19th Direct Drive and Fast Ignition Workshop

21-24 May 2024

Sorbonne University, Paris (France)

Program

Tuesday, 21 May 2024

8:00am-8:40am	**Registration**
8:40am-9:00am	**Welcome to the Laser-Plasma Interaction workshop**
9:00am-9:20am	W. Theobald: *Mitigation of laser-plasma instabilities for inertial fusion energy target designs*
9:20am-9:40am	S. Zähter: *Investigation of laser plasma instabilities driven by 527 nm laser pulses for direct drive inertial confinement fusion*
9:40am-10:00am	B. Gosling: *Investigation of Laser-Plasma Instabilities at the PALS facility using large-scale 2D PIC simulations*
10:00am-10:20am	S. Morris: *Particle-in-cell simulations of laser-plasma instabilities in shock-ignition systems*
10:20am-10:50am	**Coffee break**
10:50am-11:10am	W. Yao: *Dynamics of nanosecond laser pulses propagation and cross-talk in a magnetized underdense plasma*
11:10am-11:30am	W. Rozmus: *Bow shock formation in a plasma flowing across ICF scale randomized laser beams*
11:30am-11:50am	S. Hüller: *Theory, simulations, and 1D modeling of hydrodynamic shocks in a plasma flowing across randomized ICF scale laser beams*
11:50am-12:10am	Y. Lalaire: *3D modeling of cross beam energy transfer between spatially smoothed laser beams*
12:10pm-2:00pm	**Lunch**
2:00pm-2:20pm	D. Blackman: *Transmission of broadband laser radiation through low density homogeneous plasma*
2:20pm-2:40pm	C. Ruyer: *Analytical modeling of the spray amplification of a smoothed laser beam*
2:40pm-3:00pm	P. Moloney: *Investigation of Cross-Beam Energy Transfer in Direct-Drive Implosions with Varying Beam-to-Target Width Ratio*
3:00pm-3:20pm	E. Hume: *Recent results from experimental LPI studies approaching shock ignition conditions*
3:20pm-3:50pm	**Coffee break**
3:50pm-4:10pm	M. Khan: *The sub-MeV Bremsstrahlung Cannon (sMBC), a novel hard X-ray spectrometer for hot electron characterisation*
4:10pm-4:30pm	C. Nakatsuji: *Experimental investigation on plasma scale-length dependence of laser-plasma interactions and hot electron generation for shock ignition scheme*
4:30pm-4:50pm	K. Glize: *Preliminary observation of stimulated Raman side-scattering dependence on laser and plasma parameters in Direct-Drive experiments*
4:50pm-5:30pm	**Discussion on "Laser-Plasma Interaction"**

Wednesday, 22 May 2024

8:00am-8:40am	**Registration**
8:40am-9:00am	**Welcome to the 19th Direct Drive and Fast Ignition workshop**
9:00am-9:40am	**Keynote lecture**
	P. Wang: *The study of laser plasma interaction on broadband Kunwu Laser Facility*
	Alternative ICF schemes & IFE concepts I
9:40am-10:05am	G. Korn: *Efficient, high peak-power, short pulse lasers: a universal platform for fusion applications*
10:05am-10:30am	H. Ruhl: *Ignition of low to medium-Z fuels and high gain*
10:30am-11:00am	**Coffee break**
	Alternative ICF schemes & IFE concepts II
11:00am-11:25am	S. Atzeni: *Initial target design for a Fusion Pilot Plant*
11:25am-11:50am	R. Scott: *The Shock-Augmented Ignition Approach to Laser Inertial Fusion*
11:50am-12:15am	M. Brönner: *Isochoric compression design studies for Proton Fast Ignition*
12:15pm-2:00pm	**Lunch**
	Hydrodynamics, transport & particle acceleration
2:00pm-2:25pm	L. Savino: *A novel GPU based 3D raytracing algorithm for DUED code*
2:25pm-2:50pm	W. Garbett: *Development of an Ion Stopping Power platform at low projectile-to-thermal velocity ratio*
2:50pm-3:15pm	S. Malko: *Proton beam transport and focusing in warm dense matter*
3:15pm-3:40pm	L. Volpe: *Efficient Proton Acceleration via double pulse laser approach*
3:40pm-4:10pm	**Coffee break**
	Alternative ICF schemes & IFE concepts III
4:10pm-4:35pm	P. Patel: *A new sub-scale implosion facility for direct-drive IFE*
4:35pm-5:00pm	J. Honrubia: *Fast ignition of imploded fusion targets by laser-driven protons*
5:00pm-5:25pm	A. Mateo: *Two-Dimensional Simulations of Proton Fast Ignition Cone-in-Shell Targets*
5:25pm-6:05pm	**Discussion on "Alternative ICF schemes & IFE concepts"**
7:00pm	**Conference dinner**

Thursday, 23 May 2024

9:00am-9:40am	**Keynote lecture**
	R. Shah: *Persistent hot-spot mix in cryogenic direct drive fusion experiments*
	Direct Drive ICF I
9:40am-10:05am	T. Collins: *Modeling Target Defects in Direct-Drive Inertial Confinement Fusion*
10:05am-10:30am	W. Cayzac: *Hot spot characterization in direct-drive implosions at OMEGA*
10:30am-11:00am	**Coffee break**
	Direct Drive ICF II
11:00am-11:25am	R. Betti: *The High-Performance Direct-Drive DT-layered Implosion Campaign on the OMEGA laser*
11:25am-11:50am	J.Q. Zhu: *Direct drive campaign of initial confined fusion at the National Laboratory on High Power Laser and Physics*
11:50am-12:15am	H.Y. Song: *Optimization of laser pulses for direct-drive implosions via machine learning*
12:15pm-2:00pm	**Lunch**
	Indirect Drive ICF - LPI
2:00pm-2:25pm	A. Casner: *Overview of LMJ-PETAL experimental capabilities & guidelines for 2027-2029 call of proposals*
2:25pm-2:50pm	M. Lafon: *First inertial confinement fusion implosions using low gas-filled hohlraums on the Laser Mega Joule facility*
2:50pm-3:15pm	R. Capdessus: *Influence of Collisional Effects on Stimulated Brillouin Backscattering*
3:15pm-3:45pm	**Coffee break**
	Direct Drive ICF III
3:45pm-4:10pm	D. Barlow: *Optimization of Polar Direct Drive for Mega-Joule Laser Facilities*
4:10pm-4:35pm	M. Schmitt: *Simulation of polar direct drive wetted-foam capsule physics*
4:35pm-5:00pm	C. Freeman: *Tuning the N+1 Shock to Increase Yield*
5:00pm-5:40pm	**Discussion on "Direct Drive ICF"**

Friday, 24 May 2024

9:00am-9:40am	**Keynote lecture**
	M. Cipriani: *Foams for Inertial Confinement Fusion*
	Hydrodynamics & transport I
9:40am-10:05am	L. Hudec: *Investigation of ion temperature in low-density foams*
10:05am-10:30am	A. Gintrand: *Laser-induced shock waves in overcritical foams*
10:30am-10:55am	C. Arran: *Magnetic Cavitation Driven by Heat Flow in a Plasma*
10:55am-11:25am	**Coffee break**
	Hydrodynamics & transport II
11:25am-11:50am	C. Veauvy: *Short-time scaling of the laser-driven ablation front with 1D kinetic simulations*
11:50am-12:15am	O. Renner: *Time resolved x-ray imaging of hot electron retention and refluxing in Cu targets irradiated at shock ignition relevant laser intensities*
12:15am-12:55am	**Discussion on "Basic physics for ICF"**
0:55pm-1:10pm	**Concluding remarks**

Laser-Plasma Interaction

Mitigation of laser-plasma instabilities for inertial fusion energy target designs

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The company Focused Energy applies advanced ignition schemes such as proton fast ignition and shock ignition for the target designs of an inertial fusion pilot power plant. For the direct drive compression of the target shell both the second and the third harmonic of neodymium glass laser (2ω and 3ω) are considered. While 2ω light relaxes the requirements for the laser and the reactor, it complicates the target physics. The onset of laser plasma instability (LPI) and their growth rates scale with the laser wavelength and the plasma parameters. The longer wavelength at 2ω and a longer density scale length L_n at the quarter critical density for a 2ω design compared to a 3ω design, reduce the laser intensity thresholds for the onset of deleterious LPI mechanisms such as stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS).

The characterization of LPI at ignition relevant plasma conditions and its mitigation are of high priority. We assess LPI and its mitigation with spectrally broad bandwidth laser light through simulations with the code Laser-Plasma Simulation Environment (LPSE) [1] for ignition plasma conditions ($L_n \sim 600\,\mu m$ and $T_e \sim 4\,keV$ for our 2ω design) that are calculated by a radiation hydrodynamic code. LPSE simulation results are presented to quantify SRS thresholds and to assess the broad bandwidth requirement for our point design. In addition, FE is performing LPI experiments at 2ω to benchmark the simulations tools at sub-scale in terms of predicting the onset and the growth of LPI. We have developed and commissioned a full aperture backscatter diagnostic for LPI characterization [2] at the ELI Beamlines' L4n laser facility, which provides kJ, 527-nm wavelength, ns-duration laser pulses at a high repetition rate. An extensive data set of about 1000 shots will be discussed to measure the onset of SBS and SRS as a function of the applied laser intensity and to characterize the scattered light emission with temporal and spectral resolution [3].

