversion efficiency of 2 % above 10 MeV photon energy. Such beams have shown a high capability to provide applicable laser-driven neutron sources in secondary beam-matter interactions. These new findings allow to efficient generate neutrons with ultra-high fluxes and high angle fluences suitable for applications as mentioned above [13]. In laser pulse foam target system interactions at 10^{19} W/cm^2 intensities of sub-ps pulses, we observed ultra-high fluences of neutrons with more than 10^{11} neutrons per shot with high laser energy to neutron conversion efficiency [13]. These recent experimental and theoretical results have shown promising generation of neutrons for suitable use in nuclear physics and life science applications, which is also discussed in this presentation.

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Laser-driven quasi-static magnetic fields for magnetized high energy-density experiments

C. Vlachos[1], P. Bradford[1], V. Ospina-Bohorquez[1,2,3], G. Pérez-Callejo[1,4], M. Ehret[2], P. Guillon[1], M. Lendrin[1], X. Vaisseau[3], B. Albertazzi[5], S. Eitan[5], M. Koenig[5], S. Malko[6], R. Fedosejevs[7], M. Gjevre[7], C. Kaur[7], M. Bailly-Grandvaux[8], C. A. Walsh[9], R. Florido[10], F. Suzuki-Vidal[11], C. McGuffey[12], F. N. Beg[8], J. Saret[8], M. A. Gigosos[4], T. Chodukowski[13], T. Pisarczyk[13], Z. Rusiniak[13], J. Dostal[14], R. Dudzak[14], A. Calisti[15], S. Ferri[15], L. Volpe[2], L. Gremillet[3], and J.J. Santos[1]

[1] Université de Bordeaux, CNRS, CEA, CELIA (Centre Lasers Intenses et Applications), UMR 5107, Talence, France
[2] C.L.P.U. (Centro de Láseres Pulsados), Salamanca, Spain
[3] CEA, DAM, DIF, F-91297 Arpajon, France
[4] Departamento de Fisica Teorica, Atomica y Optica, Universidad de Valladolid, 47011 Valladolid, Spain
[5] LULI, CNRS, Ecole Polytechnique, 91128 Palaiseau Cedex, France
[6] Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[7] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta T6G 2V4, Canada
[8] Center for Energy Research, University of California, San Diego, USA
[9] Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[10] iUNAT–Departamento de F ́ısica, Universidad de Las Palmas de Gran Canaria, 35017 Las Palmas de Gran Canaria, Spain
[11] Plasma Physics Group, The Blackett Laboratory, Imperial College London, London, SW7 2AZ, UK
[12] General Atomics, San Diego, California 92121, USA
[13] Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland
[14] Institute of Plasma Physics, Czech Academy of Sciences, Prague, Czech Republic
[15] PIIM, Aix-Marseille Université, Marseille, France

Abstract

The use of seed magnetic-fields (B-fields) in laser-driven target-compression experiments may lead to > 10 kT B-fields across the compressed core due to advection of the in-flow plasma. B-fields exceeding 10 kT are promising for magneto-inertial fusion since they reduce electron thermal conduction perpendicular to the field lines and may even increase alpha-particle energy deposition in the hot spot. Studying the formation of these compressed B-fields may also improve our understanding of extreme plasma magnetization phenomena relevant to astrophysics or extended magnetohydrodynamics.

In order to reach compressed B-fields exceeding 10 kT, one important challenge is to generate strong seed B-fields on major laser facilities. Where external pulsed power hardware is not available, we can use laser-driven coil (LDC) targets to supply a multi-tesla quasi-static field. These targets allow easy access for diagnostics and do not produce a significant quantity of debris.

We have tested LDCs on several different nanosecond laser facilities under laser drive conditions relevant to the Laser MegaJoule (LMJ). The goal was to predict the B-fields that might be achieved on LMJ by benchmarking a laser-driven diode model of B-field generation [1]. At the LULI2000 and OMEGA facilities we used comparable laser intensities, ~10^{15} -10^{16} W/cm^2, at 1.06µm and 0.35µm wavelengths respectively. We generated discharge currents of ~20 kA and ~8 kA yielding B-fields of ~50 T and ~6 T respectively, with targets of different size (and inductance).

Where possible, magnetic fields were measured using proton deflectometry directed along two axes of the target. Comparing our experimental deflectograms with proton tracking simulations enables us to identify various deflection features that can be linked to the looping current or static charging of the coil's wire surface. Measured discharge currents are broadly consistent with predictions from our model for all the experimentally tested conditions, which give grounds for the successful use of LDCs on large-scale facilities like LMJ [2].

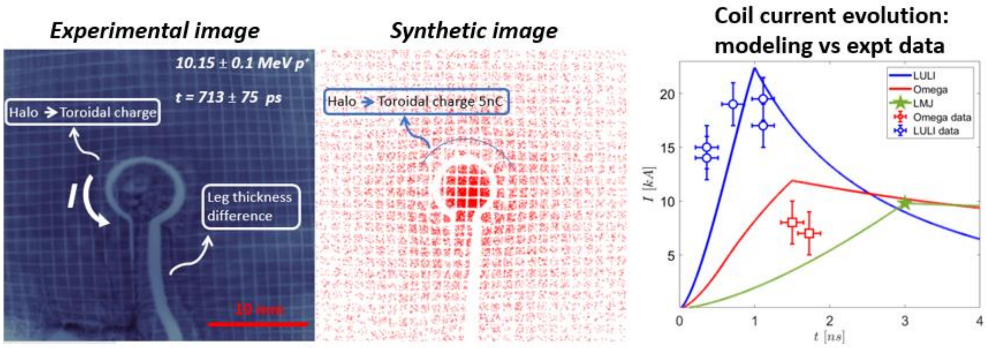

Figure 1. Results from proton deflectometry measurements and comparison with the model predictions

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Work supported by the NNSA/NLUF Grant DE-NA0003940, Grant No. PID2019-108764RB-I00 (MICINN, Spain) and EUROfusion Consortium under grant agreement No. 633053
This scientific paper has been published as part of the international project called 'PMW, co-financed by the Polish Ministry of Science and Higher Education within the framework of the scientific financial resources for 2021- 2022 under the contract no 5205/CELIA/2021/0 (project no CNRS 239915)

ECLIM 2022
36th European Conference on Laser Interaction with Matter
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X-ray synthetic diagnostics for laser-driven implosions

F. Barbato[1], L. Savino[1], S. Atzeni[1]

[1] Department SBAI, Sapienza Università di Roma, 00161, Rome, Italy

Abstract

Laser-driven implosions are used in several fields, from laboratory astrophysics to energy application (e.g. inertial confinement fusion). In all these fields, the researchers make a big effort to develop dedicated diagnostics to observe and characterize the implosion driven by a laser.
The development and deployment of a diagnostic is not only a practical matter, but it requires the use of a dedicated numerical tool to mimic the diagnostic. In this case we talk of synthetic diagnostics. A synthetic diagnostic has two main applications: first it helps the community develop the "real" diagnostic and provides support to prepare and design the experiment, second the analysis of the experimental data. The simulation codes used to reproduce the laser-matter interactions (hydrodynamic, particle-in-cell code, etc.) give as output quantities (density, temperature, etc.) that most of the time are not directly measurable in a indepent way.
For example, the signal acquired from imaging diagnostics is a function of the temperature and density spatial distribution of the observed target. A synthetic diagnostic provides the link between the simulated phenomenon and the real one.
Our work focused on the development of X-ray imaging synthetic diagnostics. In particular we have developed one code for X-ray radiography, called `PhaseX` [1] and one for X-ray emission imaging, called `EmXI`. `PhaseX` simulates X-ray radiography diagnostics working both in absorption mode and phase-contrast mode [2]. Whereas, `EmXI` simulates diagnostics based on the X-rays emitted from the target, like as framing cameras and streak cameras.
In the present work we show the two codes applied to the study of the dynamic shell formation for laser direct-drive fusion [3]. Goncharov *et al.* [4] proposed a new target design without a precast shell. The shell will be created by the laser itself, with a specific pulse shape, before the compression phase. The concept will be tested in a proof-of-principle experiment at OMEGA laser facility in LLE (Rochester, USA). We simulated the X-ray imaging diagnostics to be employed in the experiment.

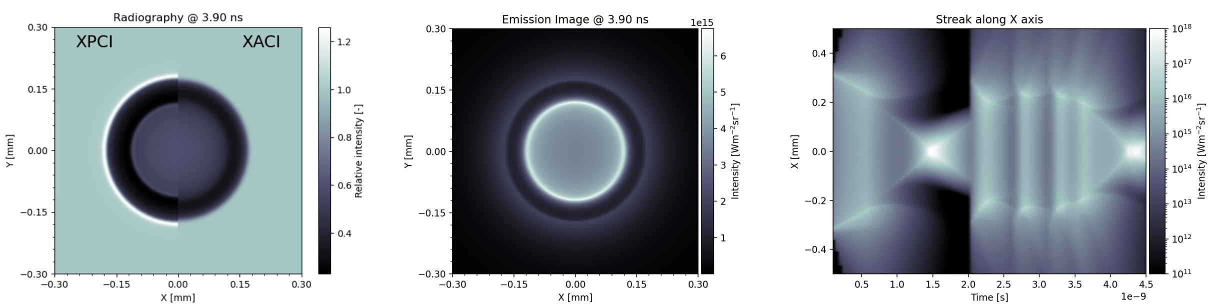

Figure 1. Synthetic diagnostics applied to dynamic shell formation; the "Absorption Image" is generated with a photon energy of 1.85 keV; the "Emission Image" and "Streak" are obtained by integrating the emission between 0.5 keV and 10 keV.

Figure 1 shows the outputs of three synthetic diagnostics. The first one shows a comparison between a X-ray phase-contrast image (*XPCI*) and X-ray absorption-contrast image (*XACI*). The two images are generated with `PhaseX` by using a monochromatic source with photon energy

equal to 1.85 keV (silicon back-lighter). The last two images are generated with `EmXI`. The "Emission Image" shows the emission that can be acquired from a framing camera. The emission is integrated over the photon energy range 0.5 keV - 10 keV. The last plot ("Streak") shows the emission along the x-axis, integrated on the same photon energy range specified before, versus time. The absorption and emission images both show the formation of the shell, at 3.90 ns after the laser interaction, as predicted from the hydrodynamic simulation.
We will also present application of the above codes to non-symmetric implosions, resulting from non uniform irradiation and/or from target deviation from perfect sphericity. All the targets, used as input for the synthetic diagnostics, are simulated with the hydrodynamic code `DUED` [5].

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Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. The involved teams have operated within the framework of the Enabling Research Project: ENR-IFE.01.CEA "Advancing shock ignition for direct-drive inertial fusion".

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36th European Conference on Laser Interaction with Matter
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Measuring the principle Hugoniot of ICF-relevant TMPTA plastic foam

R.W. Paddock[1], M. Oliver[2], D.E. Eakins[3], D.J. Chapman[3], J. Pasley[4], M. Cipriani[5], F. Consoli[5], B. Albertazzi[6], M. Koenig[6], A. S. Martynenko[7], L. Wegert[7], P. Neumayer[7], P. Tchórz[8], P. Rączka[8], P. Mabey[9], R.H.H. Scott[2], W. Garbett[10], R. Aboushelbaya[1], M.W. von der Leyen[1], and P.A. Norreys[1]

[1] Department of Physics, Clarendon Laboratory, University of Oxford, UK
[2] Central Laser Facility, STFC, Rutherford Appleton Laboratory, Didcot, UK
[3] Department of Engineering Science, University of Oxford, UK
[4] York Plasma Institute, Department of Physics, University of York, U.K
[5] ENEA — C.R. Frascati, Fusion and Nuclear Safety Department, Italy
[6] LULI, CNRS, CEA, Ecole Polytechnique, UPMC, Univ Paris 06: Sorbonne Universites, France
[7] GSI Helmholtzzentrum für Schwerionenforschung, Germany
[8] Institute of Plasma Physics and Laser Microfusion, Poland
[9] Freie Universität Berlin, Germany
[10] AWE plc, Aldermaston, Reading, UK

Abstract

Wetted-foam layers are of significant interest for ICF capsules, due to the unprecedented control they provide over the convergence ratio of the implosion, and the opportunity this affords to minimize hydrodynamic instability growth [1,2,3]. However, the equation of state (EOS) for fusion relevant foams is not well characterized, and many simulations therefore rely on modelling such foams as a homogeneous medium of the foam average density. The accuracy of this hypothesis is not known with great confidence [4]. To address this question, an experiment was performed in January 2022 using the VULCAN Laser at the Central Laser Facility. The aim was to measure the EOS of TMPTA foams at 260 mg/cc, corresponding to the density of DT-wetted-foam layers relevant to ICF research. Such a foam would be also be directly relevant for recently proposed 'hydrodynamic equivalent' capsules [5]. VISAR was used to measure the shock velocity of both the foam and a quartz reference layer, while streaked optical pyrometry was used to measure the temperature of the shocked material. Preliminary results suggest that, for the 20 – 120 GPa pressure range accessed, this material can indeed be well described using the equation of state of the homogeneous medium at the foam density.

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Acknowledgements
The authors would like to thank Rob Clarke, Chris Spindloe, Nicola Booth, and the rest of the staff both at the CLF and at the SCARF supercomputing facility who assisted with the performance and modelling of the experiment. Funding from UKRI-STFC, UKRI-EPSRC and AWE-plc is also gratefully acknowledged.

36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Helium as surrogate for deuterium in LPI studies

M. Geissel[1], A.J. Harvey-Thomson[1], K. Beckwith[1], D. Ampleford[1],J.R. Fein[1], A.M. Hansen[1], C. Jennings[1], M.W. Kimmel[1], P. Rambo[1], J.E. Shores[1], I.C. Smith[1], C.S. Speas[1], R.J. Speas[1], M.R. Weis[1], and J.L. Porter[1]

[1] Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM 87185-1193, USA

Abstract

Using helium as a surrogate fill gas for deuterium in fusion experiments can be convenient to avoid flammability hazards in an experiment. To test the degree of equivalency between deuterium and helium, experiments were conducted in the Pecos target chamber at Sandia National Laboratories.

Observables such as laser propagation, energy deposition, and signatures of laser-plasma-instabilities (LPI) were recorded for multiple laser and target configurations. It was found (Fig. 1) that some observables can differ significantly despite the apparent similarity of the gases with respect to molecular charge and weight. A qualitative behavior of the interaction may very well be studied by finding a suitable compromise of laser absorption, electron density, and LPI cross-sections, but a quantitative investigation of expected values for deuterium fills may not succeed with surrogate gases.

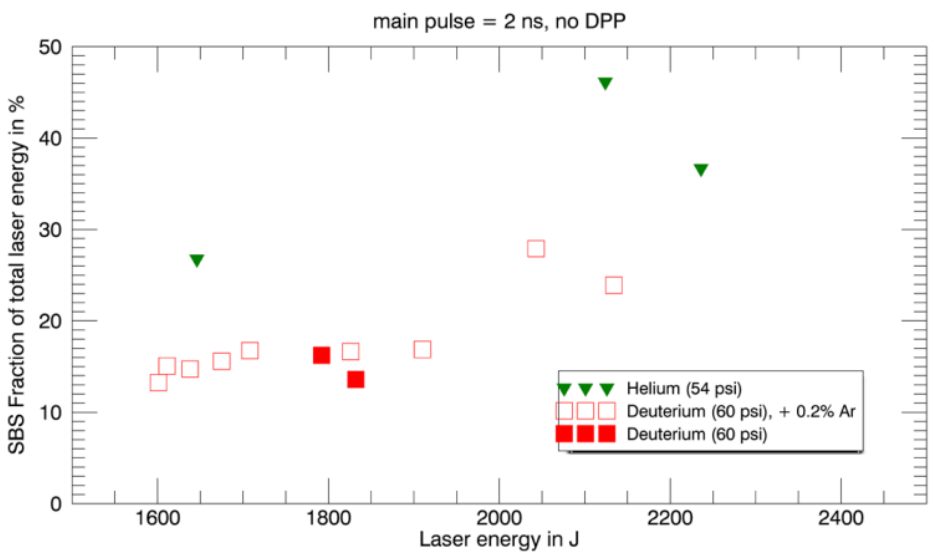

Figure 1. The backscattered fraction of laser light from SBS is significantly stronger for helium (green triangles) than for deuterium (red squares). Shown here are measurements without the use of a Distributed Phase Plate (DPP).

Acknowledgements
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

ECLIM 2022
36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Using laser irradiation to fabricate hollow nanoparticles

O. Peña-Rodríguez[1,*], J.C. Castro-Palacio[1], G. González-Rubio[2], P. Díaz-Núñez[1], A. Prada[3], R.I. Gonzalez[3], T. Milagres de Oliveira[4], W. Albrecht[4], S. Bals[4], L. Bañares[2], L.M. Liz-Marzán[5], A. Guerrero-Martínez[2], J.M. Perlado[1], J. Kohanoff[1], A. Rivera[1]

[1] Instituto de Fusión Nuclear "Guillermo Velarde", Universidad Politécnica Madrid, Spain
[2] Departamento de Química Física I, Universidad Complutense de Madrid, Spain
[3] Universidad Mayor, Santiago, Chile
[4] EMAT-University of Antwerp, Antwerp, Belgium
[5] BioNanoPlasmonics Laboratory, CIC biomaGUNE, Donostia - San Sebastián, Spain
Email: ovidio.pena@upm.es

Abstract

Metallic hollow nanoparticles exhibit interesting optical properties that can be controlled by geometrical parameters.[1] Moreover, irradiation with laser pulses has emerged recently as a valuable tool for reshaping and size modification of plasmonic metal nanoparticles, thereby enabling the synthesis of nanostructures with unique morphologies. In this work, we demonstrate how we can use the irradiation with laser pulses to fabricate hollow nanoparticles. First, we use classical molecular dynamics simulations to investigate the solid-to-hollow conversion of gold nanoparticles upon femtosecond laser irradiation. Based on these results, we suggest an efficient method to produce hollow nanoparticles under certain specific conditions.[2]

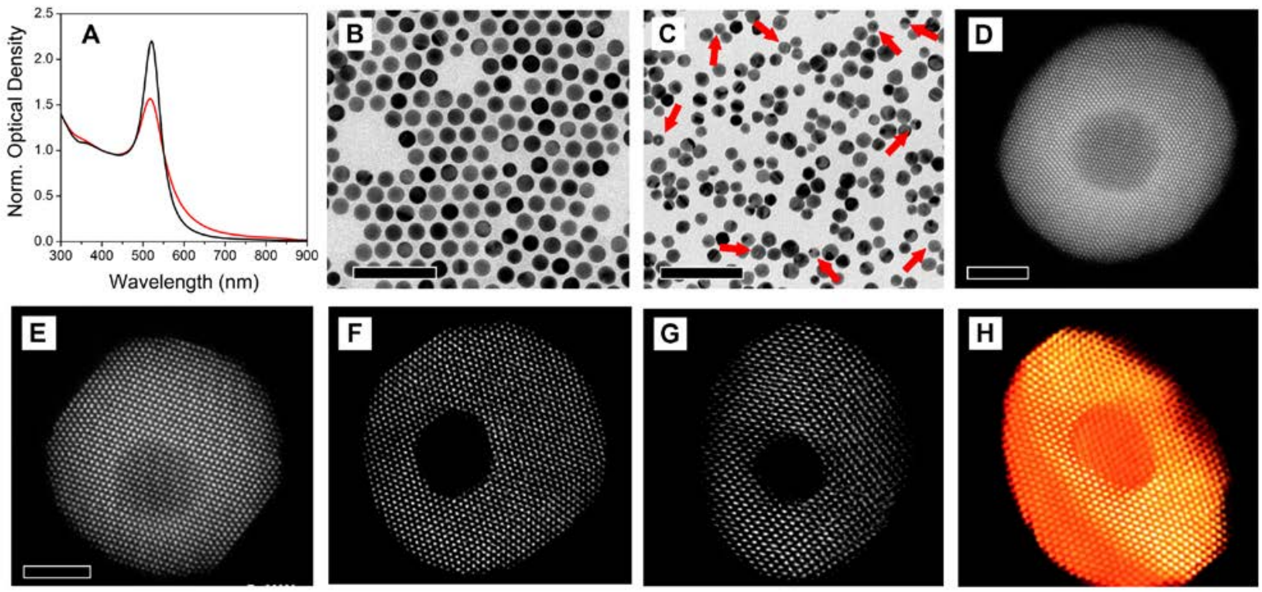

Figure 1. Irradiation of 20 nm Au NPs for 3 min with 8 ns laser pulses at a wavelength of 532 nm, a fluence of 0.2 J/cm^2, and a repetition rate of 10 Hz. (A) Normalized optical density spectra of Au NPs before (black) and after (red) irradiation. (B and C) Low-magnification ADF-STEM images of Au NPs before and after irradiation, respectively. The red arrows indicate examples of particles containing a cavity. (D, E) High-resolution HAADF-STEM images displaying the atomic structure of particles. (F, G) Orthoslices along different orientations, obtained from the atomic reconstruction of one nanoparticle using HAADF-STEM tomography. (H) Volume rendering of the reconstructed 3D structure revealing the presence of a cavity inside a Au NP. Scale bars are 50 nm (B and C) and 4 nm (D and E).

