Innovative Concepts for Inertial Fusion Energy (IC-IFE)

2026 International Physics Workshop

Hosted by UC San Diego & Lawrence Livermore National Laboratory
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May 20-22, 2026
University of California Livermore Collaboration Center
(UCLCC) Livermore, California

Scientific Committee:

- Drew Higginson (Co-Chair), LLNL
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- Sasi Palaniyappan, LANL
- João Santos, Univ. of Bordeaux
- Hiroshi Sawada, UN Reno
- Scott Wilks, LLNL (retired)

Tues, May 19

Start Time	
7:00 PM	Welcome Reception (TBD)

Weds, May 20

Start Time	dt (min)		
8:30 AM	10	Workshop Welcome	Drew Higginson
8:40 AM	40	Opening Plenary	Mike Campbell
9:20 AM	40	Inertial Fusion Energy and its potential for acceleration	Cliff Thomas
10:00 AM	**20**	**Break**	
10:20 AM	30	Magnetized laser-driven ICF	Chris Walsh
10:50 AM	30	Evaluating concepts for boosting ignition gains by magnetizing laser-driven inertial fusion implosions	Arijit Bose
11:20 AM	20	Magnetized Inertial Confinement Fusion: Transport Physics and Performance Enhancement in Pre-Magnetized	João Jorge Santos
11:40 AM	**30**	**Discussion: Magnetized laser ICF**	**Farhat Beg**
12:10 PM	**60**	**Lunch**	
1:10 PM	30	Measurement of Proton Stopping Power in Warm Dense Matter approaching the Bragg Peak	Krish Bhutwala
1:40 PM	30	Neutronic Effects on Ignition and Burn Dynamics in Fast-Ignition DT Fuel	Tomoyuki Johzaki
2:10 PM	20	Proton Stopping from Bound States in Partially Ionized Plasmas	Zachary Johnson
2:30 PM	**30**	**Discussion: Ion stopping power and transport**	**Sophia Malko**
3:00 PM	**20**	**Break**	
3:20 PM	30	Formation of compressed fuel core for fast ignition	Hideo Nagatomo
3:50 PM	30	Physics of Cone-in-Shell Implosions in OMEGA Experiments Studying Electron and Proton Fast Ignition	Andrey Solodov
4:20 PM	20	Large-scale high-yield implosions for inertial fusion energy (IFE): enhanced performance and distinct physics	Darwin Ho
4:40 PM	20	Alternative Approaches to Fast Ignition	Edison Liang
5:00 PM	**30**	**Discussion: Implosion physics**	**Drew Higginson**
5:30 PM	**90**	**Posters (+ food & drinks)**	
7:00 PM		End	

Thurs, May 21

Start Time	dt (min)		
8:30 AM	15	LLNL Director's Welcome	Kim Budil
8:45 AM	**10**	**Group Photo**	
8:55 AM	15	Livermore Institute for Fusion Technology (LIFT) Overview	Clément Goyon
9:10 AM	40	High-gain Laser Fusion Achieved by Heatwave-driven Fast Ignition for Inertial Fusion Energy	Yasuhiko Sentoku
9:50 AM	30	Fast ignition of inertial fusion targets. Laser beam energy requirements	Javier Honrubia
10:20 AM	**20**	**Break**	
10:40 AM	30	From proton heating to integrated proton fast ignition experiments on the OMEGA laser facility	Mathieu Bailly-Grandvaux
11:10 AM	20	Investigation of Proton Source Survivability and Heating in Integrated Proton Fast Ignition Experiments	Perry Samimy
11:30 AM	20	Particle-in-cell Modeling of Proton Acceleration for Fast-ignition Experiments	Marin Fontaine
11:50 AM	**30**	**Discussion: Ion fast Ignition**	**Scott Wilks**
12:20 PM	**60**	**Lunch**	
1:20 PM	30	Prospects for Inertial Fusion Energy R&D Based on an Optical Enhanced Cavity Laser System	Shinsuke Fujioka
1:50 PM	30	Could Magnetic Mirrors Change the Prospects for Electron Fast Ignition?	Alex Robinson
2:20 PM	20	Fast heatwave propagation with nonlocal electrons accelerated at a steepened plasma surface formed by PW	Naoki Okuda
2:40 PM	20	A novel fast ignitor	Hartmut Ruhl
3:00 PM	20	Theoretical model for laser propagation via relativistically induced transparency and the transition to hole boring	Hayato Yanagawa
3:20 PM	**30**	**Discussion: Electron fast Ignition**	**Hiroshi Sawada**
3:50 PM	**20**	**Break**	
4:10 PM	30	Heavy Ion Driven Inertial Fusion Energy	Peter Seidl
4:40 PM	30	Heavy Ion Fusion: Ready for Reconsideration?	Gennady Shvets
5:10 PM	20	Gas optics for high-power laser applications	Pierre Michel
5:30 PM	20	Heavy Ion Fusion Hohlraum Modeling at the GJ-scale	Drew Higginson
5:50 PM	**30**	**Discussion: Heavy ion fusion**	**John Lindl**
6:20 PM		End	

7:00 PM		Banquet

Friday, May 22

Start Time	dt (min)		
8:30 AM	40	Conceptual design for a European High Power Laser Fusion Research Facility	Luca Volpe
9:10 AM	30	On the role of self-generated magnetic fields in focused ion beams driven by intense picosecond laser pulses	Andreas Kemp
9:40 AM	20	Experimental Evaluation of Petawatt-laser-driven Nano Accelerators for IFE	Marius Schollmeier
10:00 AM	20	High-flux ion acceleration in structured foam targets	Joshua Luoma
10:20 AM	**20**	**Break**	
10:40 AM	20	Dual pulse micronozzle acceleration of GeV-class protons	Diya Pan
11:00 AM	20	Laser ion acceleration from concave targets by subpicosecond pulses	Kirill Lezhnin
11:20 AM	20	Scaling of Proton Focusing with Laser Energy	Ryan Nedbailo
11:40 AM	**30**	**Discussion: Ion acceleration and focusing**	**Natsumi Iwata**
12:10 PM	**60**	**Lunch**	
1:10 PM	30	Pulsed power driven preheat using a cryogenic Ice fiber for MagLiF experiments on Z	Chris Jennings
1:40 PM	20	FLARE: A new approach to Fast Ignition	Jonathan Skidmore
2:00 PM	20	Pulsed Liner Fusion: Advantages and Challenges for the High Current Pulsed Power Approach to IFE	Simon Bott-Suzuki
2:20 PM	**30**	**Discussion: Pulsed power magnetized ICF**	**Kyle Peterson**
2:50 PM	**20**	**Break**	
3:10 PM	20	High-Contrast Laser Interaction for Efficient Heating of Dense Plasma	Ryunosuke Takizawa
3:30 PM	20	Experimental study of resistively focused relativistic electrons for EFI	Sameen Yunus
3:50 PM	**30**	**Discussion: Electron acceleration**	**João Jorge Santos**
4:20 PM	**20**	**Break**	
4:40 PM	**30**	**Outbrief and Round Table**	
5:10 PM		End	

Poster Session

1	Sub-picosecond Coulomb explosion of nanoparticles for nonthermal ion acceleration with applications for fusion	Christopher Grayson
2	Investigation of Ion Focusing using Structured Targets for Applications to Ion Fast Ignition	Raspberry Simpson
3	Revisiting the Physics of Collisional Suppression of Hot Electron Generation	Kale Weichman
4	WarpX Exascale open-source code for kinetic laser-plasma modeling	Remi Lehe
5	Machine-Learning-Based Digital Twins of High-Repetition-Rate Laser Systems as Testbeds for Laser Driver Control	Blagoje Djordjević
6	Critical role of laser intensity above 1021 W/cm2 in fast ignition for laser fusion energy	Natsumi Iwata
7	X-ray Thomson Scattering Measurements of Fast-Electron-Heated Solid-Density Plasmas with an XFEL at LCLS	Hiroshi Sawada
8	Viscosity Measurement in Shock-compressed Epoxy	Afreen Syeda
9	Radiation-Hydrodynamics code HELIOS-CR: improved models for dense plasma effects and IFE simulations	Igor Golovkin
10	XUV Diagnostic System for Measuring the Focusing of Protons Produced by High Intensity Laser Pulses	John Gjevre
11	Indirect-drive wetted foam implosions at the National Ignition Facility	Steve MacLaren
12	First demonstration of an additively manufactured wetted foam direct-drive ICF target on the NIF	G. Elijah Kemp
13	A Brief Literature Review of Heavy Ion Fusion for Energy Applications	Vikrant Ganesan
14	Magnetic Collimation of Relativistic Electron Beams through Resistivity Gradients	Will Riedel
15	Optimizing laser-driven ion sources for applications to ion fast ignition	Tom Hodge
16	Shock propagation in cryogenic deuterium-wetted foams	Siegfried Glenzer

Abstract Table of Contents

Abstract Table of Contents cont.