References
[1] J. F. Myatt et al., Phys. Plasmas **24**, 056308 (2017).
[2] F. Wasser et al., Rev. Sci. Instrum. **94**, 093503 (2023).
[3] F. Wasser et al., Phys. Plasmas **31**, 022107 (2024).

Investigation of laser plasma instabilities driven by 527 nm laser pulses for direct drive inertial confinement fusion

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The demonstration of ignition and net energy gain at the National Ignition Facility has paved the way for inertial fusion energy. The company Focused Energy is working on a pre-conceptual design of an inertial fusion pilot plant with a target design that provides sufficient fusion gain, stable long-term operation, and cost efficiency. One consideration is to use laser light with a wavelength of 527 nm instead of 351 nm to compress the fusion capsule, which has considerable benefits for a fusion power plant including lower facility costs and higher optics damage thresholds.

One of the scientific challenges for direct-drive inertial confinement fusion, especially at a longer 527-nm wavelength are the laser plasma instabilities (LPI) such as stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), two-plasmon-decay (TPD) and cross-beam energy transfer (CBET) since they reduce the laser-energy coupling and may create hot electrons that can preheat the fuel.

Here, we report on an extensive experimental study of SBS and SRS measurements using the frequency doubled kilojoule high repetition rate L4n laser at the Extreme Light Infrastructure (ELI) – Beamlines for plasma parameters entering a regime that is relevant for direct drive inertial confinement fusion [1]. We scanned the laser intensity in the range of 0.5×10^{13}–1.1×10^{15} W cm^{-2} and took than 1300 shots to measure the onset and growth of the instabilities with a high confidence level. This dataset, which used a spectral narrow bandwidth laser light, will be used as a baseline for upcoming LPI mitigation experiments using broad spectral bandwidth laser light.

<u>References</u>
[1] F. Wasser et al., Phys. Plasmas **31**, 022107 (2024).

Investigation of Laser-Plasma Instabilities at the PALS facility using large-scale 2D PIC simulations

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Laser-plasma interaction (LPI) at the intensities often observed in shock ignition schemes are dominated by parametric instabilities, which can be detrimental to Inertial confinement fusion (ICF) implosion experiments. Experiments led by G. Cristoforetti at the PALS laser facility investigated the birthing of typical LPI Interactions such as Stimulated Raman scattering (SRS) and Two Plasmon decay (TPD), in which the timing of the LPI presence could be observed using the time-resolved frequency spectrum of 3/2 omega light, where omega is the incident laser frequency.

3/2 omega light arises from the Thomson scattering of light waves (or its harmonics) with Langmuir waves excited by parametric instabilities, thus making it a useful experimental diagnostic. The spectrum observed by G. Cristoforetti et al. at the PALS laser facility [1] drastically changes in frequency space as time passes and laser intensity changes. Earlier time signatures in the spectra suggested an early dominance of TPD, as the spectra are closely contained around 3/2 omega. As the intensity ramps up, the spectra spreads in frequency space, better explained by an SRS presence.

Using the EPOCH particle in cell code, we have performed 2D simulations, closely matching the conditions observed in the PALS experiments [1, 2]. The goal was to observe the presence of the governing LPI and reproduce the findings of the observed 3/2 omega spectrum.
These simulations clearly showed the dominant presence of TPD during the early conditions, which then transitioned into the dominance of SRS during the high-intensity phase, as seen in the PALS experiments [1,2]. The extracted 3/2 omega spectra from our simulations are shown to mimic the frequency spread behavior observed in the experiments closely.
However, a clear difference in intensity between the red and blue-shifted signals is more readily observed in the simulations than in the experiments. A simple theoretical model is also presented to explain why we observe this signal-intensity behavior.

References

[1] Cristoforetti, G. et al., Investigation on the origin of hot electrons in laser-plasma interaction at shock ignition intensities. Sci Rep 13, 20681 (2023)
[2] Cristoforetti, G. et al., Time evolution of stimulated Raman scattering and two-plasmon decay at laser intensities relevant for shock ignition in a hot plasma. High Power Laser Science and Engineering. , 7, (2019)

Particle-in-cell simulations of laser-plasma instabilities in shock-ignition systems

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The shock-ignition method for direct-drive inertial confinement fusion describes heating a target with a low-intensity laser, then driving a shock with a sudden rise to high-intensity [1]. This scheme is expected to be more robust against hydrodynamic instabilities, but the high-intensity pulse is susceptible to laser-plasma instabilities (LPI).

To explore LPI in ignition-scale plasmas, a parameter-scan has been performed with 2D particle-in-cell simulations using the EPOCH code. This work builds upon a previous LPI-modelling study [2], with a focus on parameters relevant to the N190916-002 shock ignition experiments performed at the National Ignition Facility.

A total of 27 simulations were run on the Archer2 supercomputer, with typical durations of 25ps, and domains around 600x20 μm^2 which included exponential plasma profiles from around 10-26% of the critical density. Intensities were varied between 10^{15} and $5x10^{16}$ W/cm², for uniform and speckled profiles. Additional runs investigated the effect of collisions, longitudinal flow, transverse flow (to mimic smoothing by spectral dispersion), and broadband lasers.

We present the results obtained from a newly developed LPI toolkit applied to these simulations, and aim to make this data-set open for use by the wider ICF community.

References
[1] Betti, R., et al. *Shock ignition of thermonuclear fuel with high areal density*, Phys. Rev. Lett. 98, 155001 (2007)
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Dynamics of nanosecond laser pulses propagation and cross-talk in a magnetized underdense plasma

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In a plasma, a nonlinear medium in which light waves can couple to plasma waves, a whole range of laser-plasma interaction (LPI) phenomena can develop, from filamentation, stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), to cross-talk and braiding between laser beams or cross-beam energy transfer (CBET) between neighboring laser beams. Improving our knowledge of all these effects is not only important from a fundamental perspective, but also from a practical one in the frame of Inertial Confinement Fusion (ICF), where it is critical that as much as possible of the laser energy be transferred homogeneously to the fuel.

In this context, applying magnetic fields to laser-driven plasmas has been suggested to enhance fuel confinement and heating, and mitigate laser energy losses [1]. Here, we report on experimental measurements demonstrating improved transmission and increased smoothing of a high-power laser beam propagating in a magnetized underdense plasma. We also find enhanced backscattering, which our kinetic simulations show is due to magnetic confinement of hot electrons, thus leading to reduced target preheating. Finally, we investigate the impact of magnetization on the energy transfer between two laser beams.

References
[1] W. Yao, et al., *Dynamics of nanosecond laser pulse propagation and of associated instabilities in a magnetized underdense plasma*, Phys. Rev. Lett. 130, 265101 (2023)

Bow shock formation in a plasma flowing across ICF scale randomized laser beams.

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High energy lasers interacting with flowing plasmas can produce a plasma response that leads to beam bending and, by momentum conservation, slows down the plasma flow velocity [1]. Once the incoming supersonic plasma flow decreases to a subsonic level, the action of the speckled laser beams can generate a shock within the plasma. We present theory and hydrodynamic simulations of plasma flow through randomized laser beams that demonstrate shock formation [2].

We will describe in this talk our experimental campaigns on the Omega laser facility demonstrating shock generation. In the experimental configuration expanding plasma from a foil target penetrates several crossed beams that exert strong ponderomotive force on the flow. The shock was directly observed by Thomson scattering in the upstream region from the crossing beams. The summary of ongoing theoretical and simulation studies that include thermal and kinetic effects and address plasma conditions of Omega and future NIF experiments will be also discussed.

Hydrodynamic simulations have shown large density and velocity jumps that can affect laser-plasma coupling for the ICF-relevant parameters. We will specify the required power and size of the interacting beams based on the fluid theory in addition to the necessary condition of the sonic flow across the laser beam.

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[2] J. Ludwig, S. Hüller, H.A. Rose, *et al.* Phys. Plasmas **31**, 032103 (2024).

Theory, simulations, and 1D modeling of hydrodynamic shocks in a plasma flowing across randomized ICF scale laser beams

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High-energy laser beams interacting with flowing plasmas can produce a plasma response that leads to deflection of the beam, beam bending. Such beams have usually a speckle structure generated by optical smoothing techniques that reduce the spatial and temporal coherence in the laser field pattern. The cumulative plasma response from laser speckles slows down the velocity of the incoming flow by momentum conservation.

For slightly super-sonic flow the cumulative plasma response to the ponderomotive force exerted by the beam speckle ensemble is the strongest, such that slowing down the flow to subsonic velocities leads eventually to the generation of a shock around the cross section of the beam. This scenario has been predicted theoretically and is confirmed here by our hydrodynamic simulations in two dimensions with speckled beams and in one dimension with a reduced model.

