21st Direct Drive and Fast Ignition Workshop

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Invited Talks

Hydrodynamically-scaled ignition of DT fuel on the OMEGA laser and pathways to high gains

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Abstract

Laser direct-drive implosions on the OMEGA laser have achieved core conditions [1] that would lead to gain above unity when hydrodynamically scaled to laser energies typical of the National Ignition Facility (NIF). This projection relies on the assumption that hydrodynamic efficiency remains essentially constant as the laser energy increases, allowing OMEGA performance to scale to larger targets with laser energy growing in proportion to target volume. Recent advances—including Si-doped CH ablators, machine-learning-optimized pulse shapes, and DT subcooling below the triple point—have enabled these high-performance implosions. Although current designs operate on a relatively high-adiabat/low-compressibility and with a reduced drive pressure due to cross-beam-energy-transfer (CBET) losses, progress in broadband laser technology [2] and new target designs [3,4] provide viable pathways toward the high energy gains required for inertial fusion energy and stockpile stewardship applications.

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Automated simulation-based design via multi-fidelity active learning and optimization for laser direct drive implosions

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Abstract

The design of Inertial Confinement Fusion (ICF) experiments strongly relies on simulation due to the expense and rep-rate of current ICF facilities. These simulations provide insight and guidance towards the optimal experimental set up needed to achieve the highest fusion gain. This design process can be time consuming, but it lends itself to automation as the task takes the form of modifying inputs and observing outputs. Any automated design scheme for ICF must be able to (a) simulate the relevant physics, (b) explore the large design space (10s to 100s parameters) and (c) converge to an optimal design efficiently. In this talk, we explore two modern machine learning techniques for optimisation with the aim of automating the design of laser direct drive targets and pulse shapes.

Firstly, we use gradient-free methods, namely Bayesian optimisation, coupled to the state-of-the-art multi-dimensional radiation-magnetohydrodynamics code Chimera. We use this novel capability to explore designs in increasing dimensionality with a multi-fidelity approach. Hydrodynamic instabilities can only be modelled in > 1 spatial dimension. Therefore, we will observe how designs must be modified to be robust to these instabilities. We perform design at OMEGA scale but with an objective function designed to enable high gain with a 2MJ driver [1].

Secondly, we explore gradient-based methods for ICF design. Legacy codes are not differentiable by construction, instead here we present work on the construction of a new differentiable 1D Lagrangian radiation-hydrodynamics code for laser direct drive simulations, lagradept. In this novel code, gradients with respect to design parameters are obtained via Automatic Differentiation (AD). We will show how gradient-based optimisation with order 100 laser pulse parameters is possible via this novel differentiable simulator.

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Hydrodynamic simulations of shock propagation in closed-pore hollow-sphere SiO_2 foams

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Abstract

Laser interaction with low-density foam materials is of considerable interest due to their applications in inertial confinement fusion (ICF) and as secondary radiation sources. In direct-drive ICF, foams can be used to smooth laser intensity modulations or serve as structural matrices in wetted-foam target designs. In indirect-drive ICF, foam linings are employed to inhibit wall expansion in hohlraums and to enhance laser-to-X-ray conversion efficiency. However, modeling laser–foam interaction remains challenging due to the large separation of spatial scales inherent to the internal foam microstructure.

Recent advances in high-performance computing have enabled fully resolved two-dimensional radiation-hydrodynamic simulations of foam microstructure at the full target scale, as well as three-dimensional simulations on reduced domains. In this work, we apply this approach to investigate laser interaction with novel closed-pore, thin hollow-shell SiO_2 foams developed at the Czech Technical University in Prague. We discuss possible simulation strategies and present both 2D axisymmetric and 3D radiation-hydrodynamic simulations performed with the FLASH code [1], under conditions relevant to recent experiments at the PALS facility. To investigate the homogenization of the shell-based microstructure and its impact on shock propagation, direct hydrodynamic simulations are performed at a spatial resolution sufficient to resolve the ~100 nm shell thickness. Our results indicate that, for closed-pore overcritical foams, microscale inhomogeneities have a limited influence on shock dynamics, and that some properties can be reasonably approximated using homogeneous models to reproduce the PALS experimental data.

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Experimental studies on laser-plasma coupling in interaction regime relevant to Shock Ignition

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Abstract

A major concern for the direct-drive scheme to inertial confinement fusion (ICF) is the excitation of laser-plasma instabilities (LPI) growing during the interaction of the laser with the long scalelength plasma corona. LPIs are of particular concern for the Shock Ignition (SI) approach to ICF, where the intensity of the laser is raised (~10^{16} W/cm^2) the end of the compression phase to produce a strong shock. Instabilities of primary interest in this context are Stimulated Brillouin Scattering (SBS) and Stimulated Raman Scattering (SRS) that act to couple laser energy into scattered waves, thus raising laser energy requirements for reaching ignition conditions. Two-Plasmon Decay (TPD) and SRS result in the generation of hot electrons that can preheat the fuel core. The nonlinear nature of these instabilities makes the scaling of experimental results obtained at lower laser intensities difficult. A detailed understanding of LPIs in SI relevant conditions requires dedicated experiments in interaction regimes as close as possible to those envisaged for SI.

Experimental investigations at large-scale laser facilities with planar target foils are therefore a valuable tool to study the physics of parametric instabilities. Here we report on recent experimental results from campaigns at international laser facilities aimed at investigating the role of laser and plasma parameters on the growth of SRS, TPD and SBS, and the mechanisms generating the hot electron population.

Laser parameters such as intensity, beam smoothing and spectral bandwidth were varied in the experiments. In addition to standard target foils, thin “exploding” foil targets were used to generate long density scale length plasmas. Main diagnostics include the characterization of light backscattered in the laser focusing cone in terms of energy, spectrum and temporal evolution, as well as hot electron diagnostics.

Experiments on the EoS of boron nitride, possible alternative ablator to diamond, performed in direct-drive experiments at the PALS and GEKKO laser facilities

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Abstract

Experimental studies on the Equation of State (EoS) of hexagonal boron nitride (h-BN), a material considered as a potential alternative ablator to diamond for inertial confinement fusion applications, are discussed. Boron Nitride melting temperatures and bulk modulus are lower than those of diamond [1]. Because of this, they may allow for a more adiabatic implosion, which would provide higher fusion burn gains. The experiments were performed at the Prague Asterix Laser System (PALS) [2-4] and the GEKKO XII Laser (ILE) [5,6] facilities using high-power laser-driven shock compression. At PALS, shock waves were generated using a 438 nm wavelength laser pulse with a duration of approximately 350 ps and energies up to 200 J. Shock velocities in BN and in a reference material (Al or Qz) were measured simultaneously using time- and space-resolved self-emission diagnostics with a Streak Optical Pyrometer (SOP). The EoS of BN was determined by comparing its response to that of the reference material. The experiments achieved pressures up to ~ 9 Mbar, providing new data points for the high-pressure EoS of BN [7]. By extending the available experimental dataset, these measurements contribute to a better understanding of the behavior of BN under extreme conditions and help assess its potential as an ablator material for future inertial confinement fusion target designs. Complementary measurements were carried out at the GEKKO XII laser facility, where experiments were performed using both 2ω and 3ω, delivering energies up to ~560 J with pulse duration of ~2.5 ns. Under these conditions, stable shock waves were generated and propagated through the material, providing well-controlled states suitable for investigating the equation of state (EoS) along the principal Hugoniot relevant to inertial confinement fusion. Shock dynamics were diagnosed using VISAR (Velocity Interferometer System for Any Reflector). To support the interpretation of the experimental results, one-dimensional hydrodynamic simulations were performed using the MULTI code.

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Ultra-intense sources of MeV particles and radiation using foams irradiated by PW kJ-lasers at near relativistic intensity and large focal spot

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Abstract

Low-density polymer foams are ideally suited as plasma targets for the effective direct laser acceleration (DLA) of electrons using relativistic laser pulses. In recent years, we have demonstrated highly efficient and robust DLA at the high-energy sub-PW laser PHELIX in Darmstadt.

This method allows for generating high-current, well-collimated beams of superponderomotive electrons and can be used to produce intense betatron radiation, MeV bremsstrahlung, isotopes, and neutrons with record-breaking conversion efficiencies. Our results pave the way for the application of low-density foams at kJ PW laser facilities in HED and ICF research.

In my presentation, I will discuss outstanding properties of pre-ionized polymer foams, enabling efficient electron acceleration even at near-relativistic laser intensity and large focal spot—conditions characteristic of high-energy PW lasers in ICF research.

In experiments at the PHELIX facility and the NIF's ARC (Advanced Radiographic Capability) laser, shots with a peak intensity of 1018 W/cm2 on 0.8-1 mm-thick 2 mg/cc foams resulted in an effective electron temperature of 5–10 MeV, 50–100 times higher than the ponderomotive potential of 100 keV.

Interaction of PHELIX- pulses of near relativistic intensity with a pre-ionized foam layer stacked with a millimeter-thick, high-Z converter led to generation of MeV bremsstrahlung with photon energies up to 30 MeV and an effective temperature of 4.2 MeV.

In photonuclear reactions, $2x10^{8}$ neutron per joule laser energy beyond relativistic limit were released.

Preliminary results from the foam application at ARC/NIF show a 10 times higher Au 196 yield per joule laser energy compared to the Compound Parabolic Concentrator (CPC) routinely used at ARC/NIF to redirect ~80% of the laser energy from the wings to the central spot that provides the results.

This proves once more the superiority of foam application in generating intense particle and radiation sources.

Experimental studies of plasma transport processes in magnetized HED plasmas relevant for ICF

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Abstract

Magnetization is investigated as a means to control heat and particle transport in high-energy-density plasmas relevant to inertial confinement fusion (ICF). During implosion, an externally applied magnetic field is advected and compressed to multi-kilotesla levels, reducing electron thermal conduction, enhancing α-particle confinement, and modifying energy transport in the hot spot. These effects are governed by the electron Hall parameter ($\chi \gg 1$) and by the competition between magneticflux compression and demagnetization due e.g. to Nernst advection.

In magnetized cylindrical implosions with 15 kJ laser drive, a 30 T seed field leads to a ~40% increase in electron temperature and a ~30% reduction in mass density relative to unmagnetized cases, consistent with ~10 kT fields at stagnation.[1] Spectrally resolved K-shell emission from dopant species provides quantitative constraints on core density and temperature conditions, and indirectly on magnetic-field amplification. Scaling to higher drive energies enables spatially resolved temperature measurements using dual-dopant K-shell spectroscopy[2] and diagnostics of magnetic-flux compression through angularly-resolved secondary neutron production.

Complementary experiments in underdense, laser-heated plasmas probe kinetic regimes of magnetized heat transport. For $\chi \gtrsim 50$, electron temperatures increase by a factor of ~1.4, indicating strong inhibition of cross-field heat flux, with then asymptotic behavior for $B > 10$ T. The temperature is sustained by inverse bremsstrahlung heating during laser drive, which then drops as the electron density cavitates. Thomson scattering measurements reveal non-Maxwellian electron distribution functions, demonstrating the breakdown of classical transport models.[3]

Together, these results provide direct experimental evidence of magneto-thermal insulation and nonlocal transport in strongly magnetized plasmas. Agreement with extended-MHD and Vlasov-

Fokker-Planck simulations establishes a consistent framework for heat and magnetic-flux transport, with implications for the design of magnetized ICF targets operating in high-χ regimes.

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Recent Research Progress in National Laboratory on High Power Laser and Physics

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Abstract

Fusion energy has long been a dream of humanity, and inertial confinement fusion (ICF) is one of the most promising approaches to its realization. The National Laboratory on High Power Laser and Physics (NLHPLP), founded in 1986, has developed a series of high-power laser facilities and is dedicated to research on laser inertial confinement fusion.

Laser direct drive and fast ignition represent high-efficiency, high-gain approaches to laser inertial confinement fusion. Recently, NLHPLP has launched an advanced direct-drive program targeting laser fusion energy. Related experimental campaigns have been carried out on the upgraded Shenguang-II (SG-II) laser facility, and a new, larger-scale high-power laser facility is currently under construction.

To provide superior experimental conditions for direct drive and fast ignition physics research, NLHPLP has developed advanced laser technologies, including low-coherence nanosecond laser technology, high-contrast picosecond technology and precision laser-target pointing technology. For laser fusion energy applications, the laboratory is developing next-generation laser driver technologies, including high-repetition-rate laser technology and artificial intelligence-enabled precision laser control technology.

These high-quality SG-II laser facilities and advanced high-power laser technologies can provide superior research platforms for ICF physics and laser fusion energy research.

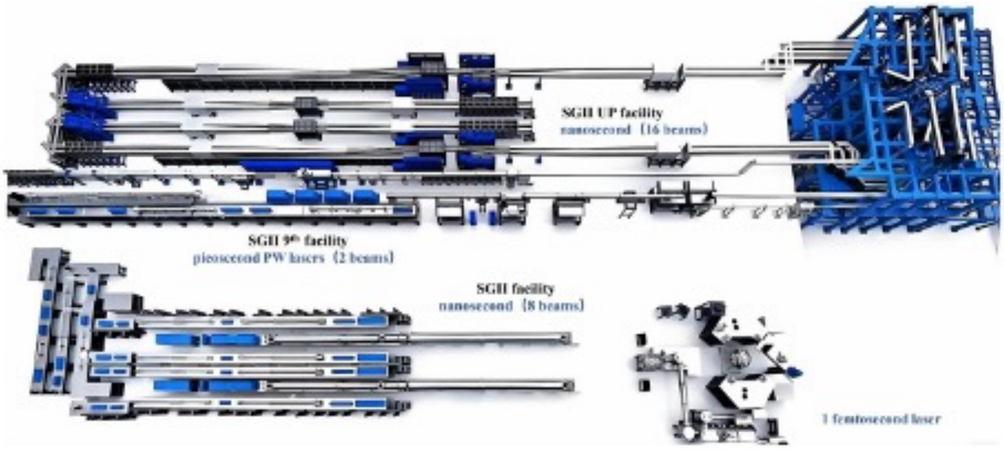

Figure 1. SG-II high power laser facilities in NLHPLP.

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Oral Talks

Sub-Nanosecond Laser-Driven Proton Acceleration and Proton–Boron Fusion Studies for Advanced Direct-Drive Inertial Fusion Concepts

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Abstract

Experiments were carried out at the Asterix Laser System (PALS) using a long-pulse laser delivering up to 600 J with a 300 ps duration. Two schemes were implemented—*in-target* and *pitcher–catcher* to investigate proton acceleration mechanisms and characterize fusion yield in proton–boron (p–^{11}B) interactions. In the pitcher–catcher configuration, protons generated at the primary (pitcher) target impinge on a secondary (catcher) target to induce nuclear reactions. Various target materials and geometries were explored in both schemes to evaluate the influence of composition and structure on proton acceleration efficiency and fusion performance.

A comprehensive suite of diagnostics was employed to characterize emitted charged particles. CR-39 detectors were placed at multiple angles relative to the target normal and covered with aluminum foils of varying thicknesses to enable LET-based particle discrimination, energy spectrum reconstruction, and species identification. Time-of-Flight (TOF) detectors, positioned at similar

angles, provided time-resolved proton energy measurements with angular resolution. Additionally, two Thomson parabola spectrometers delivered charge-to-mass and energy-resolved spectra, offering detailed insight into ion beam composition and energy distribution.

During the campaign, primary targets based on solid ammonia borane (AB) pellets (compressed powder) were investigated, yielding proton energies up to 7 MeV, the highest achieved. These results emphasize the strong role of target composition in laser-driven proton acceleration and inform optimization of proton–boron fusion schemes.

This work was conducted within the HiPER+RF initiative, addressing key challenges in laser-driven ion acceleration and proton–boron fusion for direct-drive inertial confinement fusion (ICF). The results provide critical insight into proton generation, transport, and interaction with secondary targets, supporting validation of advanced models for charged-particle transport and fusion yield in laser-produced plasmas. This contributes to the development of predictive simulation tools and optimization of target design, energy coupling, and overall performance in next-generation direct-drive ICF.

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Direct-drive target studies for a Fusion Pilot Plant

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Abstract

Focused Energy is designing a Fusion Pilot Plant, aiming at the demonstration of repeatable engineering gain larger than unity with laser direct drive. This translates into the need for robust target designs achieving target gain well in excess of 20. We adopt conventional central hot spot ignition, using frequency tripled Nd:glass laser drive (with wavelength $\lambda = 351$ nm).

We describe the process followed to identify a suitable window in parameter space, and then design targets assuming different trade-offs between risks for laser plasma instabilities and hydrodynamic instabilities. With a modified version of the gain model by Trickey et al. [1] we generate gain curves for different values of the laser intensity, the hydrodynamic safety factor (as defined in [2]) and laser zooming options. We aim at limiting laser energy to less than 1.5 MJ, accounting for some ignition safety margins. To achieve this, we assume laser pulses with a broad spectral bandwidth of 1% to suppress cross-beam energy transfer, and a 2-stage laser beam zooming. Targets are then designed using 1D numerical simulations, with the current model of the DUED code (two-temperature, with multigroup radiation diffusion, nonlocal electron transport, neutron transport, 2D laser ray-tracing). The designs are optimized by using DUED in combination with a particle-swarm-optimization technique [3,4].