Moreover, we also demonstrate that the irradiation of spherical nanoparticles with nanosecond laser pulses induces shape transformations yielding nanocrystals with an inner cavity (see Figure 1).[3] The concentration of the stabilizing surfactant, the use of moderate pulse fluences, and the size of the irradiated particles determine the efficiency of the process and the nature of the void. Hollow nanocrystals are obtained when molecules from the surrounding medium (e.g., water and organic matter derived from the surfactant) are trapped during laser pulse irradiation. These experimental observations suggest the existence of a subtle balance between the heating and cooling processes experienced by the nanocrystals, which induce their expansion and subsequent recrystallization keeping exogenous matter inside. Therefore, we advance the experimental conditions to efficiently produce hollow nanoparticles, opening a broad range of possibilities for applications in key areas, such as gas and liquid storage and catalysis.

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Acknowledgements

This work has been partly funded by the Spanish Ministry of Science, Innovation and Universities (MICIU) (grants RTI2018-095844-B-I00, PGC2018-096444-B-I00 and MAT2017-86659-R), the Madrid Regional Government (grants P2018/NMT-4389 and P2018/EMT-4437) and EUROFUSION Enable Research project -Advancing shock ignition for direct-drive inertial Fusion- CfP-FSD-AWP21-ENR-01-CEA-02. The authors gratefully acknowledge the computer resources and technical assistance provided by the Centro de Supercomputación y Visualización de Madrid (CeSViMa), as well as the facilities provided by the Center for Ultrafast Lasers at Complutense University of Madrid.

ECLIM 2022
36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Investigating the impact of magnetic fields on laser-driven cylindrical implosions using X-ray diagnostics

P. Bradford[1], M. Bailly-Grandvaux[2], R. Florido[3], G. Peréz-Callejo[1,4], C. A. Walsh[5], C. McGuffey[6], F. Suzuki-Vidal[7], C. Vlachos[1], J. Saret[2], M. A. Gigosos[4], R. C. Mancini[8], A. Calisti[9], S. Ferri[9],V. Tikhonchuk[1,10], A. Casner[1,11], X. Vaisseau[12], N. Woolsey[13], F.N. Beg[2] and J. J. Santos[1]

[1] Université de Bordeaux-CNRS-CEA, Centre Lasers Intenses et Applications (CELIA), UMR 5107, Talence, France
[2] Center for Energy Research, University of California, San Diego, USA
[3] iUNAT-Departamento de Física, Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, Spain
[4] Departamento de Física Teórica, Atómica y Óptica, Universidad de Valladolid, Valladolid, Spain
[5] Lawrence Livermore National Laboratory, Livermore, USA
[6] General Atomics, San Diego, USA
[7] Imperial College London, London, UK
[8] Department of Physics, University of Nevada, Reno, USA
[9] Aix Marseille Université, CNRS, PIIM, F-13013 Marseille, France
[10] ELI-Beamlines, Institute of Physics, Czech Academy of Sciences, 25241 Dolní Brezany, Czech Republic
[11] CEA-CESTA, CS 60001, 33116 Le Barp Cedex, France
[12] CEA, DAM, DIF, F-91297 Arpajon, France
[13] Department of Physics, University of York, Heslington YO10 5DD, United Kingdom

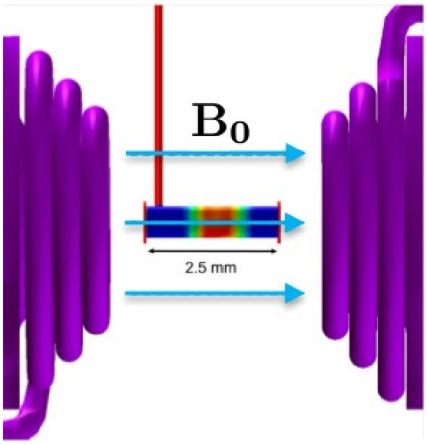
Abstract

Ongoing progress with the MagLIF fusion concept [1] and the development of external magnetic field sources at major laser facilities [2] has led to interest in using magnetic fields to increase neutron yields in inertial confinement fusion implosions [3,4]. Extended magnetohydrodynamic (MHD) simulations suggest that seed magnetic fields of 10-50 T can be amplified to over ~10 kT during capsule compression - sufficient to alter implosion dynamics and electron thermal conduction in the stagnated core [5]. Experimental validation of these predictions is crucial to understand the physics of magnetized transport and to optimize the platform for full-scale experiments. Thus far, direct measurement of the magnetic field in the compressed core has proved very difficult [6]; however indirect measurements can be made using a spectroscopic dopant to infer plasma density and temperature [7-9].

Here, we present results from a magnetized cylindrical implosion experiment at the Omega laser facility and compare them to state-of-the-art extended MHD [10], atomic kinetics and line shape simulations [11-15]. Cylindrical plastic targets were filled with Ar-doped D_2 gas and symmetrically imploded using a 14.5 kJ, 1.5 ns laser drive at 3ω. A near-uniform axial magnetic field of 24 T was supplied by the MIFEDS [2] device, which was later amplified by compression of the ionized target. Gated x-ray cameras were used to track the position of the imploding shell up to stagnation [16] and Ar K-shell emission spectra were used to extract information about conditions in the compressed core. The Ar spectra were found to be highly reproducible, with clear differences observed with and without an applied magnetic field. Synthetic Ar spectra, produced by post-processing the Gorgon 2D extended MHD results [5] and performing radiation transport calculations, show good agreement with the experimental observations. Based on these forward-directed simulations, our results for a convergence ratio similar to that measured in the experiment suggest that the mass-weighted temperature of the compressed core increases from 1 keV to

~ 1.7 keV when the target is magnetized, which is compatible with a compressed magnetic field of over 10 kT. Work is ongoing to develop a spectroscopic diagnosis method to extract representative core conditions accounting for spatial gradients in the non-magnetized scenario.

Building on our results at Omega, we plan to extend our magnetized cylindrical compression platform to the LMJ facility with ~20x larger laser drive [17]. By using larger targets and driving them with more energy, we hope to reach a higher compression ratio and more extreme conditions of magnetization. For the Omega experiment, a 24 T seed B-field produced a Hall parameter $\omega\tau$ ~ 30 and β ~ 1.4 at stagnation. On LMJ, simulations suggest we will be able to achieve higher magnetization states with Hall parameter $\omega\tau$ ~ 40 and β ~ 9 for a lower seed magnetic field of 5 T. Since there is no pulsed power discharge system available at LMJ, we will use laser-driven coils to deliver a uniform, quasi-static field along the cylinder axis. We also propose to use two dopant species for spectroscopic measurements of the imploding plasma. For temperatures above ~2.5 keV, Ar is strongly ionized and Ar K-shell spectroscopy in no longer a good temperature diagnostic. We will therefore add a small quantity of Kr to allow us to probe the higher hot spot temperatures predicted under conditions of extreme magnetization [17].



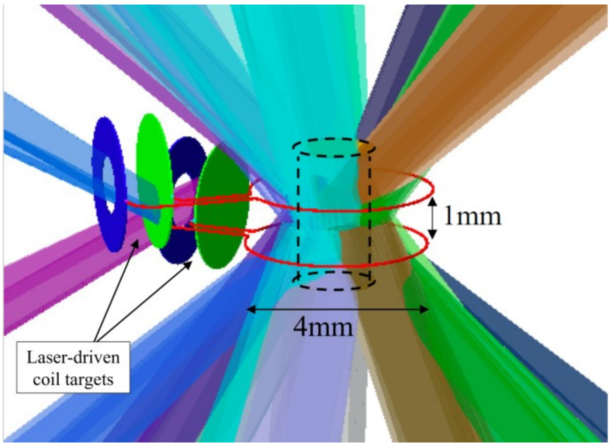


Figure 1. *LEFT:* Schematic of the Omega magnetized cylindrical implosion experiment. The MIFEDS solenoid (purple) generates a ~24T seed magnetic field B_0 along the cylinder axis. The laser irradiation pattern is visible on the surface of the target with blue, green and red colours indicating increasing intensity. *RIGHT:* Schematic representation of our proposed experiment on LMJ. The black dashed line shows the position of the cylindrical implosion target, while the 80 laser beams incident on the target surface are picked out in purple, green and blue. Two laser-driven coils, separated vertically by 1mm, are used to generate an estimated 5-10T magnetic field along the cylinder axis [17].

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Acknowledgements
Work supported by the DOE Office of Science Grant No. DE-SC0022250, NNSA/NLUF Grant No. DE-NA0003940, Grant No. PID2019-108764RB-I00 (MICINN, Spain) and the EUROfusion Consortium under Grant No. 101052200.

ECLIM 2022
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Frascati, 19-23 September 2022

Pulsed Laser Deposition of nanofoam targets for laser-driven inertial fusion experiments

A. Maffini[1], D. Orecchia[1], A. Formenti[1], V. Ciardiello[1], M. Cipriani[2], F. Consoli[2], M. Passoni[1]

[1] Politecnico di Milano, piazza Leonardo da Vinci 32, 20134 Milano , Italy
[2] ENEA, Via E. Fermi 45, 00044 Frascati (Rome), Italy

Abstract

Low-density structured materials, or foams, became in the recent years of great interest for the research in Inertial Confinement Fusion (ICF) [1]. The internal structure constituted by solid parts and voids allows the laser beam to scatter on the solid parts and into the voids, thus penetrating the material in depth, even with an average density larger than the critical density for the given laser wavelength [2]. The inhomogeneous plasma created in this way allows for a volumetric absorption of the laser energy, which contribute to smooth the spatial non-homogeneity of the laser beam [3] and to increase the absorption efficiency [4], in turn reducing the development of parametric instabilities [5]. All these features lead to an improved overall coupling between the laser and the plasma, which represents one of the critical issues for ICF. A fusion capsule having an ablator layer constituted by low-density low-Z structured material could then show an enhanced laser-plasma coupling and therefore an increased efficiency in the compression, thus leading to a higher gain from fusion reactions initiated in the plasma. On the other hand, foams constituted of high-Z materials, such as gold, allow to obtain a higher efficiency of conversion of the laser energy into X-rays compared to a homogeneous material of the same chemical composition [6]. The efficient production of X-rays with high-power lasers is of great importance for the indirect drive scheme of ICF, where the fusion capsule is suspended at the center of a gold cylinder, called the hohlraum, whose inner walls are heated by powerful lasers to produce X-rays, which in turn ablate and compress the capsule. Structured materials in this context have the two-fold advantage of allowing the increase of the absorption efficiency of the laser energy and the conversion efficiency into X-rays.

Thanks to its compatibility with virtually every kind of substrate and its capability of controlling material density, morphology and composition down to the nanoscale, Pulsed Laser Deposition (PLD) could represent an ideal tool for the production of foam-based ICF targets, although its potential for this application is largely unexplored. In PLD, laser pulses are shot on a target placed in a vacuum chamber, causing the evaporation of target surface layers. The ablated species expand in a controlled background atmosphere and are finally collected on a substrate. The resulting PLD nanofoams are composed by nanoparticles (typical size from 10 nm to 100 nm) arranged in a void-rich, fractal-like structure. PLD synthesis offers a number of potential advantages compared with standard chemical techniques, such as the capability of tailoring the density and composition profile along the target thicknesses by suitably acting on the deposition parameters. Moreover, the morphological differences between standard plastic foams and PLD nanofoams at the micro- and

nano-scale might offer an additional degree of freedom to control and improve laser-target interaction. In previous works we have shown how to exploit the PLD to tune the average density of carbon nannofoams from solid density down to few mg/cm^3, a value close to the critical plasma density for visible laser wavelength [7,8,9]. We have demonstrated the potential of near-critical PLD nanofoam targets to enhance the particle energy and number in laser-driven acceleration with super-intense ultra-short (pulse duration < 1 ps) laser pulses [10, 11, 12].

Here we discuss the potential of PLD nanofoams in ICF-relevant laser-matter interaction. We present the results concerning the deposition of carbon- , boron- , copper- and gold-based PLD nanofoams having near-critical density. In particular we show the potential of an unconventional PLD setup exploiting ultrashort pulsed (namely fs-PLD) to obtain thick (>100 µm) metallic nanofoams. The irradiation of nanofoams with energetic (~ 100 J) and nanosecond laser pulsed is simulated with the 1D hydrodymanic code MULTI-FM, which has been recently applied to the study of laser absorption and plasma behavior with porous targets [6, 13]. MULTI-FM parameters have been suitably adapted to the simulation of nanostrucured fractal-like materials as the PLD foams. Finally, we discuss a the design of a proposed experiment concerning the irradiation of PLD nanofoam targets in ICF-relevant conditions, to be realized at the ABC laser facility at ENEA Frascati, Italy.

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Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 – EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Basic Commissioning of the Laser-Plasma Ion accelerator at the ELIMAIA user beamline

F. Schillaci[1], L. Giuffrida[1], T. Chagovets[1], G.A.P. Cirrone[1, 2], M. Cuhra[1], J. Cupal[1,3], T. de Castro Silva[1], F. Grepl[1,3], M. Greplova Zakova[3, 1], A. Hadjikyriacou[3, 1], R. Horálek[1], V. Istokskaia[3, 1], V. Ivanyan[1], J. A. Jarboe[1], V. Kantarelou[1], G. Korn[1], L. Koubikova[1], T. Levato[1], G. Petringa[1, 2], J. Psikal[1, 3], D. Peceli[1], B. Rus[1], S. Stancek[1, 4], P. Szotkowski[1], M. Tosca[1], M. Tryus[1], A. Velyhan[1], and D. Margarone[1, 5]

1 ELI–Beamlines Center, Institute of Physics, Czech Academy of Sciences, Dolni Brezany, Czechia
2 Laboratori Nazionali del Sud, INFN, Catania, Italy
3 Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czechia
4 Joint Laboratory of Optics of Palacky University, Institute of Physics of Academy of Sciences of the Czech Republic, Faculty of Science, Palacky University, Olomouc, Czechia
5Centre for Plasma Physics, School of Mathematics and Physics, Queen's University Belfast, Belfast BT7 1NN, United Kingdom

Abstract

Laser-driven accelerators have gained interest in the recent years as they can offer an extremely versatile technology as the same machine can accelerate ions, electrons, and produce neutral radiation. This interest has pushed forward the development of facilities where users can exploit the unique features of laser-driven accelerators (e.g. ultrashort bunch duration) for a wide range of applications. We here report on the basic commissioning of the ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration) laser-plasma accelerator [D. Margarone et al., Quantum Beam Sci. 2018, 2, 8], using the high-repetition-rate, high peak-power L3-HAPLS laser system at the ELI Beamlines user facility in Czech Republic. The laser beam (10 J, 30 fs) was tightly focused (~2 μm, FWHM) to reach ultrahigh intensity on target (~10^{21} W/cm^2). Thin targets (10-20 μm) of different composition (e.g. Mylar, Al, Au, and Ni) were investigated to optimize the Ion Accelerator performances.

The proton beam characteristics were monitored using a complete set of ion diagnostics (Thomson Parabola spectrometer, Time-Of-Flight detectors, nuclear track detectors, and radiochromic films). Additionally, the laser-target interaction and plasma features were characterized through various optical and X/γ-ray diagnostics.

A detailed study of main interaction parameters has highlighted a strong correlation between the laser instabilities (in term of energy and in intensity on target) with proton and gamma fluctuations (in term of energy, flux and temperature).

We have successfully demonstrated the robustness of the available technology and solutions developed to have reliable and fast automation allowing operations (such as target positioning) and monitoring, diagnostics and data analysis of laser, plasma and ion features at ~1 Hz.

ECLIM 2022
36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

EPAC - A new, advanced facility for applications of laser-driven accelerators

T. de Faria Pinto, H. Ahmed, S. Blake, N. Bourgeois, T. Butcher, O. Chekhlov, R. Clarke, J. Collier, S. Dann, C. Edwards, M. Galimberti, J. Green, C. Gregory, S. Hawkes, R. Heathcote, C. Hooker, P. Mason, I. Musgrave, J. Phillips, J. Smith, N. Stuart, J. Suarez Merchan, D. Symes, Y. Tang, M. Tyldesley, T. Winstone, A. Wojtusiak, B. Wyborn, T. Zata, P. P. Rajeev, C. Hernandez-Gomez

Central Laser Facility, STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot OX11 0QX, United Kingdom

Abstract

The CLF is now constructing a new facility - the Extreme Photonics Applications Centre (EPAC). EPAC's technology is based on plasma accelerators driven by high-power laser pulses. Plasma accelerators, with their extremely high acceleration gradient, hold the promise of realising cheaper, compact accelerators for fundamental science and applications alike [1], cutting across a multitude of areas in society. We present an overview of EPAC, describing the overall architecture and some of the technical challenges in the design.

EPAC will be driven by a 10 Hz Petawatt laser, comprising an OPCPA front-end delivering energies up to 1 J in a stretched 4 ns pulse, followed by a Ti:Sapphire multi-pass amplified enabled by STFC's proprietary DiPOLE laser technology developed by CLF. After compression, EPAC will deliver a 30 J, 30 fs laser beam, centred at 800 nm, to two experimental areas: EA1 and EA2.

EA1 will be configured as a fixed geometry, long focus beamline, primarily for generating electron beams in gas targets through laser-wakefield acceleration (LWFA). The high repetition rate will enable large-scale parameter scans and the use of automated optimisation routines to study LWFA physics [2], producing high quality electron beams in the multi-GeV energy range.

EA2 has been designed as a flexible experimental area capable of undertaking laser-matter interactions with both short (*f*/3) and long focus (*f*/35) geometries, with ion acceleration being the main science driver. The primary aim of EA2 will be the delivery of high energy electrons, protons, ions, X-rays, and gamma rays.