The conditions of shock generation are given in terms of the ponderomotive pressure, speckle size and the flow velocity. The nonlinear properties of the shocks are analyzed using Rankine-Hugoniot relations.

According to linear theory, temporally smoothed laser beams exhibit a higher threshold for shock generation. Numerical simulations with beams that are smoothed by spectral dispersion compare well with the linear theory results, diverging from those produced by beams with only a random phase plates in the nonlinear regime. The conditions necessary for shock generation and their effects on the laser plasma coupling in inertial confinement fusion (ICF) experiments are also discussed.

3D modeling of cross beam energy transfer between spatially smoothed laser beams

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Optical smoothing of laser beams is widely used to better control laser propagation [1] in inertial confinement fusion experiments [2] and usually combines the use of a phase plate with smoothing by spectral dispersion. Phase plate spatial smoothing consists in breaking the laser beam in a broad beam made of small speckle structures. This technique is used in many laser facilities using nanosecond laser beams to obtain large focal spots, including the National Ignition Facility (NIF) in California and the Laser Mega Joule (LMJ) in France. Recent studies [3, 4] demonstrate that Random Phase Plate (RPP) spatial smoothing is likely to induce significant perturbations on the resonances of laser-plasma instabilities (Raman/Brillouin stimulated scattering …). In particular, it has been shown [4, 5] that Cross Beam Energy Transfer (CBET) can be greatly reduced by taking into account the realistic speckle structure of the lasers, thus possibly affecting the symmetrical compression of the fuel capsule in inertial fusion experiments [6]. An unexpected decrease in energy exchange between lasers (up to $80\ \%$) has been demonstrated analytically and verified by kinetic simulations [5]. This drastic reduction is observed if the crossing lasers have different wavelengths.

In this work, we generalize this model to 3 dimensions and address analytically the influence of a plasma flow in all spatial directions, revealing a significant reduction in energy transfer under RPP smoothing depending on the value of the drift velocity components in previously neglected directions [5]. This theory is validated by means of Smilei PIC simulations. We thus demonstrate the need to include 3D spatial smoothing effects in current plane wave CBET models of hydrodynamic codes [7, 8, 9].

References

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Transmission of broadband laser radiation through low density homogeneous plasma

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Instabilities such as stimulated Raman and Brillouin scattering (SRS and SBS) driven by laser radiation in high-temperature plasmas are of great importance for inertial confinement fusion research, in particular, for the laser intensities above 10^{15} Wcm^{-2} relevant to the shock ignition scheme. At densities lower than the plasma quarter critical density and temperatures of 1 keV or higher, the non-linear excitation of stimulated Raman scattering can occur in the kinetic inflation regime. However with narrowband lasers SBS can cause the reflection of a considerable amount of laser light at the lower densities considered. When considering broad bandwidth lasers we show that the SBS instability can be suppressed with a moderate (< 2%) bandwidth lasers. In longer scale length plasmas the suppression of SBS can result in more stable backwards SRS along with some secondary SRS. This extra excitation of SRS can include anomalously enhanced extremely energetic hot electrons even with moderate laser intensities.

Analytical modeling of the spray amplification of a smoothed laser beam

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Spatial amplification of the near-forward Brillouin scattering (FSBS) produced by a laser beam smoothed with a random phase plate (RPP) is considered by using a novel technique based on the central limit theorem [1]. It is demonstrated that FSBS amplification proceeds over a length much larger than the longitudinal speckle correlation length and, under certain conditions, scales as a square of the average gain coefficient. Analytical expressions for the spatial gain are successfully compared with paraxial electromagnetic simulations [2,3], demonstrating that the beamlet correlation through ion-acoustic waves dominates the spatial growth for intense enough laser beams. The scattered wave aperture increases with the gain and can extend beyond the small angle scattering limit. Following [4], our model is also supplemented with the optical temporal smoothing technique, often used in high-energy laser facilities, and allowing to rapidly assess the importance of the FSBS in directly and indirectly driven inertial confinement fusion experiments.

References
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Investigation of Cross-Beam Energy Transfer in Direct-Drive Implosions with Varying Beam-to-Target Width Ratio

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Cross-Beam Energy Transfer (CBET) is a laser-plasma instability which leads to a transfer of energy from the center of inbound beams to light travelling away from the capsule for direct-drive implosions. CBET reduces deposited laser energy in current direct-drive experiments by approximately 20% and enhances beam-mode asymmetries (perturbations from the beam geometry) in the stagnated hydrodynamic profiles by an order of magnitude [1]. Significant progress has been made in recent years on direct-drive experiments by employing statistical modelling to guide experimental design and to infer sources of degradation in performance metrics [2,3]. This work has highlighted that experimental yield saturates faster than simulations predict when increasing the beam width compared to the target radius (R_b/R_t), an initial condition that predominantly controls beam-mode asymmetry [3]. Understanding anomalies in this work is important to correctly scale the performance of the direct-drive program and compare it to indirect-drive implosions on larger facilities.

In this work we aim to provide simulation evidence to show that this yield saturation is due to CBET. We shall present simulations of implosions in a simplified 2D cylindrical geometry which consistently captures the effect of CBET and the growth of beam-mode asymmetries using the *SOLAS* laser model, coupled to the *CHIMERA* radiative-hydrodynamics code. This simplified setup allows many inexpensive simulations to be performed and study the mode growth behavior with different convergence, rather than running exceptionally expensive, fully 3D CBET-hydro simulations. The work demonstrates that in the presence of CBET, increasing R_b/R_t significantly enhances CBET scattering and can enhance the beam-mode asymmetries. This behavior is different to the mode growth in the absence of CBET, where the amplitude of perturbations is reduced because of enhanced illumination asymmetry.

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Recent results from experimental LPI studies approaching shock ignition conditions

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A major concern for the prospects of direct drive is the growth of parametric instabilities (LPI) during the interaction of the laser pulse with the preformed long scale length plasma. This issue is exacerbated in the shock ignition (SI) scheme [1], where a short, higher intensity (~10^{16} W/cm^2) spike is employed at the end of the drive which well-surpasses the intensity threshold for LPI growth.

Primary instabilities of interest include Stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS) which couple laser energy into scattered laser light. Typically these instabilities are investigated through measurements of backscattered light e.g. with a FABS diagnostic [2]. Side-scattered Raman (SRSS) has re-emerged lately as a prominent instability with recent measurements suggesting the amount of Raman scattered light may be severely underestimated [3]. In addition, the SRS and Two Plasmon Decay (TPD) instabilities generate a population of hot electrons which can preheat the fuel, raising the adiabat and hindering compression of the fuel. Whilst theoretical and analytical works exist that describe LPI gain, the growth of LPIs is highly non-linear and are in competition with one another. Thus, it is difficult to reliably predict LPI behaviour across the whole laser-plasma parameter space. Experimental investigations are crucial to furthering the understanding of LPIs, particularly at higher intensities relevant to SI.

In this paper we present an update on recent European experimental campaigns dedicated to investigating the growth of parametric instabilities and approaches for LPI mitigation. In particular, recent results exploring the effect of a chirped broadband laser pulse on LPI growth and the role played by SRSS under SI conditions will be addressed.

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The sub-MeV Bremsstrahlung Cannon (sMBC), a novel hard X-ray spectrometer for hot electron characterisation

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The laser intensities used in inertial confinement fusion (ICF), and all relevant laser-plasma interactions, excite parametric instabilities and generate high energy supra-thermal or "hot" electrons. These hot electrons have long mean free paths with respect to the shell thickness of typical ICF capsules and thus are capable of penetrating through to the cryogenic fuel. This can pre-heat the fusion fuel, limiting its peak compression, and reducing the yield of the implosion. Detailed characterisation of these hot electrons is essential to understand what role they may play in implosions, and thereby enabling the refinement of mitigation methods.

Hot electron characterisation is typically performed via the measurement of hard X-ray photons that are produced through the bremsstrahlung interactions with the high-Z ions. The temperature and energy of the hot electrons can be determined from the spectral shape of these hard X-rays by either analytic relations or Monte-Carlo simulations. Essential to this is a device capable of measuring these hard X-rays.

Presented here is a novel hard X-ray spectrometer, the sub-MeV Bremsstrahlung Cannon (sMBC). The design is optimised for hot electron with sub-100 keV temperatures and low total signals, providing greater sensitivity and increasing the energy range of photon detection than current bremsstrahlung cannons. The device consists of a multi-channel K-edge filter array, with readily changeable filters to provide a flexible spectral detection window. It provides greater ease of use and ease of analysis than single channel cannons, without compromising on its spectral decomposition performance. Image plates are currently used for their high sensitivity in the energy region of interest, though the diagnostic was designed to be adaptable for future upgrades, allowing for the incorporation of different detection techniques that are better suited to higher repetition rate facilities.