Abstract Table of Contents cont.

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

M. Bailly-Grandvaux (1), P. Saminy (2), S. Bolaños (3), J. Kim (4), T.R. Joshi (2), W. Theobald (5),
A. Solodov (6), S. Ivancic (6), T. Hodge (7), K. Bhutwala (8), S. Malko (8),
R. Nedbailo (9), D. Higginson (10), R. Simpson (10), S.C. Wilks (10), and F.N. Beg (2)
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(8) Princeton Plasma Physics Laboratory (USA) (9) University of Texas Austin (USA)
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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.

References

[1] M. Bailly-Grandvaux *et al.*, *Commun. Phys.* 8, 285 (2025).

Experiments were conducted at the Omega Laser Facility with beam time through the NLUF user program. Material is based upon work supported by the Department of Energy [NNSA] University of Rochester "National Inertial Confinement Fusion Program" under Award Number DE-NA0004144.

Measurement of Proton Stopping Power in Warm Dense Matter approaching the Bragg Peak

K. Bhutwala[1], X. Vaisseau[2], V. Ospina-Bohorquez[2], M. Ehret[3], J. I. Apinaniz[3], D. De Luis[3], M. Huault[3], W. Cayzac[4], J. J. Santos[5], J. Vargas[6], M. Bailly-Grandvaux[7],
C. McGuffey[8], R. Hollinger[9], S. Wang[9], G. Zeraouli[9], F. Kraus[1], W. Fox[1], D. B. Schaeffer[10],
J. Rocca[9], R. Fedosejevs[11], L. Volpe[12] and S. Malko[1]
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Understanding proton transport in plasma is foundational to inertial fusion energy (IFE), specifically for modeling alpha-particle heating and proton fast ignition. One critical parameter is the proton stopping power $d\varepsilon/dx$, governing energy deposition. While stopping models for fast protons ($v_p \gg v_{th,e}$) are well established, the regime near the Bragg peak ($v_p \approx v_{th,e}$) — where proton-plasma coupling is strongest — remains subject to intense debate. This is especially true in warm dense matter (WDM) where the interplay of electron degeneracy and strong coupling creates a uniquely intricate transport environment. The confluence of these regimes compounds the modeling complexity and creates a “modeling gap” in which predictions by the most advanced models vary by as much as 40%.

Here, we report on results from the second-generation experimental proton stopping power platform[1] at the CSU ALEPH laser, designed to benchmark this modeling gap. We measured the total energy loss of an energy-selected (500±10 keV), short-pulse (<200 ps) proton beam[2] through laser-heated warm dense carbon samples. These results are compared against predictions from leading stopping power models coupled with RALEF-2D hydrodynamic simulations of laser-heated WDM. To ensure high-fidelity benchmarking, we validated WDM temperatures using in-situ streaked optical pyrometry, measuring temperatures up to 8 eV. Our experimental results provide a critical benchmark for transport codes vital to designing high-gain IFE schemes.

[1] S. Malko et al., "Proton stopping measurements at low velocity in warm dense carbon." *Nature Communications* 13.1 (2022)
[2] J. I. Apiñaniz et al., "A quasi-monoenergetic short time duration compact proton source for probing high energy density states of matter." *Scientific Reports* 11.1 (2021)

This work was supported by the U.S. DOE Office of Science, Fusion Energy Sciences under Contract No. DE-SC0021246: the LaserNetUS initiative at Colorado State University. This work was also supported by IMPULSE (Grant Agreement No. 871161, European Union Horizon 2020 research and innovation program). The research was conducted under the Laboratory Directed Research and Development (LDRD) Program at Princeton Plasma Physics Laboratory, a national laboratory operated by Princeton University for the U.S. Department of Energy under Prime Contract No. DE-AC02-09CH11466.

Evaluating concepts for boosting ignition gains by magnetizing laser-driven inertial fusion implosions

Arijit Bose (1), Robert Spiers (1), Cameron A. Frank (1),
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Achieving robust ignition with target gains exceeding ~50 remains a central challenge in the design of inertial fusion concepts. Applying an external magnetic field (10–30 T) to laser-driven spherical implosions can improve the hotspot power balance by suppressing electron thermal conduction losses and enhancing fusion self-heating, while also offering potential mitigation of instability growth. Through these mechanisms, magnetization can significantly boost ignition gains and enable otherwise marginally igniting implosion designs to achieve robust burn.

However, predictive theoretical models for magnetized inertial fusion remain limited. The presence of magnetic field breaks spherical symmetry, making design iteration computationally expensive and often reliant on 2D radiation–magnetohydrodynamics simulations.

In this presentation, we describe new semi-analytic models [1, 2] for magnetized implosions that capture key physical processes, including: (1) the compression and evolution of axial magnetic fields, (2) effects of fields on thermal losses and fusion self-heating, and (3) concepts for generating closed magnetic field lines in the hot spot. Using these models, we identify regions of hotspot parameter space where magnetization provides the greatest performance benefit. We also assess the feasibility of novel magnetic-field generation approaches—including embedded wires, microwave-driven fields, and dynamo field generation— to further boost performance of inertial fusion designs.

References
[1] Spiers, R.; Bose, A.; Frank, C. A.; Lahmann, B.; Moody, J. D.; Sio, H; Strozzi, D. J.; *Physics of Plasmas* **32**, 072712 (2025).
[2] Spiers, R.; Bose, A.; Frank, C. A.; Moody, J. D.; Strozzi, D. J.; Walsh, C. A.; Hammel, B.; *In preparation for submission to Physics of Plasmas*

Acknowledgment
This material is supported in part by 1) DOE NNSA SSGF program DE-NA0003960, 2) URochester LLE subaward through DE-NA0004144 and 3) DOE LLNL DE-AC52-07NA27344 including LDRD 23-ERD-025.

Pulsed Liner Fusion: Advantages and Challenges for the High Current Pulsed Power Approach to IFE

Simon Bott-Suzuki[1], Matt Gomez[2], Chris Jennings[2], Kyle Peterson[2], Tom Awe[2], Paul Holligan[3], Johnathan Skidmore[3], Ryan McBride[4], Simon Bland[5], Jack Hare[6]

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Abstract: The development of the Magnetized Liner Inertial Fusion (MagLIF) concept at Sandia National Laboratories coupled with advances in pulsed power technology have opened a realistic path to high yield and energy production for high current pulsed power. Initial target designs suggested cryogenic liner loads could produce yields over 1 GJ and gains >100 for a current drive of ~60MA. Experimental programs on Z have shown that gain scalings match those seen in simulations, and advanced target designs suggest engineering gains well above unity for current drives. Alongside this, both the linear transformer driver (LTD) and the Impedance-matched Marx Generator (IMG) are now proven technologies that provide compact, rep-rate capable, modular building blocks to construct ignition scale drivers. Despite very modest federal investments over the last several decades, the MagLIF platform has achieved triple product values $>10^{21}$ keV/m^3/sec.