While a first iteration of the design assumed DT-wetted ablator and solid DT fuel, we are now considering targets with a CH ablator, a DT-wetted low-density foam, and a clean solid DT layer. We are also assessing sensitivity to preheating, and we are studying options to reduce preheating. The effects of low mode hydrodynamics perturbations, due to illumination nonuniformities and/or target mispositioning are studied by 2D simulations. High mode growth is studied using analytical models, with plasma parameters from 1D simulations.

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Numerical study of laser beam geometry effects on propagation instabilities in inertial confinement fusion plasmas

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Abstract

In the context of Inertial Confinement Fusion (ICF), the design of laser optical systems plays a critical role in controlling beam propagation through plasma and mitigating laser–plasma instabilities. As laser beams propagate into the plasma, instabilities such as Forward Stimulated Brillouin Scattering (FSBS) and Filamentation Instability (FI) can lead to beam spray above a given intensity threshold [1,2], thereby degrading energy coupling to the target. These challenges are particularly relevant for the emerging field of inertial fusion energy (IFE), where new facilities are being designed and optimized. This work focuses on how the design of laser beam optics, including near-field shaping and far-field focusing properties, influences the onset of propagation instabilities.

We investigate the impact of near-field beam shapes (Gaussian, disk, square, and rectangular) and far-field profiles (Gaussian and hyper-Gaussian) on beam spray thresholds, both at best focus and in regions surrounding the focal plane. The results are interpreted using established figures of merit (FFOM [1] and GFOM [2,3]), providing a framework to guide optical design. Our simulations show that configurations with larger numerical aperture, such as the Quad LMJ geometry, significantly increase the beam spray threshold compared to square or rectangular beams. In addition, anamorphic designs [4] such as elongated rectangular near-fields demonstrate overall reduced beam spray, hinting at the importance of anisotropic optical shaping.

Overall, the study demonstrates that optical design parameters, particularly total beam aperture, beam shaping, and focusing geometry, are key levers for controlling laser propagation. While both near-field and far-field features contribute, the dominant factor remains the effective aperture set by the optical system. These results provide practical guidelines for the design of laser optical architectures in next-generation IFE facilities, where robust beam propagation and instability mitigation must be achieved by design rather than post-correction.

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Illumination design for inertial fusion energy

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Abstract

Post-ignition [1], public and private investment has grown with the ambition of designing facilities capable of delivering inertial fusion energy (IFE) to power the electrical grid. The most developed approach, and the focus of this work, is conventional direct drive where lasers ablate the surface of a spherical capsule expanding a plasma which in turn generates a reactionary force imploding the capsule. Uniformity and pressure are required for the imploding capsule's kinetic energy to transfer to the hotspot and achieve the condition required for fusion energy. To maximise pressure, the laser continues to illuminate the plasma at high intensities ~1e15 W/cm^2 as the target implodes which leads to laser-plasma instabilities (LPI). In particular, cross beam energy transfer (CBET) is a laser-plasma instability that redistributes energy impacting uniformity and ablation pressure both at current facilities and in many designs for IFE, but modelling CBET is computationally expensive. Previously, a post-processing methodology was created to optimize illumination for polar direct drive with the effect of CBET [2].

This presentation focuses on a new method for the optimisation of illumination configurations relevant to current facilities and designing the first generation of IFE facilities. The method uses state-of-the-art CBET modelling capable of evaluating the impact of laser bandwidth [3]. The work demonstrates how to navigate the large parameter space to design illumination configurations for future facilities including laser wavelength, bandwidth, energy, number of beams, beam spot shape, and zooming. The resultant configurations inform cost benefit analysis for laser systems but also give indications of how we can design implosions that are more robust to laser plasma instabilities.

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21st Direct Drive and Fast Ignition Workshop

From proton heating to integrated proton fast ignition experiments on the OMEGA laser facility

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Abstract

Laser-driven ion beams provide unique capabilities for rapid, localized energy deposition in dense matter with minimal transport instabilities. These capabilities enable transformative applications in two key areas: controlled isochoric heating to generate and probe Warm Dense Matter (WDM), and the proton fast ignition (proton-FI) approach to inertial confinement fusion (ICF), which seeks to trigger ignition in compressed fuel separately from the compression phase, thereby allowing ignition of a larger fuel mass and thus higher gain than conventional ICF.

We conducted a series of experiments on the OMEGA laser facility, initially in a non-compressed configuration. In this setup, the high-intensity kilojoule-scale EP laser generated an intense proton beam focused down to a ~25 μm radius (~2% conversion efficiency) using a cone-enclosed curved foil. This configuration achieved nearly uniform longitudinal heating across a 25 μm solid copper layer, raising its temperature above 100 eV [1].

In the following integrated experiments, the cone was embedded in a Cu-doped spherical capsule imploded by 54 OMEGA beams, with total compression energies of 10 and 18 kJ. Under these conditions, we observed a drastic reduction of proton beam energies (<1% conversion efficiency), which together with an increased stopping to the compressed core, led to an indiscernible heating signature in the Cu K-shell spectra compared to implosion-only shots. This finding highlights a fundamental challenge for proton-FI: the increased target mass and radiation from the compression strongly perturb the delicate TNSA acceleration mechanism. Radiation-hydrodynamics and kinetic simulations corroborate this interpretation. Together, these findings reassess the robustness of the proton fast ignition concept and advance the experimental study of WDM.

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Simultaneous measurement of Ar and Kr K-shell emission in double-doped exploding pusher implosions at the OMEGA Laser Facility

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Abstract

Determination of plasma conditions in ICF experiments is achieved by injecting non-interacting species—usually Ar or Kr—within the fuel and analysing its corresponding emission spectra. Previous experimental campaigns have shown that using a single specie may be insufficient to completely characterize the entire core at maximum compression, especially when spatial gradients are expected to be large, due to the limited range of plasma temperature sensibility in such dopants. Therefore, simultaneous use of multiple dopants has been proposed as an alternative to obtain effective spatial resolution from time- and space-integrated emission spectra by combining their individual temperature sensibility range [1].

We report on a recent campaign where simultaneous Ar and Kr K-shell emission measurements were achieved. A variable energy laser drive (8-22 kJ) was applied over spherical D_2-filled glass-shell targets doped with Ar (0.15% at.) and Kr (0.05% at.). Ion temperatures in the range 4 to 8 keV and a highly reproducible fusion yield were inferred using neutron diagnosis. On-going analysis of the subsequent Ar and Kr K-shell spectra is being performed using the collisional-radiative code ABAKO [2] to independently extract plasma conditions across the core.

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Kinetic Modeling of Stimulated Brillouin Scattering in Laser-Driven Plasmas: Comparing Single-Species and Multi-Species Collisional Plasmas

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Abstract

Indirect-drive inertial confinement fusion (ICF) experiments conducted at the National Ignition Facility and the Laser Megajoule have reported high levels of Brillouin reflected light. To mitigate the growth of backward stimulated Brillouin scattering (BSBS), it has been proposed to use ion mixtures to enhance the damping rate of ion acoustic waves (IAW). Additionally, laser smoothing techniques are employed to generate complex intensity distributions composed of numerous high-intensity "speckles." We have developed a kinetic analytical model that accounts for collisional effects—including both collisional friction and inverse Bremsstrahlung heating via the Langdon effect. By solving the linear dispersion relation of IAWs, we revisit BSBS in laser-heated ICF plasmas. Our analytical results show excellent agreement with particle-in-cell (PIC) simulations, demonstrating that Coulomb collisions substantially modify IAW properties and, consequently, the Brillouin reflectivity [1]. Our findings indicate that in laser-heated, collisional Au plasmas, the Langdon effect dominates over collision-induced anisotropy effects. This results in an IAW damping rate lower than the classical Landau damping rate, leading to enhanced reflectivity compared to collisionless models. Conversely, for AuB mixtures, due ion inter-species collisions, the anisotropy effects prevail, which boosts the IAW damping rate (compared to the collisionless case) leading to a decrease in reflectivity. Using a statistical approach, we discuss the influence of speckle distribution on IB heating and compare our analytical results with PIC simulations.

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Polar Direct Drive implosions in the compressive regime on the Laser MegaJoule

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Abstract

In the past few years, direct-drive implosion experiments on the LMJ laser facility [1] were performed in the exploding-pusher regime using D_2-filled few-micrometer thick glass capsules. The initial campaign with only six LMJ laser bundles made it possible to commission the neutron time-of-flight diagnostic [2]. The follow-up campaign with ten laser bundles enabled a significantly improved optimization and characterization of this implosion regime at LMJ with the help of polar direct drive quad repointing and the use of a more complete set of diagnostics [3]. As a result, a well-controlled and robust platform for particle generation has been commissioned, though with a limited yield of up to 2×10^{11} neutrons and a small convergence ratio ≈ 3.

Here, we present preliminary results of the latest direct-drive campaign on LMJ that explored, for the first time, the compressive (or ablative) implosion regime on the facility, using D_2-filled 2-mm diameter plastic capsules driven by ten laser bundles. For the first time and especially to deal with the large capsule size, we used moderate quad defocusing as well as quad splitting on direct-drive experiments on LMJ, in addition of PDD on the quad level as already implemented in the previous experiments.

In this configuration with a 3.5 ns square laser pulse shape and a 20 μm thick ablator, we expect larger convergence ratios > 10 and smaller hot spots with higher densities and lower temperatures than in the exploding-pusher case. The compressive regime aims at significantly increasing the implosion performance such as areal density and neutron yield. This first experiment paves the way for experiments upcoming in the next years, either through academic access or in the frame of the French TARANIS project for Inertial Fusion Energy.

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High-power laser irradiation of 3D-printed foams for inertial confinement fusion research

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Abstract

The research on Inertial Confinement Fusion (ICF) requires constant research for identifying new materials. Micro-structured low-density materials, or foams, with a randomly arranged internal structure, have been shown to be able to reduce to some extent the detrimental effect of hydrodynamic instabilities seeded by non-uniform irradiation, while also increasing the laser absorption efficiency and enhancing the pressure at the shock front. Laser 3D printing represents the new way of obtaining foams with a precisely controlled morphology, gradients in density and pore size and sample shapes which would be challenging to make with other techniques.

In this work, we will present the recent results of experiments and simulations about the irradiation of 3D-printed foams at high power. The samples were irradiated at the ABC laser facility in the ENEA Centro Ricerche Frascati, at intensities of about 10^{14} W/cm^2, relevant for ICF. Features of the interaction, such as the absorption efficiency and the shock propagation will be discussed for different foam morphologies.

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Multi-Objective Bayesian Optimisation of Laser Pulse Shape in 1D Direct-Drive ICF Simulations

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Abstract

Maximising target gain is a central objective of inertial confinement fusion (ICF) research and experiment. Although high-fidelity numerical simulations can accurately predict implosion performance across a range of design configurations, their computational cost limits practical exploration of the design space. As a result, low-fidelity simulations are often used to optimise design parameters. However, designs optimised for gain in such models underperform in reality, as important physical effects are neglected. In particular, low-fidelity models do not capture deleterious effects, namely those caused by hydrodynamic and parametric instabilities. Nevertheless, several one-dimensional metrics are known to correlate with these effects: the fuel adiabat and in-flight aspect ratio (IFAR) with hydrodynamic instabilities, and the maximum convergent laser intensity [1] with parametric instabilities.

Here, we present a methodology for optimizing the temporal shape of the laser pulse for a given target design in laser direct-drive ICF. A multi-objective Bayesian optimization algorithm [2] is employed to identify pareto-optimal laser pulse designs that each uniquely balance competing objectives tied to implosion performance – target gain – and robustness against instabilities – IFAR and fuel adiabat (hydrodynamic), and maximum convergent intensity (parametric); these objectives are calculated using simulation outputs from 1D radiation-hydrodynamics simulation code MULTI-IFE [3]. This approach enables efficient exploration of pulse shapes across established ignition regimes, illustrates how ideal (1D) gain scales with instability metrics, and provides insight into the robustness of a given design to both hydrodynamic and parametric instabilities. This method aims to inform optimal pulse shape selection for a given experiment and to identify of ignition regimes beyond current capabilities, thereby highlighting potential upgrade paths for current facilities.

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Investigation of shock propagation in ablators using x-ray phase contrast imaging

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Abstract

Direct-drive inertial confinement fusion schemes are especially susceptible to drive-laser non-uniformity, where laser intensity variations incident on the target imprint structures that seed hydrodynamic instabilities. As the implosion proceeds, these seeds grow, negatively impacting implosion performance. Experimentally characterising the response of fusion-relevant ablator materials to laser imprint is central to understanding the formation of these hydrodynamic seeds and the development of predictive models needed for the design of high-energy-gain fusion targets. In this work, we present a practical comparison of two sidelighter experiments developed to investigate shock propagation within trimethylopropane triacrylate (TMPTA) foam and CH plastic targets, utilising a high-powered nanosecond laser to drive imprint and shock formation. An X-ray free electron laser (XFEL) and laser generated X-rays produced an X-ray source that captured X-ray phase contrast images of the propagating shock. The use of an XFEL presented improved spatial resolution and signal-to-noise ratio when compared to the use of laser generated X-rays allowing features of the shock that suggest microjetting to be observed.

Direct observation of the dynamics of solid-solid phase transitions in quartz and fused silica

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Abstract

Understanding the dynamics of shock compression in solids is essential for problems ranging from geophysics to inertial confinement fusion implosions. Due to the intense mechanical loadings, shock waves impose extreme pressure and temperature conditions on short timescales (ns or sub-ns), driving materials far from equilibrium and enabling direct investigation of high-pressure phases.

Quartz (crystalline SiO_2) and fused silica (amorphous SiO_2) are particularly important due to their abundance in Earth’s crust and their widespread use in optical and laser applications. Previous diffraction experiments[1,2] and molecular dynamics (MD) simulations[3] indicates, that above ~15 GPa (the Hugoniot elastic limit), quartz undergoes plastic deformation and transforms into an amorphous phase, while around 30 GPa both materials exhibit the emergence of a crystalline high-pressure phase (whose nature remains debated) through homogeneous nucleation and grain growth. Despite these results, significant uncertainties remain regarding the timescales and wave velocities of these transformations, owing to the high computational cost of MD simulations and the limited spatial resolution of diffraction measurements.

Here, we present the first direct observations of shock-induced phase transformations using x-ray radiography. Combined with multiscale MD simulations, this approach provides new insights into the spatiotemporal evolution of these transformations and establishes a new framework for studying the dynamics of shock-compressed materials.

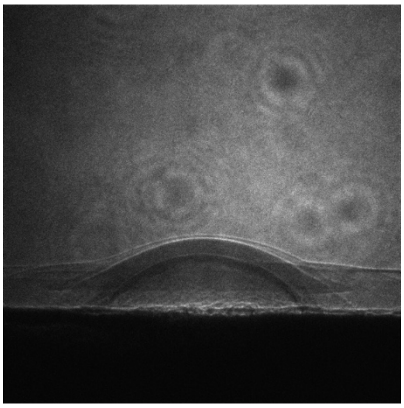

Figure 1. X-ray radiograph of shocked quartz showing an initial elastic wave, followed by a plastic wave associated with amorphization, and finally recrystallization into a high-pressure crystalline phase (dark arc)

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Improved low-noise Electro-Optical probing for transient electromagnetic field measurement emitted in a kilojoule-class laser facility

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Abstract

During the interaction of a high-intensity laser pulses with matter, strong electromagnetic pulses (EMPs) are generated. These EMPs are emitted from the interaction point into the surrounding space, reaching peak amplitudes on the order of MV/m (in the frequency range from MHz to THz) even at large distances from the source. These radiations can be harmful to the diagnostic and dangerous for human health. It has therefore been a primary concern, for several years, within the laser–plasma scientific community to investigate these electromagnetic pulses. On the other side, the study of EMPs can also be of interest for applications in aerospace, medicine, and defense.

A classical probe for monitoring EMPs is the D-DOT, which provides a time-derivative measurement of the EMP electric field. Due to its conductive structure, the probe can easily interact with the various radiation or particles emitted, potentially spoiling the measurements. Dielectric probes exploiting the Electro-Optical effect [1] have the advantage of directly providing the measured electric field, and are much less sensitive to spurious radiation. They are then more suitable for being placed directly inside the experimental chamber where the laser-matter interaction occurs. EMP detection by conductive probes is definitely not a trivial issue under these very harsh conditions [2,3].

In this work, we present an analysis of experimental data acquired with a novel and low-noise version of the EOPs at PALS (Prague Asterix Laser System, capable of producing pulses of 600 J in 350 ns), and of the comparison of these data with those from conductive probes used at different positions, providing an improved characterization of the emitted EMPs, both in time and frequency domain. The novel probes provided improved signal-to-noise ratio compared to signals obtained on the previous version of the same type of probe, in experiments performed at PALS in 2023. The resulting analysis will include also results of particle-in-cell simulations, reproducing numerically the conditions of the experiments.

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Recent Research Progress in Direct-Drive ICF at SILP

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Inertial Confinement Fusion (ICF) is a critical approach to controlled fusion energy, and the successful ignition at the National Ignition Facility (NIF) has confirmed its technical feasibility. Compared with indirect drive, direct drive theoretically offers higher laser-beam–target coupling efficiency, enabling higher fusion energy gains—essential for practical application. However, laser–plasma interaction (LPI) remains a key bottleneck in direct-drive ICF: instabilities such as SRS, SBS, hot electrons and filamentation cause laser energy loss, preheat fusion fuel, and degrade target compression, thereby reducing fusion gain . To address this, broadband laser technology is adopted to suppress LPI: by reducing laser temporal coherence and disrupting phase-matching conditions for LPI growth, it enhances laser absorption and beam-target coupling, helping overcome LPI barriers to achieve higher-gain direct-drive implosions.