The performance of the device is demonstrated with data from a recent laser plasma experiment carried out a the Vulcan Laser facility. This experiment was investigating laser-plasma instabilities relevant for direct drive ICF.

Experimental investigation on plasma scale-length dependence of laser-plasma interactions and hot electron generation for shock ignition scheme

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Shock Ignition scheme [1] has higher laser peak intensity (~10^{16} W/cm^2) and longer density scale-length (~300 µm at $n_c/4$) compared to typical direct-drive schemes for inertial confinement fusion. Consequently, detailed understandings of the laser-plasma instabilities are crucial issue for the Shock Ignition approach.

The experiment was performed at the GEKKO-XII-HIPER laser facility, in planar geometry condition by using overlapping three-beams (pre-pulse, λ = 527 nm, 300-ps duration) and seven- or nine-beams (main pulse, λ = 351 nm, 300-ps duration) for pre-plasma creation and instabilities driving, respectively. The main pulse, smoothed by random phase plates and delayed 0.2-1.4 ns relative to the pre-pulse in order to verify the scale-length effects, focused on a target surface to ~300 µm (FWHM) spot with peak intensity (2.0-3.5) × 10^{15} W/cm^2. The targets consisted of three-layer planar： a 10 µm-thick polystyrene ablation layer, a 25 µm-thick copper layer for hot electron marking via Kα emission, and a 50 µm-thick quartz layer for shock wave temperature measurement.

Figure 1 shows time-resolved spectral characterization of backscattered light due to stimulated Raman scattering (SRS) and two-plasmon decay (TPD) instability, indicating potential pump depletion via convective SRS at ~$0.05n_c$ before ~0.35 ns laser peak. It also suggests the possibility of plasma-induced laser smoothing [2], similar to findings by G. Cristoforetti *et al*. (2021). This work is supported by JSPS KAKENHI No. JP23K20038.

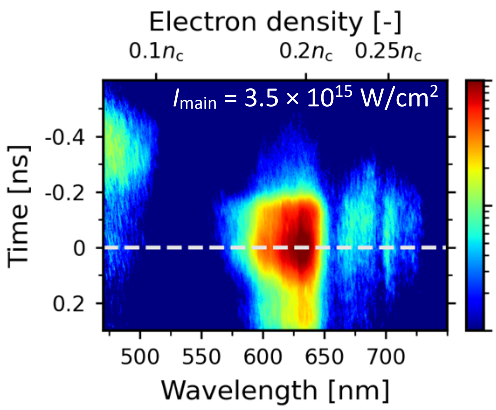

Fig. 1 Time-resolved spectral of back-scattered light (L_n ~ 120, 260 µm at $n_c/4$, 0.05 n_c, respectively, at 0 ns).

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Preliminary observation of stimulated Raman side-scattering dependence on laser and plasma parameters in Direct-Drive experiments

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Direct-drive ignition (DD) is an inertial confinement fusion (ICF) scheme in which a spherical fusion target is compressed and ignited by direct laser irradiation. Despite early results anticipating the predominance of two-plasmon decay, recent experiments clearly demonstrate the dominance of the stimulated Raman scattering (SRS). This three-wave instability leads to the scattering of the incident laser energy away from driving the compression, exciting plasma waves that generate a population of hot electrons. These electrons can preheat the core of the target further limiting the compression. In an implosion, SRS can develop in different geometries, such as the familiar back-scattering (back-SRS) and a more elusive side-scattering (side-SRS) forms. The complex geometry inherent to side-scattering has limited experimental characterisation and this is preventing a comprehensive understanding of both side-SRS and more generally SRS.

Experiments at Shenguang-II Upgrade and Vulcan laser facilities fielding a new diagnostic to measure SRS over a wide range of angles have enabled the direct comparison of back-SRS with side-SRS. These experiments explored the relative dependence of side-SRS on the incident laser energy, laser polarization and plasma density scale length. Preliminary analysis of the data will be discussed during this presentation. This data shows that side-SRS has a different intensity scaling compared to back-SRS, and at moderate laser intensity side-SRS dominates.

Influence of Collisional Effects on Stimulated Brillouin Backscattering

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Indirect-drive inertial confinement fusion experiments conducted at the National Ignition Facility and the Laser Megajoule have reported high levels of Brillouin reflected light. In order to mitigate the growth of the backward stimulated Brillouin scattering (BSBS), it has been proposed to include mixtures to enhance the Landau damping rate of ion acoustic waves (IAW).

By means of advanced particle-in-cell (PIC) simulations and a kinetic model –accounting for Coulomb collisions as well as collisional absorption through the Langdon effect–, we revisit the BSBS within gold-boron and pure gold plasmas. We derive the IAW linear dispersion relation and show that collisional effects substantially affect the IAW properties and so does the amount of Brillouin reflected light. Especially, for a laser-created collisional Au plasma, due to the Langdon effect, the IAW damping rate becomes smaller than the Landau damping rate which leads to an enhancement of the reflectivity, compared with a collisionless plasma. For a AuB plasma, the situation is different because the damping rate is essentially due to boron ions as their thermal velocity is comparable with the IAW phase velocity. Although the Langdon effect still tends to reduce the IAW damping rate, the latter is always higher than the Landau damping rate, which leads to a decrease of the reflectivity, compared with a collisionless plasma. In addition, the ion interspecies collisions enable to maintain a significant ion damping and thus, to prevent kinetic inflation leading to high level of reflectivities. Boron to be used (as liner) to reduce the Brillouin reflected light may be a good option for moderate laser intensities *i.e.* $I_0 < 4\times10^{15}$ W.cm^{-2}.

Moreover, we show that adding of boron tends to change the dominant non-linear saturation mechanism(s) through the nature of the instability (absolute for a Au plasma while convective for a AuB plasma). Analytical fits of the evolution of the SBS instantaneous reflectivity as a function of the laser intensity, for each kind of plasma, are deduced and turn out to be in good agreement with PIC simulations outcomes.

Keynote lectures

The study of laser plasma interaction on broadband Kunwu Laser Facility

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Laser plasma interaction (LPI) is one of the key issues in laser-driven inertial confinement fusion ignition (ICF), as it may affect target compression and fusion energy gain. Broadband laser technology is one novel option that may inhibit the related processes of LPI. It can be thought of a decrease of the effective light intensity felt in the plasma, which in turn may play a role in inhibiting the occurrence and development of related LPI processes in the plasma.

Several preliminary experiments into broadband-laser-driven laser plasma instabilities were carried out using the newly developed hundreds-of-joules broadband second-harmonic-generation (SHG) laser facility. Through direct comparison with the LPI results for the traditional narrowband laser, the actual LPI-suppression effect of the broadband laser was shown. The broadband laser had a clear suppression effect on both the back-stimulated Raman scattering and the back-stimulated Brillouin scattering at laser intensities below 1×10^{15} Wcm^{-2}.

The laser transmission energy with target of different thickness driven by broadband laser or narrowband laser has also been tested. We've found that it has significantly higher transmission energy for the same target driven by broadband laser than narrowband laser.

The plasma generated and coupled by laser incident on target can be such important. As it directly determines the efficiency and quality of the energy conversion. The beam energy would be absorbed. In the direct-drive approach, electrons in the target's outer would transport that energy to the denser shell material to drive the ablation and the resulting implosion. In the indirect-drive approach, the laser energy is converted to X-rays. Higher transmission energy may indicate less energy loss during the laser interact with the plasma corona of the imploding capsule. Thus, this interesting and valuable experimental phenomenon may have influence on the fundamental understanding of the related processes of laser plasma interaction of novel broadband low- coherence laser facility.

Persistent hot-spot mix in cryogenic direct drive fusion experiments

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We demonstrate that an x-ray emission signature associated with acceleration-phase mass injection [1,2] shows strong correlations with implosion design (adiabat and target mass) and performance (yield and hot-spot size) as expected for mix. The emission signature increased for a target with elevated levels of ablator particulate with stagnation parameters behaving consistently. Furthermore, we show that this anomalous x-ray emission correlates with increased hot-spot size at low x-ray energies, indicative of a peripheral hot-spot modification, also consistent with mix. The signal persists over a range of implosions designed to be stable to imprint, whereas 3D modeling with features designed to induce mass jetting is shown to provide a plausible explanation for all of these signatures. We estimate a typical high-performance implosion may have up to 2× increase of hot-spot mass at the start of deceleration as compared to a 1D calculation. Such mix may explain why high-performance implosions are unresponsive to beam smoothing[3] as well as recent work suggesting a better than purely hydrodynamic scaling of these implosions[4].

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Foams for Inertial Confinement Fusion

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High-power laser interaction with porous materials, or foams, have been studied from early nineties as potential ablators for ICF studies [1]. Foams are nowadays attracting considerable attention because of their peculiar features under irradiation of high-power lasers and of their applications to several fields, like inertial confinement fusion (ICF). In this context, foams have been employed as pressure amplifiers for the study of equations of state [2], of crucial importance for designing an efficient fusion target. In Indirect Drive, they have been suggested as hohlraum liners [3] to reduce motion of the inner walls and as hohlraum filling materials to replace the gas fill [4]. More recently, applications to the Direct Drive scheme became important and research efforts directed to reproducing, in a controlled environment, the conditions of the corona of an irradiated capsule in the Shock Ignition scheme [5] and to realize a full ICF target for the dynamic shell formation concept [6].