A number of private companies are pursuing variants of the MagLIF design, which we refer to collectively as 'Pulsed Liner Fusion'. An ignition scale system is only a factor of ~2-3 larger than the present Z machine, but a number of issues must be addressed for both high yield and commercial energy. Since the load must be in electrical contact with the driver, a replaceable electrode system must be developed and demonstrated. Whilst research carried out on Recyclable Transmission Lines designs have shown significant advantages in chamber environment robustness and target engagement, this is presently quite limited and needs further study. Additionally, many large-scale pulse power systems operate in single shot mode (i.e. once per day). Whilst the driver architectures presently in use are capable of Hz rep-rates, further study is required to determine the lifetime of components such as high voltage switches, so that operational limits can be set in reactor designs. These endeavors are supported by an active academic community training students, testing novel ideas and validating scaling models.

Here, we present a summary of the main advantages and challenges along the path to IFE for high current pulse power. We will highlight present and planned projects which directly address the needs of present high yield and IFE designs and show that Pulsed Liner Fusion remains a promising approach.

Machine-Learning-Based Digital Twins of High-Repetition-Rate Laser Systems as Testbeds for Laser Driver Control and Optimization

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Mackenzie Nelson, (1) Justin Galbraith, (1) Derek Mariscal (1)
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The development of inertial fusion energy (IFE) power plants will require drivers capable of stable, high-repetition-rate operation and real-time optimization across large parameter spaces. In this work we present a framework for constructing data-driven digital twins of high-repetition-rate laser systems using multimodal experimental data streams and machine learning (ML). Using experimental data from thousands of laser shots from the PEENING laser at UCLA, the models learn correlations across heterogeneous datasets and reproduce the dynamical behavior of the laser system. These include diagnostic images, scalar and multi-dimensional system metrics, and facility control parameters, which are combined to predict both future laser performance and associated diagnostic observables. The approach employs neural architectures that combine variational autoencoders for image diagnostics with sequence models that capture the temporal evolution of system states. In particular, multi-head attention mechanisms, central to modern transformer architectures such as ChatGPT, are used to capture long-range correlations across diagnostic channels and facility parameters. The resulting surrogate models provide a fast, differentiable representation of the laser system that can operate in real time. This capability forms the basis of a digital-twin framework in which experimental data streams continuously update predictive models deployed alongside the facility. Such models enable improved stabilization of laser drivers, rapid optimization of operating conditions, and exploration of design margins under realistic experimental conditions. Beyond forward prediction, this approach opens a pathway toward inverse modeling and closed-loop experimental control, where machine learning agents guide experimental campaigns through active learning and automated optimization. High-repetition-rate laser systems coupled to advanced ML-algorithms provide an important experimental platform for developing the control and optimization technologies required for future IFE power plants.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344 and supported by the U.S. Department of Energy's (DOE) Office of Science (SC) Fusion Energy Sciences (FES) program under SCW1942. This work was also supported by the U.S. Department of Energy's (DOE) Office of Science (SC) Fusion Energy Sciences (FES) program under DE-SC0024549: the LaserNetUS initiative at the Phoenix Laser Facility.

Particle-in-cell Modeling of Proton Acceleration for Fast-ignition Experiments

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Conventional inertial confinement fusion (ICF) relies on long-duration, nanosecond laser pulses to symmetrically compress and heat a fuel capsule, leading to thermonuclear burn, as demonstrated at the National Ignition Facility in 2022. Following this milestone, achieving the higher energy gains required for economical, grid-scale inertial fusion energy remains a central challenge. Fast ignition (FI), in which compression and heating are decoupled, has emerged as a promising alternative to reach higher gains by relaxing symmetry constraints and reducing the overall drive energy. Proton-driven fast ignition (PFI) leverages the intrinsic advantages of laser-accelerated proton beams primarily generated through the target normal sheath acceleration (TNSA) mechanism (J. C. Hernández *et al.* 2014), namely their strong focusing capability and localized, efficient energy deposition, to enhance coupling to the dense fuel and potentially improve overall gain.

Two experimental efforts have been conducted within our group to investigate key elements for improving PFI performance. The first comprises experimental campaigns recently conducted at the ALEPH and Titan laser facilities and focuses on enhancing proton acceleration efficiency using promising near-critical-density foam targets (M. Bailly-Grandvaux *et al.* 2020; Ö. Culfa *et al.* 2026). The second campaign integrated a proton beam into a direct-drive ICF implosion on the OMEGA laser facility to evaluate the resilience of TNSA proton sources to the harsh radiation environment during compression and to quantify the capsule preheating it induces.

Within this broad experimental effort, particle-in-cell (PIC) modeling was used as a complementary tool. Extensive simulations were performed with the WarpX code (J.-L. Vay *et al.* 2025) to characterize and constrain the proton source generated by laser interaction with different target types through the TNSA mechanism. These two-dimensional PIC calculations, closely reproducing the experimental configurations, were instrumental in guiding experimental design and supporting data analysis. For example, they helped select the laser pulse duration, total energy and focal spot size for the OMEGA shot day.

References

M. Bailly-Grandvaux *et al.*, *Physical Review E* **102**, 021201 (2020)

Ö. Culfa, J. Kim, M. Bailly-Grandvaux, and F. N. Beg, *Physical Review E* **113**, 015202 (2026)

J. C. Hernández *et al.*, *Nuclear Fusion* **54**, 054006 (2014)

J.-L. Vay *et al.*, *WarpX: An advanced Particle-In-Cell code*, version 25.10 (2025)

This work is part of the NNSA Center of Excellence, the Center for Matter under Extreme Conditions (CMEC), supported by the U.S. DOE-NNSA under Award Number DE-NA0004147.

Prospects for Inertial Fusion Energy R&D Based on an Optical Enhanced Cavity Laser System

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Y. Michine (3), H. Yoneda (3, 1), T. Mikami (4,1), S. Iizuka(2, 1), H. Ohta(2, 1), S. Nakamura(2)
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Inertial Fusion Energy (IFE) requires a laser driver that simultaneously achieves high peak power, high repetition rate, and high wall-plug efficiency—a combination that remains a major technological challenge. The Optical Enhanced Cavity (OEC) laser system offers a novel approach to addressing these requirements by storing optical energy coherently in a high-finesse cavity and extracting it on demand for target irradiation. In this presentation, we discuss the prospects of IFE research and development based on the OEC laser concept. By decoupling laser amplification from instantaneous target illumination, the OEC approach enables effective temporal and spatial energy compression beyond the limits of conventional single-pass high-power lasers. This architecture opens a pathway toward reactor-relevant laser parameters while leveraging advances in high-efficiency laser sources, precision optical coatings, and cavity control technologies. We will review the current status of OEC laser development, including experimental demonstrations, scaling studies, and numerical simulations that clarify the limits imposed by optical damage, scattering losses, and phase stability. The implications of OEC-based drivers for inertial fusion schemes—such as improved energy coupling, flexible pulse shaping, and compatibility with high-repetition operation—will be discussed. Finally, we outline key R&D milestones toward reactor-scale implementation and highlight how the OEC laser system may redefine the design space for future inertial fusion energy drivers. This work was supported by the Joint Us-age/Research Center Program of the Institute of Laser Engineering (ILE); the "Power Laser DX Platform" as shared research equipment under the Ministry of Education, Culture, Sports, Science and Technology Project for Promoting Public Utilization of Advanced Research Infrastructure (Program for Advanced Research Equipment Platforms, Grant No. JPMXS0450300021); the Japan Society for the Promotion of Science Core-to-Core Program (GrantNo. JPJSCCA20230003); and JST Moonshot R&D Program (GrantNo. JPMJMS25A9). The authors report grants performed under the framework of Blue Laser Fusion Energy Research Alliance Laboratory at the University of Osaka.