One broadband double-frequency laser facility (named as Kunwu) with an output energy of hundreds of joules (532nm, $\Delta\omega/\omega$: 0.6%, 700J) by using the superluminescent diode (SLD) technology has now been built by the researchers from Shanghai Institute of Laser Plasma [1]. Based on Kunwu facility, several preliminary experiments into broadband-laser-driven laser plasma instabilities were carried out. Through direct comparison with the LPI results for the traditional narrowband laser, the actual LPI-suppression effect of the broadband laser was shown. The previous work has demonstrated that broadband lasers exhibit a distinct suppression effect on both backward-stimulated Raman scattering (BSRS) and backward-stimulated Brillouin scattering (BSBS) at laser intensities below 1×10^{15} W·cm^{-2} [2-3]. The results also indicate that the target coupling and absorption efficiency of broadband lasers is higher than that of narrowband lasers [4-5].

Furthermore, we explore the synergistic suppression of LPI using broadband lasers combined with various beam smoothing techniques, and measure the ablation pressure under direct-drive conditions. These research efforts at SILP provide important support for assessing the feasibility and potential of broadband laser technology toward high-gain direct-drive inertial confinement fusion.

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Parametric studies of back- and side-scattered light generated by LPI

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Abstract

Understanding and controlling the growth of laser-plasma instabilities (LPI) is a pressing issue for the prospects of direct drive inertial fusion, particularly for variants such as shock ignition which utilise higher laser intensities. Typical investigations of LPI growth centre on measurements of backscattered light driven by stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). Experiments at NIF [1], OMEGA [2], and SGII-UP [3] revealed stimulated Raman ***side***-scattering (SRSS), involving scattered light propagating orthogonal to the electron density gradient, can experience significant growth. This instability acts as an additional source of hot electrons and can generate stronger reflectivities compared to stimulated Raman backscattering. Additionally, $3\omega/2$ light emission outside the laser cone can be generated as a secondary process from EPW driven by the two plasmon decay (TPD) instability. The spectral splitting characteristics of the $3\omega/2$ emission can be used as an indicator of the coronal electron temperature and add additional insight in the laser-plasma coupling.

Here, we present initial results from experimental campaigns at ELI-Beamlines focused on LPI measurements. A full-aperture backscatter (FABS) diagnostic station [4] and side-scatter diagnostic [5] were used to measure backscattered SBS and SRS, and side-scattered light generated by the SRS and TPD instabilities [6]. The effect of target composition (Al, CH, foams), power profile, and incidence angle on LPI growth will be discussed.

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Target Survival in Inertial Fusion Energy Reactors

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Abstract

It is essential for the success of inertial fusion energy (IFE) for cryogenic targets to survive injection and transportation to the centre of a full scale reactor. The chamber itself will be a harsh environment and will present multiple heating sources for the capsule. Implosion symmetry requirements demand that the deuterium-tritium (DT) ice not be raised significantly above the triple point such that gas formation is inhibited.

Despite being injected at high speeds of up to 400 m/s, the large size of the chamber (~10 m diameter) will result in a transit time of ~milliseconds, resulting in significant heating of the capsule. Thermal radiation will impinge upon the capsule from the ~1000 K chamber walls, where high temperatures are required for efficient electricity generation. Residual gases and plasma will be present from the previous implosions, as well potentially a low density gas fill for chamber wall protection, all of which will contribute to a convective heating of the capsule.

We investigate the heating rate of multilayered IFE targets for expected reactor conditions. The use of highly reflective coatings are explored for their ability to lower the thermal radiation incident on the capsule. The thickness of the CH ablator is found to be a crucial parameter for inhibiting the thermal wave from reaching the DT ice. The technique of sub-cooling the capsule to temperatures of ~16 K has the potential to benefit implosion performance while also providing additional margin for target heating.

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The Indirect-Drive ICF program on LMJ

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Abstract

We present here a survey of the ICF Indirect drive campaigns on LMJ from the first gas-filled experiments until the more recent shots. During all this period, the LMJ facility has been improving its capabilities, increasing the number of beams, multiplying the possible measurements thanks to new diagnostics each year, and improving the target capabilities. Accompanying this LMJ mounting phase, all these experiments aimed to gain a better understanding of the implosion and hohlraum physics and to identify the best design options for high performances at LMJ. Today, 300 kJ and 100 TW of laser energy and laser power are available on the facility for ICF experiments, twice as much next year.

During the last years, the number of neutrons has been increased by about an order of magnitude. 2D and 3D calculations, in reasonable agreement with most of the measurements, highlighted the importance of 3D effects to explain the final symmetry and yield. A model has been found, confirmed by a statistical approach, which highlights the impact of the laser energy, the convergence and the degradation mechanisms. Among those, the Laser-Plasma-Instabilities effects occur to be the more deleterious. This model provides keys for improving implosion performance in the future.

High-gain Direct-Drive inertial confinement fusion of solid fuel target at room temperature

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Abstract

This study examines the feasibility of using solid hydrides at ambient temperatures, in which hydrogen is replaced by deuterium and tritium, to achieve high-gain inertial confinement fusion (ICF). The impact of adding an inert compound with atomic number Z_a and proportion x_a on the ignition conditions of ICF targets is analyzed. It is shown that such an addition significantly reduces the self-sustaining fusion window, thereby increasing the Post temperature and strengthening the Lawson criterion by increasing the requirement on $n_{\mathrm{tot}}\,\tau$. As a result, the ignition conditions become more restrictive on ρR_{hs} and T_{hs}, and the minimum kinetic energy required for ignition increases.

MULTI-IFE simulations confirm these effects and indicate that the conventional Lawson and Post criteria are too restrictive, since ignition and combustion are nevertheless achieved for massive CDT targets at high laser energies (e.g., 411 MJ for a fuel mass of 164 mg, with a thermonuclear gain of approximately 22). A revision of these criteria is proposed, taking into account the partial reabsorption of bremsstrahlung radiation within the hot spot.

A scaling analysis of the target design allows for the identification of the self-ignition threshold and the characterization of the transition between non-igniting, marginally igniting, and fully burning regimes.

Finally, the study suggests that the use of solid fuel at room temperature can produce high gain for low values of Z_a and x_a, at the cost of higher laser energy and fine-tuning of the laser pulse profile.

Resolution-independent machine-learning heat flux closure for ICF plasmas

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Abstract

Accurate treatment of electron heat transport [1] in inertial confinement fusion plasmas requires closures that remain predictive far from local equilibrium and across disparate spatial and temporal resolutions. In this work, we develop a resolution-independent, data-driven heat flux closure using a neural operator framework trained on first-principles particle-in-cell (PIC) simulations [2]. A Fourier Neural Operator [3] is employed to learn the functional mapping from the electron temperature profile to the divergence of the heat flux, enabling a nonlocal closure that is independent of grid resolution. The model is trained on two representative transport problems, the relaxation of a hot spot and the Epperlein-Short temperature perturbation, spanning regimes with significant nonlocal effects. When embedded into the electron energy equation and solved implicitly [4], the learned closure enables stable and efficient iterative solutions, reducing computational cost, and accurately reproduces the spatiotemporal evolution of temperature and heat flux observed in PIC simulations, while outperforming the widely used Schurtz-Nicolaï-Busquet (SNB) [5] model. At the same time, the learned model shows good temporal extrapolation and generalization capability. Remarkably, models trained on coarse-resolution data remain accurate when deployed within fine-resolution solvers, demonstrating strong generalization across resolutions. These results establish a practical pathway for integrating machine-learning closures into radiation-hydrodynamic simulations and highlight the potential of neural operators as iterative solvers bridging kinetic and fluid descriptions of plasma transport.

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Design of ICF targets for energy production – TARANIS project

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Abstract

High-gain Inertial Confinement Fusion (ICF) represents a major strategic goal for carbon-free energy production. Recently, the National Ignition Facility (NIF) achieved the first net gain in ICF. In this context, the TARANIS project focuses on optimizing target designs and laser configurations to advance ICF toward practical energy production[1,2].

ICF research involves plasma physics, laser–matter interaction, and high-power laser technology. Given the complexity of the physics involved and the limited experimental access, high-performance simulations play a crucial role in refining target geometry, laser parameters, and energy output predictions.

To effectively analyze simulation results, a set of diagnostic parameters was first established in post-processing. This framework enabled a systematic optimization study across different target designs, including layered targets. For each configuration, laser parameters such as intensity and pulse shape were varied to maximize the fusion gain.

To complement this optimization approach, a robustness analysis of the laser pulse was performed using a dedicated perturbation model. Realistic variations of the laser profile, including temporally correlated noise, power-dependent fluctuations, gradient amplification, and temporal jitter, were introduced to generate ensembles of perturbed pulses representative of experimental conditions. Their impact on target performance was assessed through one-dimensional hydrodynamic simulations, enabling the identification of critical phases of the pulse and the definition of robust operating domains.

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Study of proton stopping power in warm dense matter using low-density foams at the XGIII laser facility

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Abstract

Stopping power is defined as the differential energy loss per unit path length of a charged particle traversing matter. The study of proton stopping power produced using lasers[1] is a central topic in warm dense matter (WDM), inertial confinement fusion (ICF), and laboratory astrophysics. In the WDM regime there are not much experimental data validating the theoretical models, which sensibly differ from each other in the region of the Bragg peak of protons. We performed an experiment at the XG-III[2] Laser Facility in Mianyang (China) using MeV proton beams generated by the interaction of short-pulse high-intensity lasers with solid targets via Target Normal Sheath Acceleration (TNSA). This produced a population of protons with energies extending to 12 MeV and an approximately exponential energy distribution. An energy selector placed after the TNSA target allowed selecting a narrow energy spectrum (2-5 MeV). These protons were then crossing a foam target before reaching a Thomson Parabola spectrometer where their residual energy was measured. At the same time a synchronized nanosecond beam was used to create controlled plasma conditions in the foam target, a 3D-printed low-density plastic foam (CHO 89 mg/cc) consisting in a cube of size 1 mm covered on one side by an Al foil. The longer pulse duration focused on the Al ablator/pusher allowed to create a strong shock in the foam, ensuring volumetric heating and the formation of an extended plasma with relatively smooth density gradients as compared to what could be achievable with solid-density targets. The foam density was chosen so that, upon heating, the plasma reached conditions characteristic of the warm dense matter regime, with electron densities approaching 10^{21}–10^{22} cm^{-3} and temperatures in the range of several eV, i.e. a strongly coupled and partially degenerate plasma. The shock breakout time at the rear of the foam target was measured using an SOP diagnostic, allowing to fix the delay between the nanosecond heating pulse and the picosecond proton-generating pulse, which can be precisely controlled, allowing the proton beam to probe the plasma at selected stages of its hydrodynamic evolution. In this preliminary experiment, however, we just limited ourselves to measure the stopping power in the cold plastic foam.

In conclusion, the combination of picosecond TNSA proton generation and nanosecond-driven foam plasma production can enable a controlled study of proton stopping power in warm dense matter conditions. These results contribute to the broader understanding of ion transport in matter in extreme conditions and provide experimental constraints for advanced stopping power theories relevant to fusion and astrophysical plasmas.

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Laser-Driven Electromagnetic Pulses for the Manipulation of Charged Beams

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Abstract

The interaction of high-intensity laser pulses with matter gives rise to a rich variety of phenomena, including particle acceleration and the emission of broadband electromagnetic radiation, spanning from ionizing components (γ, X, UV) to non-ionizing electromagnetic pulses (EMPs) in the MHz-THz range[1]. EMPs can reach field strengths on the order of MV/m at around one meter from the interaction point. For this reason, they have always been considered harmful for electronic devices and personnel in experimental facilities, and a hot topic for inertial confinement fusion, especially for advanced Direct-Drive schemes such as Shock Ignition and Fast Ignition. However, a growing interest has recently emerged in exploiting these fields as a resource for innovative applications.

In this framework, a recently patented scheme developed at ENEA - Centro Ricerche Frascati enables the generation of intense transient electric fields (of the order of MV/m or higher) over extended volumes, with specific spatial distributions[2]. The uniqueness of these fields lies in their high intensity and ultrafast rise and fall times, which overcome the limitations of conventional pulsed-power generators, opening the way to a wide range of applications in particle acceleration and beam manipulation, medicine, biology, electromagnetic compatibility, materials science, aerospace, electronics and sensor.

In this work, we investigate the potential of such EMP-driven fields for the manipulation and conditioning of charged particle beams. In particular, we explore their application as beam choppers for conventionally accelerated beams and as energy selectors for laser-driven beams, typically characterized by broad energy spectra. The study combines analytical modelling of single-particle dynamics with dedicated numerical simulations to describe realistic beam conditions.

The results show that these EMP-driven devices can be considered a promising solution for the manipulation of charged particle beams, providing high field strengths, ultrafast rise times, and more compact setups compared to conventional techniques. The unique features provided by these novel techniques are of particular importance for direct application to manipulation of laser-accelerated proton beams in proton Fast Ignition schemes, as it will be discussed in the presentation.

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Influence of Spectral Bandwidth on the Nonlinear Kinetic Regime of Stimulated Raman Scattering for Spatially Smoothed Laser Beams

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Abstract

The main challenge for efficient laser energy deposition in inertial confinement fusion (ICF) is stimulated laser scattering on plasma waves. Various optical laser beam smoothing techniques used over the years, such as random phase plates (RPP) and smoothing by spectral dispersion (SSD), appear to be inadequate for mitigating parametric instabilities. Following the successful ignition at the National Ignition Facility, there is renewed interest in finding improved smoothing techniques for developing a new laser facility for Inertial Fusion Energy. Consequently, techniques such as broadband lasers and Induced Spatial Incoherence (ISI) are being revisited.

To study these optical smoothing techniques in the context of laser-plasma instabilities, particularly in the nonlinear kinetic regime of Stimulated Raman Scattering, 2D Particle-In-Cell (PIC) simulations are necessary. As a result, all these techniques have been implemented in the PIC code SMILEI.

In the talk, we will present the results of these 2D simulations, where different bandwidths for an RPP-broadband laser, ranging from 1% to 10%, are simulated in 2D and compared to a broadband laser and ISI with the same bandwidth. We will demonstrate that the nonlinear kinetic regime of Stimulated Raman Scattering can be mitigated at certain intensities when ISI is used with a broadband laser. Comparisons will also be presented when these techniques are combined with polarization smoothing. The effect of these different smoothing techniques on Stimulated Brillouin Scattering will also be discussed.

Numerical and experimental activities on nanostructured carbon foams for Inertial Confinement Fusion at Politecnico di Milano

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Abstract

Porous materials are gaining increasing attention as potential ablators for direct-drive inertial confinement fusion (DD-ICF). Their low average density enhances laser absorption, increasing the ablation loading compared with standard targets and affecting the pressure at the shock front [1]. Moreover, scattering and deep penetration of the laser field through the void network promote volumetric heating and homogenization dynamics at the nanometric scale [2,3]. These effects influence instability growth and shock-wave propagation, two key issues in DD-ICF. Recent results [4] obtained with the ABC laser are encouraging and suggest that the properties of porous materials like nanostructured carbon foams can be tailored to further improve their performance as ablation layers.

Here, we present an overview of the theoretical, numerical, and experimental activities carried out at the Department of Energy of Politecnico di Milano, in collaboration with the Nuclear Department of ENEA C.R. Frascati, while their future developments will be performed within the Hyper+ project [5].

On the theoretical and numerical side, we discuss recent studies on the kinetics of nanofoam homogenization at picosecond-scales, since they can impact on nanosecond-scale dynamics through modifications of laser absorption and target expansion. These investigations [2] are performed by means of 2D and 3D Particle-In-Cell simulations using the Smilei code [6]. In parallel, nanofoam-structure effects have been implemented in the 1D MULTI-FM code [7], accounting for both the mean pore size and the average size of the solid nanofoam elements (i.e., the nanoparticle clusters interacting). Future work will focus on coupling these approaches by providing hydrodynamic codes, such as MULTI-FM and FLASH [8], with inputs derived from PIC simulations of the homogenization process.

Experimentally, low-density foams are produced by Pulsed Laser Deposition (PLD) [3,9], a technique based on laser ablation of a target material. By tuning the relevant process parameters, PLD enables control of nanoscale morphology and density for a wide range of deposited materials, including carbon, a mid-Z material of interest for ablator applications. We present our results on the production and characterization of PLD-deposited foams. Future activities to extend the investigation of nanosecond high-power laser interaction with different nanostructures are foreseen.

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Impact of Cross-Beam Energy Transfer and Beam-Mode on OMEGA Implosions

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Abstract

High-performance inertial confinement fusion implosions require highly symmetric fuel compression and efficient coupling of driver energy to the target. In direct-drive implosions, a major source of compression asymmetry arises from the number, layout, and profiles of the drive beams, known as beam-mode (BM) compression asymmetries. On OMEGA, these effects produce a dominant Legendre mode-10 in the power deposition. Cross-beam energy transfer (CBET) is another important degradation mechanism. This is a laser-plasma instability that reduces absorption by transferring energy from incident beams to outward-travelling, unabsorbed "blowby" light from other beams. CBET reduces energy deposition by approximately 20% in typical OMEGA implosions and can further amplify BM asymmetries by modifying the intensity profiles of the incoming beams.