In this talk, experimental and theoretical aspects of the interaction of a high-power laser beam with foam targets will be discussed, starting from the earlier works and then focusing on the several recent results. The discussion of the experimental results will also include manufacturing technologies, up to the potential of modern additive manufacturing. The overview of modeling activities will detail the efforts towards a proper incorporation of the physics of the laser interaction with foams in the simulations, both with sub-grid models and with direct reproduction of the foam structure in radiation-hydrodynamic codes.

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Alternative ICF schemes & IFE concepts

Efficient, high peak-power, short pulse lasers: a universal platform for fusion applications

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We will discuss the principal physical concepts and technologies for developing high efficiency PW lasers for igniting a novel class of fuels containing low to medium-Z constituents and DT (see abstract and talk of Hartmut Ruhl). Using directly diode-pumped broadband laser materials and state of the art optics and photonics technologies a new generation of compact high contrast PW lasers with high wall plug efficiencies and increased repetition rates (10 Hz) in the sub-100fs can now be envisioned and build as a universal laser platform enabling ignition and high gain with reduced laser energies. Combining multiple beams opens a path to multi-PW and Exawatt peak-power generation for fusion applications including the new fusion concept driven by efficient laser to ion conversion in nanostructured materials [1, 2, 3]. We will discuss the parameters of the laser platform and how to achieve high wall-plug-efficiencies (WPE).

The petawatt laser is based on optical parametric chirped pulse amplification (OPCPA) and subsequent broadband amplification followed by grating compression [4]. High (WPE) is possible by use of diode pumping, efficient energy extraction in the broadband power amplifier, and minimizing losses during compression. Multilayer dielectric gratings with large aperture, sufficient bandwidth, and good laser induced damage threshold have been demonstrated [5], which enable compression with 90-95% efficiency, and an overall WPE above 10%. Marvel Fusion has successfully performed contrast-improving measures at several petawatt facilities such as second harmonic generation (SHG) of petawatt pulses [6] to evaluate its feasibility for laser systems.

Furthermore, direct-drive fusion compression experiments will benefit as well from shaped pulse nanosecond pulses with increased bandwidth followed by SHG which can be generated with the same laser amplifier technology. This will allow better control of plasma instabilities due to a decreased coherence length of laser beams. The proposed laser platform is currently under development and will have widespread use in different laser fusion schemes which are currently investigated.

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Ignition of low to medium-Z fuels and high fusion gain

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Abstract

While pure DT is considered the standard fuel for IFE it might not be the best fuel for commercial fusion energy production. As it turns out a novel class of fuels containing low to medium-Z constituents and DT is capable of ignition and high gain. These fuels are solids at room temperature and promise to require less fuel mass potentially leading to reduced compression requirements. In the talk we address potential low to medium-Z fuel compounds and discuss with the help of analytical modeling and MULTI1D simulations [1] under which conditions they ignite. To show that high fusion gain with low to medium-Z fuels is possible we detail a simple high fusion gain concept ($Q_F > 100$) based on these advanced fuels potentially sufficient for fusion energy production. Low to medium-Z fuels require fast ignition at elevated ignition temperatures. In the talk presented by Georg Korn a novel ignition concept based on highly efficient diode-pumped ultra-short high-power laser pulses and tailored nanostructures is sketched. The lasers being the most important element are explained in some detail. An early stage of our work is given in [2, 3].

Keywords: ignition of low to medium-*Z* fuels, high fusion gain, MULTI1D simulations, fast ignition

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Initial target design for a Fusion Pilot Plant

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The private company Focused Energy is developing a pre-conceptual design of a Fusion Pilot Plant. This will require efficient lasers operating at a few hertz, as well as high gain (G) cheap targets.

Here we discuss the design of a G ~ 100 target, based on laser direct-drive, moderate velocity compression, followed by advanced ignition. As a reference scheme we pursue compression by a 2ω laser (λ = 530 nm) and proton fast ignition (pFI) [1], but we also evaluate 3ω laser drive and shock ignition (SI) [2]. We used simple scaling expressions for compression [3], pFI [4] and SI [5] to identify a design window in parameter space. These scaling laws also evidence the need for trade-offs between such quantities as laser intensity and in-flight-aspect-ratio, implosion velocity and energy required for fast ignition, etc.

We then developed a preliminary target design for pFI, based on 1D and 2D simulations. Here we present results of 1D MULTI-IFE simulations and 2D DUED simulations, which addressed (under somewhat ideal conditions) all the stages of target evolution, from laser irradiation and compression to proton ignition and fusion burn, as well as the computation of the output neutron, X-ray and particle spectra. (Other simulations of pFI with the FLASH and PETRA codes are presented elsewhere in this workshop [6].)

Model and simulations clearly show where gaps in present knowledge need to be addressed to perform a robust design, and consequently set priorities for near term Focused Energy research activity. These include, in particular, laser-plasma interactions, low adiabat implosions, proton generation and transport.

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The Shock-Augmented Ignition Approach to Laser Inertial Fusion

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Shock-Augmented Ignition[1] (SAI) is a new Laser Inertial Fusion concept which seeks to tread an optimal middle ground between Central Hotspot Ignition[2] and Shock Ignition[3]. By employing a dip in laser-power followed by a rapid rise, simulations indicate that for direct drive implosions, SAI enables the generation of a strong shock without the high laser intensity conventionally thought to be required for shock ignition. This in turn enables higher fusion energy-gain at a lower implosion velocity.

Our work shows that SAI should also be beneficial for indirect drive, although due to the limited rise rate in the radiation temperature, the physics is somewhat different. According to simulations the power dip results in higher yield with more stable implosions which also increase the yield over clean. In addition, the power dip reduces the impact of the 'n+1' shock.

In this talk I will discuss the Shock-Augmented Ignition concept, results from simulations, and experiments performed on both the National Ignition Facility, Lawrence Livermore National Laboratory and the Omega laser facility at the Laboratory for Laser Energetics.

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Isochoric compression design studies for Proton Fast Ignition

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In Proton Fast Ignition (PFI) [1,2] an inertial fusion target is compressed to densities of the order of hundreds of g/cc using nanosecond-duration lasers. To reach the necessary temperature for ignition, a picosecond laser generated high-energy beam of MeV protons is focused into the compressed fusion fuel. In contrast, in the conventional inertial fusion scheme, the fuel is ignited by coupling enough energy into a central hot spot, which typically creates an isobaric state between the hot spot and the colder and much denser fuel shell. In PFI the creation of a central hot spot is not necessary, resulting in relaxed conditions for the fuel compression and different constraints on the driver. This allows fast ignition designs to compress the fuel to an isochoric state with lower implosion velocity, enabling the use of more fuel mass, which is beneficial for high gain designs.

We show the results of design studies with the goal to produce negligible hot spots with a thick surrounding isochoric density profile. The designs are based on simulations with the radiation-hydrodynamics code MULTI-IFE [3] and are obtained by an optimization technique called particle-swarm-optimization [4]. The starting point is the self-similar isochoric design by Clark and Tabak [5]. Using appropriate evaluation functions for the optimization, we found several implosions with flat compressed density profiles and small hot spots. We will discuss the influence of parameters like the central gas density and the laser power contrast on the achieved density profiles.

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A new sub-scale implosion facility for direct-drive IFE

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Experiments on the NIF have demonstrated the viability of laser-based inertial fusion for achieving ignition and target net energy gain. Major scientific and technical challenges remain, however, to progress to a commercial fusion power plant. Scientific challenges include developing and testing new target designs capable of significantly higher gains than achieved so far on the NIF (a further ~40X increase) and exhibiting improved robustness to drive symmetry and target quality. Technical challenges specific to IFE include developing high rep-rate, energy efficient, low-cost laser drivers, mass produced low-cost targets, target injection and tracking, and operations at high shot rates required a high degree of automation in controls systems, diagnostics, and data interpretation.

While the goal is a high yield, high gain demonstration facility operating at high repetition rate (~10 Hz), we postulate that a sub-scale facility is needed along the path to test and optimize advanced high-gain ignition designs and to demonstrate key IFE technologies. We describe a concept for such a facility that would combine symmetrically configured long-pulse compression lasers with short-pulse ignitor and backlighting lasers that would allow for studying a variety of direct-drive ICF approaches. The use of liquid-cooled amplifier beamlines capable of hundreds of shots per day would enable rapid exploration and optimization of target designs over large parameter spaces. Funded through public-private partnership, and dedicated to IFE, such a facility could significantly accelerate the timeline towards a full-scale fusion pilot plant demonstrator.