XUV Diagnostic System for Measuring the Focusing of Protons Produced by High Intensity Laser Pulses

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Proton fast ignition schemes for inertial confinement fusion require a high flux beam of high energy protons on target. [1] Protons can be emitted perpendicular to the rear surface of thin foils hit by high intensity laser pulses through the well-known TNSA mechanism [2]. The generated protons can be focused by using a hemispherically shaped thin foil target. [2,3]. Proton flux achieved can be determined from the heating of a secondary thin foil target placed close to proton focus, where the secondary foil is heated to temperatures of several eV. [3] Heat from the target is radiated through Planckian blackbody emission allowing for temperature to be extracted based on photon energy and flux. To study proton focusing, an experiment, as described above, was performed at the ZEUS laser facility at the University of Michigan. Temperature was studied by imaging the rear side of the secondary target over a narrow band of XUV emission centered on 93eV. The time integrated photon flux at this energy allows target temperature to be found, which can be compared to Hydrodynamic modeling of the interaction. The XUV imaging diagnostic, simulations, and analysis techniques are discussed along with initial heating images.

1 – M. Roth, et. al. “Fast Ignition by Intense Laser-Accelerated Proton Beams”, Phys. Rev. Lett. Vol. 86, 436, (2001)

2 – T. Bartal, et. al. “Focusing of short-pulse high-intensity laser-accelerated proton beams”, Nat. Phys. Vol. 8, pp. 139-142, (2012)

3 - P.K. Patel, et al. "Isochoric heating of solid-density matter with an ultrafast proton beam." Phys. Rev. Lett. Vol. 91, No. 12, (2003)

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Radiation-Hydrodynamics code HELIOS-CR: improved models for dense plasma effects and IFE simulations

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HELIOS-CR is a 1-D radiation-magnetohydrodynamics code that is used to simulate the dynamic evolution of plasmas created in high energy density physics (HEDP) experiments [1]. The energy sources include lasers, radiation sources, electric currents (in cylindrical geometry), and particle beams. It has been extensively used for modelling low-yield ICF experiments. We will discuss several model improvements that makes HELIOS more suitable for IFE simulations including accounting for burned fuel, improved fusion cross-sections, more accurate and efficient charged particle transport algorithms, and support for non-monoenergetic particle beam specifications. In addition, we will present new models that account for dense plasma effects on atomic structures and their effect on the results of hydrodynamics simulations with inline collisional-radiative atomic kinetics. Development of a new model for the laser energy deposition suitable for sub-picosecond laser pulses will also be discussed. In this approach, Maxwell's equations will be solved explicitly to obtain the radiation field and will account for laser-matter interaction in the presence of steep density gradients. We will demonstrate the need to re-evaluate the models for the thermal fluxes and electron–ion relaxation in the plasmas with extreme temperature gradients.

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Sub-picosecond Coulomb explosion of nanoparticles for nonthermal ion acceleration with applications for fusion ignition*

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We investigate laser-driven ion acceleration using ultrashort relativistic pulses interacting with subwavelength target structures, rather than the micron–millimeter scale geometries typical of structured laser targets. Our approach seeds the pre-plasma with high-Z conductive nanostructures (e.g., Au, Ag) engineered for plasmonic resonance with the incident ultrafast pulse. In the 10–100 fs regime, rapid electron evacuation from nanoscale conductors can outpace charge neutralization and occur before significant heavy-ion motion, producing large, spatially structured electrostatic potentials. The resulting Coulomb explosion of the high-Z framework can drive directed acceleration of nearby low-Z ions (H, C, D, He, B), enabling efficient conversion of laser energy into electrostatic potential energy and subsequently into ion kinetic energy, without relying on collisional electron–ion energy coupling.

Particle-in-cell simulations of resonant nanoshell geometries predict sub-picosecond, highly synchronous dynamics including prompt electron depletion, rapid shell charging and expansion, and simultaneous inward compression/acceleration of lighter ions. These dynamics can produce transient density amplification and hundreds of keV ion energies. Because the mechanism is nanoscopic and field-dominated, it mitigates hydrodynamic growth of classical instabilities and reduces pulse-energy requirements via resonant near-field enhancement.

To directly probe ion energization on 10–100 fs timescales, we propose a reaction-based diagnostic in which Coulomb-explosion–accelerated low-Z ions drive fusion reactions whose yields encode the underlying ultrafast accelerating fields. This approach motivates a path toward compact, high-repetition-rate (100 -1 kHz), yet low driver-energy (10-100mJ) aneutronic fusion concepts and ion-driven inertial fusion energy (IFE) at the kW scale.

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Heavy Ion Fusion Hohlraum Modeling at the GJ-scale

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We present a design for an indirect drive, heavy ion fusion (HIF) target with simulated yields on the order of a gigajoule. Building on the distributed radiator hohlraum of Callahan and Tabak[1], we scale the capsule and hohlraum geometry by a factor of 1.6 to reach gigajoule fusion yields while maintaining robust ignition and target gain of ~90. The design preserves ion range through a simple density scaling, keeps the original beam energies, and optimizes the beam power history to match an improved beryllium capsule design that incorporates lessons from three decades of laser driven ICF.

We use multidimensional radiation hydrodynamics simulations with increased spatial resolution to quantify capsule performance, energy balance, and burn dynamics. The scaled design produces very high burn averaged ion temperatures, with peak instantaneous burn weighted T_i exceeding order 100 keV and achieving high capsule and driver gain. We show that HIF hohlraums can be kept relatively close to pressure equilibrium, which significantly reduces hydrodynamic motion in the wall and simplifies symmetry control compared with traditional laser driven hohlraums. We show that by varying the beam energy we adjust the ion stopping range and hence the relative weighting of pole versus equator energy deposition, providing a practical knob on the P_2 Legendre mode of the ablation pressure. The energetics of HIF designs are compared to conventional laser-driven indirect hohlraums to provide a better understanding of the advantages and limitations of each approach.

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Large-scale high-yield implosions for inertial fusion energy (IFE): enhanced performance and distinct physics characteristics*

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Following the achievement of multi-megajoule yield implosions at the National Ignition Facility (NIF), the next objective is to attain an even higher yield. As the sizes of the capsules and their projected yields increase, several performance improvements occur: (a) The peak radiation drive temperature decreases with larger capsule sizes. (b) The burn fraction becomes less susceptible to perturbations when the hotspot temperature exceeds ∼30 keV. (c) The dopant layer, located in the inner region of the ablator, is essential for maintaining a neutral Atwood number at peak velocity. The thickness ratio of this layer to that of the ablator decreases as the size of the capsule increases. This reduction results in reduced remaining ablator mass fraction, and enhanced rocket efficiency. (d) For a given level of surface roughness, the percentage of yield reduction caused by Rayleigh-Taylor instability decreases despite an increase in growth factor at the ablation front. Gain curves and gain scaling, along with the neutron and x-ray spectra, relevant to first-wall designs for IFE reactors, will be presented. In all implosions conducted at NIF, the burn wave is a subsonic deflagration. However, as the capsule size increases and the burn becomes more robust, the burn front transitions from subsonic to supersonic. This supersonic burn front is driven by the alpha-particle absorption flux, distinct from the supersonic nuclear detonation that occurs in a Type Ia supernova. A supersonic burn wave allows the maximum burn rate to be achieved before the fuel-layer undergoes significant expansion. We will provide a scaling formula that characterizes this transition. The supersonic burn wave triggers an explosion in the fuel layer, compressing the core of the hotspot to extreme density and temperature. As a result, the electrons become mildly thermal-relativistic. We will present relativistic corrections to the thermodynamics and transport processes in large-scale implosions.

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Fast ignition of inertial fusion targets. Laser beam energy requirements

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We have studied the generation and propagation of proton beams in millimeter-scale cones for proton fast ignition applications (pFI). The goal has been to better understand the complex dynamics of proton transport and magnetic field structures that may contribute to beam divergence. Realistic particle-in-cell (PIC) simulations have been conducted to maximize laser-to-proton conversion efficiency (CE) and minimize beam divergence in the pFI scenario. Our studies have shown that a significant reduction in beam divergence can be achieved by using laser pulses with intensities of a few times 10^{19} W/cm2, focused into large spots to enable quasi-one-dimensional acceleration. We found a substantially higher CE than in previous experiments, which can be partially explained by the large spot size.