This work aims to quantify (1) the extent to which OMEGA implosions are degraded by BM asymmetries and CBET, and (2) how these effects modify optimal target and laser pulse-shape designs. To this end, an ensemble of radiation-hydrodynamics simulations is performed in 1- and 2-D (without and with BM degradation) and with and without CBET. These simulations are coupled to the multi-fidelity Bayesian analysis and optimisation toolkit Millefeuille. Surrogate models are constructed for each case over an eight-parameter design space, comprising three target parameters and five laser pulse parameters, enabling identification of optimal implosions and inference of how changes in target design affect performance. The simulations are conducted using the 3-D Eulerian radiation-hydrodynamics code CHIMERA, coupled to the SOLAS ray-tracing library.

The results of this simulation campaign demonstrate that the optimal implosion's generalised Lawson criterion is reduced by approximately 10% due to BM asymmetries and by approximately 30% due to CBET. CBET systematically alters the optimal design, favouring targets with larger outer radii to minimise blowby light and lower target masses to account for reduced energy coupling. As shown in the figure, optimisation of the generalised Lawson parameter using the surrogate models indicates that, for designs with small target outer radii relative to the beam spot size, 2-D performance remains close to 1-D performance and degradation is dominated by CBET. Conversely, for designs with larger outer radii, CBET effects are reduced due to suppressed blowby light, and performance degradation is dominated by BM asymmetries.

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21st Direct Drive and Fast Ignition Workshop

Scaling Laws of Multi-Shock Implosions toward the Quasi-Isentropic Limit

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Abstract

We present a unified theoretical and numerical framework for self-similar multi-shock implosions achieving ultra-high compression in a uniform solid spherical target. Extending the classical Guderley model to N-stacked, spherically converging shocks, we derive self-similar solutions and the scaling law for the final density of the form $\rho_r/\rho_0 \propto \hat{P}^{\,\beta(N-1)}$, where $\hat{P}$ is the stage pressure ratio and β is determined by the adiabatic index γ. One-dimensional Lagrangian hydrodynamic simulations confirm this relation over a broad range of parameters, from the weakly to the strongly non- linear regime ($\Pi \sim 70$). The results show that cumulative compression increases systematically with the number of stacked shocks while entropy generation is strongly suppressed, asymptotically approaching a quasi-isentropic limit as $N \rightarrow \infty$. This volumetric scheme strongly suppresses the Rayleigh–Taylor instability that plagues shell-based implosions and thus provides a robust, largely instability-resistant compression pathway applicable to inertial confinement fusion (ICF) and other high-energy-density systems. The framework bridges similarity theory with realistic multi-shock dynamics, guiding the design of advanced laser-driven compression schemes.

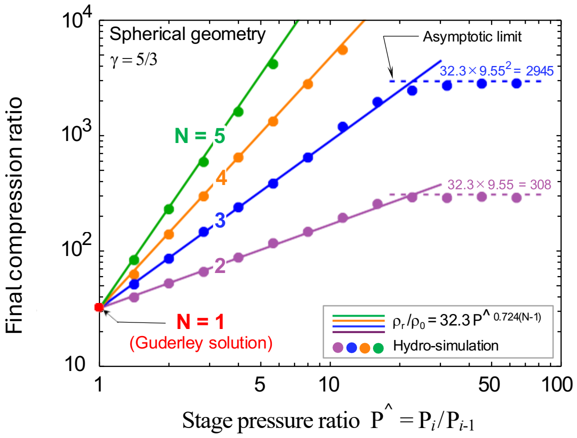

Figure 1. Final compression ρ_r/ρ_0 versus stage pressure ratio $\hat{P}$ for $N = 1$–5 stacked shocks. ρ_r is the reflected-shock crest density immediately after on-axis coalescence and is subsequently advected outward with the diverging shock. Dashed lines indicate the asymptotic limits.

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Mitigation study of laser plasma interactions with broadband lasers at Focused Energy

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Abstract

Laser plasma interactions (LPIs) play a critical role in the success of direct-drive inertial confinement fusion. At the high laser intensities required for ignition, instabilities such as cross-beam energy transfer (CBET), stimulated Raman scattering (SRS), and two-plasmon decay (TPD) can significantly degrade energy coupling by redirecting laser light into unwanted directions and trigger fuel preheating by generating supra thermal hot electrons. To mitigate these effects, the use of broadband lasers has emerged as a promising solution. By increasing the spectral bandwidth, the phase-matching conditions required for these instabilities to grow are disrupted through temporal incoherence of the laser. At Focused Energy, we conducted integrated experiments at the PHELIX facility (GSI, Germany) using a 527 nm laser with a spectral bandwidth of approximately 0.5%. A series of vector particle-in-cell (VPIC) simulations were also performed to qualitatively reproduce the experiments. We will present the preliminary results from these supporting simulations, demonstrating the efficacy of broadband lasers in suppressing LPIs.

Acknowledgements
The authors gratefully acknowledge the PHELIX group at GSI for providing the laser facility and experimental support. Numerical simulations were performed on the **JUWELS** supercomputer at the Jülich Supercomputing Centre. We further acknowledge the **EuroHPC Joint Undertaking** for providing the computational resources required for this study under the allocation EHPC-2025R02-305.

Benchmarking non-local models of heat flow in direct drive laser-ablation simulations

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Abstract

Predictive simulations of inertial confinement fusion (ICF) require accurate models for electron thermal transport, particularly in regions of steep temperature gradients where local, diffusive transport models break down. We have recently developed a coupled electron Vlasov-Fokker-Planck (VFP) and ion hydrodynamics code (K2-Gorgon) which allows tractable, 2D hydrodynamic simulations of ICF-relevant experiments with an inline high-fidelity kinetic electron transport model. In this work, we demonstrate the applicability of this code to direct-drive simulations by studying planar plastic target ablation. Results from this platform are used to benchmark the solutions from commonly used transport models – flux-limited diffusion and the reduced kinetic "Schurtz-Nicolai- Busquets" (SNB) model – against the VFP approach. These results demonstrate the inadequacy of the flux-limited model, which shows substantial differences in predicted coronal temperatures (> 200 eV) when tuned to match other observables. SNB more accurately captures observables, including shock velocity, coronal temperature and non-local preheat, with minor quantitative differences. Extension of this work to 2D planar targets allows us to study the self-generation of magnetic fields and non-local effects on the transverse smoothing of perturbations. These effects are not well captured under the assumptions of SNB, and a preliminary analysis of 2D simulations will be discussed. Understanding the role of higher-dimensional kinetic effects and the limitations of current transport models is a critical factor in the design of next-generation ICF facilities.

Acknowledgements
This work was undertaken as part of UPLiFT (UK Programme of Laser Inertial Fusion Technology for Energy) and is funded by the UK's Department for Energy Security and Net Zero. This work was also supported by the EPSRC and First Light Fusion under the AMPLIFI Prosperity Partnership - EP/X025373/1

Measuring laser imprint and subsequent Rayleigh-Taylor growth on a new platform at OMEGA for UPLiFT

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Abstract

Laser imprint is one of the key challenges facing direct-drive IFE, as it is known to be a significant seed of instability growth. The first UPLiFT (UK Programme of Laser inertial Fusion Technology for Energy) experiment aimed to explore this phenomenon, using a newly developed platform on OMEGA. A planar CH target was driven using 8 overlapped beams, consisting of an initial picket followed by a main drive. Two key measurements were made on each shot: 2D VISAR measurements were made shortly after the picket in order to measure the velocity profile of the initial shock (containing any perturbations due to imprint), with face-on x-ray radiography measurements made after the main drive to measure density perturbations due to the subsequent Rayleigh-Taylor growth (which are expected to be seeded by these perturbations). Side-on radiography was also used to measure the trajectory of the accelerated foil. Shots were performed with varying levels of SSD (smoothing by spectral dispersion), to quantify the effectiveness of this technique in mitigating imprint.

This talk will describe how the platform enabled these measurements, and present preliminary results from the ongoing analysis. The analysis of the 2D VISAR data will be discussed, and the velocity profiles of the shock for different levels of SSD will be presented. These profiles will also be compared with both target metrology and the on-shot radiography, to attempt to directly identify correlation between target structure, laser imprint, and Rayleigh-Taylor growth.

Versatile kJ-class laser based on OPA front-end for inertial fusion research

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Abstract

The strategy to achieve high gain in Inertial Confinement Fusion (ICF) necessitates flexible laser beamlines capable of delivering diverse temporal characteristics at the kJ energy level. While direct drive target compression demands broad-bandwidth nanosecond pulses, specific ignition schemes require short pulses to generate penetrating particles. Consequently, advanced spectral management is critical in both regimes.

In this work, we present versatile kJ-class laser seeded by a multi-Joule front-end solution based on Optical Parametric Amplification (OPA). The front-end system leverages two proprietary pump lasers specifically optimized for OPA applications: a high-repetition-rate unit (3J at 5–10Hz, 532nm) and a high-energy unit (>30J at 1 shot/min, 527nm). Both pump lasers deliver top-hat beam profiles with a high Strehl ratio, ensuring ideal conditions for OPA pumping. Furthermore, they feature adjustable temporal shaping (3–20ns) and are available in circular or square beam formats. The main amplifiers are based on flash-lamped Nd:glass amplifiers, designed to amplify these pulses to the kJ level while keeping a broadbandwidth and versatile temporal and spectral characteristics. We will demonstrate how this modular OPA front-end architecture offers the necessary parameter flexibility for both short- and long-pulse operations in next-generation research facilities.

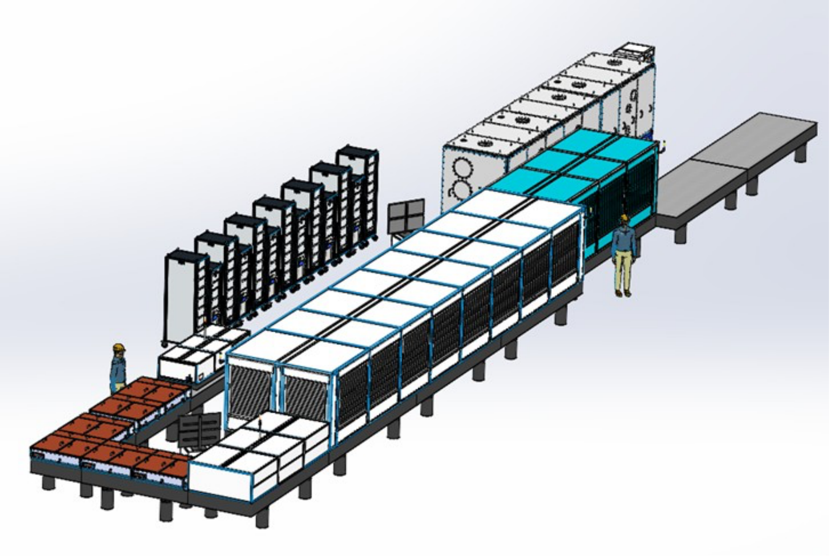

Figure 1. Design of the kJ broadband laser for fusion research.

Ion Discrimination Methodology in Laser-Plasma Experiments via Synthetic Time-of-Flight Signal Modeling

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Abstract

The interpretation of multi-species ion emission in laser-plasma experiments is often limited by the intrinsic ambiguities of individual diagnostics, especially when different ion species share similar time-of-flight (TOF) signatures. We present a synthetic methodology for improving ion discrimination based on the forward reconstruction and comparison of diagnostic signals. The approach relies on generating synthetic detector responses starting from hypothetical ion spectra, combining particle transport modeling with stopping power calculations and detector response functions. TOF signals are reconstructed for diamond-based detectors, including multi-layer configurations and compared across layers within a self-consistent framework. This self-cross check methodology enables internal validation by verifying whether a single assumed spectrum can simultaneously reproduce the signals observed in multiple detector layers. The same framework is extended to complementary diagnostics, enabling the generation of synthetic signals for systems such as Thomson Parabola Spectrometers (TPS) and CR-39 detectors. By projecting a given particle spectrum into the TOF measurement domain, the method provides a unified way to assess consistency and reduce ambiguities in species identification, particularly in cases where charge-to-mass degeneracy or overlapping spectral features are present. In addition, the methodology provides a diagnostic tool for identifying limitations and non-ideal effects in TOF detectors. Deviations between measured and synthetic signals can reveal contributions not associated with the physical particle flux, such as electronic artifacts, spurious signals, or distortions introduced by the readout chain, which may otherwise be misinterpreted as genuine ion features. Preliminary applications demonstrate that the combined use of synthetic reconstruction and signal consistency checks enhances the robustness of ion discrimination and provides deeper insight into complex particle spectra. The methodology is general and can be adapted to different detector geometries and experimental configurations, offering a powerful tool for the analysis and design of diagnostics in high-energy-density plasma experiments.

Acknowledgements

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Hot Electron Transport in Magnetized Targets

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Abstract

We present updated simulations of an experiment conducted on the OMEGA-EP laser system [1] that investigates hot-electron transport in magnetized planar targets. While a 20 Tesla magnetic field was expected to divert hot electrons and suppress the heating of a copper fluor layer, experimental Kα yields remained remarkably similar regardless of the field's presence. Furthermore, the application of the magnetic field resulted in an unanticipated duplication of the copper Kα lines, complicating the intended differentiation between radiative and hot-electron preheating.

To interpret the experimental results, we have conducted 2-D MHD simulations with the FLASH code [2] and hot-electron transport simulations in a magnetized target with the 3D hybrid code PETRA [3]. A possible explanation, consistent with the findings of Enright and Burnett [4], is that the magnetic field increases the average energy of hot electrons, which are primarily generated via SRS or Absolute SRS. Thanks to the higher energy, the electrons can reach the fluor layer and produce an increased Kα emission, similar to that achieved in the absence of the magnetic field. In the shots including the magnetic field, the Kα emission from the copper layer appears to be broadened, and the causes for these results are still under investigation. These findings could help in managing hot-electron preheating in direct-drive central hot-spot ignition and shock-ignition targets.

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The new center for IFE in Germany - Biblis

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Abstract

Germany has decided to make a bold move towards fusion energy. The federal government will support fusion efforts with around 9 Billion Euros for the next 10 years. This time the money will be split equally between MFE and IFE with the development of three fusion HUB's, one for magnetic fusion, one for inertial fusion and one for fuel cycle and materials.

For IFE, the former site of the nuclear power plant Biblis is pushed forward by Focused Energy, supported by academia and a large industry consortium.

I will present the roadmap towards a fusion power plant including supporting facilities and the immediate efforts to build first facilities in 2026/2027.

As the fusion HUB shall bring together startups, industry and academia I will present opportunities and benefits for collaborating for national and international partners.

21st Direct Drive and Fast Ignition Workshop

Advanced Models for Laser-Plasma Interaction in Radiative Hydrodynamic Simulations

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Abstract

The prediction and interpretation of fusion experiments require radiative hydrodynamic (RH) simulations, where the laser beam propagation is often modeled using crude ray tracing packages [1]. Laser-plasma interaction (LPI) and associated parametric instabilities are often grossly accounted for or treated with complementary theoretical and numerical analyses based on the accurate propagation of the laser [2]. Recent developments on backward stimulated Brillouin scattering (BSBS) or cross beam energy transfer (CBET) account for the impact of the speckle micro-structure of the laser wave in the LPI linear modeling [3,4,5,6]. Additionally, the backscattering level due to stimulated Raman scattering (BSRS) can now be predicted in its non-linear stage [7]. These models, implemented in the RH code Troll [1], compare well with various experimental measurements or reference numerical results, thus offering a new LPI platform for predicting and analyzing inertial confinement fusion related experiments.

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Acknowledgements

This work has been done under the auspices of CEA-DAM and the simulations were performed using HPC resources at TGCC/CCRT and CEA-DAM/TERA

Characterisation of implosion core and shell conditions using the multi-monochromatic X-ray Imager

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Abstract

In the central hotspot approach to inertial confinement fusion, the conditions of the hotspot and assembled fuel are highly sensitive to drive asymmetries, hydrodynamic instabilities and impurities. Measuring the hotspot, from formation to the final density and temperature conditions, is essential in optimising the thermonuclear burn initiated at the core and its propagation into the surrounding high-density fuel. To achieve this, a forward model is presented which combines a collisional-radiative, spectral synthesis code with measurements from the multi-monochromatic X-ray imager (MMI). The MMI can be used to record time-gated, spectrally resolved images of hotspot dynamics at peak compression. Doping the gaseous core with trace amounts of Ar enables the extraction of electron density and temperature in the hotspot as well as the shell areal density, all as a function of time. The analysis enables the reconstruction of 2D electron density and temperature profiles, further aiding the understanding of the implosion physics via comparison with radiation-hydrodynamic simulations. With this approach, we present the initial results of core and shell conditions extracted from MMI measurements of Ar-doped implosions on the OMEGA laser system.

UPLiFT: UK Programme of Laser Inertial Fusion Technology for Energy

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Abstract

UPLiFT is an ambitious programme of scientific and technological development which aims to lay the foundations to enable a future demonstration of laser inertial fusion energy. The technological developments are currently focussed on implosion target manufacturing and characterisation, and broadband, high efficiency, high repetition rate lasers which are designed specifically to reduce cost.

UPLiFT's science is focussed on understanding the physics of direct drive, and specifically that which differentiates it from indirect drive; laser-plasma instabilities, imprint, and non-local transport. A focussed programme of inline model development, combined with dedicated experiments to benchmark the models, will de-risk implosion designs for a future laser system.