Fast ignition of imploded fusion targets by laser-driven protons

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Ion fast ignition is an alternative for igniting thermonuclear fuels with lower laser energy and drive symmetry requirements [1,2]. The ion beam characteristics estimated for fast ignition so far are based on strong assumptions about beam focusing and ideal beam-plasma interaction. However, new effects have been reported, such as the divergence of laser-driven protons generated in hollow cones [3,4] and its consequences on beam energy deposition [5].

We have conducted integrated simulations of proton fast ignition by combining PIC, hybrid, and radiation-hydrodynamic calculations. Here, we analyse proton acceleration by two-dimensional PIC simulations of millimetre-scale cones. A special design of the cone and the laser pulse has been used to reduce the magnetic fields generated by the return currents and the subsequent beam divergence.

The proton distribution function obtained from PIC calculations and the configuration of the imploded DT core described in [6] have been used to conduct hybrid simulations coupled to radiation-hydrodynamics and ignition physics. The goal has been to get realistic laser energy requirements to fast-ignite compressed fuel configurations with energy gains of about 100. These realistic ignition energies are compared with those obtained for ideal proton pulse and Supergaussian density distributions of the compressed core to estimate the extra laser energy costs due to realistic proton beam and target configurations. This will help assess the potential of proton-fast ignition as an alternative scheme for Inertial Fusion Energy.

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Two-Dimensional Simulations of Proton Fast Ignition Cone-in-Shell Targets

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The direct drive proton fast ignition scheme [1] is a candidate for producing energy at scale. It relaxes the compression requirements and mitigates the development of Rayleigh-Taylor instability, allowing for the reduction of number of beams, increase of laser energy coupling and the large-scale manufacturing of low-cost targets. For a proton beam to reach and heat the compressed fuel, a cone-in-shell target is required. Thus, at least two-dimensional simulations of the target compression and ignition are needed to obtain the laser and target engineering requirements [2].

Simulations with the radiation-hydrodynamics code FLASH [3] have been conducted to study cone-in-shell target design. The insertion of the cone leads to a non-spherically symmetric shape of the imploded fuel [4] with a high-pressure jet piercing the cone tip. This compressed configuration is then given to the PETRA hybrid code (charged particle transport coupled with radiation-hydrodynamics and ignition physics) to calculate the ignition energy, which is very sensitive to both fuel density and proton beam properties [5].

An integrated analysis of a reference target design will be presented here, looking at the different stages of implosion of the shell, compression of the fuel when reaching stagnation, ignition with a proton beam and propagation of the thermonuclear burn wave. The performance of the full process will be assessed, providing a study of the gain and required energy for the compression and the ignition laser pulses.

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Hydrodynamics, transport & particle acceleration

A novel GPU based 3D raytracing algorithm for DUED code

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An Inertial Confinement Fusion (IFE) experiment involves many physical phenomena [1] that need an accurate description. Among those, laser power coupling to the plasma is one of the most crucial for designing IFE targets and assessing their robustness in terms of stability of implosion and fusion yield. Power imbalance between different rays or mis-pointing of the beams could lead to hydrodynamic instabilities which ultimately degrade the plasma ignition. To this purpose the 2D DUED Lagrangean radiation-hydro-nuclear code ([2], [3]) has been improved with a new 3D laser ray-tracing scheme, which allows to study realistic multi-beam irradiation geometries. To keep the numerical noise at low level, a large number of rays (propagating in 3D space), typically 100k-1M, are traced at each step producing a 3D power absorption distribution, which is then mapped onto the DUED 2-D axially symmetric mesh. Resort to massive parallelism turned out necessary to make simulation times acceptable.
Nowadays GPUs offer computing power as many as several hundred CPUs for specific scenarios in conventional server/workstation. This makes it possible to write parallel code that can be used in-house, avoiding, in some cases, the use of supercomputers.
The new raytracing code is written using the OpenCL framework [4] to work directly on GPUs.
Preliminary performance shows a 200-fold reduction in computation time compared with serial code. The novel code correctly simulates the configuration of the Omega Laser (Rochester NY) [5], thus allowing investigation of geometry-induced perturbations (along the zenith). Experiments conducted at Omega Laser in August 2022 [6]*, are under further investigation.

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Development of an Ion Stopping Power platform at low projectile-to-thermal velocity ratio

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An experimental platform is being developed at the Omega laser to measure the energy loss of charged particles in plasma. Understanding the energy loss of ions in plasma is of broad interest, including understanding ignition thresholds and burn in ICF plasmas [1], the heating of samples by ion beams, and the basic science of energy exchange and transport processes in plasmas.

The concept uses a novel supersonically heated foam sample to access the near Bragg-peak stopping regime, where the ratio of the projectile velocity to plasma thermal velocity is close to unity. In this regime there is substantial theoretical uncertainty and limited direct measurements. Supersonic heating is intended to achieve sufficiently high sample temperatures whilst maintaining uniform density conditions. 3MeV protons are generated from deuterium fusion reactions using a directly driven thin shell capsule implosion, and the energy loss through the sample is measured with charged particle spectrometers. To compensate for the sample heating beams, the implosion uses a pointing scheme with a subset of beams based on [2]. The heated target is characterized using X-ray absorption spectroscopy using a capsule backlighter.

Initial experiments were recently fielded to demonstrate and characterize the different aspects of the platform [3]; the sample, proton source and backlighter capsules. The experimental platform will be described along with preliminary results and plans for further experiments.

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Proton beam transport and focusing in warm dense matter

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Proton transport is a crucial physical process in several fusion approaches, including inertial confinement fusion (ICF), proton and ion-driven fast ignition methods, and heavy ion fusion. Factors such as stopping power and beam focusing play significant roles, particularly in alpha particle deposition in ICF and the proton beam drivers for fast ignition [1].

Describing proton transport theoretically in the high-energy-density plasma encountered in ICF poses challenges, especially in plasmas characterized by strong coupling and electron degeneracy such as warm dense matter (WDM). Extensive experimental database is required to enhance modeling capabilities and optimize fusion schemes. Here, we introduce an international effort focused on experimental [2] and numerical studies of proton transport in warm dense matter. Proton stopping power measurements in WDM, along with investigations into proton focusing and heating of WDM using hemispherical targets, were conducted at the LaserNetUS CSU ALEPH laser facilities.

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Efficient Proton Acceleration via double pulse laser approach

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Double pulse Laser has been proposed as method for collimate electron beams [1] in the context of Fast Ignition approach to Laser Fusion and experiments have been performed in the last decades [2, 3]. The main idea is based on the possibility to enhance the focusing effect of the azimuthal magnetic field that is generated by the strong electron current into the target. Indeed, the first pulse (the seed beam) generate an azimuthal magnetic field and the second pulse (main beam) will generate the main electron beam which will be naturally guided by the pre-formed magnetic field.

The use of double pulse scheme in the femtosecond regime has been recently proposed to increase proton acceleration avoiding complicated target design and artificial schemes. Indeed, theoretical considerations and numerical simulations suggest a possible increasing of the electron density in the solid target due to the guiding effect induced by the formation of the azimuthal Magnetic field which confine the electrons in a smaller target volume.

A preliminary experiment has been performed by using the PW laser VEGA 3 at the Centro de Laseres Pulsados in Salamanca with the aim to study the effect of the double pulse scheme for enhancing the laser-driven proton production.

During the experiment two collinear laser pulses coming from VEGA 3 and with an energy ratio 20/80 were focused onto a thin copper target with respective laser Intensities ranging from 10^{19} W/cm^2 up to 10^{20} W/cm^2. The arrival of the two beams was controlled from 30 fs to 20 ps and both fast electrons in the target and the relative protons coming from the TNSA process were analyzed respectively thorough X-ray spectroscopy and direct proton detection in dedicated scintillator detectors.

The main features of the experiment together with prelaminar results are presented.

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Investigation of ion temperature in low-density foams

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Laser interaction with foam materials of low average density is a topic of great interest due to various applications in ICF or as secondary radiation sources. The addition of an extra foam layer to the ICF target capsule can improve implosion symmetry and suppress the formation of hydrodynamic instabilities in direct-drive ICF or increase the efficiency of laser to X-ray conversion in indirect drive. However, modeling of laser-foam interaction is difficult due to very different scale lengths involved, and the predictive capability of numerical simulations has not been proven yet. We present a recently developed multiscale model [1] along with the results from the concurrent experimental campaigns at the PALS laser facility that are used to benchmark the accuracy of the model. Our multiscale approach describes the laser-driven homogenization of individual foam elements as a competition between isothermal expansion (due to volumetric heating by electron heat flux) and surface ablation by the incident laser. The microscale model is formulated in terms of ordinary differential equations for mass, momentum, and energy conservation, and its parameters are chosen according to the detailed PIC simulations of laser-cylinder interaction [2]. Our results suggest that the ion temperature in foam materials should be significantly higher than the electron temperature due to the internal collisions of the plasma flows originating from the heterogeneous foam microstructure. This foam-specific property could provide an additional benefit in the context of ICF, as plasmas with elevated ion temperature could potentially help mitigate laser-driven parametric instabilities (such as Stimulated Brillouin Scattering) due to stronger damping of ion-acoustic waves. The impact of foam microstructure on ion temperature has been demonstrated in the latest PALS experiments where the plasma temperatures were determined from X-ray spectroscopy. The predictions from our hybrid foam model are in good agreement with the data acquired in these experimental campaigns.