The core idea presented here is to enhance proton beam focusing by adjusting the cone geometry. Specifically, we varied the curvature of the proton-rich foil, the cone length, and the tip diameter. Our results indicate that the cone geometry plays a crucial role in optimizing beam generation. This finding is significant not only for pFI but also for the generation of warm-dense matter and other applications.

We have estimated the laser energy requirements to achieve high gain in a proton beam with optimized focusing by using the code described in [1]. We used a deuterium-tritium fuel configuration obtained from cone-in-shell simulations [2]. Our analysis will help assess the potential of pFI as an alternative approach for Inertial Fusion Energy.

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Critical role of laser intensity above 10^{21} W/cm^2 in fast ignition for laser fusion energy

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Laser fusion energy applications require efficient laser-plasma energy coupling. In the fast ignition scheme, short-pulse relativistic intensity laser light produces a high energy flux of fast electrons to heat the dense fuel plasma imploded by separate nanosecond lasers. The efficiency of energy transfer from the heating laser to the core plasma depends on the laser energy transport in the coronal plasma region by the hole boring and on the energy transfer from the fast electrons to the bulk plasma particles.

We theoretically studied the heating process including the hole boring by the heating laser and the subsequent bulk electron heating in the dense fuel plasma. We found that increasing the intensity of the heating laser to the level of 10^{21} W/cm^2 as well as making the pulse duration longer than multi-picoseconds (ps) is critical to achieve fusion burning with high efficiency. In the hole boring process, a stable and fast laser propagation is found to appear with a strong magnetic field generation at the pulse front. The magnetic field evacuates ions from the laser path that results a stable laser propagation. We derived a required laser intensity $I_{\mathrm{HB}} \gtrsim 10^{21}$ W/cm^2 for the stable hole boring, considering the displacement current originated from the electric field at the pulse front moving at the hole boring speed. After the pulse reaches the overdense region, the laser pressure pushes the plasma surface to make a sharp density gradient until the pressure balance between laser light and electrons is established on a ps time scale [1, 2]. At the steepened interface, non-thermal electrons whose average energy is more than ten times lower than the ponderomotive energy are generated. Those non-thermal electrons deposit energy near the laser-plasma interface that assists the diffusive heating toward the core plasma region. We found that energy flux of the non-thermal electrons $> 10^{20}$ W/cm^2 is required to drive the heatwave to a core plasma with temperature ~ 10 keV to initiate fusion burning, indicating the required laser energy flux $\gtrsim 10^{21}$ W/cm^2 assuming the laser absorption rate around 10% at the plasma surface. We confirmed the above hole boring and heating mechanisms by using collisional PIC simulations by PICLS [3] and heat transport simulations considering the drag and diffusive heating processes.

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Pulsed power driven preheat using a cryogenic Ice fiber for MagLiF experiments on Z

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In the Magnetized Liner Inertial Fusion scheme (MagLIF), metal liners are rapidly imploded by a fast-rising current (~20MA in ~100ns) to compress a magnetized, preheated fuel and efficiently reach fusion conditions [1]. Experiments on the Z facility use the Z-Beamlet laser to deposit up to ~2kJ of energy into the fuel prior to compression by the liner implosion. This preheat energy is limited by both the available laser energy, and backscatter risk for higher fuel densities [2]. These experiments have achieved ion temperatures > 3keV and deuterium-deuterium fusion yields >1e13 [3]. However, the limited preheat energy results in high convergence implosions making the stagnation susceptible to implosion instabilities that can limit target performance. We present simulations of an alternate method of fuel preheat where the traditional deuterium gas fill is replaced by a cryogenic deuterium ice fiber inside the MagLIF liner. Electrodes connecting to the target are then reconfigured to divert a fraction of the current (~4MA) to implode and heat the ice fiber prior to liner implosion. This preheat method can couple a higher energy to the fuel (>8kJ) that can then be systematically varied by adjusting the electrode configuration. We present simulation results exploring the design of MagLIF experiments to be tested on Z that use this preheat method to increase fuel preheat, reduce convergence and hence improve target performance while reducing susceptibility to implosion instabilities. As we consider scaling MagLIF to higher currents on either an upgraded Z facility, or a future pulsed power capability, this method would naturally allow higher preheat energies without the need for new or upgraded laser systems. This approach is also compatible with an ice layer on the inner liner surface that in the near term can reduce liner/fuel mix but will eventually be needed on future facilities to achieve high fusion yields.

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Proton Stopping from Bound States in Partially Ionized Plasmas

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In partially ionized plasmas and at velocities above the Bragg peak, the electronic stopping of fast ions can depend as much on bound state excitations as on free electron scattering. Most existing models of electronic stopping of fast ions in plasmas have very course grained atomic physics, with bound states treated via local density approximations or single excitation energies. Alternatively, there are all-electron time-dependent-density-functional-theory (TD-DFT) simulations, which are extremely accurate, but are also exceedingly expensive, even prohibitively so in low density, high temperature or high Z plasmas. There is a need for an interemediate fidelity calculation that can be run fast enough for tabulation and experimental fits, whilst being accurate enough to capture the proper physics.

Our model for stopping in plasmas in linear response approximation with average atom matrix elements (SLAM) fills this niche. We compute target response from bound-bound and bound-free electron transitions explicitly via average atom matrix element calculations and incorporate them consistently with standard free electron scattering response methods. For proton stopping we find very good agreement with state-of-the-art all-electron TD-DFT simulations when restricted to velocities above the Bragg peak. We show many results including an application to the Malko et al proton stopping in carbon experiment [1], where we apply small corrections to the TD-DFT data, and show how it likely extends to the low density regimes for which it wasn't computed.

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Neutronic Effects on Ignition and Burn Dynamics in Fast-Ignition DT Fuel

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In fusion plasmas, heating by fusion products plays an essential role in ignition and burn processes. In high-density DT plasmas, in addition to 3.5-MeV α-particles, heating induced by 14-MeV neutrons can contribute to plasma heating.

The mean free path of 14-MeV neutrons in DT plasma is $\rho\lambda_n \approx 4.7$ g cm^{-2}, which is comparable to the areal density of high-gain fuel. Although the collision frequency of neutrons in the fuel is relatively small, their initial energy is about four times larger than that of α-particles, and the energy transfer per collision is correspondingly large. In DT plasma, neutrons interact with fuel ions through nuclear elastic scattering and (n,2n) reactions, producing energetic recoil ions and secondary particles. Through the transport of these energetic particles, neutrons can heat the fuel over a wide region (neutron heating) from the ignition phase to the burn phase, thereby influencing ignition and burn propagation dynamics.

In this study, neutronic effects on fast-ignition DT fuel are evaluated using the two-dimensional burn simulation code FIBMET [1], where the energetic particle transport (α-particles, neutrons, recoil deuterons and tritons, and secondary particles produced by the D(n,2n)p reaction) is solved using a particle scheme.

In this workshop, we present how neutron heating affects ignition and burn dynamics in fast-ignition DT fuel, including its effects on the ignition energy requirement, burn mode, burn fraction, and the emitted particle spectra.

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On the role of self-generated magnetic fields in focused ion beams driven by intense picosecond laser pulses

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We investigate the physics of ion beam focusing in the interaction of intense picosecond laser pulses with concave foils, using two-dimensional particle-in-cell simulations. Curved targets have been observed to deliver brighter multi-MeV ion beams than flat targets and they could be used to ignite pre-compressed ICF fusion capsules in a scheme called ion fast ignition.

Focusing is achieved by shaping the target and relying on an ion acceleration mechanism where the ions are accelerated normal to the target surface; subsequently the plasma expansion grows magnetic fields that advect with the plasma and deflect ions away from the target symmetry axis, causing the focal spot to shift downstream from its geometric location; the drop in both electric and magnetic field strengths in the expanding plasma makes the ion beam envelope asymmetric with respect to the focusing plane.