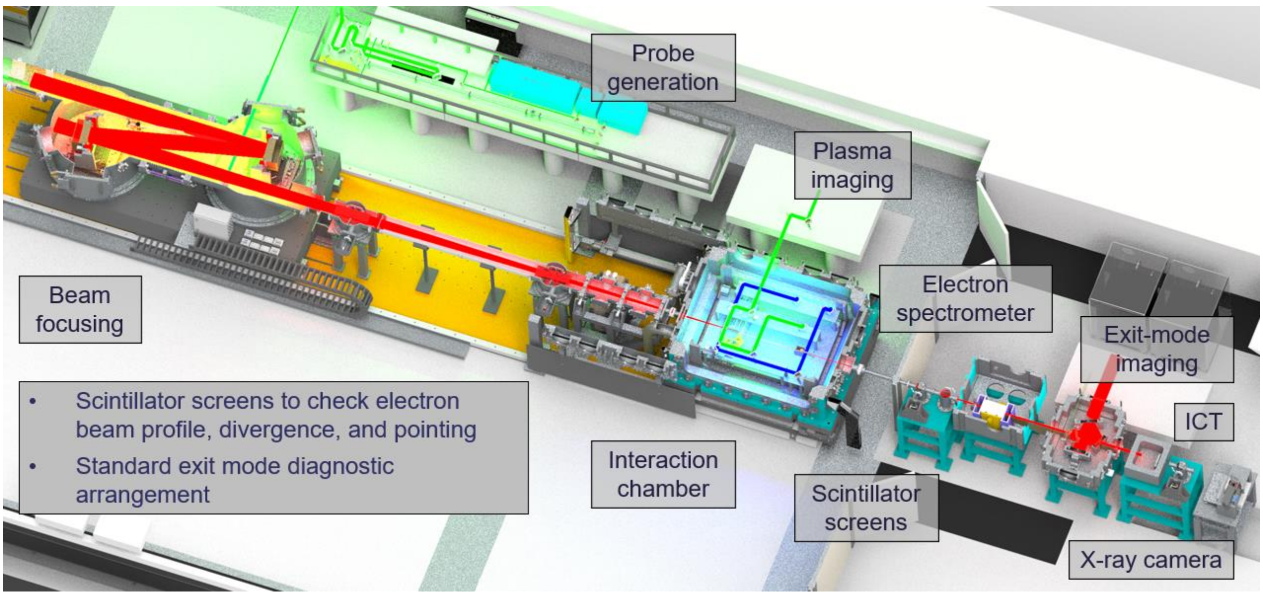

Figure 1. Overview of the first planned experiment in EA1, to deliver and characterize an electron beam generated from LWFA.

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Acknowledgements
The CLF is part UK Research and Innovation (UKRI), a public body of the Government of the United Kingdom that directs research and innovation funding, funded through the science budget of the Department for Business, Energy and Industrial Strategy.

ECLIM 2022
36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Complex ultrashort pulses for extreme light experiments at ELI-NP

Daniel Ursescu[1,2]

[1] ELI-NP, Horia Hulubei National Institute for Physics and Nuclear Engineering, 30 Reactorului Street, 077125 Magurele, Ilfov, Romania
[2] Faculty of Physics, University of Bucharest, 405 Atomistilor Street, 077125 Magurele, Romania

Abstract

The Extreme Light Infrastructure – Nuclear Physics (ELI-NP) facility reported the architecture, operation [1] and peak performance [2] of the 2x10PW high power laser system (HPLS). This is for the first time when 10 PW pulses were demonstrated, worldwide. Control of such pulses becomes critical in experiments; hence several development directions are actively followed at ELI-NP and in collaboration, in order to provide the users community with the most versatile field recipes.

Measurements aiming at the detailed characterization of the spatio-temporal couplings in ultrashort pulses are performed at the ELI-NP Optics Lab. Complementary, a propagation code for ultrashort pulses with spatio-temporal couplings (STC) was developed, based on spatial-spectral Gausslet decomposition [3]. The code allows to describe the 4-dimensional effects in the focused ultrashort pulses beyond the linear STC contribution.

In addition, ultrashort helical pulses generation set-up is now available at the 1 PW output of HPLS. The impact of the residual STC on the ultrashort helical pulses was also studied [4] using the newly developed code. The helical pulses singularity rotation is predicted as a consequence of the STC presence, helping in the doughnut profile optimization for future experiments that use helical pulses.

Spectral broadening of ultrashort pulses was also experimentally investigated, at LASERIX and APOLLON European facilities [5,6] but also at HPLS in ELI-NP, with preliminary spectral broadening results using glass and plastic materials indicating potential post-compression below 10 fs.

Further, combination of two ultrashort pulses, similar to the ones provided in the five experimental areas of ELI-NP, was studied with an innovative method based on an ultrafast non-linear optical switch. Preliminary results of the jitter measurement between the two 100 TW outputs in HPLS indicate the short-term jitter is as low as the compressed pulse duration itself (23 fs), suitable for the Compton scattering experiments that simultaneously use the full power of the two arms of HPLS, as previously proposed [7,8].

The potential synergy of these developments towards qualitative improvements of the laser field control will be discussed in order raise the awareness of the scientific community for this unique worldwide European laser facility, in particular in relation with the joint calls of the ELI-ERIC – ELI-NP for beamtime proposals. The first call was already launched in June 2022, aiming to attract the scientific community dedicated to advance the already operational HPLS beyond the 10PW and 10^{23} W/cm^2 current state of the art parameters in the near future.

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Acknowledgements
This work was supported by Extreme Light Infrastructure Nuclear Physics (ELI-NP) Phase II, a project co-financed by the Romanian Government and the European Union through the European Regional Development Fund, the Competitiveness Operational Programme (1/07.07.2016, COP, ID 1334), by ELI-RO projects 3/2020, 4/2020 and 16/2020 funded through Institutul de Fizica Atomica, Romania, by the Ministry of Education and Research, CNCS-UEFISCDI (project no. PN-IIIP4-ID-PCCF-2016–0164), within PNCDI III and IMPULSE project funded by the European Union Framework Program for Research and Innovation Horizon 2020 under grant agreement No 871161.

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

A steady-state approach to implementing laser-plasma instabilities in hydrodynamics codes

A. V. N. Nutter[1,2], R. H. H. Scott[2], A. Ruocco[2], and N. C. Woolsey[1]

[1] York Plasma Institute, University of York, United Kingdom
[2] Central Laser Facility, STFC Rutherford Appleton Laboratory, United Kingdom

Abstract

The exciting, recent developments in inertial confinement fusion (ICF) after results at the National Ignition Facility (NIF)[1] have ignited increased interest and motivation for ICF based projects in many countries. To maximise progress in ICF, we need to be able to accurately model an implosion, this will enable better designs and improve the analysis of experiments. Driving an implosion efficiently requires laser energy to be absorbed via inverse bremsstrahlung, which heats the coronal plasma that ablates a shell, compressing the fuel while keeping it cold.[2] The coupling of laser energy into the corona and resulting implosion velocity is reduced by the presence of laser-plasma instabilities (LPI). These instabilities couple laser energy into electromagnetic and electrostatic waves in the plasma that can also accelerate hot electrons, which may preheat the cold fuel and reduce compression.[3]

Implosion dynamics are typically modelled using radiation hydrodynamics codes, but these codes do not include the wave physics needed to describe LPI and instead use multipliers to account for these processes. To address this and ensure LPI are included we are creating a fast, computational model for the following LPI processes: (i) stimulated Raman scattering,[4] (ii) stimulated Brillouin scattering and (iii) two plasmon decay. These models will run in-line with laser ray-tracing routines as part of hydrodynamics codes. This will enable the codes to calculate the energy losses to LPI driven scattering of laser light and generation of hot electrons. The models employ linear theory for the LPI growth rates and combine this with non-linear saturation mechanisms such as pump depletion. An essential aspect of our work is for the models to be computationally efficient consequently we are working in a steady-state approximation where our instability levels are calculated at their saturated level between each timestep of the hydrodynamic calculation. Outputs such as laser depletion, plasma heating and hot electron generation will be passed back to the hydrocode for its next timestep.

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Acknowledgements

I would like to thank EPSRC and STFC UK for providing me with funding for my PhD, which has allowed me to carry out this research.

ECLIM 2022
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Frascati, 19-23 September 2022

Laboratory observation of C and O emission lines of White Dwarf H1504+65-like atmosphere model

Dieter H.H. Hoffmann and Laser and Particle Beams Group Headed by Professor Zhao Yongtao at XJTU

Xi'An Jiaotong University, Xi'An, Shaanxi, P.R. China
E-mail : hoffmann@physik.tu-darmstadt.de

Abstract

H1504+65, a bare stellar nucleus, is an unusual white dwarf with a Carbon- and Oxygen-dominated atmosphere. The composition cannot be explained by current stellar evolution models. The analysis of the elemental abundance and the improvement of stellar atmospheric models depends heavily on spectral measurements and accurate spectral data. We used soft x-ray emission from a laser heated hohlraum to irradiate a foam target and obtained a Carbon-Oxygen plasma emission spectrum with temperature T=195 000K±10 000K and mass fraction ratio C/O=0.85, similar to that of H1504+65. We performed a detailed comparison of our spectra with the H1504+65 Chandra spectrum, and do observe the same O VI emission lines. Moreover, intense ion- and laser beams are complimentary tools to induce High Energy Density in matter. The development of this field is intimately connected to technological advances of the field. We will give an overview of the projects in High Energy Density science that we currently address at Xi'An Jiaotong University [1-3].

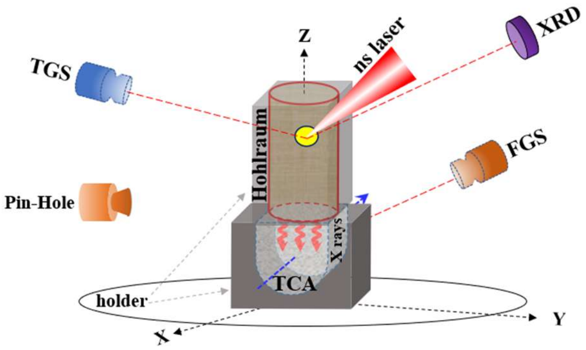

Figure 1. Geometry of the set-up. The target consists of TCA foam attached to the lower side of the cylindrical Au-hohlraum. The foam and the hohlraum were supported by a stainless steel holder. There are two free surfaces perpendicular to the blue dashed arrow for diagnostics. The flat field grating spectrometer (FGS) was obliquely positioned towards the backside of the foam target to measure the plasma radiation. Thus, the hohlraum radiation was effectively shielded. The X ray diode (XRD) as well as the transmission grating spectrometer (TGS) with a single-order diffraction grating was directed towards the laser entrance hole to measure the hohlraum radiation. The Pin- Hole (PH) camera was aimed at about 50° relative to the X axis to image the expansion of hohlraum and foam plasma emitted from the laser entrance hole and the free surface of the foam target in the X axis direction, respectively.

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Observation of high-order frequency mixing in silicon in vacuum ultraviolet spectral region

Pawan Suthar[1], Martin Kozák[1]

[1] Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 12116 Prague 2, Czech Republic

Abstract

Recent advances in high harmonic spectroscopy have enabled new methods to study ultrafast coherent dynamics of excited electron-hole wave packets in condensed matter. Electron-hole pairs are generated by the strong non-resonant light field via quantum tunneling and accelerated in the lattice to high energies. The electron and hole can eventually recombine leading to production of high-energy photons in the form of high harmonic frequencies. The three-step generation process is further supplemented by the presence of intraband anharmonic currents due to non-parabolic dispersion of electrons and holes in solid-state materials. The spectral and temporal properties of the output radiation and its dependence on the polarization state of the driving field reflects the crystal structure and ultrafast carrier dynamics. Besides the standard production of high harmonics using a single-frequency driving pulse [1], high-order frequency mixing can be induced by using two-color illumination. If a resonant pulse is used to coherently excite the electron-hole pairs, which are then driven by the non-resonant strong field, so-called high order sidebands are produced. The output photons have energies equal to $\omega_{excitation} + 2\,n * \omega_{non-resonant}$ where $\omega_{excitation}$ and $\omega_{non-resonant}$ are the frequencies of resonant and the non-resonant driving lasers respectively and n is an integer number. Odd-order sidebands are absent in a centrosymmetric crystal. The high-order sidebands were studied using terahertz driving pulses in bulk semiconductors, but mid-infrared pulses have not been used till now [2] [3].

In this contribution, we report on the observation of high-order frequency mixing and sideband generation in crystalline silicon using broadband near-infrared femtosecond pulses generated in a noncollinear optical parametric amplifier (650-950 nm) which serve for excitation of carriers and mid-infrared pulses (central wavelength of 2000 nm) for driving the excited carriers non-resonantly. The pulses are collinear, and the generated radiation is collected in the reflection geometry which is used to avoid propagation effects in the material. We study the generated high-energy photon spectra in the vacuum ultraviolet (VUV) spectral region. We focus on the dependence of the output radiation on the polarization of the driving laser pulses with respect to the crystal orientation of the sample. This may potentially allow to trace the electron dynamics as the electrons are accelerated by the non-resonant pulse after the initial excitation to the specific location in the Brillouin zone by the excitation pulse. We experimentally study the generation mechanisms and compare the efficiencies of high harmonic and high order sideband generation in the same material. The two-color illumination leads to a significant enhancement of the VUV emission compared to single-color high harmonic generation, which may bring interesting applications in high energy photon sources based on nonperturbative nonlinear optics in solids.

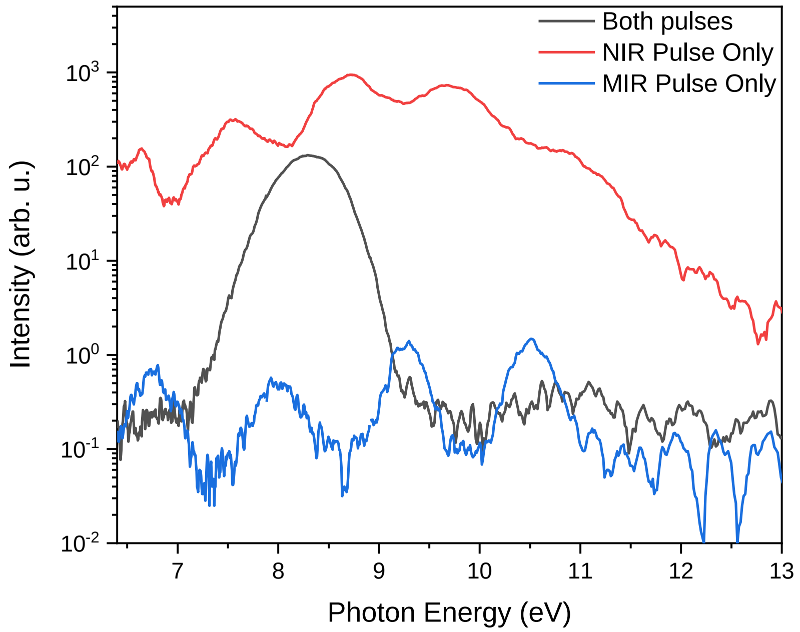

Figure 1. High harmonic spectra generated in silicon by the near-infrared few-cycle pulses with central photon energy of 1.65 eV (black curve), mid-infrared few-cycle pulses with central photon energy of 0.62 eV (blue curve) and the high-order frequency mixing spectrum generated by both pulses incident on the sample in the same time (red curve). The spectra are not corrected for the spectra sensitivity of the grating and the MCP detector.

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Acknowledgements

Financial support from Charles University (GAUK Project No. – 349921, UNCE/SCI/010, SVV-2020-260590 and PRIMUS/19/SCI/05).

36th European Conference on Laser Interaction with Matter
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Laser-matter interaction as an innovative source of intense radiofrequency-microwave fields

F. Consoli[1]*, P.L. Andreoli[1], M. Cipriani[1], M. Scisciò[1], G. Cristofari[1], R. De Angelis[1], G. Di Giorgio[1], M. Salvadori[1], C. Verona[2]
[1]ENEA, Fusion and Technology for Nuclear Safety and Security Department, C.R. Frascati, Italy
[2]Industrial Engineering Department, University of Rome "Tor Vergata", Rome, Italy

*fabrizio.consoli@enea.it

Abstract

The interaction of high energy and high intensity laser pulses with matter produces a wide band of electromagnetic and particle radiation of remarkable intensity, easily overcoming several hundreds of megawatt. In particular, the electromagnetic content includes radiofrequency, microwave, infrared, visible, UV, X and γ components. The low frequency part of this emission constitutes the well-known "Electromagnetic Pulses" (EMPs), omnipresent effect of laser-matter interactions in all the regimes. It was experimentally found that they scale with the energy and especially with the intensity of the incoming laser pulses [1]. Planned new laser facilities with enhanced features are thus expected to show very high levels of EMPs. Their intensity can be in several cases so high – MV/m order - to make them a serious issue for every electronic device placed within and nearby the experimental chamber. This is the reason why they are a very hot research topic for both Inertial Confinement Fusion and Laser-Plasma Acceleration studies.

Although the main push has been devoted to mitigation techniques for these EMP fields, there is a number of interesting and promising studies aiming at exploiting the mechanisms at the base of their generation. They include the generation of kilotesla transient magnetic fields [2] and of traveling waves for particle acceleration and focusing [3].

A new application has been recently proposed in ENEA – Centro Ricerche Frascati [4] for creating large-intensity (MV/m and beyond) transient electric fields, with specific spatial distributions and existing in big volumes of space, for a large number of applications such as: medicine, biology, electromagnetic compatibility, material science, aerospace, electronics, sensors. Fields can have spatial distributions that can be tailored to the specific application: quasi-uniform, quasi-linear gradients, …

We will describe here the methodology proposed, the associated numerical modeling and then the experiments performed with ENEA-ABC nanosecond laser facility (30 J, 3 ns) that proved the effectiveness of the proposed setup.

The methodology resolves in an original way the classical problem of generating quasi-uniform electric fields over large volumes and with very fast transients. This has the great potential to enable present and future laser plants to be innovative sources of tailored radiofrequency-microwave transient fields for a wide number of important applications.

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Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. The involved teams have operated within the framework of the Enabling Research Project: ENR-IFE.01.CEA "Advancing shock ignition for direct-drive inertial fusion".

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Electro-optical sensing of intense electromagnetic pulses in a multi-hundred joule laser facility

M. Scisciò[1], L. Duvillaret[2], P.L. Andreoli[1], V. Kmetik[3,4], J. Krása[3], P. Rączka[5], T. Burian[2], M. Červeňák[2], J. Cikhardt[6,7], J. Dostál[2], R. Dudžák[2], M. Krupka[2], M. Pfeifer[3,6], S. K. Singh[6], S. Stanček[4], M. Krůs[2] and F. Consoli[1]

[1] ENEA, Fusion and Technologies for Nuclear Safety Department, C.R. Frascati, Frascati, Italy
[2] Kapteos SAS, Bâtiment Cleanspace Alpespace, Sainte-Hélène du Lac, France
[3] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[4] ELI Beamlines, Dolní Břežany, Czech Republic
[5] Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland
[6] Institute of Plasma Physics of the Czech Academy of Sciences, Prague, Czech Republic
[7] Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic

Electromagnetic pulses (EMPs) generated by the interaction between energetic laser pulses and matter represent a hazard for the safe operation of laser-plasma experiments at high-power facilities and, at the same time, they promise interesting applications where intense (up to the MV/m) pulsed fields (with durations in the order of ns) are required. Therefore, their characterization and absolute measurement is a topic of high interest. In the last years, numerous measuring techniques and devices have been implemented for detecting EMPs, in terms of both electric and magnetic component of the generated wave, among which conductive probes and electro-optical sensors have been used.
The latter have the potential advantage (over the more commonly used conductive probes) of being less subject to the interaction with plasma particles and radiation and electromagnetically couple less efficiently with surrounding metal objects, due to the absence of conductive components. These features make them very useful for EMP measurements close to the interaction point, but they were only tested in facilities with tens of Joules energy, nanosecond long laser pulses. When higher energies are involved, even electro-optical methods for EMP detection might be affected by the large amount of produced ionizing radiation.
Here we present experimental data obtained at the PALS laser facility (~600 J pulses in 350 ps) where electro-optical detectors have been successfully implemented at short distance from target (<0.5 m). We addressed the delicate issue of high ionizing radiation produced, and we characterized the EMP emission in terms of intensity and spectral components with these probes. We compared the results with those from a conductive probe placed close to the electro-optical ones. The electro-optical probes, here used for the first time on a multi-hundred Joule facility, provided results consistent with the ones of the conductive antenna and proved therefore to be a suitable alternative of high performance for EMP measurements.