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Laser-induced shock waves in overcritical foams

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The interaction of a laser with a foam target is of great interest for the high energy density physics. In application to the direct drive inertial fusion, foams are a promising material to smooth out the laser intensity modulations [1]. Compared to homogeneous targets, the laser propagation in foam is a more complicated problem. One has to account for the interaction between the laser or a shock wave and the foam micro-structure to describe the material properties at the macroscopic scale. This micro-structure is composed of identical pores containing a solid element inside. Here, the pore is defined as a cube filled with ambient low density Helium gas with a solid plastic cylinders in the middle.
This model correspond to an overcritical foam targets with a high density ratio. It is investigated numerically using the hydrodynamic code FLASH. Unlike the wetted-foam case [2,3] of much lower density ratio, we observe huge differences of the shock wave propagation compared to an homogeneous target of the same average density. Two representative cases are considered. If the foam structure is directly exposed to the laser, a shock wave is formed and has similar properties compared to the homogeneous case. In the second case, when the solid structural elements are homogenized by a shock wave, the propagation speed and internal structure of the transient zone is different, and a significant amount of energy is stored in the turbulent kinetic energy [4,5]. The properties of turbulence are also discussed.

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Measurement of Magnetic Cavitation Driven by Heat Flow in a Plasma

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In hot plasmas heat flow and magnetic fields are strongly coupled. Our simulations of high temperature laser-plasma experiments show that strong heat flows cause significant changes in the magnetic field but it has long proven difficult to measure these changes experimentally. A particular challenge in magnetized high-energy-density plasma experiments is Nernst-driven magnetic cavitation, in which heat flow causes expulsion of the magnetic field from the hottest regions of a plasma much faster than the bulk plasma flow [1,2]. This reduces the effectiveness of magnetized fusion techniques, where strong magnetic fields are used to confine the heat inside the plasma and increase yield [3,4].

We describe the direct measurement of the expulsion of a magnetic field from a plasma driven by heat flow. Using a laser to heat a column of gas within an applied magnetic field, we isolate Nernst advection and show how it changes the field over a nanosecond timescale. By reconstructing the magnetic field map using proton radiographs, we demonstrate that the field is advected by heat flow before the plasma expansion. The measured Nernst advection velocity of (600±200) km/s is faster than the ion sound speed, with the magnetic field dynamics dominated by the motion of hot electrons. Despite the steep temperature gradient, we found that the heat flow is localised at relatively low magnetic field strengths. This causes extended magnetohydrodynamic simulations to agree surprisingly well in this regime with both the experimental results and computationally expensive kinetic simulations.

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Short-time scaling of the laser-driven ablation front with 1D kinetic simulations

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DDFIW

Inertial Confinement Fusion is a promising way to produce carbon-free energy. One method to reach thermonuclear reaction conditions is to compress a target of Deuterium Tritium surrounded by a Carbon Hydrogen layer with a hundred of laser beams. The laser-heated outter layer expands outward creating a shock into the undisturbed material by rocket effect. After the shock transit time, the CH layer implodes and begins its acceleration phase. This flow regime, known as laser-driven ablation front, can be splitted into 3 zones. The laser propagation and energy deposition occurs in the plasma corona, where the electronic density (n_e) is below the critical density (n_{cr}). Then, the energy is carried by the electrons from the corona to the shock region in the conduction zone $n_e > n_{cr}$. The third region is the shock itself. Important quantities such as the ablation pressure and the ablation mass rate are strongly correlated to the thermal conduction in the conduction zone. Finding or improving energy transport models to describe the ablation flow is then unarguably necessary. To date, the only reliable method to simulate an ablation front over the space scales and time scales relevant to an experiment (centimeter, nanosecond) is to use hydrodynamic codes which are highly dependent on the heat flux closure. We performed highly-resolved 1D laser-driven ablation front simulations with the kinetic code Smilei [1]. These simulations resolve the electron and ion distribution functions and capture the self-consistent evolution of the electron thermal transport together with the laser-ablation front. Important quantities such as the ablation pressure and mass ablation rate are expressed as a power law of the absorbed intensity and are compared against known scalings as in Ref. [2]. The electron distribution function anisotropy is characterized in the conduction zone. Our simulations confirm the non-locality of the heat flux and will be a reference to existing [3−4] and futur non-local model in the hydrodynamic code TROLL [5].

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Time resolved x-ray imaging of hot electron retention and refluxing in Cu targets irradiated at shock ignition relevant laser intensities

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The role of hot electrons in a development of diverse scenarios for inertial confinement fusion, detailed mechanisms of their generation and impact on formation and dynamics of strong shocks are not fully understood yet [1]. Time- and 1D space-resolved generation of hot electrons was studied at Prague PALS facility providing laser intensities at the level of 2×10^{16} W/cm^2 incident on planar massive and 1-μm-thick Cu targets. Monochromatic images characterizing temporal evolution of the Cu K-shell emission due to the hot electron action in moderately heated targets were recorded by an x-ray imager combining the spherically bent crystal of quartz (422) with a high dynamic range Hamamatsu streak camera. The optimized experimental setup provided highly resolved data correlating the hot electron generation with the laser radiation incident on targets. The rising edge of the hot electron generation at massive Cu targets delays by approximately 80 ps compared to the laser profile whereas its decaying part practically coincides with that of the laser. In contrast, the duration of the hot electron-induced Cu Kα emission observed at foil targets extends to a hundred of ps vs the laser maximum which confirms previously published spectroscopic observations of the hot electron-induced emission from thin Cu foils [2]. The diverse character of the hot electron generation at foils reveals also in a considerably faster growth of the hot electron deposition area. Benefiting from a combination of the hydrodynamic simulations postprocessed by the PIC code, these phenomena are interpreted in terms of the hot electron retention and refluxing at surfaces of laser irradiated targets. Detailed knowledge of these processes contributes to better understanding of the physics of hot electron generation and transport under the laser fusion conditions.

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Direct Drive ICF

Modeling Target Defects in Direct-Drive Inertial Confinement Fusion

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A range of evidence from both radiation-hydrodynamic simulations and experiments suggests that isolated defects on the outside of cryogenic targets are able to play a significant role in degrading direct-drive inertial confinement fusion implosion performance. The highly non-linear growth is not ablatively stabilized and can be an important degradation even for current best performing, OMEGA cryogenic implosions. A cryogenic target may have thousands of surface defects, which originate during the high-pressure permeation fill and cooling cycle, and range in size from microns to tens of microns. Previous modeling of defects tens of microns in size has shown that the resulting local perturbation growth can inject ablator mass into the hot spot, contributing to radiative cooling and loss of performance [1]. In this talk we present the results of 2-D rad-hydro simulations with DRACO of smaller (micron-scale) defects in the context of more recent cryogenic target designs, addressing the transport of ablator material into the hot spot, fuel into the corona, and dependence of shell disruption on implosion stability. This material is based upon work supported by the Department of Energy [National Nuclear Security Administration] University of Rochester "National Inertial Confinement Fusion Program" under Award Number DE-NA0004144.

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Hot spot characterization in direct-drive implosions at OMEGA

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Direct-drive implosion experiments have been performed by CEA on the OMEGA laser facility for about ten years with a main focus on implosion and hot spot physics [1,2].
Here, we present preliminary results of a recent campaign dedicated to the detailed hot-spot characterization for two different implosion regimes for thin glass capsules using different fusible gas fillings. On the one hand, we studied a strong-shock (exploding-pusher) configuration with a square pulse shape and a thin ablator, resulting in a moderate convergence ratio and large hot spots with high temperatures. On the other hand, we investigated a compressive regime using a shaped impulsion and a thicker ablator, which led to higher convergence ratios and smaller hot spots with lower temperatures. A large number of space-resolved and time-resolved diagnostics has been implemented for extracting the distribution and the evolution of the ion and the electron temperature, and for comparing the two implosion regimes.

2D and 3D pre-shot and post-shot simulations show a good agreement with the experiment on the neutron yields. A more complete comparison between the simulation and the measurements is in progress.