Implosion design work will evaluate both conventional direct drive, and Shock-Augmented Ignition[1] approaches. Shock-Augmented Ignition is a relatively new Laser Inertial Fusion concept which, based on our work to-date, may enable higher yield with implosions that are less exposed to deleterious hydrodynamic and/or laser-plasma instabilities.

In this talk I will briefly outline the programme and provide an update on progress with an emphasis on laser technology.

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Acceleration Phase Mix Width in Direct Drive

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Abstract

When the capsule accelerates, perturbations, primarily from laser speckle, lead to a “mix width” in which the dense ablator is compromised by low density ablated plasma. Here we first present quantitative acceleration phase inferences of the mix width in imploding plastic shells, driven by pulse shapes similar to modern ignition scaling experiments, and with full beam smoothing. The mix widths (of order 1 to 5 μm) are obtained at traveled distances sufficiently small (~30 to 100 μm) such that the growth is in the linear to weakly non-linear phases, which are most relevant to future facility scaling experiments. The experiments use hollow shells (as well as solid spheres) in which Si doping (4 to 8% by atom) is present at known depths, and the mix width is inferred from the time resolved He-like Si emission. The results (both with and without speckle smoothing) are compared with modeling (high resolution code and simplified growth factor analysis) and we will relate the results to cryogenic and ambient experiments. Additionally, we will describe the experiments planned to test expected mix width reductions with a new test broadband beamline (FLUX laser) at OMEGA.

Acknowledgements
Department of Energy (DOE) National Nuclear Security Administration University of Rochester National Inertial Confinement Fusion Program, Award Number DE-NA0004144 and DOE Office of Science, Fusion Energy Sciences, Award No. DE-SC0024863: IFE-STAR.

Laser technology for Taranis IFE project

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Abstract

Following the breakthrough achieved by first ignition demonstration at NIF in December 2022 and further improvements obtained since with now scientific gains exceeding 4, the inertial confinement scheme involving lasers has become an ever more credible solution for production of clean energy in the future.

It has accelerated the emergence of initiatives for IFE (Inertial Fusion Energy) from both academic and industrial worlds. In France this has led in 2024 to the beginning of Taranis project which has been selected for funding by the French government. Taranis involves a consortium associating academic research institutions (CEA-DAM, CNRS) and industry (Gen F – a IFE dedicated start-up – and Thales).

Taranis is based upon direct drive scheme which in combination with the use of more efficient lasers, based on laser diode pumping of solid-state materials, could allow to reach target gains exceeding 50, what is required to deliver electricity to the grid at a competitive price. For Taranis project, a first design point has been published in ref 1, leading to the potential achievement of a target gain exceeding 100 with a laser energy of 3 MJ at 3ω at a repetition rate of 10 Hz.

A crucial requirement for the lasers involved in a direct drive scheme will be their spectral bandwidth which will have to be large enough to get rid of detrimental effects such as Laser Plasma Instabilities (LPI). It is considered that a relative spectral bandwidth $\Delta\omega/\omega$ of 1% or more will be required to mitigate LPI.

In this paper we will review the laser requirements, the potential laser system architectures with a focus on high energy diode-pumped laser amplifiers , emphasizing the necessity of careful selection of amplification materials as depicted in ref 2, taking into account different constraints as their cross section, their gain bandwidth, their thermal properties and their availability at industrial scale in large enough apertures.

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This project is supported by the French government as part of France 2030 (AAP Reacteurs Nucleaires Innovants—Grant No DOS0237680/00).

Kinetic modelling of non-local preheat in direct-drive ICF using coupled VFP-hydrodynamic simulations

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Abstract

In regimes characterised by direct-drive configurations, steep temperature gradients at the critical surface can lead to a breakdown of classical diffusive heat transport. The electron distribution function departs from Maxwellian behaviour, giving rise to non-local electron populations capable of transporting energy ahead of the main shock front. This results in preheat within the inner deuterium–tritium (DT) gas-fill, modifying ablation dynamics and perturbing shock propagation and timing.
Results are presented from coupled Vlasov–Fokker–Planck (VFP) and hydrodynamic simulations of inertial confinement fusion (ICF) layered targets in a 1D planar geometry, performed using the recently developed K2-Gorgon code [1]. This kinetic–fluid framework enables self-consistent modelling of non-local electron transport and its impact on direct-drive target evolution. Comparisons between coupled VFP–hydrodynamic simulations and conventional flux-limited hydrodynamic models demonstrate substantial differences in energy transport and laser–plasma coupling, highlighting the limitations of diffusive approximations in this regime. VFP-only simulations of non-local electron transport across a single high-density layer show the formation of preheat in the absence of hydrodynamic motion. Fully integrated simulations show that this non-local heat flux dynamically modifies the hydrodynamic evolution, leading to measurable changes in ablation behaviour and shock dynamics.

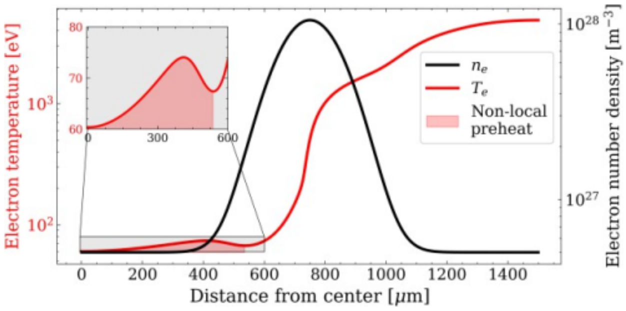

Figure 1. Electron number density (black) and temperature (red) profiles showing the non-local preheat across the density profile representing an ICF layer.

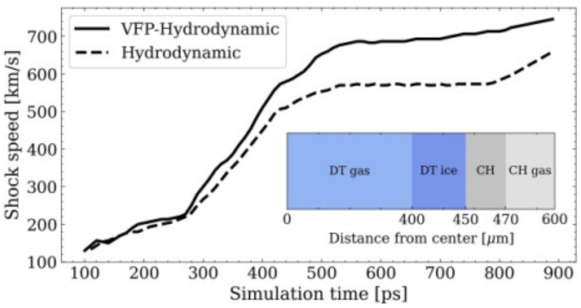

Figure 2. Shock speed comparison between VFP-hydrodynamic and hydrodynamic simulations with the inset showing the initial target configuration.

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Acknowledgements

This work was undertaken as part of UPLiFT (UK Programme of Laser Inertial Fusion Technology for Energy) and is funded by the UK's Department for Energy Security and Net Zero.

Stimulated scattering of a spectrally broadened laser beam in inhomogeneous plasma

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Abstract

Spectral smoothing of laser pulses offers a promising method for controlling parametric instabilities and enhancing laser-plasma coupling in inertial fusion research. Limited experiments with broadband lasers and contradicting theoretical results call for a broader evaluation of how pump bandwidth affects the excitation of parametric instabilities in a spatially inhomogeneous plasma. Here, we present studies of forward and backward scattering in such plasma by comparing a monochromatic pump, a phase-modulated pump, and a pump with random phase modulation. In the time domain, both phase-modulated and random pumps have a similar effect, reducing the temporal growth rate roughly inversely proportional to the bandwidth, in agreement with predictions from the random-phase approximation. However, notable differences appear in cases involving convective amplification with a spatially limited pump and in inhomogeneous plasma. The saturation level of scattered light increases and is associated with large temporal and statistical fluctuations when the pump correlation time is longer or comparable to the instability growth time. These fluctuations result from high-intensity spikes or groups of spikes in the pump field. The one-dimensional analysis of parametric instabilities is extended to speckled laser beams, assuming each speckle generates scattered light independently. While laser bandwidth can suppress scattering from low-intensity speckles, high-intensity speckles may still dominate the response. A criterion is proposed for suppressing stimulated scattering in speckled beams via laser bandwidth control.

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Acknowledgements

This work was performed in the framework of the TARANIS project supported by the French government as part of France 2030 (AAP Réacteurs Nucléaires Innovants - #DOS0237680/00) and the EUROfusion Enabling Research Project: CfP-FSD-AWP26-ENR-01 “Conceptual design for a European High Power Laser Fusion Research Facility” (HiPER+RF), funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion).

Adaptive Resolution two-photon polymerization as enabling technology for polymer laser targets in high-energy-density experiments

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Abstract

Two-photon polymerization (2PP) is a powerful high-resolution 3D printing technology that can produce tailored microstructures from submicron volumetric units called voxels. As voxels are scanned in a line-by-line fashion, print time scales with volume. Faster printing can be achieved by increasing the rate of volume processed per time. This is made possible by recent technological advances such as *Adaptive Resolution*, where the voxel size is dynamically adjusted to the local resolution requirements. As a result, complex macroscopic parts with microscopic features can be fabricated directly with 2PP within reasonable time. Besides improvements in fabrication time, *Adaptive Resolution* 2PP allows to create smooth surface finishes through precise voxel size tuning.

The relevance of 2PP microfabrication for high-energy-density physics has recently been highlighted in several studies. Moestopo et al. reported the fabrication of fully 2PP-printed prototype capsules incorporating additively manufactured foam architectures for liquid-DT wetted-foam polar direct drive concepts using UpNano's NanoOne system.[1] Wegert et al. employed high-resolution 2PP-printed foam-like microstructures sourced from UpNano GmbH in pump–probe experiments, demonstrating their applicability as microstructured targets under extreme conditions.[2]

In this contribution, we present recent developments in *Adaptive Resolution* 2PP and demonstrate how these advances extend polymer target platforms to regimes relevant for high-intensity laser interactions. These advances enable rapid iteration of complex target geometries including foam-based and architected polymer targets and support the exploration of next-generation fusion and extreme light–matter interaction experiments.

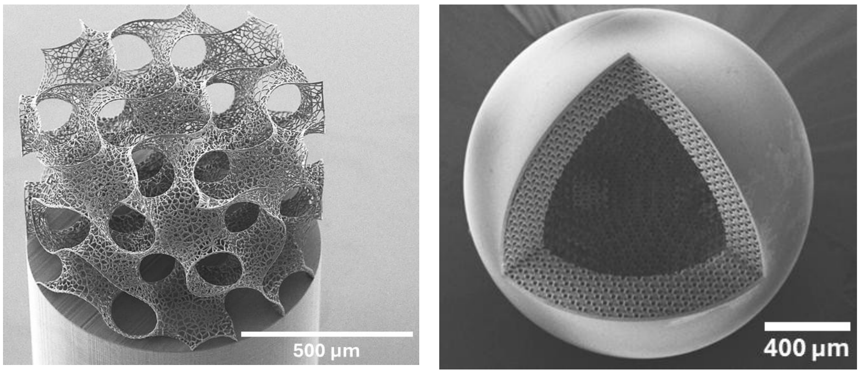

Figure 1. 2PP printed voronoified gyroid structure on target holder and foam capsule concept with gyroid layer.

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Laser-driven shock propagation in low-density foam targets investigated by time-resolved X-ray radiography and hydrodynamic simulations

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Abstract

We report an experimental and numerical investigation of laser-driven shock propagation in low-density foam targets, relevant to inertial confinement fusion applications. The experiment was performed at the Vulcan Target Area West laser facility, where a nanosecond laser pulse generated a shock through an ablator pusher package into a cylindrical TMPTA foam target with density 0.1 g cm^{-3}. The shock evolution was diagnosed using side-on, time-resolved X-ray radiography based on a picosecond laser-driven copper backlighter. Radiographic images were obtained at delays of 15 ns, 25 ns, and 35 ns, allowing the temporal evolution of both the pusher and the shock front to be resolved.

The experimental results were analyzed and compared with one- and two-dimensional hydrodynamic simulations performed using the MULTI and FLASH codes. A good quantitative agreement between experimental observations and simulations was found for an effective on-target laser intensity of approximately 5×10^{13} W cm^{-2}. The comparison confirms that, under the present experimental conditions, the foam response can be accurately modelled as a homogeneous medium with the same average density, providing experimental validation of hydrodynamic modelling assumptions relevant to inertial fusion target design.

Broadband Laser Absorption Study Based on Radiochromic Film Combined with Fiber-Optic Probes at the Low-Coherence Kunwu Laser Facility

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Abstract

Laser absorption efficiency is crucial for robust ignition in direct-drive inertial confinement fusion. However, significant energy loss can occur due to scattering from laser-plasma instabilities (LPI). At the low-coherence Kunwu laser facility, we developed and validated a novel diagnostic system combining radiochromic film (RCF) with fiber-optic probes, enabling continuous spatial mapping over approximately π steradians, thus allowing a more complete assessment of scattered light. We compared LPI behavior and absorption efficiency for monochromatic and 0.6% bandwidth lasers irradiating planar CH targets at intensities of 3-5×10^{14} W cm^{-2}. The key results are: Introducing a 0.6% bandwidth increasing the laser absorption efficiency from ~65-70% to ~85-92%. The bandwidth robustly suppressed stimulated Brillouin scattering (SBS), but enhanced stimulated Raman scattering (SRS) at high intensities. The RCF results agreed well with fiber-optic probe measurements at overlapping angles and successfully extended the diagnostic coverage to regions beyond the probes, confirming the feasibility and advantage of this combined scheme for accurate beam-target coupling evaluation. This work not only provides direct experimental evidence for bandwidth-induced LPI mitigation and coupling improvement but also develops a new diagnostic technique with large solid-angle coverage applicable to future larger-scale facilities, which is of great significance for advancing direct-drive fusion energy research.

Recent results on laser plasma instabilities with broadband laser pulses at PHELIX

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Abstract

Laser–plasma instabilities (LPI) significantly limit implosion performance in laser-driven inertial confinement fusion by scattering laser light and generating hot electrons that preheat the target. In our previous work, we investigated the effect of increased laser bandwidth using the upgraded PHELIX laser system. By comparing monochromatic and broadband (up to 0.5%) frequency-doubled Nd:glass pulses at 527 nm with 2 ns duration, we observed reduced two-plasmon decay (TPD) and stimulated Brillouin scattering (SBS), alongside enhanced stimulated Raman scattering (SRS) and increased hot-electron signals for broadband pulses [1].

Here, we present results from a new experimental campaign designed to extend and consolidate these findings. Measurements were performed over a significantly broader laser-intensity range, enabling a more systematic comparison with theoretical predictions. The plasma density was directly measured using interferometry to better constrain the experimental conditions. In addition, a low-intensity pedestal pulse was implemented to preheat the plasma, and its impact on LPI was investigated.

Preliminary analysis confirms the previously observed bandwidth-dependent trends in TPD, SBS, SRS, and hot-electron generation. The expanded parameter range, improved plasma diagnostics, and the introduction of a controllable pedestal pulse provide new insight into the role of broadband laser pulses in driving LPI in inertial confinement fusion experiments.

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Mapping of plasma critical surface with chirped laser pulses

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Abstract

Laser-driven inertial confinement fusion diagnostics play a crucial role in understanding the complex physical processes. Interaction between high-power laser and ablation materials leads to the formation of plasma critical surface which reduces the efficiency of the laser energy converted into the implosive kinetic energy. Effective diagnostic methods for the critical surface remain elusive. Here we present an optical diagnostic approach to investigate the plasma critical surface and has been experimentally validated. The schematic of the experimental setup is shown in figure 1, using the SG II nanosecond laser facility and the SG II femtosecond laser beam. The results demonstrate that the plasma critical surface has an oscillation in terms of the radiation pressure, and the velocity measured agrees well with the numerical simulation in the range of 1×10^5–2×10^5 m/s. The method has a potential for enhancing the uniformity of the driving laser and target surface, improving efficiency of the compressing nanosecond laser energy.

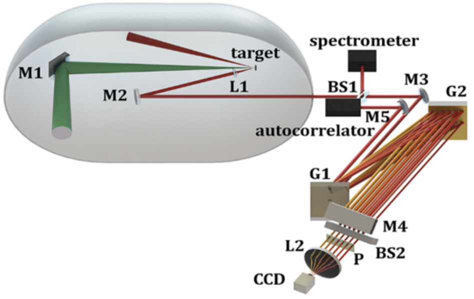

Figure 1. The experimental setup for plasma critical surface mapping with chirped laser pulses.

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Phase and absorption based X-ray imaging of laser-driven shocks – a platform for laser imprint studies

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Abstract

X-ray phase contrast imaging (XPCI) is a cutting-edge diagnostic technique that enables the recording of the phase and absorption as an X-ray beam with some transverse coherence passes through a target. The phase information supports the detection of steep density gradients, as a result XPCI is particularly well-suited for imaging laser-driven shock propagation inside low and high opacity targets. In this work, we advanced the platform originally developed by *L. Antonelli et al* [*EPL* **125**, 35002 (2019)] at the GSI PHELIX laser facility. A short-pulse laser was focused onto different targets to generate a point-like X-ray characteristic and bremsstrahlung backlighter with a source–to–object distance of 24 cm, and an image plate detector placed to record images with a magnification of 9. We discuss the use of different target materials and geometries to optimize the backlighter performance. This system is applied to the study of shock waves propagating through planar plastic and low-density foam targets. We demonstrate high-quality imaging and impact of ongoing efforts to extend this platform toward direct imaging of early-time, laser-imprinted perturbations. This is a critical topic for understanding hydrodynamic instability growth in laser direct-drive inertial confinement fusion and developing predictive implosion designs.