Acknowledgements
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. The involved teams have operated within the framework of the Enabling Research Project: ENR-IFE.01.CEA "Advancing shock ignition for direct-drive inertial fusion"

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EMP measurements from MF to UHF at VEGA - a comparison of solid targets and gas targets in different interaction regimes

M. Ehret* [1], R. Lera Matellanes [1],
J. I. Apiñaniz [1], A. Curcio [1], J. Hernández [1], R. Hernández Martín [1],
J. A. Pérez [1], P. Puyuelo Valdés [1], and G. Gatti [1], L. Volpe [1]

[1] Centro de Láseres Pulsados, Salamanca, Spain

mehret@clpu.es

Abstract

We present and compare experimental studies of electromagnetic pulses (EMP) produced at the high-power 30 fs lasers VEGA-2 with 200 TW and VEGA-3 with 1 PW. The seed space charge fields are triggered by the interaction of the laser pulses focused to relativistic intensities onto solid density and gas targets, at intensities ranging from several 10^{19} W/cm^2 to several 10^{20} W/cm^2. The detection of EMP is achieved by passive calibrated B-field and E-field antennas with large bandwidth from 9 kHz to 400 MHz and 300 MHz to 8 GHz respectively.

Outstanding features are the excited cavity modes, clearly detected by the compact antenna system, that can be tailored by modification of the experimental geometry. The detected magnetic fields inside the interaction chamber show amplitudes ranging from tens to hundreds of µT, which is up to ten times stronger than earth's magnetic field. Electric fields in the vicinity of the interaction chamber show amplitudes of hundreds of V/m, which is of the order of fields encountered in cm distance to GSM mobile phones. In the experimental hall, amplitudes hint at a dipole-like radiation field that bears the order of one ten-thousandth of the laser pulse energy.

Building upon the study, we present prospects for a target geometry mitigating EMP and perspectives to make use of systematic quantitative evaluation of EMP.

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

High-power laser interaction with additively manufactured micro-structured materials

M. Cipriani[1], M. Malinauskas[2], F. Consoli[1], P. Andreoli[1], T. Baldacchini[3], G. Cristofari[1], G. Di Giorgio[1], M. Scisciò[1], A. Solovjovas[2]

[1] ENEA, Fusion and Technologies for Nuclear Safety Department, C.R. Frascati, Frascati, Italy
[2] Vilnius University, Physics Faculty, Laser Research Center, (Saulėtekio Ave. 10, LT-10223) Vilnius, Lithuania
[3] Department of Chemistry, University of California, Irvine, CA 92697, United States of America

Abstract

The research on Inertial Confinement Fusion (ICF) is always requiring the development of new types of materials. The structure of the fusion capsule has to be precisely tailored to ensure an optimal performance for the implosion and ignition, and also a reliable reproducibility of the plasma behavior from shot to shot, in the view of a future fusion reactor. Among the various processes affecting the performance of the capsule, hydrodynamic instabilities, such as the Rayleigh-Taylor instability, and parametric instabilities, such as the stimulated Brillouin scattering, the stimulated Raman scattering and the two-plasmon decay, play a detrimental role. Hydrodynamic instabilities degrade the compression efficiency, while the parametric instabilities reduce the absorption of the laser energy in the fusion target, scattering the laser light and producing suprathermal particles which cause a typically unwanted preheat of the fuel.

Micro-structured low-density materials, such as porous materials, or foams, with a randomly arranged internal structure have been shown in the last decades to be able to reduce to some extent the aforementioned issues. They can increase the efficiency of the absorption of the laser in the plasma [1], reduce hydrodynamic and parametric instabilities [2] and also increase the pressure at the shock front [3]. All these advantages are due to the peculiar features of their internal structure, constituted by solid parts, in the shape of filaments and membranes, and by empty spaces. The size of the empty spaces can be either of the order of 1 μm or of tens of μm and the average density can range from a few mg/cm^3 to hundreds of mg/cm^3. Therefore, foams with an average density lower or higher than the critical density for the given laser wavelength can be selected.

In the decades, a notable control on the average material parameters during manufacturing has been achieved, but the techniques traditionally used do not give the ability to finely tune the internal structure on the basis of the experimental needs. Each foam is a unique piece and the parameters, such as the density and the size of the empty spaces are usually the same over the whole sample. Also, stacking various layers of foams with different parameters can be hardly done with the traditional techniques. However, accessing these capabilities may improve the performances of the material during the interaction with a high-power laser and permit the design of even complicated geometries for a new class of targets.

The techniques for manufacturing micro- and nano-structured materials with the use of ultrashort pulsed lasers which are currently being developed allow to realize complex structures and internal architectures with a high precision, which can be as lower as a few tens of nanometers.

Ultrafast laser direct write 3D micro-/nano-lithography (also known as two-photon polymerization or multi-photon lithography) is becoming an established tool for precission 3D printing. Using tight focusing and exploiting spatially confined light-matter interaction allow fabrication of arbitrary objects with accurately defined features out of diverse cross-linkable organic and hybrid organic-inorganic materials [4]. The state-of-the-art technique empowers additive manufacturing of structures having ~100 nm individual resolved features with overall object dimensions up to mm in scales [5].

Micro-structured materials fabricated in this way will have several advantages. Every feature of the internal structure can be engineered with precision and freedom, by realizing a computer model which will then be faithfully reproduced by the printing process. This allows to tune the sample parameters, such as the density, the thickness or the separation between the printed filaments, with precision and freedom, also ensuring a high reproducibility of the targets from shot to shot.
In this work we will present the preliminary results of a campaign conducted at the ABC laser facility in the ENEA Research Center in Frascati, in which we irradiated micro-structured materials realized at the Vilnius Laser Research Center by additive manufacturing. We will discuss the fabrication strategy of the targets, which involved two different printing techniques. The foam sample was obtained by direct laser writing and it was kept in place on the target holder in the experimental chamber by a support structure 3D printed with a UV table-top lithographic commercial printer (Asiga Pico 2 UV). We will then describe the behavior of the plasma under irradiation at about 10^{14} W/cm^2 at the fundamental wavelength of the ABC laser. The data collected show a high reproducibility from shot to shot and peculiar features compared to foams produced with traditional methods.

Acknowledgements
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them. The involved teams have operated within the framework of the Enabling Research Project: ENR-IFE.01.CEA "Advancing shock ignition for direct-drive inertial fusion"
This research was funded by the Research Council of Lithuania (project No. S-MIP-20-17) and received funding from EU Horizon 2020, Research and Innovation program LASERLAB-EUROPE JRA Project No. 871124.

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Time resolved x-ray imaging of hot electron generation at SI-relevant laser-matter coupling parameters

O. Renner[1,2], D. Batani[3], G. Cristoforetti[4], M. Červeňák[2], R. Dudžák[1,2], E. Filippov[5,6], P. Gajdoš[2], L.A. Gizzi[4], L. Juha[1], Ph. Korneev[7], P. Koester[4], M. Krůs[2], A. Martynenko[8], P. Nicolai[3], S. Pikuz[5], V.T. Tikhonchuk[1,3], S. Weber[1]

[1] Institute of Physics & ELI-Beamlines, CAS, Prague, Czech Republic
[2] Institute of Plasma Physics, CAS, Prague, Czech Republic
[3] Université Bordeaux, CNRS, CEA, CELIA, Talence, France
[4] National Institute of Optics, CNR, Pisa and Florence, Italy
[5] Joint Institute of High Temperature of RAS, Moscow, Russian Federation
[6] Institute of Applied Physics of RAS, Nizhny Novgorod, Russian Federation
[7] P.N. Lebedev Physical Institute of RAS & MEPHI, Moscow, Russian Federation
[8] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

Abstract

The interaction of high intensity laser radiation with solid targets is accompanied by strongly nonlinear phenomena which define the environmental conditions in the hot dense plasma created. Despite a considerable progress in theoretical description of relevant processes [1], the laser energy deposition into the target is not fully understood yet in particular at moderate laser coupling parameters $I\lambda^2 = 10^{15}$ - 10^{16} W μm^2/cm^2 where I is the intensity and λ the wavelength of the focused laser beam. At these intensities, the laser energy deposition switches from collisional absorption to mechanisms governed by resonance excitation of large-amplitude plasma waves, namely by stimulated Brillouin and Raman scattering and two plasmon decay [2]. In the same time, these parametric instabilities dominate the generation of hot electrons (HE) compared to alternate processes, e.g., resonant absorption and vacuum heating.

The detailed investigation of HE production and their interaction with matter is of paramount interest for fundamental directed research in the fields of laboratory astrophysics and in general high-energy-density physics [3]. The more practical applications refer to the HE role in a development of diverse scenarios for inertial confinement fusion, where the laser coupling to fast electrons and their transport inside the ICF capsules affects the efficiency of the energy delivery to the ignition region but prospectively also induce an undesired preheat of the fuel. This is particularly true for the shock ignition (SI) scheme anticipating the ignition by the sub-ns-laser spike with intensity close to 10^{16} W/cm^2. At these conditions the threshold for growth of parametric instabilities is definitely exceeded [4] and a significant amount of the laser energy is transferred to HE. The kinetics of HE generation and their impact on formation of strong shocks however have not been fully understood yet. The hitherto simulations do not predict in a sufficient detail the desired time resolved information on HE formation, transport, slowing down and energy deposition inside the targets which affects the dynamics of strong shocks. The aim of experiments conducted at the Prague PALS laser facility is to collect precise data needed for development of theoretical models describing the HE formation, transport, and energy deposition inside the targets which affect the dynamics of strong shocks.

Here we report x-ray measurements characterizing HE generation via 1D space-time resolved imaging of HE-induced Kα emission inside the cold target material. The experiments were performed at intensities up to 2×10^{16} W/cm^2, i.e., at parameters of the laser-plasma coupling suitable to address the physics of the laser spike induced shock wave igniting the fusion reaction [5]. The experimental setup schematically shown in Fig. 1 combines the spherically bent crystal of quartz (422) with the Hamamatsu high dynamic range x-ray streak camera to obtain magnified time and space resolved monochromatic images of the K-shell emission from laser irradiated Cu targets.

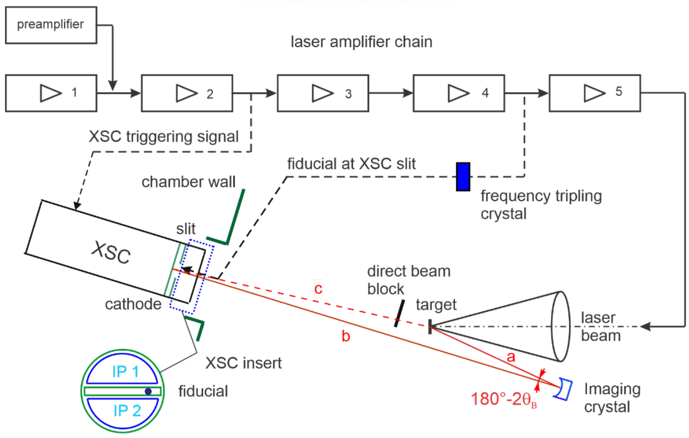

Figure 1. A scheme of the imaging system combining the spherically bent crystal with the X-ray streak camera (XSC).

The images of the HE-induced Cu Kα emission were recorded with the spatial resolution of 3.9 µm, the HE emission was absolutely calibrated vs the temporal profile of the laser beam with a standard deviation of ±40 ps. In one series of shots, this correlation could be specified to ±15 ps due to coincidence of the HE signal with oscillations in the declining part of the laser profile. An example of the processed experimental data is shown in Fig. 2. Further results obtained at the laser irradiated bare and structured Cu targets, including a comparison with spectroscopically determined parameters of the HE production at thin Cu foils [6], are presented and discussed in detail.

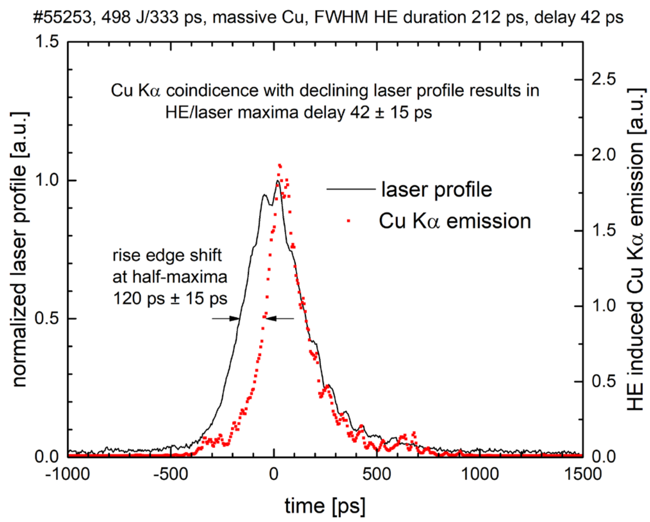

Figure 2. HE production at massive Cu target irradiated with the 1ω PALS laser beam (498 J, 1.315 µm, 333 ps). The correlation of the laser profile with the Cu Kα emission reveals a delayed rise and temporal shift of the HE generation.

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Acknowledgements
The authors acknowledge a support of the PALS Infrastructure within the Czech Republic Ministry of Education, Youth and Sports project No. LM2018114. This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither European Union nor the European Commission can be held responsible for them. The involved teams have operated within the framework of the Enabling Research Project: ENR-IFE.01.CEA "Advancing shock ignition for direct-drive inertial fusion".

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Data analysis and numerical modelling of laser-plasma instabilities in NIF shock ignition experiments

A. Ruocco[1], K. Glize[2,3], M. J. Rosenberg[4], A. A. Solodov[4], T. D. Arber[5], T. Goffrey[5], K. Bennet[5], A. Nutter[1,6], S.J. Spencer[7] and R. H. H. Scott[1]

[1] Central Laser Facility, STFC Rutherford Appleton Laboratory, Oxford, UK
[2] Key Laboratory for Laser Plasmas (MOE), Shanghai Jiao Tong University, Shanghai, China
[3] Collaborative Innovation Center for IFSA, Shanghai, China
[4] Laboratory for Laser Energetics, University of Rochester, Rochester, New York, USA
[5] Centre for Fusion, Space and Astrophysics, University of Warwick, UK
[6] Department of Physics, University of York, York, UK
[7] University of California, Los Angeles, USA

Abstract

The shock ignition approach (SI) [1] to inertial confinement fusion (ICF) [2] relaxes the ignition requirements by splitting the compression phase, led by a low-intensity laser pulse, from the ignition phase, driven by laser pulses of intensity around 10^{16} W/cm^2. Albeit more robust against hydrodynamics instabilities, SI is more vulnerable to laser-plasma instabilities (LPI) [3], which produce undesired scattering of laser light and hot-electron (HE).

Here we report on the preliminary analysis of a planar experiment carried out on the National Ignition Facility (NIF) laboratory aimed to investigate LPI at SI conditions to understand the origin of HE and characterise the light scattering processes. In the experiment, the laser pulse irradiates a planar CH target and reaches an on-target spike intensity of 10^{16} W/cm^2, with beams arranged in two cones.

The data analysis shows an angular dependence of Raman scattering: at 50° Raman signal displays side-scattered-like behaviour [4]. The average HE temperature measured is around 50 keV, with hot electron energy conversion efficiency of around 12%. This does not match the measured time averaged low Raman reflectivity. From the near-backscattered imager (NBI), we estimate that only 30% of the scattered light is recorded by the light station. In order to understand the processes involved, we perform two-dimensional particle-in-cell simulations at relevant laser and plasma conditions.

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ECLIM 2022
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Frascati, 19-23 September 2022

Impact of Laser Bandwidth on LPI in Conditions Relevant for Shock Ignition

L.A.Gizzi[1], S.Atzeni[2], D.Batani[3], G.Cristoforetti[1], M.Galimberti[4], S.Hüller[5], K.Jakubowska[2], M.Khan[6], P.Koester[1], K.Lancaster[6], P.Oliveira[4], A.Schiavi[2], N.Woolsey[6]

[1]Istituto Nazionale di Ottica, CNR, Pisa, ITALY,
[2]Università di Roma - La Sapienza, Roma, ITALY,
[3]Universite de Bordeaux, FRANCE
[4]Science and Technology Facilities Council, UNITED KINGDOM,
[5]CNRS UMR 7644, FRANCE,
[6]University of York, UNITED KINGDOM,

Abstract

With the recent outstanding progress towards Inertial Confinement Fusion (ICF) ignition at the National Ignition Facility, the interest for high gain Inertial Fusion Energy (IFE) is rapidly expanding. Shock ignition (SI) is based on direct drive and relies on a strong shock wave (>300 Mbar) to be launched by means of a short laser spike (300-500 ps) irradiation at intensities around 10^{16} W cm^{-2} [1,2] at the end of the compression phase to initiate ignition. The success of the SI concept depends mainly on the coupling of the laser spike with the plasma surrounding the imploding shell, where the onset of parametric instabilities, including Stimulated Brillouin Scattering (SBS), Stimulated Raman Scattering (SRS) and Two-Plasmon Decay (TPD), can lead to a degradation of the laser-plasma coupling. Moreover, TPD and SRS generate electron plasma waves (EPW) that give rise to hot electrons (HE) which, depending on their energy, may affect the shock pressure or preheat the pre-compressed fuel. The onset of laser-driven instabilities is, in turn, affected by the growth of micrometer-scale filamentation, which produces a local enhancement of laser intensity and a modification of plasma density profile. Modelling of the interaction of the ignition shock laser pulse [3] with the coronal plasma is made complex by the presence of highly non-linear kinetic effects - notably collective speckles effects and ponderomotive electron dynamics - and by the competition of the various processes, whose modelling is beyond the current full-scale kinetic simulations capabilities.