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WarpX Exascale open-source code for kinetic laser-plasma modeling – latest developments and applications to IFE

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WarpX[1] is a fully open-source, exascale-capable Particle-In-Cell code designed for high-fidelity kinetic modeling of laser-plasma interactions in inertial fusion energy (IFE) applications. The code is highly portable, running seamlessly across platforms from laptops to the largest supercomputers, on multi-core CPUs and various GPU architectures (NVIDIA, AMD, and Intel). With its versatile and modular architecture, WarpX supports a wide range of physics and geometries, including Cartesian, cylindrical, and spherical coordinates, as well as multi-physics packages for ionization, atomic, fusion, and collisional physics. WarpX's flexibility is further enhanced by its Python interface, which allows users to easily extend the code to incorporate additional physics, couple it to other codes, or integrate it with AI/ML frameworks.

Recent advancements in WarpX, developed under the auspices of the US DOE FES SciDAC project on Kinetic IFE Simulations at Multiscale with Exascale Technology (KISMET), include the development of an efficient GPU parallelization strategy for binary collisions[2], as well as the implementation of advanced energy and momentum-conserving explicit and implicit particle-in-cell algorithms[3,4,5]. These new features enable more accurate and efficient simulations of complex laser-plasma interactions in IFE-relevant regimes, which are crucial for advancing the development of inertial fusion energy.

We will present these recent advancements alongside applications to key inertial fusion energy modeling challenges.

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Laser ion acceleration from concave targets by subpicosecond pulses

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Proton fast ignition (pFI) is a promising approach to inertial fusion energy. Realizing this approach requires tight focusing of energetic proton beams and high laser-to-proton energy conversion efficiency for effective target heating. Concave targets are a well-established way of focusing fast laser-driven protons [1,2]. Yet, the proton beam parameters achievable today still lag behind pFI requirements. To support an ongoing multi-facility experimental campaign [3] and develop a general understanding of laser-driven proton focusing by hemispherical targets in the short pulse regime (duration <=10^2 fs), we perform a numerical study using the fully kinetic, relativistic Particle-In-Cell code EPOCH [4]. We investigate proton acceleration mechanisms, assess the roles of target radius and opening angle, characterize proton focusing properties, and evaluate the influence of laser parameters on proton focusing. Implications for experimental measurements are discussed.

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Alternative Approaches to Fast Ignition

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Abstract

We have studied the injection of extra energy at the center of a fully compressed DT fusion plasma using short pulse gamma-rays irradiating high-Z dopants. We conclude that up to 10 percent or more of the gamma-ray energy can in principle be converted to heat in the hot dense plasma core. Their net effects on the DT fusion process and Lawson criterion are currently under investigation. The use of gamma-rays, which are transparent to the DT capsule, bypasses many of the known problems and hurdles of using charged particle beams for Fast Ignition. In this paper we will present detailed computer simulation results related to this concept and propose experimental test beds for this idea.

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High-flux ion acceleration in structured foam targets

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Abstract

Laser-driven ion sources are critical for fast ignition schemes in inertial confinement fusion. Short-pulse, kilo-Joule class lasers are excellent tools for generating relativistic ion beams, but achieving the ion flux demanded by fast ignition remains an open challenge. Custom 3D-printed targets, enabled by two-photon polymerization, can tune average plasma densities to the near-critical limit and greatly increase laser-to-ion conversion efficiency. Particle-in-cell simulations reveal that tuning targets to the relativistically transparent regime enables an extended period of electron heating by direct laser acceleration (DLA). The DLA heating drives a long-lived sheath allowing high-flux and high-energy ion acceleration. 2D simulations estimate nearly a 3-fold improvement in the J/J proton dose (> 10 MeV) using structured targets over foils. This enhanced yield, combined with the scalability of two-photon polymerization, makes 3D-printed microstructures a prime candidate for ion-based fast ignition schemes.

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Gas optics for high-power laser applications

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Optics damage is a ubiquitous challenge for high-power lasers and largely dictates the size and cost of these facilities. The issue is particularly challenging for the final optical elements in future IFE facilities, as these elements will be exposed to extreme radiation flux and target debris accumulation. Here, we are developing a new technology that uses gas as a transient optical medium instead of solids. Our method imprints density modulations as holograms in a gas, achieved via absorption of a spatially modulated “writing beam” by a small fraction of dopant introduced in the gas, followed by localized heating. We have experimentally demonstrated gaseous diffraction gratings and holographic lenses in the laboratory. Gas optics have damage thresholds 2 to 3 orders of magnitude beyond those of solids, and operate at high repetition rates, making them intrinsically immune to any type of cumulative damage, from laser light or target debris. We have demonstrated operations for any laser wavelength from deep UV to IR, and pulse durations from femtoseconds to nanoseconds. As diffractive elements, these optics provide excellent phase front quality for the diffracted laser beam. We have demonstrated stable operation at 10 Hz with diffraction efficiencies up to 99%, and shown that the lifetime of gas optics can be controlled and adjusted from nanoseconds to microseconds, making them well suited for IFE facilities and other industrial applications where optics damage is a concern.

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Magnetized laser-driven ICF

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External magnetization of direct or indirect drive ignition designs can reduce electron thermal conduction losses, increasing hot spot temperature and improving implosion performance. Additional predicted benefits of an applied magnetic field include reduced mix-driven instability growth and mitigation of degradation from low-mode hot spot asymmetries. Experiments on the National Ignition Facility (NIF) applying a uniform 26 T field to D2-filled gas-capsule implosions [1-3] demonstrated the predicted ~40% increase in hot spot temperature and an unexpectedly large, approximately threefold increase in neutron yield. This talk reviews these gas-capsule experiments and summarizes the theoretical and modeling basis for how an applied field can mitigate implosion degradation mechanisms [4]. Recent design studies aimed at maximizing the benefits of an applied field identify key design choices that reduce implosion velocity while also lowering ablation-front instability growth, enabling high gain. [5]. We also describe particle-in-cell and semi-analytic kinetic modeling of cross-beam energy transfer in the presence of an applied field [6,7], which can be important for both direct-drive and indirect-drive ICF.

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and by LLNL-LDRD programs under Project Numbers 23-ERD-025 and 20-SI-002.

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Formation of compressed fuel core for fast ignition

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The implosion phase of fast ignition requires the formation of a high areal density fuel core using nanoscale implosion lasers. Isentropic compression is effective because it does not require the temperature requirement for ignition in the phase.

We have carried out the solid spherical target implosion using a multi-step laser pulse to control the shockwaves for the compression at ILE Osaka [1-2]. The main advantage of implosion with a solid spherical target is that it is less susceptible to hydrodynamic instabilities caused by nonuniformity of laser irradiation or target surface roughness. It is effective in experiments using Gekko XII laser system size. However, some disadvantages are also discussed. The conversion efficiency from laser energy to internal energy via the shockwaves alone in a solid spherical target is not sufficient. If the kinetic energy of the accelerated shell target can be utilized effectively, the conversion efficiency can be improved. Another disadvantage is the extremely uneven density distribution at maximum compression, which reduces the heating efficiency. Also, it is not suitable due to the long-scale density distribution, where non-linear laser plasma interaction is unavoidable for the direct heating process.

To ensure ignition of the fast ignition scheme, it is necessary to re-design a target with improved hydrodynamic efficiency. Multi-objective optimization is required, including achieving high efficiency, being less susceptible to hydrodynamic instabilities, high areal density, and an optimum density profile for the heating process. 1-D and 2-D radiation hydrodynamic simulations and hydrodynamic instability models are considered for the optimization, not only for the implosion of a solid target, but also for that of slow implosion [3]. We will report on the numerical and analytical methods and the results obtained so far.

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Scaling of Proton Focusing with Laser Energy

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Over the past two decades, ample research has been directed at the proton-focusing capabilities of curved targets for inertial fusion energy (IFE) and warm dense matter (WDM) heating[1,2]. It is well-established that hemispherical foils can effectively focus laser-driven proton beams[3]. However, important questions remain regarding how this focusing behavior scales to ignitor-class facilities, which are expected to require hundreds of kilojoules of short-pulse laser energy to generate sufficiently energetic proton beams. Because no current or near-term facilities can access these energy and intensity regimes, experimental scaling must rely on extrapolation from existing platforms.