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Acknowledgements

The results presented in this manuscript are based on the experiment P-24-00229, which was performed at the target station PTA at the GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt (Germany) in the frame of FAIR Phase-0. This research was supported by the EPSRC and First Light Fusion under the AMPLIFI Prosperity Partnership - EP/X025373/1. The research leading to these results has received funding from LASERLAB-EUROPE (grant agreement no. 871124, EU's Horizon 2020 research and innovation programme. We greatly acknowledge the support of the Vulcan dark period community support programme 24-3.

Ion thermalization mechanisms in laser-irradiated low- density foams

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Abstract

Low-density foams are studied in inertial confinement fusion (ICF) as capsule ablators to enhance laser absorption and mitigate hydrodynamic instabilities. Modeling the interaction between intense laser pulses and foams is challenging due to the wide range of spatial scales between the solid filaments and voids. In this work, two-dimensional particle-in-cell (PIC) simulations were performed with the SMILEI code on the ENEA CRESCO8 HPC infrastructure [1]. A high-power laser pulse (wavelength 0.35 µm, intensity 10^{14} W/cm^2) interacting with a plastic foam of average density 1 g/cm^3 was investigated. Periodic boundary conditions were used to model the expansion of a single 0.1 µm-radius plastic filament, representing an element of an infinite periodic lattice, following the approach in reference [2].

The simulations show that foam homogenization is driven by both collisional and resonance absorption, with ablation being significant only during the first few picoseconds. Although the expanding plasma remains overall quasi-neutral, the filament expansion generates local electrostatic fields that accelerate ions into the void regions.

Based on the PIC results, a standalone analytical kinetic model was developed to estimate the characteristic ion–ion thermalization time as a function of the foam's geometrical parameters. The model identifies two main stages of thermalization: an initial velocity broadening due to collisions with hot electrons, followed by a phase dominated by ion–ion diffusion as plasmas from adjacent pores interpenetrate. This approach provides a predictive tool to estimate the plasma equilibration times observed in the simulations.

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Posters

Reproducibility analysis and angular distribution of TNSA-accelerated protons in High Repetition Rate laser-plasma experiments

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Abstract

Intense ion beams can be accelerated by powerful laser-matter interaction, through several mechanisms. Target Normal Sheath Acceleration (TNSA) [1-3] is one of the most explored, also for the wide range of applications that can enable. We present here a study aimed at optimizing the TNSA ions in High Repetition Rate (HRR) schemes. This was conducted by analyzing several nominally identical shots in an experimental campaign at the VEGA III laser (CLPU, Salamanca), with pulses having duration about 220 fs, intensities up to 10^{20} W cm^{-2} and about 25 J energy on thin foil (Al) solid targets. Diagnostics implemented for the experiment were suitable for the HRR regime and for accelerated proton detection: Time Of Flight (TOF) diamond detectors and Thomson Spectrometers. They were fielded at different angles, to have a suitable description of the emitted fluxes. Shot reproducibility resulted rather not ideal, due to several potential causes. We took into consideration both target nonuniformity and variation of laser main parameters, which can influence TNSA accelerated particle dynamics. In detail, we studied proton angular distribution to emphasize how critical the two contributions can be to grant uniform reproducibility. We found that the latter is worsened at emission angles farer from the target normal and identified potential sources of this effect. According to the well-known TNSA model, presented results will be discussed in relation with

the expected effects on the hot electrons accelerated by the ponderomotive force, responsible for the acceleration of the highest energy protons and of the recirculated electrons instead considered [4,5] the source of angled proton emission [6].
These results show the important role of target quality to grant the shot reproducibility required to fully exploit the potential of modern High Repetition Rate laser facilities. This is fundamental for their use for the effective investigation of complex physical phenomena with large statistics in relatively short time. Moreover, this study is of high importance for HRR proton Fast Ignition schemes.

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Investigation of Laser-Produced Energetic Electrons in Alternative Inertial Confinement Fusion Schemes

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Abstract

The interaction of ultra-intense lasers with solid targets is an active area of research with potential benefits for a variety of fields including laboratory astrophysics, bright x-ray sources, advanced fusion ignition schemes and particle acceleration. The efficiency of the laser-target energy coupling is a crucial parameter in these interactions and is governed by laser and target parameters. This makes the interaction a highly non-linear one, resulting in challenges when trying to unpick the fundamental coupling physics.

Recent advancements using structured nanowire targets have demonstrated enhanced laser absorption efficiency compared to planar targets [1-4]. Theory suggests structured targets extend the laser penetration depth and provide a greater surface area for interaction, resulting in increased energy deposition. However, experimental results in the ultra-intense, femtosecond regime remain scarce and existing data exhibits promising but highly variable results. Moreover, the exact absorption and acceleration mechanisms in structured targets at this regime are also under-researched and not well characterised.

This project investigates the use of nanowire targets to study how ultra-intense lasers couple energy into relativistic electrons and to evaluate the extent to which nanowire structures enhance absorption. This will be achieved through experimental and simulation work analysing outputs such as the distribution functions, electron energy spectra and electron beam emittance.

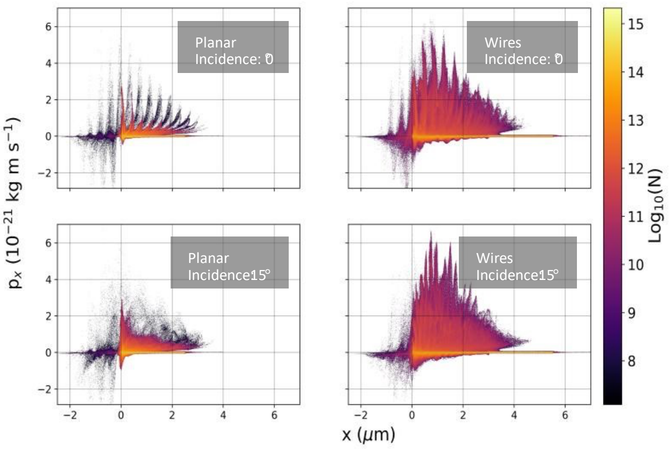

Figure 1 x−p_x distribution function at 40fs of planar (left column) and nanowire (right column) titanium targets for a laser at normal incidence (top row) and angled at 15° (bottom row) demonstrating varied absorption mechanisms.

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Side-Scatter Parametric Instabilities for Direct-Drive ICF: High-Statistics Study at 2ω

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Abstract

Side-scatter parametric instabilities have attracted renewed attention in the inertial confinement fusion (ICF) community[1], [2], [3], particularly for direct-drive schemes where they strongly impact laser-plasma coupling and hot-electron generation. To combat the growth of LPI one approach is to introduce dopants into the target to modify the Landau damping rates. An experiment was conducted at the ELI Beamlines facility using the L4n nanosecond-class, kilojoule-level laser system operating at 526 nm [4], with on-target intensities up to 8×10^{14} W cm^{-2}.

We investigated stimulated Raman scattering (SRS) in backscatter and side-scatter configurations, two-plasmon decay (TPD) in side scatter, and stimulated Brillouin scattering (SBS) in backscatter.

Experiments were performed using CH foil targets with controlled silicon doping concentrations (0–15%), with the aim of assessing the potential of Si-doped targets[5], [6] to mitigate hot electron preheat and reduce laser-plasma instabilities (LPIs). Plasma conditions were characterized by optical interferometry and supported by hydrodynamic simulations to determine density profiles and scale lengths.

The high repetition rate of L4n allowed the acquisition of approximately 500 shots, providing unprecedented statistics for experiments of this type.

We present the influence of silicon dopant concentration on the growth rates and spectral characteristics of SRS, SBS, and TPD, along with the effect of a pre-pulse laser pedestal on instability development. This comprehensive dataset provides insights for optimizing direct-drive schemes at the second harmonic.

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Statistical framework for nonlinear SRS bursts in broadband speckled laser fields

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Abstract

Broadband lasers are usually expected to suppress stimulated Raman scattering (SRS) because the linear growth rate decreases approximately as $1/\Delta\omega$. Yet 2D kinetic PIC simulations of incoherent speckled pumps still exhibit intermittent nonlinear SRS bursts, driven by rare high intensity envelope spikes that seed electron trapping and burst-like amplification even when the bandwidth exceeds the nominal linear growth rate. We present a statistical framework for these events in broadband speckled laser fields. Using Kac–Rice statistics for spike amplitudes and event rates, together with associated waiting-time statistics and a trapping-motivated burst criterion, benchmarked against Monte Carlo realizations, we map the probability and finite-realization variance of burst occurrence as functions of intensity, bandwidth, and observation-window duration. This allows finite PIC windows to be interpreted within the statistics of much longer laser pulses, separating typical behaviour from rare but expected events that dominate nonlinear onset. The framework is now being tested directly against 2D PIC simulations in the regime where nominal linear bandwidth-suppression arguments fail.

To connect these statistics to realistic optical delivery, we also model the spatio-temporal coupling of a broadband random-phase-plate beam focused with a dispersive quartz lens. Quartz dispersion introduces longitudinal chromatic aberration, so different spectral components focus at different axial positions and produce partially shifted speckle realizations set by the phase-plate structure, rather than sampling a common speckle pattern. We have developed a Huygens–Fresnel focal-field code that computes the full 3D complex field of such multi-frequency, phase-platefocused beams and generates ensemble focal spots over bandwidth, phase-plate, and dispersion parameters. These calculations resolve how optical frequency is distributed across the focal volume, how the effective focal region elongates toward the coherence scale imposed by the phase-plate structure, and how the resulting spatio-temporal coupling breaks the standard factorization of spatial and temporal statistics used in conventional bandwidth-suppression models. Together, the burst framework and the focal-field calculations provide PIC-ready inputs and identify the conditions under which broadband speckled beams continue to seed nonlinear SRS despite nominal bandwidth suppression.

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2D PIC simulations of stimulated Raman scattering with spatially smoothed and quasi-broadband lasers.

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Abstract

Hydrodynamic instabilities and Laser Plasma Instabilities (LPI) both play a crucial role in laser-driven Inertial Confinement Fusion (ICF) and much work has been done to try and mitigate their adverse effects[1,2]. As part of the Taranis project, novel target illumination schemes and beam smoothing techniques are being developed to address these issues in a direct drive configuration.

In this work, we investigate, through 2D Particle-In-Cell (PIC) simulations performed with SMILEI[3], the impact of bandwidth and spatial smoothing of the laser on the development of LPI in regimes typical of direct drive ICF.

Using newly implemented tools to simulate quasi-broadband pulses with multi-polarisation and Random Phase Plates (RPP), we are able to control the speckle structure of the laser pulse to better reproduce realistic beams[4].

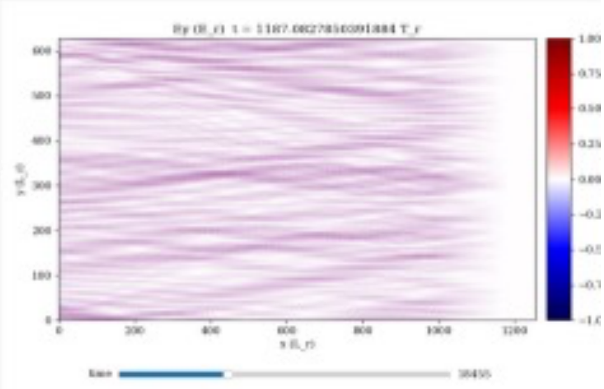

Figure 1. Laser speckles generated by 1D RPP of 50 elements as they appear in our 2D PIC simulations performed with SMILEI.

The development of Stimulated Raman Scattering (SRS) and Two Plasmon Decays (TPD) and their impact on back and side scattering depending on the smoothing parameters and plasma conditions were investigated. Understanding and controlling these phenomena is also essential to control the generation of hot electrons which are a critical source of pre-heating in ICF.

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Medium - to High – Spatial - Mode Control using a Multi-Color Laser Beam Bundle

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Abstract

In direct-drive inertial confinement fusion (ICF), capsules are directly irradiated by multiple symmetrically arranged laser beams. Non-uniformities in the laser focal spot can seed hydrodynamic instabilities and significantly degrade target implosion performance, making beam smoothing techniques essential for achieving high gain. These techniques act to reduce spatial intensity modulations in the focal spot.

We have developed a numerical model that integrates several smoothing techniques, including two-dimensional smoothing by spectral dispersion (2D SSD) and induced spatial incoherence combined with angular dispersion (ISI+AD).

In this work, we demonstrate the ability to control medium- to high-spatial-frequency modes imprinted on the capsule. This control is achieved by employing multiple laser beams with distinct central frequencies, each independently smoothed using either 2D SSD or ISI+AD. With this tunable multi-color design, we show that medium-mode amplitudes can be reduced on timescales significantly shorter than those achieved on the Omega laser facility.

Effect of residual gas pressure on ablation plasma properties in ns-kJ laser-solid interactions

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Abstract

The interaction between a ns-kJ laser and a solid target has been studied for decades. As a key topic in many fields, in particular inertial confinement fusion, numerous studies have aimed to improve the coupling of the laser pulse energy to the target by various means (temporal shaping, optical and/or temporal smoothing, etc.).

In this study, carried out with the ns-kJ L4n laser at ELI Beamlines (Prague), we show the effect on the ablation plasma of increasing the air pressure in the chamber from 10^{-5} to 1 mbar. The high-repetition rate of the laser (1 shot every 3 min) allows the recording of a solid dataset with clear statistics. The target was thick PVC and thanks to the use of high-spatial and high-spectral resolution X-ray spectroscopy, we observe a significant effect of the vacuum pressure on the H-like Cl ions population. We observe that increasing the vacuum pressure makes it possible to significantly increase the electron temperature of the hottest and densest part of the plasma by about 20% while leading to a substantial reduction of the measured Raman backscatter (SRS).

We present these results together with detailed simulations aimed at explaining the underlying phenomena. We also discuss the potential impact of these findings on the design of the first wall for a future reaction chamber of an IFE reactor.

Acknowledgements
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Modelling of Beam Smoothing for Direct-Drive Central-Hot Spot Ignition

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Abstract

In direct-drive inertial confinement fusion, a millimeter-scale capsule filled with deuterium–tritium is compressed and heated by hundreds to thousands of laser beams. Each beam produces a focal spot with a top-hat or hyper-Gaussian profile, with a diameter comparable to the capsule size. At smaller scales, the intensity distribution consists of thousands of micrometer-sized speckles arising from diffraction. These localized intensity modulations induce target inhomogeneities that seed hydrodynamic instabilities.

To mitigate this effect, beam smoothing techniques are employed to induce high-frequency motion of the speckle pattern. When time-integrated, this motion reduces spatial non-uniformities and smooths the focal spot.

We have developed two complementary models to accurately compute the power spectral density of the focal spot under various smoothing techniques. The first model is based on analytical formulations describing the field at and around the focal plane and is parallelized using OpenMP/MPI, enabling efficient calculations for large numbers of beams. The second model, valid at focus, provides a simplified formulation used to validate the analytical approach and to offer a simpler computational alternative.

These models incorporate multiple smoothing techniques, including one- and two-dimensional smoothing by spectral dispersion (SSD) for coherent beams, as well as SSD with angular dispersion and induced spatial incoherence combined with angular dispersion (ISI+AD) for partially incoherent beams.

Experimental Observation of Temporal Bursts of Stimulated Raman Scattering at 2ω

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Abstract

Stimulated Raman Scattering (SRS) is a well-known parametric instability in inertial confinement fusion (ICF) experiments, where it drives energy transfer out of the laser beam and generates suprathermal electrons leading to preheat of the fuel. Its characterization typically relies on a combination of radiation-hydrodynamic simulations, and particle-in-cell (PIC) simulations, which resolve the kinetic physics of the instability at the sub-wavelength scale inaccessible to hydrodynamic codes.

In experiments conducted at ELI Beamlines (Czech Republic) using the L4ni laser at 2ω, we report the reproducible observation of SRS emission in temporally confined bursts of 10s of ps duration, at wavelengths shorter than the convective SRS region. This behaviour was recorded across more than 700 laser shots spanning multiple experimental campaigns, firmly establishing it as a robust physical regime rather than a diagnostic artifact. While qualitatively similar low-wavelength signatures have been reported at other facilities, they have never been fully investigated.

We present the experimental scaling of this burst regime as a function of the relevant laser and plasma parameters, supported by PIC simulations aimed at identifying the underlying physical mechanism. Two candidate explanations are currently under investigation: electron trapping, driven by the growth of the electron acoustic wave, and laser filamentation induced by the speckle structure of the phase-plate beam. Resolving this regime has direct implications for the predictive accuracy of radiation-hydrodynamic codes used in ICF design, which could potentially overlook this specific regime.

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Modulations on Thomson parabolic-like ion-patterns caused by ElectroMagnetic Pulses

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Abstract

High-intensity lasers, interacting with matter, produces many processes which lead to the generation of intense electromagnetic fields, in a spectrum ranging from MHz to THz, known as electromagnetic pulses (EMPs). The effects of the EMPs on the instrumentation are long-time studied topic, especially in laser-driven ion acceleration and nuclear-fusion experiments.

We studied the effects of such fields on the Thomson Spectrometer (TS), a widely used device for the detection of the mass-to-charge ratio and energy spread of emitted ion beams in laser-matter interaction experiments. This detector separates particles by their mass-to-charge ratio and their energy using electrostatic and magnetostatic fields, producing characteristic parabolic traces. Spurious EMPs affect the static fields inside the TP, causing ripples in the particle traces. From the analysis of the ripples, we retrieved the relative intensity and the temporal evolution of the intercepted EMP. With this method, we could measure in the same shot the electromagnetic signal captured by the TP-electrodes, which acts as a voltage variation between them, and the particle traces imaged in the detection plane of the TP. Previous studies examined EMP effects on proton-associated parabolas.