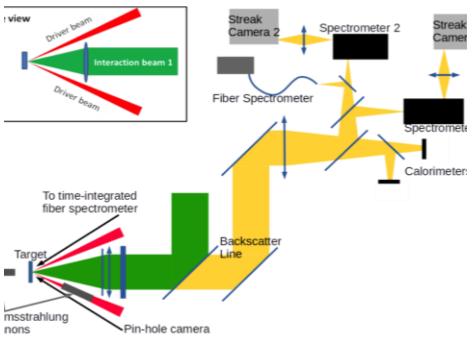

Figure 1. *Experimental setup showing laser beams geometry and back-scattering diagnostics.*

In a recent experimental campaign we investigated the impact of parametric instabilities – in particular SRS and TPD – and the generation of HE on the interaction of a laser pulse at SI intensity (~10^{16} W cm^{-2}) with a preformed, long scale-length plasma mimicking the ICF corona. In the experiment [4] a long scale-length, hot plasma was generated by using 4 *driver heating beams* (250 J, 1053 nm, 3 ns) at an intensity on target of ~3×10^{13} W/cm^2 per beam, simultaneously focused with a F/10 optics at angles of 25° and -25° in the vertical plane (Fig.1). Random Phase Plates on the beams gave a focal spot of 800 μm (FWHM) on a flat foil targets consisting of a 50 μm thick plastic to mimic the low-Z ablating capsule material in a direct drive ICF compression. A separate *interaction beam* (85 J, 527 nm, 500 ps) was focused on the approximately 1D expanding plasma [4] with an F/2.5 optics and with p-polarization, to mimic the shock driving beam in the SI scheme. A Random Phase Plate was used which resulted in a FWHM ≈ 30 μm spot and in a laser intensity of ~10^{16} W/cm^2. The interaction beam was delayed by 0.3 ns to 3 ns with respect to the rise time of the driver beams. Simulations with the 2D hydro-code DUED show that density scale-length in the interaction region ($0.04\ n_c < n_e < 0.25\ n_c$) can be in this way tuned in the range 90-500 μm at the beginning of the interaction and electron temperatures range between 1 keV and 5 keV in the underdense plasma. Diagnostics included time resolved optical spectroscopy for SRS, TPD and SBS, and broadband X-ray emission for hot electron generation [5] using recently developed analysis tools [12] to compare HE temperatires expected from SRS and TPD. The interaction of the narrow-band interaction pulse was compared with the stretched laser pulse obtained by the amplification of a larger bandwidth oscillator, resulting in a laser bandwidth $\Delta\lambda/\lambda \approx 0.3\%$ but maintaining the same intensity on target and the same pulse duration as the narrow-band pulse.

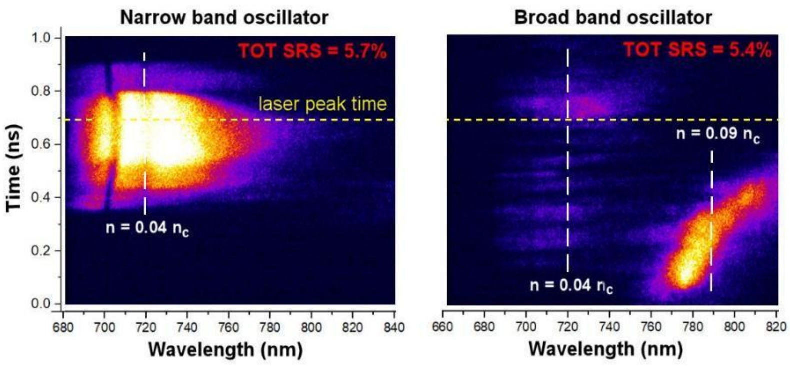

Figure 2. Time resolved SRS spectra obtained during the previous TAW experiment using narrow band (left) and broadband (right) oscillator. A significant change of emission wavelength indicates a change of LPI conditions.

Remarkably, as shown in Fig.1(right), the shots with broad-band stretched pulse yielded a strong spectral signature of SRS driven at higher densities, with a strong reduction of the SRS driven at lower density compared with the narrow-band interaction. This can be explained by the short coherence time τ_p of the laser light in this configuration (~ 1 ps), inhibiting filamentation at low plasma densities and reducing the plasma-smoothing of the laser propagating in denser regions. In fact it is well known that in classical Direct-Drive interaction regime, at intensities around 1E14 W cm^{-2}, a reduction of laser coherence time results in the inhibition of both SBS and filamentation, and consequently also of SRS which is – in those conditions - under threshold [7,8]. This motivated [9] the use of Induced Spatial Incoherence (ISI) or Smoothing by Spectral Dispersion (SSD) on the laser beams, which reduces the SRS to negligible levels [10]. The picture, however, could dramatically change at the higher laser intensities of the SI conditions. Here, as suggested by the preliminary new results given above, the inhibition of filamentation at low densities could produce a stronger LPI (SRS, and possibly TPD) in denser regions and in principle also the generation of more energetic HE. We stress that such coherence time of the pulse with broadband oscillator, $\tau_p \approx 1$ ps, is of the same order of magnitude of the filamentation growth time and, based on the above results, can account for an on/off effect on the filamentation of speckles at low density.

Acknowledgements

The authors acknowledge financial support from the LASERLAB-EUROPE Access to Research Infrastructure activity within the EC's seventh Framework Program (Application No. 18110033).

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Optimisation of multi-petawatt laser-driven proton acceleration in the relativistic transparency regime

J. Goodman[1], M. King[1,2], R. Wilson[1], R. J. Gray[1] and P. McKenna[1,2]

[1] SUPA Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom
[2] The Cockcroft Institute, Sci-Tech Daresbury, Warrington WA4 4AD, United Kingdom

Abstract

Over the past two decades, short pulse laser-driven ion acceleration has emerged as a potentially compact approach for the generation of pulses of ions with tens-of-MeV energies [1]. This is possible due to the high magnitude electric fields, of the order of MV μm^{-1}, produced in plasma irradiated by relativistically intense laser light. The resulting ion bunches are ultra-short in duration (of the order of the laser pulse duration at source), high flux, typically broadband in energy, and have a small virtual source size.

Numerous potential applications have been proposed including hadron therapy, radioisotope generation, as a driver for the fast ignition approach to inertial confinement fusion, as well as fundamental science applications in ultra-fast imaging, nuclear physics and warm dense matter physics [1]. Significant challenges remain in the development of these novel accelerators, including finding pathways to increase the achievable ion energies, decrease beam divergence, and improve laser-to-ion energy conversion efficiency and shot-to-shot stability. Much of the work done to address these challenges has focussed on the investigation and development of acceleration mechanisms.

Laser-driven ion acceleration can occur in underdense (gaseous) plasma via the generation and propagation of collisionless shock waves [2]. Higher ion energies are typically achieved using thin foil targets and the most widely explored mechanism to date is target normal sheath acceleration (TNSA) [3]. This occurs when fast electrons generated by the laser interaction at the target front side, propagate within the foil and generate MV μm^{-1} electric fields at the surfaces. Ions originating near the surfaces and within surface contaminant layers are accelerated, with measured proton energies up to ~85 MeV attributed to this mechanism [4]. While TNSA is a robust scheme, the scaling of the fast electron temperature with the square root of laser intensity (for relativistic laser intensities) means that ultra-high intensities are required to achieve the high ion energies needed for applications such as hadron therapy [1].

Radiation pressure acceleration (RPA) [5, 6] also occurs in dense plasma and utilises laser light pressure, resulting in a much faster maximum ion energy scaling with intensity. The highest energies are achieved for ultrathin foils, via the light sail mode of RPA (LS-RPA) [5]. This mode is, however, susceptible to transverse instabilities and undesirable plasma heating as the target deforms under the radiation pressure [7]. RPA is also curtailed if relativistic self-induced transparency (RSIT) [8, 9], driven by the relativistic increase in the mass of plasma electrons oscillating in response to the laser field, occurs. The resulting decrease in the plasma frequency, or effective increase in the relativistic critical density $n'_c = \gamma_e n_c$, where γ_e is the Lorentz factor of the electrons and n_c is the classical critical density, enables laser light transmission. As relativistic transparency occurs at the most intense part of the focussed laser light, a relativistic plasma aperture forms in the foil [10]. The transmitted laser light results in additional heating of the plasma electrons in the region through which it propagates, which can enhance the electric fields and thus ion energies. This forms the basis of the transparency-enhanced hybrid RPA–TNSA scheme [11].

Although RSIT has been demonstrated to enhance the maximum ion energies achievable [11, 12] optimisation and control of this approach is challenging as it depends strongly on rapid nonlinear

heating and expansion of the plasma electron population, and is highly susceptible to changes in the laser temporal-intensity profile. At the upper limit of laser intensities achievable up to now, the maximum ion energy has been shown to depend on the onset time of transparency [11, 12]. The exploration of this approach to ion acceleration at the ultrahigh intensities achievable at multi-PW scale laser facilities, for which strong-field effects such as radiation reaction and pair production are expected to become important [13], is just beginning.

We report on a numerical investigation of the optimisation of laser-driven proton acceleration in CH foils that undergo RSIT [14], for laser intensities between 5×10^{20}–2×10^{23} W cm^{-2}, which are expected to be achievable at multi-PW laser facilities coming on line in the near future. We demonstrate the dependency of the maximum ion energy and overall laser energy conversion to ions on the onset time of RSIT and explore the underlying physics. We investigate the effects of the laser polarisation and the rising edge component of the laser temporal-intensity contrast. Radiation reaction is also considered for the highest intensity of linearly polarised light simulated. The results inform the design of experiments to optimise laser-driven ion acceleration at next-generation high power laser facilities, and more generally demonstrates RSIT onset time to be a key parameter in these interactions.

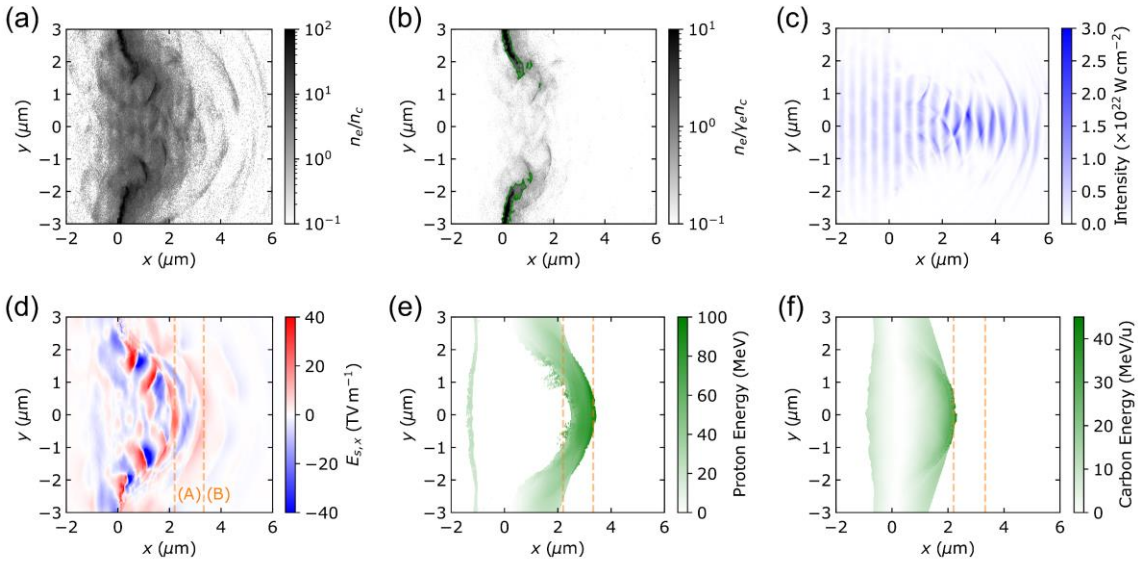

Figure 1. A snapshot of a simulation for a 125nm thick foil and laser intensity of 5×10^{21} W cm^{-2} after the onset of RSIT showing proton acceleration. (a) Electron density. (b) Electron density normalised by the relativistic critical density, with contour lines where $n_e = \gamma_e n_c$ (green). (c) Intensity of the laser light. (d) Electrostatic field in the x-direction. (e) Average proton energy within each grid cell. (f) Average carbon ion energy within each grid cell. Features (A) and (B) in (d)–(f) indicate the positions for y = 0 of the positive fields co-moving with the accelerating ions.

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Efficient generation of new orbital angular momentum beams by backward and forward stimulated Raman scattering

Q. S. Feng[1], R. Aboushelbaya[1], M. W. von der Leyen[1], W. P. Wang[2], R. M. G. M. Trines[3], B. T. Spiers[1], R. W. Paddock[1], I. Ouatu[1], R. Timmis[1], R. H. W. Wang[1], R. Bingham[3], and P. A. Norreys[1,4]

[1] Department of Physics, Atomic and Laser Physics sub-Department, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom

[2] State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

[3] Central Laser Facility, UKRI-STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, Oxfordshire OX11 0QX, UK

[4] John Adams Institute, Denys Wilkinson Building, Oxford OX1 3RH, United Kingdom

Abstract

Laser beams carrying orbital angular momentum (OAM) provide an additional degree of freedom and have found wide applications ranging from optical communications and optical manipulation to quantum information. The efficient generation and operation of ultra-intense OAM beams is a big challenge that has to be met, currently setting a limit to the potential applications of ultra-intense OAM beams in high-energy-density physics studies. Here, we theoretically and numerically demonstrate for the first time that a pump beam with a new OAM state is generated by coupling of the seed pulse with OAM-carrying Langmuir waves arising from both backward and forward stimulated Raman scattering mechanisms. Advantage is taken of the high energy transfer efficiency from pump to amplified seed beams by operating in the non-linear regime, as this significantly reduces the size of amplification system and promotes access to high-intensity OAM laser beams for scientific and industrial applications.

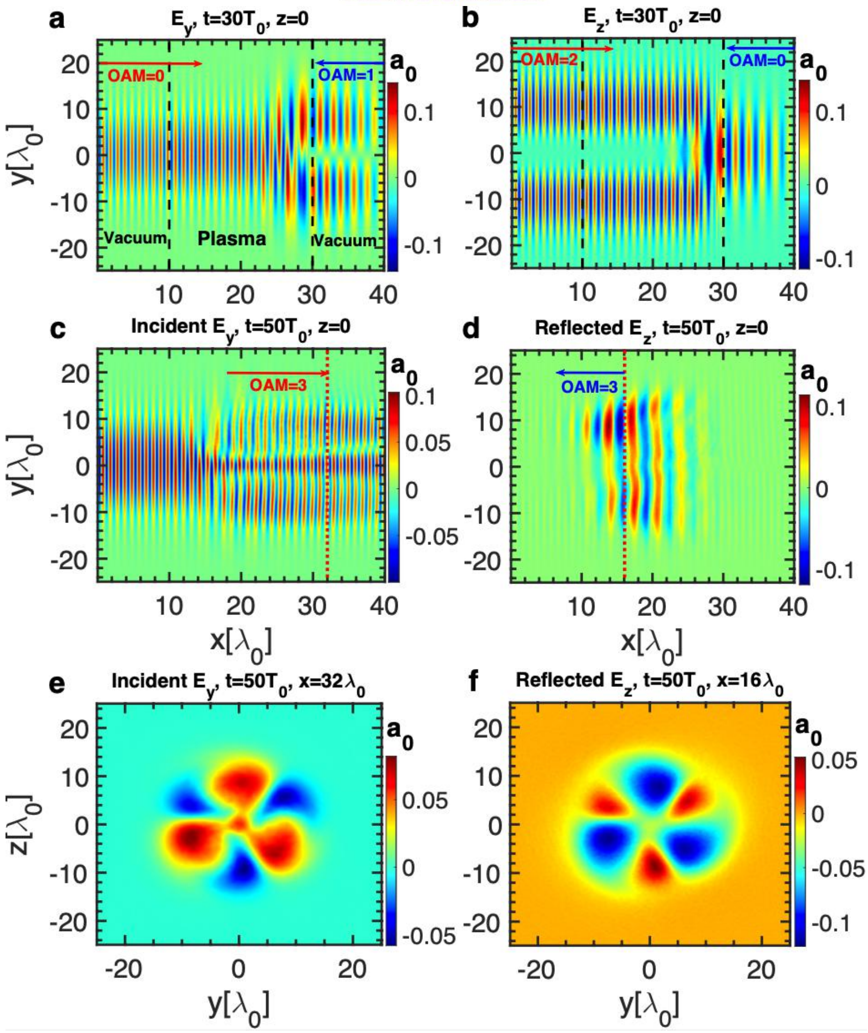

Figure 1. Generation of the pump and seed pulses with new OAM.

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Acknowledgements

We would like to acknowledge useful discussions with L. B. Ju, C. Z. Xiao and Q. Wang. The authors gratefully acknowledge the support of the ARCHER2 UK National Supercomputing Service, all of the staff of the Central Laser Facility and the Scientific Computing Department's SCARF supercomputing facility at the UKRI-STFC Rutherford Appleton Laboratory.

This research was supported by the Oxford-ShanghaiTech collaboration, the UKRI-EPSRC funded e674 ARCHER2 project under grant number EP/R029148/1 and the National Natural Science Foundation of China (Grant Nos. 12005021).

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Frascati, 19-23 September 2022

Experimental fast electron studies in relativistic laser-solid interaction with flat and nanostructured targets

F. Baffigi[1], P. Koester[1], A. Marasciulli[1], F. Brandi[1], G. Cristoforetti[1], L. Fulgentini[1], L. A. Gizzi[1], E. Hume[2], L. Labate[1], K. Lancaster[2], D. Palla[1], M. Salvadori[1]

[1] Intense Laser Irradiation Laboratory, INO-CNR, 56124 Pisa, Italy
[2] York Plasma Institute, Department of Physics, University of York, York YO10 5DD, United Kingdom

Abstract

The investigation of the generation of fast electrons in high-intensity laser-solid interactions and their transport is important both from a fundamental physics point of view as well as for applications such as the development of ultra-short X-ray and proton sources and the fast ignition approach to Inertial Confinement Fusion.

An experimental campaign was carried out using the femtosecond 200 TW laser system at the Intense Laser Irradiation Laboratory (ILIL) in Pisa. Flat foil targets and targets with nanowires on a substrate were irradiated at laser intensities > 10^{20} W/cm^2 at the fundamental laser wavelength (800 nm) and with the frequency doubled laser beam at intensities > 10^{19} W/cm^2.

In the experiment a range of diagnostics were used, including spectrally resolved scattering of the laser light in reflection direction from the target, proton and ion diagnostics (time-of-flight and Thomson parabola) and imaging and spectroscopy of optical transition radiation generated as electrons exit the rear target surface.

The experimental results are shown for the different target types and for 1w and 2w laser irradiation. The interpretation of the experimental results is supported through simulations with hydrodynamic codes for the preplasma characterization and PIC code for the high-intensity laser-solid interaction.

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Dynamics of harmonic generation of laser with optical channeling and density transition in relativistic-magneto plasma

Arvinder Singh[1] , Aman Bhatia[1], Keshav Walia[2],

[1] Dr B R Ambedkar National Institute of Technology Jalandhar Punjab, India
[2] DAV University Jalandhar Punjab, India

Abstract

This paper presents the spatial dynamics of second harmonic generation of the Laguerre-Gaussian (L-G) laser beam in plasma. Different modes of L-G laser beam (L_n^m) have been investigated depending upon the radial index n and angular momentum m of the laser beam. Collective effect of Plasma channeling and density ramp/transition has been investigated on the self-focusing and second harmonic generation in the relativistic magneto plasma. Highly intense laser beams propagating through plasma raise the oscillatory velocity of electrons near to light's velocity and mass of electrons to relativistic mass, which further change the dielectric function of plasma. Moment theory approach has been used for the analysis of self-focusing and second harmonic yield. Numerical results have been obtained by Runge-Kutta fourth order method. Along with the optical channeling and density transition, the effect of magnetic field on self-focusing and harmonic yield have been also investigated.

Acknowledgements
Authors are thankful for the continuous financial assistance from the Ministry of Human and Research Development, India.