We present results from an ongoing experimental roadmap designed to investigate proton focusing across a wide range of laser parameters. Drawing on data from campaigns conducted at the ALEPH, ZEUS, and OMEGA laser facilities, we have assembled a comprehensive dataset spanning multiple laser intensities and energy scales. Proton beam properties were characterized using mesh radiography, where ballistic back-propagation through a known mesh geometry enables reconstruction of a virtual proton source location and size[4].

In addition, we compare the focusing performance of several target geometries, including hemispherical targets, cylindrical targets, and flat foils. These comparative studies provide insight into the role of target curvature in proton beam formation and transport. The results presented here will enhance WDM heating platforms for warm dense matter research at these facilities and help inform us on the path toward integrated proton fast-ignition studies at future high-energy laser facilities.

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The experiment was conducted at the Omega Laser Facility with the beam time through the National Laser Users' Facility user program. 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(s) DE-NA0004144. Work performed under the auspices of the U.S. Department of Energy by General Atomics under NNSA Contract 89233124CNA000365. The research was conducted under the Laboratory Directed Research and Development (LDRD) Program at Princeton Plasma Physics Laboratory, a national laboratory operated by Princeton University for the U.S. Department of Energy under Prime Contract No. DE-AC02-09CH11466

Fast heatwave propagation with nonlocal electrons accelerated at a steepened plasma surface formed by PW relativistic laser

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Relativistic laser irradiation of overdense targets drives electrons with energies ranging from a few tens of keV up to several hundred MeV, establishing strong energy fluxes with current density > TA/cm^2 and forming High-Energy-Density (HED) states. While the ponderomotive energy and the relativistic critical density typically characterize the mean energy and beam density of the fast electron group, efficient conversion of their energy into bulk heating is often limited. This limitation arises from the low collision rate of relativistic electrons and the relatively low beam density compared to background plasmas. Therefore, generating electrons with lower energy and higher density improves the energy coupling, enabling access to HED states or ignition temperature in laser fusion relevant configurations.

In this work, we focus on the dynamics of the laser–plasma interface previously studied in [1,2]. Collisional particle-in-cell simulations with continuous irradiation of laser with normalized amplitude $a_0 = 5 - 30$ demonstrate hole-boring up to the density several ten times higher than the relativistic critical density. The hole-boring forms a sharp density gradient at the laser-plasma interface and eventually the interface becomes stationary when the electron bulk pressure balances the laser irradiation pressure. The bulk electron temperature at the mechanical equilibrium state reaches > 100keV behind the interface. This process maintains the high temperature interface (heat bath) from which a dense population of electrons with mean energies below the ponderomotive energy is injected into the dense plasma region. We present a theory for the saturation density, temperature and the characteristic time for the structure formation.

To evaluate the bulk electron heating, we investigated the heat transport in a dense plasma by considering the diffusive and non-local heating. Under the situation where electrons with temperature of a few hundreds of keV flow in from the interface, we find that reducing the fast-electron mean energy enhances the diffusive heat flux and accelerates the heat-front propagation. Near the laser–plasma interface, drag heating dominates due to strong electron stopping within the short mean free paths, and assists the diffusive heating into the dense plasma. As a result of the efficient heating, the heat front at temperature $T_e \sim 10$ keV propagates with the speed $\sim 0.03c$ in the plasma with average density about 5000 times the critical density. The temporal evolution of the heatwave front position will be discussed theoretically.

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Dual pulse micronozzle acceleration of GeV-class protons

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Achieving GeV-class proton beams with high laser-to-proton conversion efficiency remains challenging because the accelerating field rapidly dephases from the ion population and the bunch thermally debunches during sheath-dominated expansion. We propose and numerically demonstrate a dual-pulse micronozzle acceleration (DP–MNA) scheme that alleviates this efficiency–energy trade-off by enforcing source–field synchronization in a confined, source–field-separated target.

In DP–MNA, a tightly focused prepulse extracts and pre-bunches a compact proton front from a hydrogen rod placed at the entrance of an aluminum micronozzle. After a controlled delay Δt, a larger-spot main pulse deposits most of the laser energy into the nozzle cavity and drives a quasi-static axial electric field. Within a delay-defined synchronization window, the proton front is injected into and remains embedded within a narrow accelerating channel that is advected downstream with the bunch. This phase locking suppresses longitudinal dephasing and thermal debunching, preserving bunch integrity and extending the effective acceleration stage.

Fully relativistic particle-in-cell simulations with the EPOCH code show that, at moderate main-pulse intensities of the order of 10^{21} W/cm^2, DP–MNA reaches GeV-class proton cutoffs ($\varepsilon_{p,max} \approx$ 0.8–1.0 GeV) with a total conversion efficiency $\eta \approx 20\%$. Crucially, the efficiency into the application-relevant high-energy component remains exceptionally high: $\eta_{>100} \approx$ 12–13% for protons above 100 MeV, indicating preferential energy loading into a compact, directed proton population rather than quasi-thermal sheath expansion. Compared with an unconfined dual-pulse hydrogen-rod target under identical laser conditions, DP–MNA develops a markedly harder spectral tail; the cutoff extends to $\geq$ 760 MeV versus ~460 MeV without nozzle confinement. A systematic scan over Δt and relative pulse energy sharing identifies a robust synchronization band at $\Delta t \approx$ 0–40 fs, within which both η and $\eta_{>100}$ are simultaneously maximized.

These results establish femtosecond timing control combined with geometric confinement—rather than brute-force intensity scaling—as a practical design principle for compact, high-yield GeV-class proton drivers, with direct relevance to pion/muon production, laser-based neutron sources and accelerator-driven subcritical systems.

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Could Magnetic Mirrors Change the Prospects for Electron Fast Ignition?

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There has been a massive confidence shift in inertial fusion since the seminal results obtained on the National Ignition Facility (NIF, USA) were announced demonstrating ignition and gain. At the time of writing, a gain in excess of 4 has now been demonstrated. This has brought the prospect of fusion as an energy source considerably closer, but large steps are still needed to reach that goal. In particular, a fusion scheme that can achieve gains around 100 will really be needed to make IFE a real possibility.

Advanced Ignition schemes, including electron-based Fast Ignition [1], have long been an interesting route to achieving high gain whilst possibly reducing the capital costs of a future power plant. However, research into electron Fast Ignition encountered a number of key difficulties [2] : a wide angular distribution of fast electrons, and issues with matching the fast electron spectrum needed for effective stopping and hot spot formation to the need to have sufficient intensity to supply the energy required. A number of solutions were proposed to deal with the fast electron divergence issue, but the issue of the energy spectrum has been harder to tackle.

Recently, A.R.Bell has put forward the idea that Magnetic Mirrors may be a route to solving these issues. This synergizes well with what has already been demonstrated in experiments aimed at magnetized ICF. If a uniform, axial magnetic field is present prior to compression, then the magnetic field configuration in the compressed fuel should naturally form a magnetic mirror structure. In this talk we will present the recent progress that our group has made in this area, and we will discuss the advantages that magnetic mirrors might have for the evolution of electron-based fast ignition.

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A novel fast ignitor

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Marvel Fusion is developing a novel fast-ignition concept aimed at improving the performance of a broad class of fusion targets for inertial fusion energy (IFE) applications.

The core elements of the proposed concept are arrays of precisely engineered nanostructures, driven by ultra-short laser pulses and embedded within pre-compressed fusion fuel [1]. It has been demonstrated that nanowire arrays optimized for interaction with short-pulse lasers can absorb and efficiently convert nearly all of the incident laser energy into secondary energy carriers [2], such as energetic electrons, ions, and radiation, which are well suited for the rapid heating of dense, pre-compressed fuel.