We applied them and also extended the methodology to study EMP-induced modulations on parabolas created by heavier ions, with promising results. The TS could serve as a novel diagnostic tool for measuring EMPs, furnishing a new tool for a deeper insight into the laser-plasma interaction dynamics and the generation of these phenomena.

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Simulations of asymmetric implosions in magnetised direct drive cylindrical targets on NIF and OMEGA

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Abstract

Applying external magnetic fields to inertial-confinement fusion implosions has been observed to improve ion temperature and fusion yield at both NIF [1] and OMEGA [2], primarily by suppressing thermal conduction losses in the hotspot. Accurately modelling this behaviour requires the inclusion of extended MHD effects that impact magnetic flux compression [3]. These effects can be more readily studied through cylindrical implosion experiments, as such geometries are simpler to diagnose than spherical ones while still capturing relevant extended MHD phenomena.

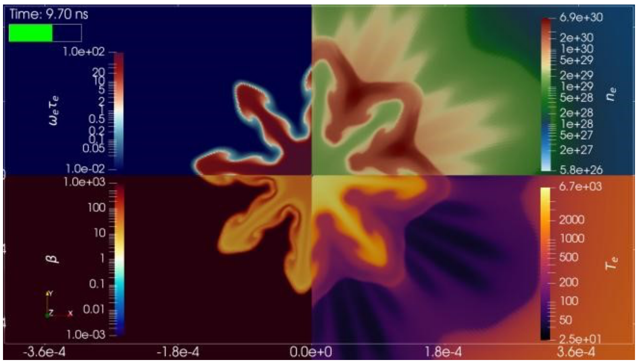

Figure 1. Simulated mode-8 from beam pointing used at NIF for the magnetised cylindrical implosions.

Although promising, results from recent direct-drive experiments involving imploding magnetised D₂ gas-filled cylinders at OMEGA [4] and NIF have fallen short of the compression ratios and yields predicted by simulations assuming azimuthal symmetry. In this work we use the CHIMERA radiative-MHD code to investigate how long-wavelength azimuthal asymmetries – seeded by the laser beam geometry used at these facilities – can lead spatially integrated diagnostics to overestimate the core radius and thus misrepresent stagnation conditions.

Previous implosion simulations have typically assumed angular symmetry [4], but ongoing 2D/3D simulations incorporating azimuthal variation indicate that NIF-like laser conditions introduce a major mode-8 instability (Fig. 1) in the stagnation phase, leading to lower fusion yields due to reduced energy retention. Corresponding simulations of similar experiments on OMEGA also demonstrate the development of a mode-5 instability from beam-pointing geometry. Synthetic x-ray self-emission diagnostics confirm that these instabilities lead to reduced experimental compression metrics when including azimuthal variations, which agrees with experimental results.

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A Roadmap for Integrating Plasma-Aware Charged-Particle Transport Models into the Geant4 Toolkit

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Abstract

Geant4 is a widely used Monte Carlo toolkit for particle transport in matter, featuring well-established electromagnetic physics models optimized for cold and condensed media. However, in fusion-relevant plasmas, the slowing down and energy deposition of charged particles are strongly influenced by freeelectron screening and collective plasma response, limiting the predictive capability of simulations for inertial confinement fusion. Within the HiPER+RF framework, INFN-LNS is addressing these challenges by advancing plasmadependent stopping-power models and experimental diagnostic benchmarking to extend transport descriptions toward realistic warm dense plasma conditions.

This work presents a technical roadmap for integrating plasma-aware chargedparticle transport into Geant4 through two staged capabilities: (i) a Modified Li– Petrasso (MLP) stopping-power model for continuous energy loss (CSDA/continuous slowing-down), and (ii) a forward-compatible dielectricresponse framework (RPA–LDA class) for warm dense matter extensions. The roadmap emphasizes class design (G4VEmModel and continuous processes), physics-list integration, plasma-state parameter injection via materials, and a verification strategy anchored to published benchmarks and representative laser-driven p-^{11}B experiments.

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Particle-In-Cell Simulations of Proton Fast Ignition in Magneto-Inertial Confinement Systems

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Abstract

Fast Ignition is an advanced approach for Inertial Confinement Fusion where the compression and ignition of the fuel are decoupled, reducing the symmetry and energy requirements for fuel compression [1].

The private company First Light Fusion in the United Kingdom are currently designing a magnetoinertial concept device, FLARE [2], where a large volume of cold, dense fuel is first assembled via magnetically-driven liner compression, followed by an intense laser-driven beam of electrons or protons to one end of the compressed fuel cylinder to spark fast ignition.

Initial work has been done to adapt an existing particle-in-cell module originally written for alpha heating, to allow for modelling the delivery of particle beams to fuel. Additional beam diagnostics were implemented, enabling tracking of the heat deposited into the fuel by the beam. These changes allow for the simulation of fast ignition, where a particle beam heats a volume of compressed fuel, and the subsequent generation of fusion alphas that drive a propagating burn throughout the fuel can be studied. This work aims to identify the minimum energy requirements in compressing fuel and delivering energy via a particle beam to achieve ignition in magneto-inertial confinement systems like FLARE.

These studies have investigated the energy dynamics of the hotspot formed upon the delivery of a proton beam of varying power, radius, and duration, which must exceed the corresponding losses due to thermal conduction, radiative and PdV energy losses of the deuterium fuel volume at varied initial densities, ρR and temperatures upon compression.

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Stimulated Raman scattering in underdense plasma from low-density SiO_2 foam driven by a kilojoule-class laser at PALS

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Abstract

The interaction of high-power laser pulses with low-density porous materials is of significant interest for inertial confinement fusion (ICF) and high-energy-density physics. We report on experimental studies supported by hydrodynamic and kinetic simulations of laser interaction with ultra-low-density SiO_2 foam. The experiments were performed at the Prague Asterix Laser System (PALS). The third harmonic of a kilojoule-class iodine laser ($\lambda = 438$ nm, $\tau \approx 350$ ps) was focused to intensities of ~10^{16} W/cm^2. An additional heating beam with an energy of 50 J was applied with a variable delay of 0.5–2 ns prior to the main pulse to preheat the foam and generate an extended plasma density profile. The targets consisted of closed-pore foams composed of ultra-thin SiO_2 shells with an average density of ~40 mg/cm^3.

We present a combined experimental and numerical analysis of the underdense plasma formed from the foam and its dependence on the delay between the heating and main beams. Scattered-light diagnostics are analyzed as a function of this delay and interpreted with the support of laser–plasma interaction simulations. The results show that, in the density range relevant for stimulated Raman scattering (SRS), the longitudinal plasma profiles are only weakly affected by the heating beam. However, plasma homogenization in the underdense region remains incomplete during the interaction with the main pulse unless the heating beam is applied with a sufficiently long delay. The effect of the residual density perturbations on the SRS enhancement is studied using kinetic simulations and discussed in connection with the measured scattered-light signals.

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2D Stimulated Raman backscattering of a broadband laser propagating in an inhomogeneous plasma

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Abstract

Laser-plasma instabilities (LPI) are still a major issue for achieving thermonuclear gain in inertial confinement fusion (ICF) schemes. In particular, looking at the direct drive scheme, some instabilities like the stimulated Raman scattering (SRS) are still not sufficiently mitigated. One promising solution is too use broad band lasers. It is already well known that enlarging the laser spectrum is beneficial to the laser-target coupling, this is proven for many years by using the so-called optical smoothing by spectral dispersion (SSD). However, those techniques produce a relative small bandwidth, typically 0.1% of the central frequency, where at least 1% is needed for SRS. Going to higher bandwidths is feasible, but depending of the laser technics, those larger bandwidths posseses some drawbacks, like the appearance of high intensity temporal spikes. We recently investigated the physics at play with the help of a simplified model and simulations in a mono-dimensional (1D) homogeneous plasma [1]. We now investigate the stimulated Raman backscattering of a Gaussian beam in two spatial dimensions (2D) and in an inhomogeneous plasma using the HERA paraxial code. The inhomogeneity is controlled by using a linear gradient, giving rise to spatial amplification governed by the Rosenbluth gain. This fine tuning allows us to explore regimes spanning from weak to strong inhomogeneity, irradiated by a monochromatic laser and various laser bandwidths. We show that broadband lasers, as in the homogeneous case, may enhance the reflectivity if the bandwith is too small. Some criteria for achieving LPI mitigation will also be discussed.

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Study of Equation of State of Boron compounds in extreme conditions

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Abstract

Cubic boron nitride (*c*-BN) emerged as a possible alternative to diamond (HDC) as ablator material for ICF capsules. Both materials share properties crucial for ICF: low atomic number, high density, high bulk modulus and superior chemical resistance. BN also offers an additional advantage as a real-time fusion diagnostic through gamma-emitting nuclear reactions induced by neutrons and protons interacting with B and N nuclei. Also, *c*-BN has a lower melting temperature than HDC, which could facilitate shock-induced melting at lower pressures, potentially enabling ICF implosions with reduced laser foot intensity. However, experimental data for BN at high compression are very limited. We performed an experimental campaign at the GEKKO laser system of ILE, Osaka, to obtain Equation of State (EoS) data points for *c*-BN (3.48 g/cm^3) and hexagonal BN (*h*-BN, 2.05 g/cm^3). Experiments employed second and third harmonic beams, focused on a spot size of 600 μm diameter, producing intensities from 10^{13} to 10^{14} W/cm^2 and ablation pressures of tens of Megabars. Velocity Interferometer System for Any Reflector (VISAR) and Streaked Optical Pyrometers (SOP and SSOP) were used for shock velocity and temperature measurements. The impedance mismatch technique was employed to determine the EoS points by measuring shock velocities in quartz (reference material) and the sample materials. Shock temperatures were simultaneously determined through thermal self-emission to provide independent thermodynamic constraints on the Equation of State.

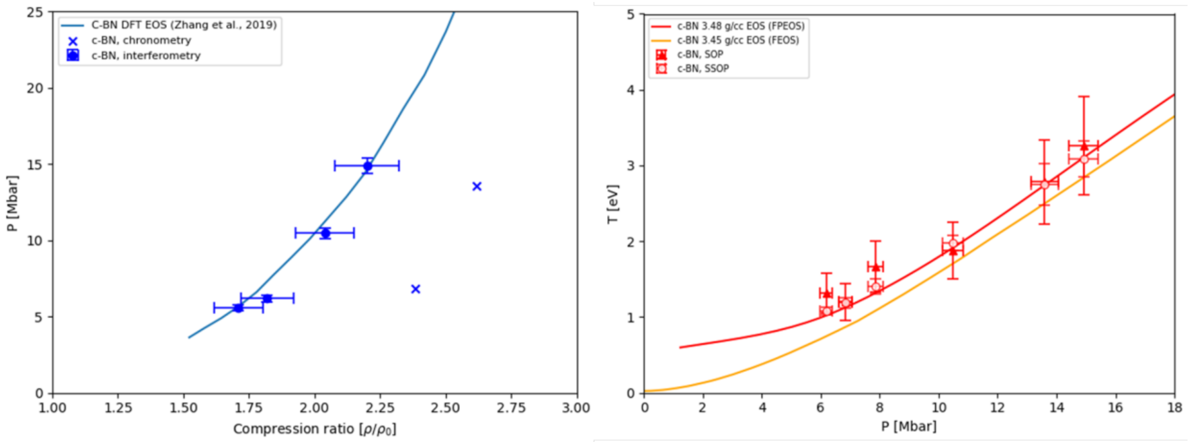

Figure 1. Measured EOS points of cubic Boron Nitrate and amorphous Carbon compared with theoretical models..

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Updates on SBS and synthetic diagnostics in an in-line laser-plasma instability model

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Abstract

Laser-plasma instabilities (LPI) are a class of absorption mechanisms that occur when a sufficiently intense laser couples with and amplifies waves in a plasma. LPI are a significant issue for direct drive inertial confinement fusion as they prevent the laser from being collisionally absorbed, instead redirecting the energy into increasing the amplitudes of problematic plasma waves and acceleration of hot electrons.

As the field of ICF moves develops different approaches to modelling LPI, we present here updates from our LPI model, which is designed to run in-line with ray tracing routines. It includes the instabilities stimulated Raman scattering (SRS), stimulated Brillouin scattering (SBS) and two-plasmon decay (TPD) which are saturated via pump depletion, wave dephasing for convective SRS and SBS, and the Langmuir decay instability for absolute SRS and TPD. Recent updates to be presented include an improved SBS model and ray tracing of scattered light waves to create synthetic scattered light diagnostics for experimental validation, including an explanation of the Raman gap.

Kinetic Modelling of Magnetic Instabilities in ICF Plasmas

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Abstract

Thermal transport in inertial confinement fusion (ICF) is often non-local and can be significantly modified by large, self-generated magnetic fields. This coupling can drive instabilities within the magnetic field itself, such as the magnetothermal instability [1], which alters the distribution of thermal energy in the plasma. The growth of the magnetothermal instability in the non-local, collisional regime is poorly understood, and predicting its behaviour in this regime requires a full kinetic treatment. Recent development of the Vlasov–Fokker–Planck (VFP) code K2 allows such investigation to high physical accuracy and fidelity. We present a comparison between the classical and kinetic growth rate for the collisional magnetothermal instability using the hydrodynamic code CTC and kinetic code K2 respectively, and explore the impact of higher order corrections across multiple initial wavenumbers. This study reveals how anisotropy influences the magnetothermal instability and the subsequent effect on thermal evolution. Full understanding of these effects is vital for improving predictive modelling of kinetic instabilities in ICF plasmas and for next-generation ICF experimental facilities.

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X-Ray and Neutron Diagnostics for Laser-Plasma Experiments

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Abstract

X-rays monitoring produced as a result of laser–target interaction is complicated by the nearly simultaneous emission of photons, which makes it impossible to distinguish individual events in laser-produced plasmas, thus leading to the so-called multi-photon regime. We present two complementary X-ray diagnostics developed for laser–plasma experiments, which can operate either independently or in a combined configuration.

The first diagnostic is a Gas Electron Multiplier (GEM) detector [1] working in the "side-on configuration". In this approach, photons enter the gas volume and release charge along the detector depth, allowing reconstruction of the absorption profile in the 2–50 keV energy range using an Ar/CO_2 gas mixture, extendable to higher energies with Xe or Kr. With an active area of about 10 × 10 cm^2 and a 10 cm gas depth, the GEM performs 1D spectroscopic measurements exploiting photon absorption along the gas volume. The detector features side entrance and exit windows (6 × 80 mm^2) and a PCB anode divided into four lines of 64 pads (1.5 × 20 mm^2 each). The readout is based on the GEMINI chip, which in single-photon regime measures position (X,Y), charge, and photon energy via Time-over-Threshold (ToT) technique together with Time-of-Arrival (ToA) with nanosecond accuracy [2]. It enables single-shot measurements and sensitivity to the thermal plasma emission.

The second diagnostic is a Timepix3 pixel detector with 55 μm × 55 μm pixels and 14 mm × 14 mm active area, providing simultaneous ToA and ToT measurements and morphological track identification [3]. Using the full silicon depth, it detects hard X-rays (50–500 keV) and gamma rays (0.5–10 MeV) [4], complementing the soft X-ray information provided by the GEM. The two systems can operate separately or be combined along the same line of sight to form a compact broadband spectroscopic system. In the combined configuration, the GEM measures the soft X-ray absorption profile, while higher-energy photons exiting the gas chamber are detected by a downstream Timepix3 detector positioned side-on at the GEM exit. Experimental results, conducted at the ILIL facility of the CNR-INO Institute of Pisa, demonstrate simultaneous detection of soft and hard X-ray emission, with the GEM providing information on the thermal spectrum and the Timepix3 identifying distinct higher-energy photon populations [5]. Timepix3 detectors can also be configured for neutron detection using a CVD diamond TPX3 with 14 × 14 mm^2 active area [6] or a silicon TPX3 coupled to a polyethylene converter. In experiments performed at the L3 laser facility at ELI-Beamlines, deuterium–deuterium fusion reactions were investigated using high-intensity laser interaction (~10^{21} W/cm^2) with deuterated plastic targets, aiming at detecting 2.45 MeV fusion neutrons. The detection system included a silicon Quad Timepix3 detector (four-chip assembly, 100 μm thickness) coupled to a polyethylene converter placed about 1 mm from the sensor surface. The converter enables detection of recoil protons generated by neutron interactions, which are identified through track morphology and time-of-flight analysis.

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2D Modelling of Backscatter from Direct Drive Implosions

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Abstract

Laser-plasma instabilities (LPIs), e.g. Cross Beam Energy Transfer (CBET) and Stimulated Brillouin Scattering (SBS), couple incident laser energy to outgoing light waves via plasma wave interactions. In direct drive experiments, CBET and SBS redistribute incident laser energy, potentially leading to inefficient laser deposition and asymmetric compression [1]. Therefore, reduced models for these instabilities must be included in ray-based codes, used in radiation hydrodynamics simulations, to more accurately predict energy losses and model suprathermal electrons, which degrade compression via pre-heat. The evolution of these instabilities can be inferred from backscatter diagnostics, although pinpointing exact instability effects, without codes capable of producing synthetic data, is challenging.