36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Narrow-band, GeV gold ion beams from ultra-thin foils irradiated by intense sub-picosecond pulses

P. Martin[1], H. Ahmed[2], A. Alejo[3], M. Cerchez[4], D. Doria[5], D. Gwynne[1], F. Hanton[1], J. Green[2], A. Macchi[7,8], D. Maclellan[9], P. McKenna[9], J. A. Ruiz[6], M. Swantusch[4], O. Willi[4], S. Zhai[1,10], M. Borghesi[1] and S. Kar[1]

1 Centre for Plasma Physics, School of Mathematics and Physics, Queen's University Belfast, BT7 1NN, UK
2 Central Laser Facility, Rutherford Appleton Laboratory, Didcot, United Kingdom
3 IGFAE, Universidade de Santiago de Compostela, Santiago de Compostela, Spain
4 Heinrich-Heine-Universität, Düsseldorf, Germany
5ELI-NP, Magurele, Ilfov, Romania
6 Universidad Polytécnica de Madrid, Madrid, Spain
7 Istituto Nazionale di Ottica, CNR, Pisa, Italy
8 Department of Physics "E. Fermi", Pisa, Italy
9University of Strathclyde, Glasgow, United Kingdom
10Department of Mathematics and Physics, Shanghai Normal University, Shanghai, China

Abstract

Narrow energy band bunches of ions were produced from the interaction of intense (>10^{20} W/cm2), sub-picosecond-duration laser pulses with ultra-thin (15 nm) gold foils. These included the bulk target species, in particular the Au ions which are accelerated with spectral peaks centred at 1.5 GeV and with fluxes on the order of 10^{12} particles per steradian, far surpassing Au ion fluxes reported by previous works by orders of magnitude [1,2]. 2D particle-in-cell simulations show a complex interplay between different acceleration mechanisms at different stages of interaction, suggesting the Au bunches stem from strong radiation pressure acceleration on a heavy-ion dominant plasma in the moments just before transparency, followed by an efficient acceleration due to transparency-enhanced mechanisms. We show that this effect is scalable to future multi-PW systems, where Au ion bunches at energies of several GeV are feasible.

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Laser-matter interaction for the fight against food fraud

L. Fiorani[1], F. Artuso[1], I. Giardina[1], A. Lai[1], I. Menicucci[1], M. Nuvoli[1], A. Pasquo[1], M. Pistilli[1], F. Pollastrone[1], A. Puiu[1]

[1] FSN Department – ENEA, Via Enrico Fermi 45, 00044 Frascati, Italy

Abstract

Economically motivated adulterations (EMAs) of food pose a serious threat to our health. While several accurate analytical methods are available for detecting fraudulent ingredients in the supply chain, there is still a lack of quick and easy-to-use techniques, especially if a reliable implementation is required in industrial settings. The DIM Laboratory of FSN Department – ENEA applies spectroscopic techniques to fraud detection in fruit juice, oil, oregano, milk, pollens, rice, saffron, and seafood. Although a wide range of cutting-edge methods is in the DIM Laboratory armory – laser-induced breakdown spectroscopy (LIBS), Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, spectrofluorometry, laser-induced fluorescence (LIF), and remote sensing – its flagship technology is laser photoacoustic spectroscopy (LPAS). Recently, a portable and robust LPAS prototype based on a quantum cascade laser (QCL) to quickly identify EMAs has been developed (Figure 1). Its block diagram is shown in Figure 2. The continuous wave (cw) emitted by the QCL is modulated at an audio frequency by the chopper and sent by the mirror to the food sample inside the photoacoustic (PA) cell. The radiation is absorbed by the sample, resulting in: 1) increase in temperature, 2) adiabatic expansion, and 3) generation of sound. The acoustic resonance amplifies the signal that is picked up by the microphone (M) coupled to the lock-in amplifier. A small part of the laser beam is sent by the beam splitter to the power meter (PM) that monitors the QCL output. A personal computer (PC) controls the experiment.

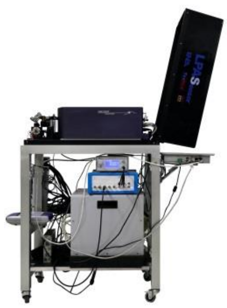

Figure 1. LPAS prototype.

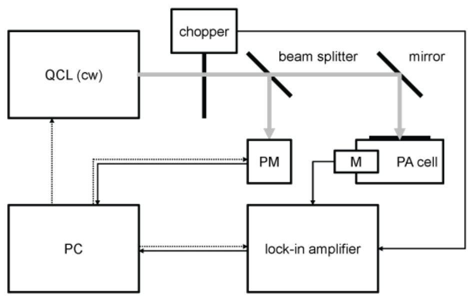

Figure 2. Block diagram of the LPAS prototype.

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Laser patterning strategies for quantum dots micro-displays: the MILEDI project approach

Francesco Antolini[1]

[1]Fusion and Technologies for Nuclear Safety and Security Department, Physical Technologies for Safety and Health Division, Photonics Micro and Nanostructures Laboratory, ENEA C.R. Frascati, Via E. Fermi 45, 00044 Frascati (RM), Italy

Abstract

The patterning of quantum dots (QDs) it a crucial step for the manufacturing of pixels in displays and micro-displays. The most used techniques for patterning are the photolithography, the contact printing and the ink-jet printing. All these techniques show pro and cons and industries are always looking for new methodologies to improve costs and performances.

MILEDI project (https://www.miledi-h2020.eu/) explored the direct laser patterning as alternative strategy to localize the formation of QDs and modulating their optical properties to realize RGB micro-displays (figure 1).

The project results showed that is possible to obtain QDs by using lasers and to modulate their optical properties by changing the laser parameters. This is possible both with cadmium telluride (CdTe) [1] and perovskite nanocrystals [2] by preparing film with suitable chemistry.

In the case of CdTe materials the polymer/precursor mix is deposited in form of films on quartz/glass substrates, and then the laser treatment is carried out by changing the laser power and the beam frequency and the effect produced by the laser irradiation on the film is investigated by fluorescence microscopy and optical spectroscopies.

The results show that only for certain combinations of power and laser frequencies it is possible to obtain red or green emitting areas.

Further studies are in progress to improve the QDs stability and intensity that are necessary to develop a working quantum dot LED/OLED.

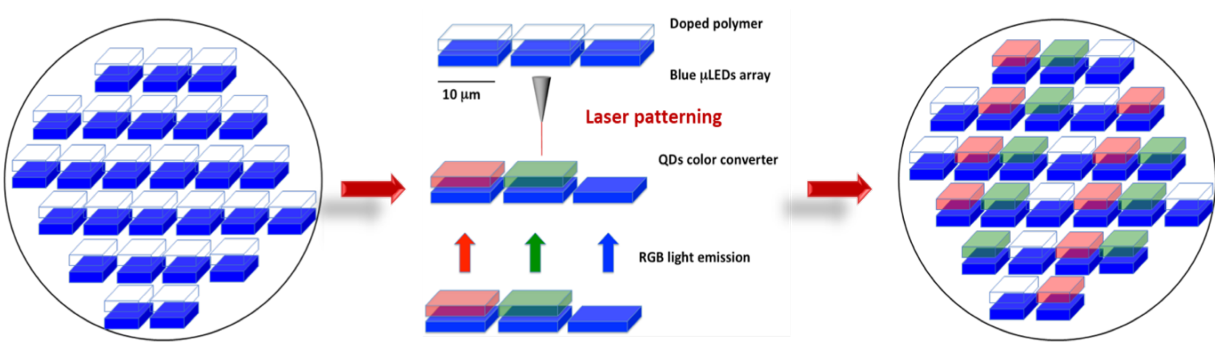

Figure 1. Scheme of the basic idea of the MiLEDI project: the blue micro-LED/OLEDs (right circle) are covered with a film that is removed or converted in red and green areas by using laser to obtain an RGB matrix (right circle).

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Acknowledgements
This research was funded by the European Union Horizon 2020 research and innovation programme (Photonics21, public private partnership), Grant Agreement n. 779373, project MILEDI (MIcro quantum dot Light Emitting diode and organic light emitting diodes DIrect patterning.

Posters

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FPGA Implementation of Laser Spot Detection Algorithm

Y. E. Bölükbaşı[1], H. S. Bilge[2]
[1] ASELSAN Inc., Gazi University 1. PK No:1 Akyurt/ANKARA/TÜRKİYE
[2] Gazi University, Electronics Engineering Department, Çankaya/ANKARA/TÜRKİYE

Abstract

It is aimed to effectively detect the laser spot which are frequently used in defense industry systems, even in adverse weather conditions such as fog and rain, on the FPGA by eliminating moving elements. To detect the laser spot in such previous studies, using two video frames, one with laser trace and the other without laser spot. Values above the applied threshold are assumed as laser spot. Although it was observed that the old algorithm, which was tested to work synchronously with a system capable of laser shooting, works properly in open air conditions and can detect the location of the laser mark in the system which has a short wave infrared camera, the desired success to be achieved in adverse weather conditions. In this study which is the subject of this article, three video frames were taken consecutively and it was accepted that the first of them carried a laser spot and the second and third did not. The reason for this preference is that the instantaneous and pulsed laser signal is detected by a receiver equipment designed at the working frequency value, shortly after the laser marked video frame is detected. In this way, moving elements such as birds, airplanes, helicopters, unmanned aerial vehicles, people or animals which have an image close to the laser spot, will be separated from the laser and more efficient results will be obtained in foggy conditions.

In order to get better results than the method used in previous studies, three video frames taken will be run on separated flows from the two branches and these branches will be combined in the last step of the algorithm. In the first flow, the difference matrix will be created by subtracting the next video frame without laser spot from the photo frame with laser spot, and non-linear median filtering method will be applied on this matrix in order to reduce the salt and pepper noise in the image at certain dimensions. Afterwards, it is aimed to soften the image in proportion to the selected mask value by outputting low-frequency video signals with the average filter from the convolution filters. In the third stage, after a threshold value calculation is made, the pixels above this value will be kept on the flow. Operations in the first flow will be completed to these in order to preserve the laser spot. In the second flow, which will continue in parallel with the first flow, the difference matrix of two consecutive laser unspotted frames will be created and the same methods with the first flow will be applied. Unlike the first flow, the second flow will be eroded with image erosion after the threshold filtering step. After the image dilation process which is one of the morphological image processing methods, the image will be extented. In the first flow, in order to remove the moving elements in the image known to be lasered, after this process, morphological image processing techniques will be applied again in the second flow. Afterwards, the information from the matrices from the first and second flows will be combined to determine whether there is laser spot information and in which row and column it is located.

Laser target marking device is capable of making laser pulses at determined frequencies, and it is guaranteed by the system requirements that a second laser pulse cannot be obtained in the time required for taking three video frames. Morphological image processing methods applied to achieve the result will be explained and the performance of the new algorithm will be measured by comparing the simulation results of the codes written in the VHDL language with the data obtained in the MATLAB calculation tool.

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Characterization of bright x-ray pulses from interaction of petawatt laser with a near critical plasma

J. Cikhardt, M. Gyrdymov, P. Tavana, S. Zähter, M. Günther, J. Jacoby, O. Rosmej

Abstract

This contribution describes experiments aimed at the generation of intense x-ray radiation via interaction of the laser beam with the near-critical density (NCD) plasma at the PHELIX petawatt facility. In these experiments, the NCD plasma is formed by a pre-ionization of the low-density foam (2-5 mg/cc) with a help of a nanosecond laser pre-pulse. The formed NCD plasma is irradiated by the focused laser beam with a 700fs pulse length and intensity of 10¹⁹ W/cm². During this interaction, electrons are efficiently accelerated up to the energy of 100 MeV, and an unexpectedly-bright broad-energy x-ray pulse is generated by the betatron, inverse-Compton, and bremsstrahlung mechanisms. The x-ray pulse was characterized using various diagnostics methods including absorption and Ross-filter spectrometry, semiconductor diode, slit imaging, etc. Such a characterization of the short bright x-ray pulse is necessary for both basic research and high-tech applications.

36th European Conference on Laser Interaction with Matter
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Different regimes of the electron and proton acceleration in interaction of sub-ps relativistic laser pulses with pre-ionized near critical polymer aerogels

M. Gyrdymov[1], N. Bukharskii[3], J. Cikhardt[4], P. Tavana[1], N. G. Borisenko[5], S. Yu. Gus'kov[5], V. G. Pimenov[6], M. M. Guenther[2], J. Jacoby[1], N. E. Andreev[7,8], and O. N. Rosmej[1,2]

[1] Goethe-University, Frankfurt, Max-von-Laue-Str. 1, 60438 Frankfurt am Main, Germany
[2] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr.1, 64291 Darmstadt, Germany
[3] National Research Nuclear University MEPhI, Kashirskoe shosse 31, 115409 Moscow, Russia
[4] Faculty of Electrical Engineering, Czech Technical University in Prague, Technicka 2, 16627 Prague, Czech Republic
[5] P. N. Lebedev Physical Institute, RAS, Leninsky Prospekt 53, 119991 Moscow, Russia
[6] N. D. Zelinsky Institute of Organic Chemistry, Leninsky Prospect, 47, 119991 Moscow, Russia
[7] Joint Institute for High Temperatures, RAS, Izhorskaya st.13, Bldg. 2, 125412 Moscow, Russia
[8] Moscow Institute of Physics and Technology (State University), Institutskiy Pereulok 9, 141700 Dolgoprudny Moscow Region, Russia

Abstract

We report new results on acceleration of electrons and protons in interaction of relativistic laser pulses with polymer aerogels of near critical density [1], obtained in the experiment on the PHELIX facility in October - November 2021. For the registration of the electrons and protons magntetic spectrometers (0.25T-, 0.99T-MS), cylinder diagnostics, and RCF-boxes were used.

By varying aerogel foam thickness and parameters of the ns-laser pulse used to ionize foams, it was possible to register different regimes of acceleration of electrons and protons at 10^{19} W/cm^2 relativistic laser pulse that was send on target with 3-4 ns delay to the ns-pulse.

In the case of 0.8 mm thick foam layers pre-ionized with ~ 5×10^{13} W/cm^2 ns laser pulse, the electrons were accelerated by the relativistic pulse up to 90-100 MeV and protons - up to 15-20 MeV. Electron energy distribution was approximated with the exponential function with effective temperature of 14-19 MeV. This regime demonstrated a high level of stability of the direct laser acceleration (DLA) process [2 - 4].

In the case of 0.3-0.4 mm thin foams pre-ionized with > 10^{14} W/cm^2 ns laser pulse, the achieved energies of electrons and protons were lower. This can be explained by strong expansion of the rear foam side that lead to only partial absorption of the relativistic laser pulse in plasma and generation of the weak acceleration field at the rear foam side. At the same time, electron beams were stronger collimated than in the first case and showed up a non-Maxwellian distribution.

In addition, interpretation of the experimental data using results of 2D-hydrodynamic simulation of the ns-pulse interaction with structured foams using code NUTCY-F [5] will be presentet.

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High reflectivity and backward propagation of laser plasma generated by high power KrF laser

I.B. Földes[1,2], S. Kálvin[3] and S. Szatmári[4]

[1] Wigner Research Centre for Physics, H-1525 Budapest POB 49, Hungary
[2] ELI-Beamlines Center, Institute of Physics, 25241 Dolní Břežany, Czech Republic
[3]independent researcher, H-8692 Gyugy, Hungary
[4]University of Szeged, H-6720 Szeged, Hungary

Abstract

The short wavelength of KrF lasers enables them to become alternative candidates as driver for inertial confinement fusion. The short wavelength also means that the interaction with electrons will remain nonrelativistic even at high intensities. The investigation of laser-plasmas generated by KrF lasers thus deserves interest. Early investigations showed fast, even macroscopic expansion of plasmas generated on solid surfaces by 248 nm wavelength laser pulses[1].

In order to study the interactions under clean conditions our laser system was upgraded. The new Fourier-filtering pulse-cleaning technique[2] allowed us to obtain more than 10^{18} W/cm^2 intensity in 600 fs pulses on target with more than 12 order of magnitude contrast. As KrF laser pulses do not have shoulders of picosecond duration, the contrast is really so high.

Both the reflected intensity and the spectrum of the reflected radiation were studied from 10^{15} to 10^{18} W/cm^2 and additionally the x-ray conversion was monitored. The results for clean pulses were compared with those with pulses without Fourier-filtering, in which case a prepulse with nanosecond duration with less than 6 orders of magnitude contrast was present.

The results demonstrated decreasing reflectivity with increasing intensity with the maximum absorption at the highest intensities above 90%. In the same time the Doppler shift of the reflected radiation[3] refers to a backward propagating plasma for clean pulses reaching a velocityof nearly $6{\cdot}10^5$ m/s. The velocity in case of prepulses was lower, strongly saturating at high intensities.

Simulations with the MULTI-fs hydrocode was in good agreement concerning the backward propagation, showing even the difference between clean pulses and that with prepulses. However they overestimate the velocity and do not show the saturating behaviour at the highest intensities. Moreover these 1D simulations show decreasing absorption above 10^{16} W/cm^2 in contrast to the observations. Possible mechanisms causing this deviation are discussed. Light pressure should be taken into account for high power UV lasers because it scales with the intensity and not with $I\lambda^2$. Brunel absorption can gain importance at the highest intensities. The most important are however probably the 2D effects, as they may cause the rippling of critical surface[4] and increasing absorption[5].

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Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200| EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reect those of the European Union or the EuropeanCommission.

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A Gaussian Process Augmented Ray-Tracing Framework for Multi-Scale Modelling of Stimulated Raman Scattering in ICF

A.Angus[1], T.Arber[1]

[1] Centre for Fusion, Space, and Astrophysics, University of Warwick, Coventry, United Kingdom

Abstract

Stimulated Raman Scattering (SRS) is a process of significant importance in laser-driven inertial confinement fusion (ICF) implosions. It is a process which reduces the efficiency of the implosion, both by direct scattering of light away from the fuel target, and by creation of hot electrons which preheat the target core. These effects are the result of unstable growth of electromagnetic and electron plasma daughter waves respectively, in a three-wave coupling mechanism with the laser pump.

SRS occurs in the coronal plasma on timescales and lengthscales on the order of picoseconds and microns, whereas the hydrodynamic progression of the plasma occurs on the order of nanoseconds and millimetres. This separation of scales means that predictive modelling of SRS in ignition-scale ICF simulations is a significant challenge. Accurate predictive modelling of SRS at this scale would mean simulations could be used to investigate minimisation strategies for the deleterious effects associated with the process, hence furthering the advance towards commercially viable fusion energy.

Contemporary predictive modelling of SRS in fluid codes relies on 1D linear kinetic theory in the strong damping limit, bolted on to traditional laser ray-tracing [1]. This theory reduces the problem to a set of two coupled ODEs for the spatial change in laser and Raman light intensities respectively. The newly proposed modelling scheme is an extension of the method outlined by Debayle et al. [2]. It is an iterative method, which progressively updates cell-averaged intensities, wavenumbers, and frequencies for laser and Raman light until steady-state is reached. Cell averaged quantities are used to model convective SRS along laser ray paths, with Raman rays created and propagated in addition to the laser rays. Inaccuracies in this method will arise from the ray-tracing method itself and the underlying SRS model, but also from hydrodynamic cell size as it assumes linear energy exchange based on constant cell-averaged quantities, which in reality will vary across a cell.

It is proposed to add a Gaussian process (GP) surrogate model into this scheme which predicts effective linear convective SRS gains in each cell based on the fully resolved solution to a 1D boundary value problem over the laser ray path in that cell. In figure 1, a basic sketch of the relevant GP inputs associated with a hydrodynamic cell are shown. These inputs will be cell quantities for electron density and temperature, cell-averaged laser intensity, cell-averaged Raman frequency and intensity, the length of the laser ray path, and the electron density gradient along that path. On-the-fly training allows for efficient fitting of the GP in regions of input space relevant to ICF. A training point will be added when the predicted SRS gain variance in a cell during a hydrodynamic simulation is above a threshold value.