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The High-Performance Direct-Drive DT-layered Implosion Campaign on the OMEGA laser

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Recent progress in implosion experiments on the OMEGA laser have considerably improved the prospects for achieving ignition and energy gains with megajoule-class lasers via direct drive. By hydrodynamically scaling the core conditions of highest performing OMEGA implosions [1], fusion yields in excess of 1.5 MJ are predicted for ~ 2 MJ of symmetric laser illumination [2]. Those implosions exhibited a significant increase in performance resulting from a statistical approach used in designing targets and laser pulse shapes [3,4]. This led to target designs with the highest implosion velocity while maintaining hydrodynamic stability. A dimensionless form of the statistical model [4] is used to quantify the different degradation mechanisms affecting OMEGA implosions. It is now possible to separate individual contributions to the yield degradation providing a more complete physics picture for each implosion. To test individual degradation mechanisms, dedicated implosion experiments have been carried out by implementing single parameter scans. Scans of the SSD (Smoothing by Spectral Dispersion) bandwidth [5,6] at different adiabat are used to study laser imprinting; scans of the stalk size are used to study effects of engineering features; scans of the vapor pressure are used to study the effects of higher convergence.
An overview of the implosion optimization effort and of the dedicated physics experiments at the OMEGA laser will be provided.

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Direct drive campaign of initial confined fusion at the National Laboratory on High Power Laser and Physics

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With the greatest achievements in both direct and indirect drive of the laser confined fusion reactions in most recent three years, the has been portrayed over tens of years, the perspective for future fusion energy utilization is now coming to the actuality. The National Laboratory on High Power Laser and Physics, Shanghai Institute of Optics and Fine Mechanics, dedicated in high power laser driver of the ICF for over 40 years, recently, has launched a program aims to the fusion energy yielding by means of the direct drive of the laser confined fusion. The program includes four phases to achieve the goal, upgrade the present laser system, build a new lager laser system, physical experiments and the blueprint of a demo power plant. In this presentation, we will present the synopsis of the program and progress made in upgrading our laser facilities of picosecond and nanosecond beams, as well as the experimental activities at the laboratory.

Optimization of laser pulses for direct-drive implosions via machine learning

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Abstract of the contribution:

The optimization of laser pulse shape [1,2] is of great importance for the design of target compression in laser-driven fusion. Here, we propose an artificially intelligent method to perform laser pulse optimization via hydrodynamic simulations guided by the genetic algorithm [3]. The one-dimensional MULTI-IFE code [4,5] is employed to determine the implosion performance under given laser pulse shapes and target parameters. The genetic algorithm is used to guide the hydrodynamic simulations within a vast parameter space. During the optimization processes, up to thousands of different laser pulse shapes are evaluated, which can be utilized for constructing the hydrodynamic scaling relations [6,7]. It is found that a large fuel mass and a high areal density required for high-gain fusion can be obtained simultaneously by optimizing the implosion velocity with less compression laser energy. The obtained scaling relations are applied to the implosion design for the double-cone ignition scheme [Zhang et al., "Double-cone ignition scheme for inertial confinement fusion," Philos. Trans. R. Soc., A 378(2184), 20200015 (2020)]. Our methods and results may be useful for the optimization of fusion experiments toward high-gain fusion.

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Optimization of Polar Direct Drive for Mega-Joule Laser Facilities

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The National Ignition Facility (NIF) has achieved ignition [1] using an indirect drive approach to inertial confinement fusion (ICF), where a roughly 1mm radius spherical target was compressed to less than 0.1mm by x-rays. Stable compression requires highly uniform, spherical illumination, which is achieved for indirect drive with the use of a cylindrical hohlraum where laser light enters at the poles and is converted to thermal x-rays before driving the target. This helps to improve irradiation uniformity, but at the cost of laser-target coupling efficiency when compared to a direct-drive (DD) approach. Due to its efficiency, DD is a promising candidate when moving beyond ignition towards a future energy source. However, testing DD at ignition scale is challenging as the mega-joule laser facilities (National Ignition Facility, NIF and Laser Méga-joule, LMJ) are configured with beams entering the target chamber in the polar region for indirect-drive, and so require optimization to enable DD compatible illumination. The NIF features: 48 quads of beams entering from different ports with independent pointing, power balance, and defocusing. A polar direct-drive (PDD) scheme has already been tested on the NIF [2], but it is likely not the optimal solution as there is a large parameter space and evaluating it requires expensive experimental/computational methods.

This talk presents an efficient, new, algorithmic approach for illumination optimization. The procedure optimizes illumination uniformity in the presence of temporally varying plasma and cross-beam energy transfer [3]. The automated process has been used to create more uniform illuminations for PDD, and it can be modified for other configurations. The process is currently being applied to aid in the design of experiments for both the NIF and LMJ.

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Simulation of polar direct drive wetted-foam capsule physics

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We investigate the feasibility to achieve high nuclear yields using a liquid DT-wetted layer capsule directly driven by the National Ignition Facility's (NIF's) current laser capabilities[1]. The capsule is composed of a thin plastic shell used to enclose a thick annular 3D-printed matrix layer that contains the liquid DT fuel. Comparisons across several simulation codes indicate that a high level of laser absorption can occur that drives a central gas pocket convergence of 15 enabling higher levels of gain and the potential to robustly ignite (using the current laser energy available at NIF). High laser absorption is consistent with previous polar direct drive (PDD) MJ-class NIF experiments where >95% capsule absorption of the laser drive energy was achieved using a 5 mm diameter plastic capsule[2]. The results of simulations using the HYDRA radiation-hydrodynamics code will be shown to elucidate the laser driven asymmetry in the implosion of these capsules. Fabrication efforts using 3D printing techniques are currently underway to construct the hybrid capsules for NIF experiments later this year. Since the fuel layer consists of a heterogeneous combination of a 3D-printed plastic lattice and liquid hydrogen fuel, dedicated planar cryogenic laser ablation experiments will be performed soon to assess the effects of heterogeneous ablation and propagation on the hydrodynamic evolution of these materials. An overview of these multi-Laboratory efforts will be presented.

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Tuning the N+1 Shock to Increase Yield

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Shock Augmented Ignition offers the possibility of increased yield by combining the benefits of central hotspot ignition and shock ignition. One of the factors leading to increased yield is refered to as ‘N+1 tuning’, here the N+1 shock refers to the shock which forms when the ‘N’ main drive shocks reflect off surfaces within the capsule to form a single merged shock.

Tuning the NIF 3 shock design so that all 3 main shocks coalese close to the ice-gas interface is known to increase yield by reducing the fuel’s adiabat (and therefore maintaining high compressability). However, the reflections of these shocks also introduce entropy into the fuel, which can also reduce compressability.

Simulations will be presented suggesting that by tuning the N+1 shock merger so that it occurs closer to the ice-gas interface, the yield of an implosion can be increased.

Indirect Drive ICF

Overview of LMJ-PETAL experimental capabilities

Guidelines for 2027-2029 Call of proposals

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Since its commissioning experiments at the end of 2014 with 1 bundle and a single x-ray imager [1,2], the Laser Megajoule (LMJ) has been steadily improved in terms of beam number, available energy at target center chamber, and plasma diagnostics. Indirect drive Inertial Confinement Fusion (ICF) implosions are now routinely performed with up to 88 beams delivering 100 TW / 300 kJ on target, and can be characterized with 23 plasma diagnostics of various kind [4]. While not devoted and optimized for direct-drive ICF studies, some proof-of-concept experiments could nevertheless be performed [5], taking advantage of state-of-the-art diagnostics such as a time resolved NBI [6] or a 2 colors (1w and 2w) VISAR. The PETAL* laser [6] with sub-ps duration and up to 650 J, focused on a 50 microns focal spot can deliver on target intensities of several 10^{18} W/cm^2, enabling production of multi-MeV proton beams [7, 8], and hard x-ray (tens of keV) radiography sources.

I will quickly summarize the LMJ PETAL experimental capabilities, as well as its final completion stages until 2026. The guidelines for the 2027-2029 LMJ PETAL ALPES (Academic Laser Program for Excellent Science) Call of proposals will also presented, as the next call will be issued in the following months by Association Laser Plasma (ALP).

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First inertial confinement fusion implosions using low gas-filled hohlraums on the Laser Mega Joule facility

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The inertial confinement fusion (ICF) platform in the indirect-drive configuration on the Laser Mega Joule (LMJ) facility has been considerably extended since the first fusion experiments performed in 2019 [1]. The LMJ facility is now capable of delivering up to 270 kJ of UV energy on target using eighty beams evenly distributed among four rings allowing for a symmetric irradiation inside a hohlraum for the first time.

Here, we report on recent experimental progress on the first indirect-drive implosion campaigns carried out over the past three years to achieve an ablative compression regime using this unprecedented irradiation configuration. In those experiments, D_2-filled silicon-doped plastic capsules were imploded using low gas-filled rugby-shaped, elliptical and cylindrical gold hohlraums using 2-shocks and drooping pulses. The commissioning of new plasma diagnostics has allowed observing X-ray images of the hot spot emission for the first time on LMJ.

Integrated 2D and 3D simulations using the radiation hydrodynamics code TROLL [2] are performed to investigate the experimental results including neutron yield, radiation temperature, implosion symmetry and X-ray images of the stagnating hot spot as well as the gold wall motion inside the holhraum. We also report on significantly different levels of measured backscattered energy and cross-beam energy transfer between inner and outer beams for the three hohlraum shapes. Finally, we show how these results will guide the future designs for the inertial confinement fusion campaigns on LMJ in the upcoming years.

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