SOLAS is a ray-based code for laser-plasma interactions, currently capable of modelling CBET [2]. It is coupled to the Eulerian radiation hydrodynamics code, CHIMERA, which is used to simulate direct drive implosions [3]. In this work, we present the development of SOLAS to model additional LPIs, including SBS, Stimulated Raman Scattering and Two Plasmon Decay. This is planned to be an inline capability, so more predictive simulations can be run at larger scale. We aim to validate these models using a time-and-wavelength resolved synthetic scattered light diagnostic. We demonstrate this for the CBET model, by comparing results to those of simulations conducted using the DRACO laser fusion code [4].

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21st Direct Drive and Fast Ignition Workshop

Low-energy particle spectrometry for Inertial Confinement Fusion and laser-plasma applications

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Abstract

Studying and characterizing particle beams generated from laser-plasma interaction at high intensity is relevant for several applications, including inertial confinement fusion (ICF) experiments with schemes of fast ignition and shock ignition [1,2]. In ICF, low energy electrons (in the few tens of keV range) provide information about the hot-spot formation, the energy transport and the charged-particle stopping. Measuring their energy distribution is useful to study laser–plasma instabilities and preheat, providing a feedback on laser-target coupling efficiency [1,2]. Moreover, measuring the electron emission in the keV range in laser-plasma experiments is useful for studying the generation of electromagnetic pulses and transient fields, that are potentially exploitable for magnetized ICF [3]. Positive ions and protons in the MeV and sub-MeV energy range, carry sensitive information about fusion reaction yield, rate, and spatial emission profile; their energy distribution can be linked to the electron temperature [1,4]. Moreover, they can be used for probing electric and magnetic fields in configurations of magnetized ICF schemes [5]. In addition to ICF scenarios, the characterization of low energy ions is crucial in laser-plasma experiments aiming at applications in, e.g., low-rate fusion reactions such as proton-boron, warm dense matter and material science [6,7]. In this work, we show the development of low-energy particle diagnostics, i.e. one of the main activities of the ICF group at ENEA-Frascati, for more than one decade. In the last years we designed, fabricated and implemented various prototypes of Thomson spectrometers, capable of detecting protons and ion species from <100 keV to several MeV (proton energy). These devices have been constantly improved, finally achieving an optimal resolution/sensitivity, adaptability to different detector types and exploitability in harsh working conditions (EMP and radiation robustness). We will also present recent results concerning the design and development of magnetic spectrometers for low energy electrons. These devices have magnetic and mechanical features that allow measuring electrons from ~20 keV to >2 MeV. These diagnostics have been tested in experiments of generation of LPIs and laser-irradiation of 3D-printed foam targets. Preliminary results will be presented.

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Exact solution of the Gaunt-modified Landau–Lifshitz equation in a plane wave

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Abstract

Ultra-intense laser–plasma interactions and plasma-based electron accelerators provide access to regimes where radiation reaction significantly influences particle dynamics. The Landau–Lifshitz (LL) equation provides the standard classical description and admits exact analytical solutions in a plane-wave background, as demonstrated by Di Piazza [1]. In this geometry, the solution can be expressed in terms of integrals over the plane-wave phase, allowing closed-form expressions for the four-velocity and trajectory.

When the quantum nonlinearity parameter χ reaches the moderately quantum regime, $\chi \sim 0.1$–1, the classical LL equation overestimates radiative losses, as quantum recoil suppresses the average emitted power [2, 3]. A fully quantum treatment based on stochastic photon emission captures the discrete nature of radiation but generally requires probabilistic or numerical methods. In large-scale particle-in-cell simulations, quantum effects are therefore commonly incorporated through a deterministic semiclassical correction in which the classical radiation-reaction force is multiplied by a χ-dependent Gaunt factor $g(\chi)$ [2]. While this approach reproduces the quantum-suppressed mean emission rate, it does not describe stochastic broadening effects [4].

Here we show that the Gaunt-modified LL equation remains exactly integrable in a planewave background. Using the fact that the quantum parameter χ depends only on the plane-wave phase, the dynamics can be reduced to a single quadrature determining the four-velocity and trajectory, from which energy and momentum components follow.

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FLARE: A Low-Power Assembly and Fast-Ignition Approach to Inertial Fusion Energy

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Abstract

We present FLARE, First Light Fusion's concept for inertial fusion energy based on Fusion via Low-power Assembly and Rapid Excitation, and discuss its relevance to fast-ignition target design. FLARE is built on three coupled ideas: quasi-isentropic fuel assembly using low-power pulsed compression, ignition by rapid auxiliary heating, and reactor integration through a liquid-lithium blanket concept. In this presentation, we focus primarily on the first two elements, namely low-power fuel assembly and rapid ignition. In contrast to conventional hotspot approaches, FLARE seeks to decouple compression and ignition, thereby reducing driver power requirements and relaxing symmetry constraints while preserving a pathway to high target gain. The target architecture uses a dense, high-opacity pusher to enhance confinement and reduce radiative losses, creating conditions favourable for ignition of a small fuel region followed by burn propagation into a larger assembled fuel mass. We will outline the physical basis of the concept and candidate routes to ignition, including short-pulse laser coupling. We will also briefly place this target concept in the wider FLARE reactor framework, in which a liquid-lithium blanket is intended to support neutron absorption, tritium breeding, and reactor protection. This integrated approach aims to provide a robust and potentially lower-cost route towards inertial fusion energy.

Nuclear Micro-Fusion compression and ignition by X-Ray Direct Drive in Double-Shell Fuel-Pellet Driven by High Power Lasers

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Abstract

Nuclear Micro-Fusion Fuel-Pellets have been successfully ignited by X-Ray Indirect-Drive in the NIF high power laser heated Hohlraum [1] yielding recently [2], a ‘scientific gain’ of ~ 4x = (E_{Fusion} ~ 8MJ)/ (E_{Laser} ~ 2MJ). The Pellet is compressed and ignited from a Hot-Spot, by Soft X-Ray ablation inside the Hohlraum. The measured [2] Hohlraum coupling efficiency is $\eta_{hohl} \sim 12\%$ = (Energy X-ray absorbed by Fuel Pellet/ Energy of Laser Driver). We split η_{hohl} into: Laser-to-Xray conversion efficiency estimated at $\eta_{L\text{-}X} \sim 70\%$ from Gold (Au) inner wall [1] of the Hohlraum cylinder and a geometric coupling which we define as $\eta_{Geom} = \eta_{hohl} / \eta_{L\text{-}X} \sim 17\%$ for the above. A ~10% ‘Hohlraum coupling’ is generally considered too small for using Indirect Drive in a Nuclear Fusion Power Plant.

We estimate an increased coupling to $\eta_{hohl} \sim 35\%$ from our new scheme of X-Ray Direct Drive Nuclear Microfusion in Double-Spherical-Shell driven by High Power Lasers. Such an increase in ‘coupling’ could reduce the required Laser Driver energy from 2 MJ (NIF) to less than 1MJ. The inner sphere contains the Nuclear Fuel, like the Indirect Drive scheme. The Soft X-ray ‘beams’ are emitted from multiple laser-plasma- point-sources generated on the inside of the gold surface of the outer sphere by focused High Power Lasers, as shown in Figure 1. The plasma X-rays propagate as ‘beams’ with a ‘cosine θ’ distribution around the normal to the inner surface which points to the common centre of the two concentric spheres.

The new X-ray Direct-Drive scheme is estimated to increases the geometric coupling of X-rays emitted by the laser-plasma to $\eta_{geom} \sim 50\%$ for a ratio of 1.5 between the radius of the outer and inner spheres: R2 = 1.5 R1. In this case $\eta_{hohl} \sim 35\% = (\eta_{L\text{-}X} \sim 70\%) \times (\eta_{geom} \sim 50\%)$. The required uniformity of X-ray irradiation of the inner sphere would be achieved by overlapping the ‘edges’ multiple ‘X-ray beams’ as shown schematically in Fig.1.

We eliminate the X-ray losses at the laser entrance holes since the X-ray propagate directly from the laser-plasma on the outer-sphere to the Fuel-Pellet inner-sphere - X-rays do not bounce off walls like in Hohlraum. Large laser entrance holes could be beneficial in reduce the number of X-Ray ablated ions trapped between the two shells: they can escape through holes. The ‘X-ray Beams’ will follow instantaneously the temporal shaping of the Driver Laser Pulse. All the other advantages of X-ray indirect drive would be maintained in the X-Ray direct drive scheme: excellent laser to X-ray conversion ~70-80%; reduced Laser-Plasma-Instabilities (LPI); and increased ablation of X-rays in comparison to Laser Direct Drive schemes. The Driver laser beams will be distribution will be closer to a spherical geometry [Fig. 1] compared to Indirect Drive geometry [1]. The alignment of the Laser beams may become simpler. The target insertion/positioning mechanism need be equally precise as in the case of X-Ray Indirect Drive.

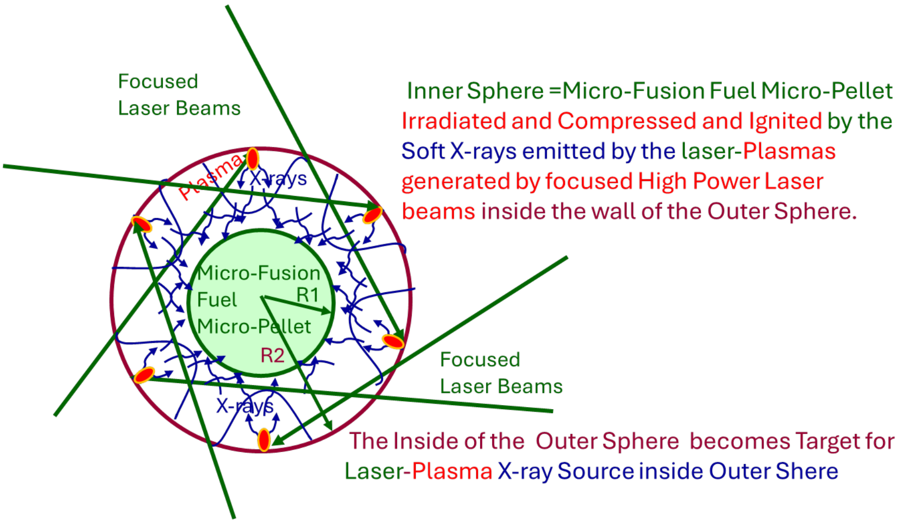

Figura 1 Nuclear Micro-Fusion compression and ignition by X-Ray Direct Drive inside Double – Shell Fuel-Pellet Driven by High Power Lasers: Schematic Crossection

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Nuclear Fusion Power Reactor First Wall Life-Time Increase from ~2 to >40 Years

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Abstract

Accepted concepts of Fusion Power Reactors [1] have very short Reactor “First Wall” Life-Time of ‘Seconds’ from Fusion Ion damage in vacuum [4] and 1-2 Years from Fusion Neutron Damage [1, 3, 4]. To eliminate Wall damage from the Fusion Ions we introduce low-pressure Buffer Gas, 10mBar Helium, in the Reactor Core as presented at DDFIW-2025 [2].

The 14MeV neutron radiation power from DT Micro-Fusion laser driven, or Tokamak, GWe class, Power Reactors will damage the Reactor First Wall making structure materials brittle. The maximum damage commercial materials can withstand is 20 to 30 [dpa] (displacements per atom) from 14MeV neutrons [3]. “The typical Tokamak or ‘dry-wall’ IFE concept accumulates roughly 10 to 20 [dpa] per year [3], and therefore any fusion system utilizing solid First Wall would need to replace all exposed structural elements every 1 to 2 years….Structures become highly radio-activated [3]” and need “cooling” period before maintenance by “radiation-hardened remote-handling robots... [3]” This… “significantly increases downtime, maintenance complexity, and operating cost [3]”.

We propose to increase the First Wall Life-Time to the required >40 years continuous operation which is the typical Life-Time of Commercial Fission Reactors. This could be achieved by reducing the Neutron Flux on the Wall by ~25x while keeping the Neutron Radiation Power the same, e.g. GWe class like in HiPER [1], but increasing 5x the Radius of the Reactor Wall from R~6m like in HiPER [1] to R~30m. The 25x Reduction in Neutron Flux will reduce 25x the number of [dpa]/Year hence increase the Wall Life-time from ~2 Years to ~50 Years. A large radius Reactor Wall is shown in Fig.1 in Ref 2. in which Reactor core.

The 5x larger First Wall Radius will increase the amount of Wall material by 25x since the Wall thickness will remain the same as in [1, 4] for example. We can compare the economic cost of initially constructing a Wall with 25x larger mass to the cost and downtime to dismantle ~25 times the radioactive core and to replacing it with a new First Wall during the ~50 Years reactor operation [3].

A solid First Wall is required for Laser-Fusion Geometries with many, hundreds, of laser beams penetrating the wall, like HiPER [1, 4].

There is an alternative to the ‘solid First Wall’ as described in [3]: “A liquid first wall made out of low-Z materials, such as FLiBe or FLiNaK molten salts or molten lithium, thick enough (at least tens of centimeters) to moderate fusion neutrons, can eliminate these challenges with plasma-facing structural components. …. However, conventional solid-state laser fusion architectures like those derived from the NIF are not compatible with thick-liquid walls due to a large number of laser beams and high shot repetition rate.” Such a ‘liquid wall’ is considered for 2x Driver Beams Indirect Drive Fusion Scheme [3].

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Robustness study of illumination designs for inertial fusion energy

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Abstract

Recent National Ignition Facility (NIF) experiments [1,2] have achieved ignition, demonstrating the potential of inertial confinement fusion (ICF) for energy production. Direct-drive ignition, with its simpler target designs and improved laser-target coupling, has emerged as a compelling alternative and is now actively pursued by both public programs and private fusion initiatives.

However, direct-drive implosions are highly sensitive to illumination non-uniformities and system errors (e.g., beam mispointing, target offset and power imbalance). These introduce low-mode asymmetries – large-scale distortions imposed on the target surface – that degrade implosion symmetry and performance. Additionally, cross-beam energy transfer (CBET), a laser-plasma instability, further redistributes energy and reduces coupling efficiency. To date, no ignition-scale laser facility has been configured for standard direct-drive operation.

In this work, we investigate target irradiation and low-mode perturbations using the ray-tracing code IFRIIT [3]. We optimize novel chamber configurations based on solid-sphere illuminations, comparing the robustness of icosahedron-based geometries to alternative designs. Our results show that icosahedral illumination improves uniformity and resilience to system errors, particularly when using large beams and low super-gaussian exponents, although this must be balanced with absorption efficiency. Finally, we evaluate the combined impact of plasma conditions and CBET on target illumination for representative ignition-scale implosions, providing guidance for the design of future direct-drive facilities.

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Addressing the measurement gap in laser–plasma instability studies via fibre-based scattered light diagnostics

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Abstract

Addressing the measurement gap in laser–plasma instabilities (LPIs) is essential for advancing direct-drive inertial confinement fusion (ICF) and designing next-generation laser facilities. Conventional backscatter diagnostics are often inadequate to capture complex LPI processes inherent in multi-beam configurations and side-scattering geometries. These configurations generate scattered light in non-backscattering direction and with strong angular dependence, which remain poorly characterised by standard methods.

To address this gap, we have developed fibre-based scattered light diagnostics[1,2] that leverages the inherent flexibility and modularity of optical fibres to sample LPI scattered light over extensive angular range. This platform enables the simultaneous observation of multiple LPI mechanisms from diverse angles within a single laser shot, effectively decoupling the LPI physics from shot-to-shot plasma fluctuations. Such adaptable fibre-based scattered-light spectroscopy techniques offer enormous potential for unraveling the complexities of LPIs across all laser-driven fusion concepts.

In this work, we demonstrate how this diagnostic platform enables the acquisition of unprecedentedly rich, single-shot datasets on LPI scattered light that substantially advance our scientific understanding of LPI physics and address the measurement gap in the LPI community. We detail recent developments in its multi-angle, time-resolved measurement capabilities and discuss design considerations for scaling this technology to large-scale, multi-beam ICF facilities.

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A perspective on advanced data management for high-power laser facilities

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Abstract

In high-power laser experiments, data management is often treated as a secondary task rather than a core part of the experiment. Most experiments currently utilize unstructured folders and manual shotsheets, which are prone to formatting errors and information gaps. This lack of standardization makes it difficult to reconstruct experimental conditions, often leading to lost information and makes valuable data hard to use over time. As laser facilities move toward high-repetition-rate (HRR) operations, these manual methods can no longer handle the large amount of data being produced and have become a major bottleneck.

This perspective proposes an approach to manage data by focusing on two key methods:

1. **Metadata Encoding:** Instead of keeping notes and data files separate, we suggest embedding diagnostic configurations directly within the raw data files. This makes the data "self-explaining" where the diagnostic setup (e.g., filter configurations) is permanently linked to the results. It ensures that the experimental state can be easily retrieved and understood, so anyone can understand the data even years later.
2. **A Unified Linking System:** We propose a central system that connects different types of information. This system links laser parameters, target details, and diagnostic configurations into one searchable structure. This moves beyond simple record-keeping and creates a clear map of how every part of the experiment relates to the others.

By adopting these standard procedures, users and facilities can move away from unreliable manual work and build a data system that is ready for the future. This change is necessary to handle the high data volumes of modern HRR experiments and to maximize the scientific value extracted from every shot.

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