This basic augmentation with a GP surrogate provides robustness to hydrodynamic grid resolution and increased accuracy of solution to the underlying equations. Going forward, the scheme should allow, with minor modification, inclusion of additional physics in a hierarchical manner; removal of the strong damping limit approximation, inclusion of time dependency, and inclusion of 1D kinetic effects are all potential paths forward. The latter two of these paths would entail use of the LPSE fluid plasma wave-solver and EPOCH particle-in-cell codes respectively, as the underlying solvers used to train the GP.

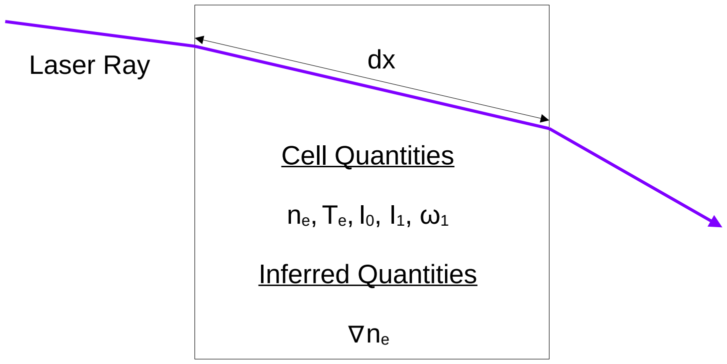

Figure 1. Schematic of relevant quantities within a hydrodynamic cell which are inputs to the Gaussian process for SRS convective gain prediction.

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Acknowledgements

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Simulations of ICF implosion asymmetry in the shock ignition regime, seeded by laser and hot electron perturbations

A. Rees,[1] T. Arber,[1] K. Bennett[1], and T. Goffrey[1]

[1] Centre for Fusion, Space and Astrophysics, University of Warwick, Coventry, UK

Abstract

Direct-drive Inertial Confinement Fusion (ICF) is particularly sensitive to the laser configuration. Idealized beam geometries have been found that illuminate the targets uniformly but are rarely realized in real experiments. These departures from uniform illumination can be significant with energy delivery varying by as much as 20% between laser beams. Differences such as these become more significant in the shock ignition regime, which uses a high intensity spike at the end of the laser drive to compress the target. Using experimental laser profiles for shock ignition and OMEGA beam layouts provided through *VisRAD*, we conducted a series of simulations to quantify the implosion asymmetry caused by these laser power imbalances. The simulations were run using the 2D ALE radiation-hydrodynamics code *Odin* with 3D refractive rays and hot electrons. In shock ignition, there is a more significant generation of hot electrons, compared with conventional hot spot ignition, as LPIs (Laser Plasma Instabilities) scale with intensity. We compare the implosion performance from simulations including both the laser and hot electrons, and the laser alone, to establish whether hot electrons can smooth perturbations caused by laser power asymmetries, or further degrade performance.

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Bremsstrahlung suppression in high field laser-plasma interactions

Mahdi Habibi [1], Alexey V. Arefiev [2] and Toma Toncian [1]

[1] *Institute for Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, e.V., 01328 Dresden, Germany*
[2] *Mechanical & Aerospace Engineering, University of California San Diego, La Jolla, CA 92093, USA*

Abstract

Ultra-relativistic charged particles and strong magnetic fields play a key role in various quantum electrodynamics phenomena. Such extreme conditions are expected to be within the reach of recently commissioned high-power laser facilities in a novel regime of laser-matter interactions known as relativistically induced transparency (RIT). In this regime, a high-intensity laser pulse can penetrate deeply into a dense plasma as the optical properties of the plasma change due to the relativistic motion of the electrons. By transferring the energy of the laser to electrons, the RIT regime is able to generate ultra-relativistic electrons and produce Megatesla levels of magnetic field strength[1-3]. Bremsstrahlung, one of the most important processes for generating impulsive photons, can be emitted by these relativistic electrons. However, depending on the environment in which the interaction takes place, bremsstrahlung cross-sections can change dramatically, resulting in significant emission suppression[4]. Strong magnetic fields can act as a magnetic suppression environmental factor and have been identified previously as significant combinations of electron energies and magnetic field strengths as found, for example, in high-energy cosmic rays in the earth's magnetic field (10^{20} eV and 50 μT)[4] or at the Compact Muon Solenoid experiment at the Large Hadron Collider (LHC) with its bending magnets (1 TeV and 4 T)[5]. Evaluation of the total cross-section ratio of bremsstrahlung with and without the magnetic suppression (MS) effect as a function of electron energy and magnetic field strength predicts, at parameter ranges found in laser-plasma interactions in the RIT regime, a considerable decrease in the overall yield of bremsstrahlung, as shown in figure 1.

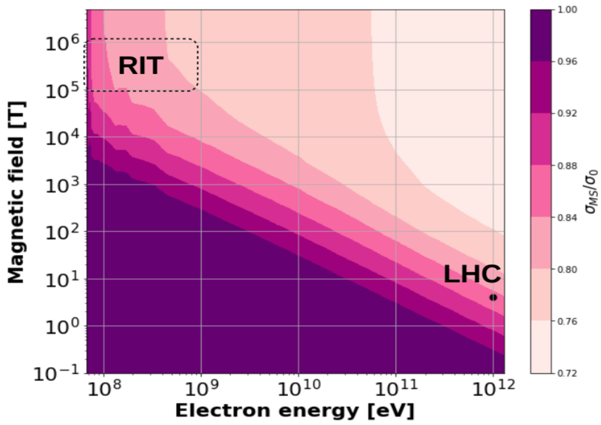

Figure 1. Relative reduction of the bremsstrahlung yield, σ_{MS}/σ_0, as a function of electron energy and magnetic strength.

Here, we propose and discuss a generalized suppression mechanism in which both electric and magnetic fields (EMS) found in high-field laser-plasma interactions are accounted for when evaluating the yield of bremsstrahlung emissions. We implemented this mechanism as a new module, adding both magnetic alone and the combined effect of EMS into the standard bremsstrahlung module provided by the EPOCH particle-in-cell code framework.

We demonstrate that this mechanism, not only suppresses low-energy emissions but also has an impact on the dynamics of the radiating electrons in the RIT regime (see figure 2).

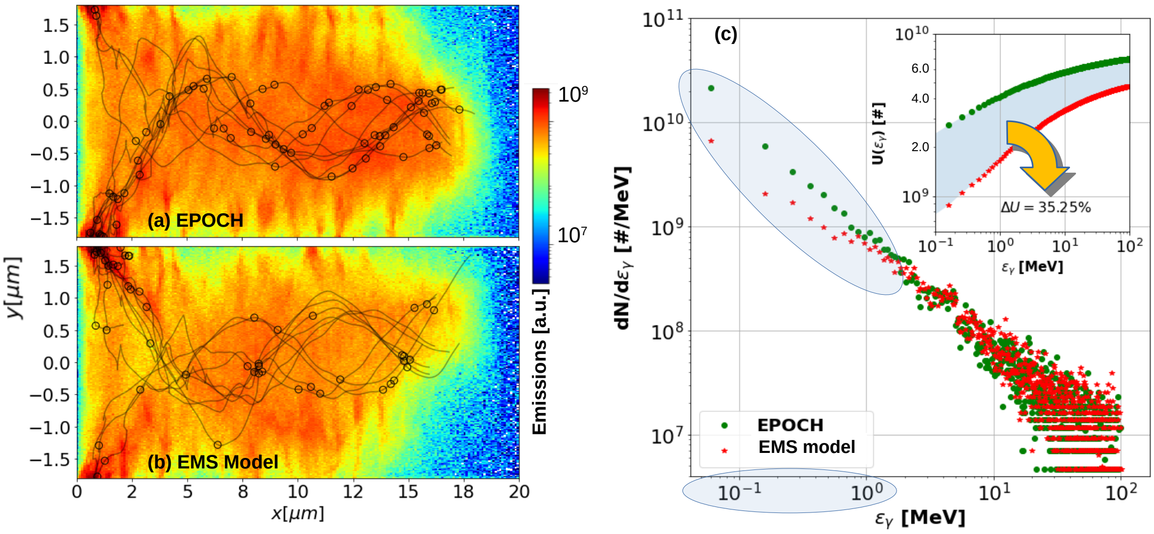

Figure 2. (a)&(b) Trajectories of 8 sampled electrons with energies > 500 MeV and their bremsstrahlung vertices inside the channel. The background color shows the density of < 10 MeV emissions till t=185 fs. The localization of low-energy emissions is missing in the EMS model. EPOCH and EMS models' bremsstrahlung energy distributions and cumulative distribution functions U(ϵ_γ) for a subset of 95-105 MeV electrons passing through 0.41-0.44 normalized fields are compared.

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Simulations were performed with EPOCH (developed under UK EPSRC Grants EP/G054950/1, EP/G056803/1, EP/G055165/1 and EP/ M022463/1).

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36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Shot-by-shot stability of the discharge produced plasmas in suitably shaped capillaries

M.P. Anania[1], S. Arjmand[1], A. Biagioni[1], A. Cianchi[2], E. Chiadroni[1], G. Costa[1], G. Di Pirro[1], M. Ferrario[1], M. Galletti[1], D. Giulietti[1], V. Lollo[1], D. Pellegrini[1], R. Pompili[1], A. Zigler[3]

[1] INFN - Laboratori Nazionali di Frascati, Via Enrico Fermi 54, 00044 Frascati, Italy
[2] INFN-Tor Vergata, Via Ricerca Scientifica 1, 00133 Rome, Italy
[3]Racah Institute of Physics, Hebrew University, Jerusalem 91904, Israel

Abstract

Plasma wakefield acceleration is a promising novel technique able to reach very high values of the accelerating gradient in the GV/m scale, which is several orders of magnitude larger than the ones in the conventional accelerators [1, 2]. In this innovative plasma-based acceleration technology, a driver, either an intense laser pulse (Laser Wakefield Acceleration, LWFA) [3, 4] or an energetic particle bunch (Plasma Wakefield Acceleration, PWFA) [5, 6], excites large amplitude plasma waves transferring energy to a suitable injected electron bunch [1, 7, 8]. Nowadays, several approaches have been utilized to produce the plasma in which the electron acceleration develops among them, and the most used are the neutral gas ionization induced by an intense laser pulse [9] or a high-voltage (HV) discharge [10]. In our experiment, a thin cylindrical tube of capillary aperture has used to produce and confine the plasma. The capillary material is a commercial acrylate polymer transparent to visible light. The gas is ionized by a high-voltage discharge (HVDC) [11] applied through two Copper electrodes. One or more gas inlets feed the capillary's channel with Hydrogen gas. Both longitudinal and transverse electron density strongly depends on the initial neutral gas pressure, the plasma temperature, the applied voltage, and the capillary geometry. To maintain the vacuum level below 10-8 mbar, the repetition rate of the plasma formation is fixed at 1Hz. Since a driver will be injected into such a plasma, followed by the electron bunch to be accelerated, it is mandatory the main characteristics of the plasma are maintained shot by shot, otherwise the final quality of the accelerated electrons will deteriorate. Indeed, strong oscillations of the discharge ignition can introduce an evident change in the plasma density within the capillary [12], which, in turn, will produce a shot-to-shot variation of the accelerating plasma gradient. Thus, to prevent any electron bunch degradation, in terms of energy spread and emittance, the discharge triggering must be optimized to reduce the plasma density oscillations due to the timing jitter of the gas ionization. The experimental apparatus used for both plasma formation and characterization are reported in Figure 1. It is composed of two main sections. The first section concerns the feeding of the neutral gas in the capillary and the plasma generation. The gas is injected into the capillary channel through two inlets by a Hydrogen generator. A pressure regulator sets the inlet pressure of the Hydrogen inside the capillary at 10-15 mbar. A high voltage discharge circuit (resistor-capacitor) supplies 5-17 kV to produce the current along the capillary through two Copper electrodes. The second section concerns the plasma diagnostic system, consisting of the spectrometer, the optical system to collect and direct the plasma light into the spectrometer, and the intensified camera to record the images. In this way, time-resolved measurements of the electronic density profile in the capillary can be performed. Eventually, a delay-generator synchronizes all events in two sections, the gas injection, the voltage pulse, and the plasma density measurements [13]. The plasma source characterization has been performed by measuring both electron densities along the longitudinal coordinate of the capillary and the current pulses during

the gas ionization. A spectroscopic technique based on the Stark-broadening effect is employed to detect the plasma electron density [14, 15].

We observed that the plasma stability strongly depends on the applied voltage and the gas pressure inside the capillary. In fact, time jitter is reduced for higher voltages, while it increases for lower gas pressures (see Fig 2.).

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Acknowledgements

This research activity has partially been supported by the EU Commission in the Seventh Framework Program, Grant Agreement 312453-EuCARD-2, the European Union Horizon 2020 research, innovation program with the Grant Agreement No. 653782 (EuPRAXIA), and the INFN with the GRANT73/PLADIP.

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Frascati, 19-23 September 2022

Dynamics of two cross focused Bessel-Gaussian laser beams and their effect on electron acceleration in relativistic magnetoplasma

Proxy Kad, Arvinder Singh

Department of Physics, Dr. B.R. Ambedkar National Institute of Technology, Jalandhar-144011, Punjab (India)

Abstract

In this paper, the self-focusing of two cross-focused Bessel-Gaussian laser beams having frequency difference equal to plasma frequency has been presented. An external magnetic field has been also considered along the axis of propagation of the two beams. The dynamics of both the laser beams have been governed through two second-order non-linear coupled differential equations, which have been obtained by using the moment theory approach. The coupled laser beam acting as a perturbation in the plasma medium, excites a wakefield that helps in the acceleration of trapped plasma electrons. The combined effect of variation in spot size of both the beams on electron acceleration has been studied. The effect of the different transverse width parameters, laser intensities, different values of applied magnetic field and plasma densities on electron acceleration have been investigated and have been found to be very useful for electron acceleration.

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Dynamics of cross focused Bessel-Gaussian beams and its effect on electron acceleration in relativistic-ponderomotive regime

Proxy Kad, Arvinder Singh

Department of Physics, Dr. B.R. Ambedkar National Institute of Technology, Jalandhar-144011, Punjab (India)

Abstract

In the present work, self-focusing of two cross focused Bessel-Gaussian laser beams with frequency difference equal to the plasma frequency have been examined. The variation in the mass of plasma electrons, due to the occurrence of relativistic effects and electron density variation, due to the ponderomotive force by laser plasma interaction have been taken into consideration. Two second order non-linear coupled differential equations governing the spatial width variation of the laser profile have been obtained by using the moment theory approach and are numerically solved. The propagation of the coupled beam through plasma medium excites the wake field, which is responsible for electron acceleration. The coupled effect of spatial variation of both beams on acceleration of plasma electrons has been studied. Effects of different transverse extent of coupled laser beam intensities, laser intensities and plasma densities on electron acceleration have been investigated and are found to be very useful for electron acceleration.

36th European Conference on Laser Interaction with Matter
Frascati, 19-23 September 2022

Collective effect of preformed plasma channel and plasma density ramp on second harmonic generation of laser

Aman Bhatia[1], Keshav Walia[2], Arvinder Singh[1]

[1] Dr B R Ambedkar National Institute of Technology Jalandhar Punjab, India
[2] DAV University Jalandhar Punjab, India

Abstract

This study examines the well-known phenomenon by which a laser beam begins to focus as it propagates into plasma as a result of the relativistic non-linearity due to the electronic mass variation when the plasma electrons oscillate at high velocities close to the light's velocity. Focusing is always contradicted by the diffractive nature of the laser beam. To overcome such diffraction that leads to laser power loss a preformed plasma channel and an exponential density ramp have been used. Studies have also been done on the incident laser beam's second harmonic generation. The laser profile taken is Laguerre-Gaussian (LG) laser beam. The moment theory has been used to identify laser beam self-focusing. The Runge-Kutta 4th order approach has been used to numerically tackle non-linear differential equations. It has been determined that the density transition and the plasma channel both significantly increase the second harmonic yield (SHY) of the incident laser beam. It is further observed that the different modes (L_n^m) of the LG laser beam are more productive for the harmonic generation than the Gaussian beam.

Acknowledgements
Authors are thankful for the continuous financial assistance from the Ministry of Human and Research Development, India.

ECLIM 2022
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Frascati, 19-23 September 2022

Hot electron emission characteristics from thin metal foil targets irradiated by terawatt laser

M. Krupka[1,2,3], S. Singh[2,3], J. Krása[3], V. Istokskaia[5], J. Dostál[2,3], R. Dudžák[2,3], T. Pisarczyk[4], J. Cikhardt[6,2], D. Klír[6], K. Řezáč[6], L. Giufridda[5], T. Chodukowski[4], Z. Rusiniak[4], T. Burian[3,2] and L. Juha[3]

[1] Faculty of Nuclear Science and Physical Engineering, Czech Technical University in Prague, Břehová 7, 115 19 Prague, Czech Republic
[2] Institute of Plasma Physics of the Czech Academy of Science, U Slovanky 2525/1, 182 00 Prague, Czech Republic
[3] Institute of Physics of the Czech Academy of Science, Na Slovance 1999/2, 182 21 Prague, Czech Republic
[4] Institute of Plasma Physics and Laser Microfusion, 23 Hery Street, 01-497 Warsaw, Poland
[5] ELI Beamlines, Za Radnicí 835, 252 41 Dolní Břežany, Czech Republic
[6] Faculty of Electrical Engineering, Czech Technical University in Prague, Technická 2, 160 00 Prague, Czech Republic

Abstract

The interaction of focused high power laser beam with solid targets leads to generation of accelerated charged particles among other non-linear effects in the plasma. In this experiment, the hot electrons are characterized from the interaction of sub-nanosecond and kilo-joule class laser pulse with thin metal foil targets (copper, tantalum, lead, and titanium). The energy distribution functions of electrons were measured by angular array of multi-channel electron spectrometer. The hot electron temperatures were observed in range between 40 keV and up to 100 keV for laser intensities between ~10^{15} and 10^{16} W.cm^{-2}. The energy distribution and electron temperature were compared with published results and known scaling laws at higher laser intensities. In addition, mono-energetic peaks having exponential distribution with energies over 1 MeV are observed in the hot electron energy distribution. We investigate the spatial and statistical characteristics of these mono-energetic peaks along with possible mechanism behind the acceleration of these energetic particles. The scale lengths of plasma density and strengths of accelerating electric fields are estimated to correlate with the accelerated hot electrons. Moreover, the complex interferometry measurements indicate the modulation of the electron density of the plasma along the laser axis. The possible mechanisms behind the density modulation could be caused by the hydrodynamicial effects or ablation instabilities which are under investigation.

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Acknowledgements

The research presented in this paper was supported by the Access to the PALS RI under the EU LASERLAB IV project (Grant Agreement No. 654148), by the Czech Republic's Ministry of Education, Youth and Sports - the projects: Prague Asterix Laser System (LM2018114) and Creating and probing dense plasmas at the PALS facility (CZ.02.1.01/0.0/0.0/16_013/0001552). The research leading to these results has received funding from the Czech Science Foundation (Grant No. 19-02545S and 19-24619S). The support of CTU student support project "Research on optical (nano) structures and laser plasma" SGS19/192/OHK4/3T/14 is gratefully acknowledged as well as the support by the Ministry of Science and Higher Education, Republic of Poland (Decision No. 3880/H2020/2018/2). This scientific work was partly supported by the Polish Ministry of Science and Higher Education within the framework of the scientific financial resources in the year 2020 allocated for the realization of the international co-financed project No.5118/H2020/EURATOM/2020/2.

ECLIM 2022
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Diagnostic of Laser-Accelerated MeV Proton Beams from Near Critical Density Foam Targets Using Nuclear Activation Technique and Radiochromic Film Imaging Spectroscopy

P. M.Tavana[1,2], M. Gyrdymov[1], J. Cikhardt[3], M. M. Günther[4], S. Zähter[4], N. Bukharskii[5], N. G. Borisenko[6], U. Spillmann[4], J. Hornung[4], J. Jacoby[1], C.Spielmann[2] , O. N. Rosmej[1,4]*

[1] Institute for Applied Physics (IAP), Goethe University, Germany; [2] Friedrich-Schiller Universität Jena, Germany; [3] *Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic,* [4] GSI Helmholtzzentrum für Schwerionenforschung, Germany, [5] Moscow Engineering Physics Institute, Russia, [6] P. N. Lebedev Physical Institute, Russia

Abstract

At the PHELIX, two pilot experiments on interaction of 10^{19} W/cm^2 laser pulse with pre-ionized low-density polymer foams demonstrated more than 10 times increase of the effective electron temperature above ponderomotive potential caused by direct laser acceleration (DLA) of electrons in the relativistic plasma channel [1,2].

In the newest experiment in 2021, to enhance the proton acceleration from interaction of high intensity short-pulse laser with plasma, we have used near-critical density (NCD) foam targets stacked with metallic foil.

Two different methods, namely Nuclear Activation Technique and Radiochromic Film Imaging Spec- troscopy were combined to characterize the proton beam. In the former, a multilayer detector of thin metallic foils with different energy thresholds for (p,xn)- reaction allows for reconstruction of proton spectral distribution over a wide range of proton energies.

It was experimentally verified that for the same laser intensity, the application of foam targets increases the number and cut-off energy of laser accelerated protons in comparison of thin metallic targets.

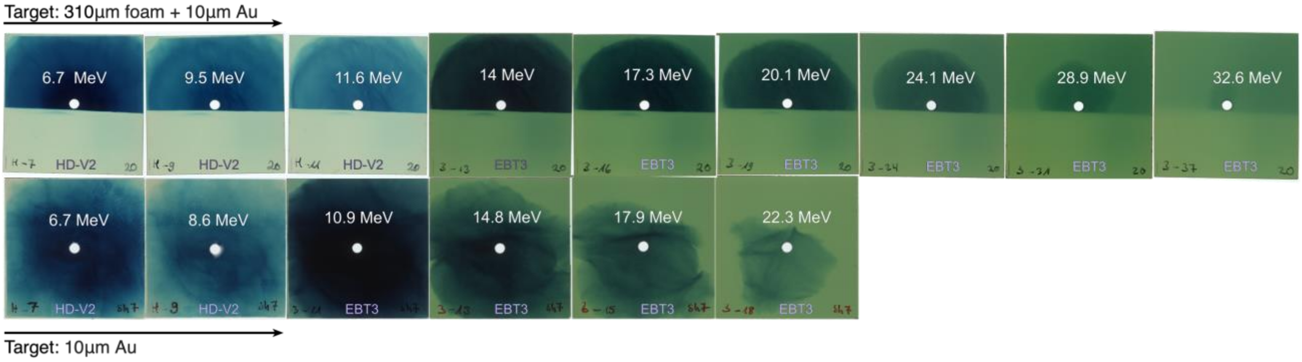

Figure 1. Results of RCF Stack with 32.6 MeV cut off energy in the case of foam+foil target and homogeneous proton beam and 22.

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ECLIM 2022
36th European Conference on Laser Interaction with Matter
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A compact high spectral resolution Thomson parabola spectrometer using magnetic gradient field profiles

A. Morabito [1], K. Nelissen[2] , M. Migliorati[3] and S. Ter Avetisyan[4]

[1] Centro de Laseres Pulsados (CLPU), Edicio M5. Parque Cientco. C/ Adaja, 8. 37185 Villamayor, Salamanca, Spain,
[2] ELI-ALPS, ELI-HU Non-Profit Ltd., Wolfgang Sandner utca 3.,Szeged, H-6728, Hungary
[3] INFN & University of Rome, Via Scarpa 14, 00161 Roma, Italy
[4] National Laser-Initiated Transmutation Laboratory, University of Szeged, 6720, Szeged, Hungary

Abstract

The prospect of generating multi-species charged particle beams with energies of hundreds of MeV through the use of high intense (I > 10^^{22} $W \cdot cm^{-2}$) laser systems has made imperative to develop diagnostic systems for comprehensive characterization of plasma processes, their dynamics and evolution in this new ‘’unexplored” interaction regimes. In a conventional Thomson parabola spectrometer (TP) the magnetic field or distance towards the detector plane is increased in order to resolve ultra-high particle energies at the expense that low energy particles remain undetected. We propose a novel spectrometer design using a quadrupole magnetic field capable of detecting the laser generated proton energy range that can arrive up to hundreds of MeV in order to resolve both low particle and high particles energies. For this purpose, different sequences of magnetic and electric field profiles have been studied systematically, varying the fields’ parameters. The optimized parameters of the spectrometer allow the study of high energetic particle emission from ultra-intensity laser-matter interaction in a broad energy range providing high energy.

ECLIM 2022
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Optical shaping of gas-jet target profiles for Magnetic Vortex Acceleration in the near-critical density regime

I. Tazes[1,2], G. Andrianaki[1,3], A. Grigoriadis[1,4], S. Passalidis[5], A. Skoulakis[1], E. Kaselouris[1], E. Vrouvaki[1,2], J. Chatzakis[1,2], I. Fitilis[1,2], M. Bakarezos[1], E.P. Benis[1,4], V. Dimitriou[1], N.A. Papadogiannis[1] and M. Tatarakis[1,2]

[1]*Institute of Plasma Physics & Lasers - IPPL, Hellenic Mediterranean University Research Centre, Greece*
[2]*Department of Electronic Engineering, Hellenic Mediterranean University, Greece*
[3]*School of Production Engineering and Management, Technical University of Crete, Greece*
[4]*Department of Physics, University of Ioannina, 45110, Ioannina, Greece*
[5]*Sorbonne Université, CNRS, Laboratoire de Chimie Physique-Matière et Rayonnement, France*

Abstract

Laser-induced particle acceleration is a subject of great interest due to its numerous potential applications, among others in Inertial Fusion Energy (IFE) and in biomedical applications (i.e., hadron therapy). We present research activities using the 45 TW, fs laser system ZEUS, hosted at the Institute of Plasma Physics and Lasers (IPPL) [1] of the Hellenic Mediterranean University (HMU). Laser-plasma accelerators are often based on the interaction of an intense laser pulse with a solid target (over-dense regime), e.g. by the well-studied Target Normal Sheath Acceleration mechanism (TNSA) [2,3]. In TNSA, the targets are destroyed upon irradiation and must be replaced and repositioned, not allowing their use for high repetition rate (HRR) proton sources. Extreme pressure gas-jets, able to reach the near-critical density (NCR) regime, are considered suitable candidate targets for HRR, debris-free proton sources [4,5]. In the NCR regime, Magnetic Vortex Acceleration (MVA) [6-9] is one of the most promising proton acceleration mechanisms. While state-of-the-art simulations predict hundreds of MeV of protons by super-intense, short wavelength, fs laser pulses, MVA remains experimentally challenging due to the extremely steep density gradient plasma profiles required [7-9]. Here, we present Magnetohydrodynamic (MHD) simulation results [10] on the capability of delivering optically shaped targets [11-13] through the interaction of secondary laser pulses with high-density gas-jet profiles. Multiple laser-generated Blastwave (BW) schemes capable to compress the gas-jet into NCR steep density gradient slabs of a few μm thickness are reported [13,14]. The capability of proton acceleration by the interaction of the optically shaped NCR targets, with the tightly focused laser pulse of the ZEUS, with intensity exceeding 10^{20} W/cm^2, is demonstrated by 3D Particle-In-Cell (PIC) simulations [15]. Finally, experimental characterization of the gas-jet profiles, delivered by a solenoid valve along with an air-driven hydrogen gas booster, able to support 1000 bar of backing pressure is presented.

Acknowledgments
This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them."
The simulations were performed in the National HPC facility—ARIS—using the computational time granted from the Greek Research & Technology Network (GRNET) under project ID pr011027—LaMPIOS.

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Optimization of γ-photon sources using near-critical density targets towards electron-positron pairs generation through the linear and nonlinear Breit-Wheeler processes

I.M. Vladisavlevici[1,2], X. Ribeyre[1], D. Vizman[2], E. d'Humières[1]

[1]University of Bordeaux – CNRS – CEA, CELIA, 33405 Talence, France
[2]West University of Timisoara, Faculty of Physics, 300023 Timisoara, Romania

Abstract

At the interaction between an ultra-high intensity laser pulse (I > 10^{22} W/cm^2) with matter, the electrons will be accelerated up to ultra-relativistic velocities and will emit a copious amount of synchrotron gamma photons. For eve n higher intensities (I > 10^{24} W/cm^2), the emitted gamma photons can interact with the laser field and create electron-positron pairs by the nonlinear Breit-Wheeler (BW) process [1]. Studies on various absorption mechanisms using different target configurations, showed a conversion efficiency of the laser energy to gamma photons from 15% [2] up to 35% [3].

Our main goal is to investigate the high energy synchrotron radiation emitted by electrons in the laser-plasma interaction, eventually leading to production of electron-positron pairs via the linear and nonlinear Breit-Wheeler processes. Through 2D Particle-in-Cell (PIC) simulations using SMILEI [4], we studied the case of an ultra-high intensity laser pulse interacting with a near critical density target. In optimal configuration for the maximum conversion efficiency of the laser energy to gamma photons [5], we investigated the pair production by the nonlinear BW process. Considering the interaction between two identical gamma beams [6-7] (prior produced in the laser-plasma interaction) at a distance of 0.1cm and at different incident angles, we analysed the total number of pairs produced and their collimation by the linear BW process.

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Acknowledgements

Computer time for this study was provided by the computing facilities MCIA (Mésocentre de Calcul Intensif Aquitain) of the Université de Bordeaux and of the Université de Pau et des Pays de l'Adour.
This work was supported by Romanian National Authority for Scientific Research PN 75/2018, Agence Nationale de la Recherche project ANR-17-CE30-0026-Pinnacle, WUT - JINR collaboration project 05-6-1119-2014/2023 (2/2019; 86/2020; 103/2021) and Erasmus+ Student grant (2018/2019; 2019/2020; 2020/2021).

ECLIM 2022
36th European Conference on Laser Interaction with Matter
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Fast diamond detectors for characterizing the ENEA extreme ultraviolet radiation discharge produced plasma source

L. Mezi[1], S. Bollanti[1], F. Bombarda[2], S. Cesaroni[3], P. Di Lazzaro[1], F. Flora[1], M. Marinelli[3], D. Murra[1], S. Palomba[3], C. Verona[3], G. Verona Rinati[3]

[1] ENEA, Fusion and Technologies for Nuclear Safety Department; Plasma Studies Division; Plasma Applications and Interdisciplinary Experiments Laboratory, Via E. Fermi 45, 00044 Frascati (Rome), Italy
[2] ENEA, Fusion and Technologies for Nuclear Safety Department; Plasma Studies Division; DTT machine realization Laboratory, Via E. Fermi 45, 00044 Frascati (Rome), Italy.
[3] Department of Industrial Engineering of the University of Rome, "Tor Vergata", Via del Politecnico 1, 00133 Rome, Italy

Abstract

After a brief introduction, including a summary of the main characteristics of the Extreme Ultraviolet (EUV) radiation, we describe the ENEA xenon-fed Discharge Produced Plasma (DPP) EUV source [1, 2]. The DPP emits 100-ns duration EUV pulses in the λ=10-18 nm wavelength spectral range. The in-band energy per pulse is about 30 mJ/sr at 10 Hz repetition rate. In addition to the already performed characterizations [3, 4], we recently exploited high purity monocrystalline diamond detectors developed at the Department of Industrial Engineering of the University of Rome "Tor Vergata" [5].

The configuration of the electrodes of the used diamond detectors was the interdigitated one, particularly suitable for fast measurements. Thanks to the rapid temporal response of these detectors, the fast peaks of EUV emission (7-8 ns FWHM), superimposed on the main pulses, have been characterized much better than when using silicon PIN diodes [6]. This EUV fast overshooting indicates that the plasma column has reached its maximum heating and its maximum radial compression (1/10 with respect to the initial diameter in our case), and that, by few ns, the kinetic energy collected by the collapsing plasma cylindrical shock wave is converted into thermal energy [7]. To investigate the plasma dynamics, we studied the dependence of the amplitude of the fast EUV peak on the initial Xe average density. We observed that, to obtain the plasma fast transverse collapse and the kinetic thermal contribution, the initial Xe density must be high enough [6]. In particular, in the small range of the density variation allowed by our experimental set up (about 1.0×10^{16} – 4.0×10^{16} cm^{-3}), if the initial Xe density is greater than a minimum value (about 1.8×10^{16} cm^{-3}), that could be interpreted as a threshold of the process, the higher the density, the higher the amplitude of the fast EUV peak. Probably, to obtain a considerable kinetic thermal contribution, a certain quantity of matter in the plasma column is needed, while, below threshold, the additional kinetic heating contribution disappears.

Finally, by using the DPP source, a useful characterization and calibration of the diamond detectors has been obtained in the λ=10-18 nm range, by comparison with a reference absolute PIN diode.

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Frascati, 19-23 September 2022

Picosecond laser plasma impulse transfer

M. Barbuta[1], A.Marcu[1], M.Stafe[2], R.Ungureanu[1], M. Serbanescu[1] and N. Puscas[2]

[1] National Institute for Laser, Plasma and Radiation Physics, 409 Atomistilor, Magurele, 077125, Romania
[2] University Politehnica of Bucharest, Splaiul Independentei 313, Bucharest, 060042, Romania

Abstract

In the last years, pulsed laser ablation became a widely used technique with a large range of applications, from material science to engineering and space science. One of the particularities of the ablation plume particles is their initial velocity. Particle velocity of the ablated species could differentiate the results of the pulsed laser ablation technique approach from other techniques. For example, similar nanostructures grown by pulsed laser ablation [1] or from a chemical vapour deposition will have very different structural properties, varying from single crystal to poly-crystaline or even amorphous structures formation. Furthermore, particle velocity from the laser produced plasma could be important in different applications, and big particle filtering technique from the ablation plume is another example where plume particle velocity needs to be into a specific range for the technique to be effective [2].

From macroscopic point of view, this initial speed of the ablated particles leads to a very small impulse transfer to the target, which could be neglected in most applications. However, in some particular conditions and for specific applications, this impulse could become significant and microscopically measurable. Using a picosecond solid-state Nd:YAG laser with a tunable repetition rate (Lumera-ULTRARAPID) and a Ti:Sapphire femtosecond laser (TEWALASS facility from CETAL-NILPRP) with tunable pulse duration from tens of femtoseconds to tens of picoseconds, we have investigated dependence of laser impulse transfer and laser parameters on ablation process and laser pulse parameters. From our results, maximal kinetic energy transfer of a laser pulse to a macroscopic target corresponds to laser power densities approximately 500 times higher than the ablation threshold for the specific pulse duration, as presented in Fig. 1.

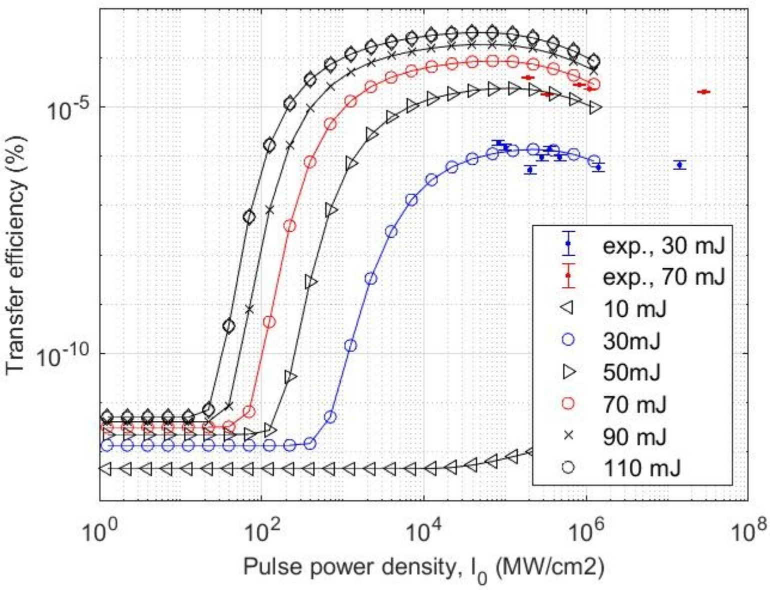

Figure 1. Kinetic energy transfer efficiency dependence on power density, at different pulse energies.

In the case of a multi-pulse train irradiation, (which is the case for many industrial lasers) repetition rate frequency as well as train duration (and respectively filling factor) are important in controling the transferred impulse. Figure 2 presents the dependence of the transfer efficiency on the number of pulses, for several train frequencies at comparable laser power densities. For all curves the dependence trend is similar, but the maximal transfer efficiency values is depending more on the train frequency than on the beam power density.

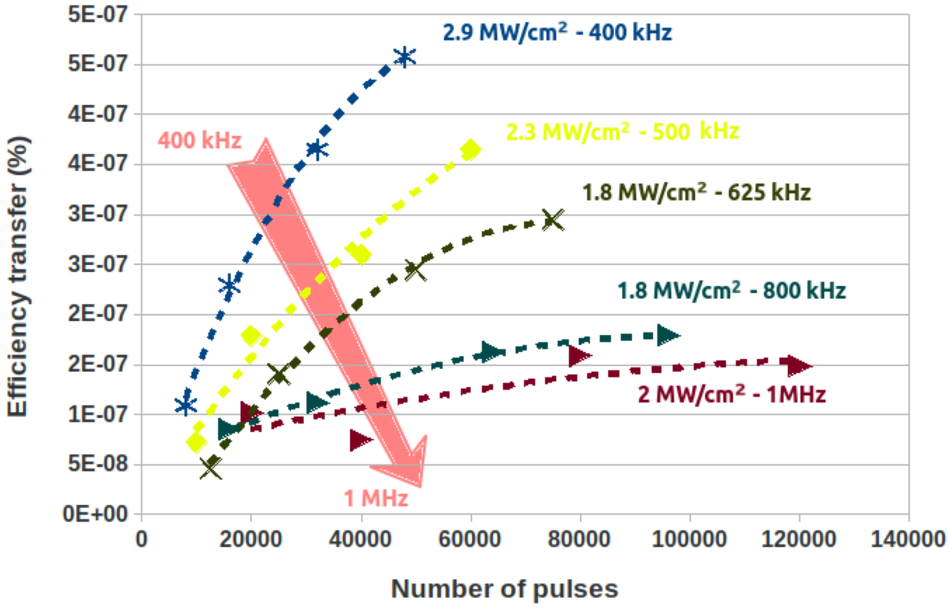

Figure 1. Kinetic energy transfer efficiency dependence on the number of laser pulses at different repletion rates.

Thus, according to our photonic impulse and heat transfer based simulations matching our experimental results, kinetic energy transfer could reach values up to 0.002% of the laser energy. For the case of multi-pulse regime, a lower repetition rate train will transfer more kinetic energy while the laser pulse train energy will have a rather limited influence.

References

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Acknowledgements

We acknowledge founds from ROSA-STAR 189/2017, ELI-RO 13/16.10.2020 and PCE 93/2021 projects