In this contribution, we describe the novelty of the proposed fast-ignition concept and explain why it may be practically viable for the first time. We discuss Kidder-type cumulative compression solutions [3] and analyze the volumetric interaction of ultra-short laser pulses with nanorod arrays [1]. Based on this framework, we assess hotspot ignition criteria [3], present stopping-power calculations of the surrounding fuel and the associated fuel-heating rates, and derive fusion-gain estimates. Our analysis indicates that the fusion gain of baseline direct- or indirect-drive fusion targets can be significantly enhanced at reduced ignition energy. Owing to the high efficiency and power of the proposed fast igniter, fusion gains Q>100 appear achievable with laser energies in the few MJ range.

We note that experiments investigating the interaction of ultra-short laser pulses with nanowire targets have already been performed using the HPLS laser at the Extreme Light Infrastructure – Nuclear Physics (ELI-NP). In these experiments, pulse energies of approximately 200 J were delivered at a pulse duration of 23 fs, corresponding to peak powers of about 8 PW. Further details of the laser–nanowire interaction at reduced scales will be investigated at the upcoming joint Marvel Fusion–Colorado State University Advanced Technology Lasers for Applications and Science (ATLAS laser facility) facility.

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Investigation of Proton Source Survivability and Heating in Integrated Proton Fast Ignition Experiments

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The first integrated Proton Fast Ignition campaign at the Omega Laser Facility that included both the compression and ignition beams was carried out to 1) measure the temperature increase in the compressed core due to heating by protons and 2) visualize where the protons deposited their energy in the compressed plasma. In these experiments, the proton beam was generated from a curved hemispherical foil embedded within a cobalt-coated gold cone by the short-pulse OMEGA EP beam and was then focused into a copper-doped CH capsule imploded by the OMEGA 60 long-pulse beams. The implosion velocity extracted from experimental x-ray images roughly agrees with the predicted velocity from 2D radiation hydrodynamics simulations. Preliminary analysis of Cu K-shell x-ray emission spectroscopy measurements has revealed insignificant differences between implosion only shots and those including the EP-driven proton beam. Measurements also suggest a lower conversion efficiency than our previous EP-only experiments for protons with kinetic energies > 10 MeV that primarily heat the core. This is presumably due to greater target mass combined with a degradation of TNSA resulting from radiation-driven expansion of the hemisphere rear surface. In upcoming experiments we plan to reduce the OMEGA EP pulse duration from 10 ps to 0.7 ps, which may enhance coupling to > 10 MeV protons. As such, comparing measurements between the two pulse durations will shed more light on the proton energy coupling.

Experiments were conducted at the Omega Laser Facility with beam time through the NLUF user program. Material is based upon work supported by the Department of Energy [NNSA] University of Rochester "National Inertial Confinement Fusion Program" under Award Number(s) DE-NA0004144. Work was also performed under the auspices of the U.S. Department of Energy by General Atomics under NNSA Contract 89233124CNA000365 and was supported by the U.S. Department of Energy, Office of Fusion through the STARFIRE grant DOE-SCW1835.

Magnetized Inertial Confinement Fusion: Transport Physics and Performance Enhancement in Pre-Magnetized Implosions

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Magnetization is investigated as a strategy to enhance α-particle confinement, suppress thermal conduction losses, and increase fusion yield in inertial confinement fusion (ICF) implosions. An externally applied magnetic field is advected and amplified during compression, reaching multi-kilotesla levels at stagnation and modifying heat and particle transport in the hot spot.

Magnetized cylindrical implosions have been performed at the OMEGA Laser Facility and the National Ignition Facility (NIF), with preparations underway at the Laser Mégajoule. At OMEGA, 15 kJ D_2-filled cylindrical implosions seeded with a 30 T magnetic field [1] show a 40% increase in electron temperature and a 30% reduction in mass density consistent with ~10 kT stagnation fields, relative to unmagnetized shots. These were inferred through K-shell emission spectroscopy of dopant Ar and a multi-zone spectroscopic model based on artificial-neural-network analysis.

Scaling to 20× higher laser energies, we pursue spatially resolved core-temperature measurements using dual-dopant (Ar+Kr) K-shell spectroscopy [2] and diagnostics of magnetic-field compressibility via angularly resolved secondary neutron measurements. A NIF implosion with a 16.5 T initial field showed a 3× increase in primary neutron yield compared with a unmagnetized shot, although secondary neutron production remained limited due to moderate compression. Optimized target and laser-drive designs now aim at higher compression ratios and stronger magnetic confinement.

Complementary extended-MHD modeling supports the interpretation and optimization of heat and magnetic-flux transport in the strongly magnetized high-energy-density plasmas, guiding future high-performance magnetized ICF experiments.

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X-ray Thomson Scattering Measurements of Fast-Electron-Heated Solid-Density Plasmas with an XFEL at LCLS

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Energetic charged particles generated by high-intensity, short-pulse lasers are a key plasma heating source for fast ignition laser fusion. However, spatiotemporal characterization of high-density plasmas heated by such particle beams remains challenging due to strong electromagnetic pulse noise produced during laser-target interactions, non-uniform heating on short timescales, and the intrinsically high plasma density. In particular, accurate instantaneous measurements are crucial for understanding the heating level, optimizing laser parameters, and validating simulation codes. To investigate the underlying physics in fast-electron-driven solid-density plasmas, we conducted an X-ray Thomson scattering (XRTS) experiment using an X-ray Free Electron Laser (XFEL) at the Matter in Extreme Conditions endstation of the Linac Coherent Light Source. A high-power femtosecond optical laser irradiated plastic or titanium foil targets at intensities ranging from 3×10^{18} W/cm^2 to 3×10^{19} W/cm^2. The plasma conditions were diagnosed using XRTS with a 15 keV, 30-μm diameter, 50-fs hard X-ray probe pulse at various delays after laser irradiation. Scattering signals were measured using a newly developed, heavily shielded X-ray transmission crystal spectrometer at a scattering angle corresponding to the non-collective scattering regime. Scattering signals were successfully obtained despite the high background from laser-target interactions using the well-shielded spectrometer and by accumulating 20 shots for each laser and target condition. For plastic targets, both elastic and inelastic components were clearly observed for cold and driven conditions, whereas only elastic scattering signals were obtained for titanium targets. Changes in the spectra between cold and heated plastic targets were observed only at a delay of 1000 ps. Details of the experiment, results, and the diagnostic sensitivity to fast-electron heating will be discussed.

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Experimental Evaluation of Petawatt-laser-driven Nano Accelerators for IFE

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Highly ordered nanowire arrays with sub-wavelength diameter can be engineered to absorb multi-PW laser pulses with intensities above 10^{20} W/cm^2, ultra-high-contrast and sub-100-fs duration with an efficiency nearing 100%. The laser penetrates deep into the nanowire volume, depositing its energy over tens of microns and converting a large fraction to high-current ion flows in a controlled manner [1]. The ion flow generated by such a Nano Accelerator can then heat fusible material made of hydrogen, boron, deuterium and tritium [2] to IFE-relevant conditions.

In this contribution, we present measurements of the Nano Accelerator driven by the HPLS laser at the Extreme Light Infrastructure for Nuclear Physics (ELI-NP), which delivered 200 J of energy at a pulse duration of 23 fs (8 PW). The original focusing geometry was modified from F/60 to F/20 using a double plasma mirror telescope [3], leading to a focal spot of 8×10^{20} W/cm^2 intensity with enhanced temporal contrast within a uniform focal spot volume of 20 µm FWHM and >200 µm Rayleigh length. The laser was used to irradiate 100×100 µm^2 patches of highly aligned, near-critical-density nanowires. Monitoring the ion emission via multiple Thomson Parabola & CR-39 spectrometers, we report first experimental evidence of volumetric laser interaction scaling to tens of microns propagation length, in line with theoretical expectations [1].

These initial results form the basis for more detailed investigations of the laser-nanowire interaction, as well as secondary applications for this Nano Accelerator, at PW laser facilities in Europe as well as at the upcoming joint Marvel Fusion - Colorado State University (CSU) Advanced Technology Lasers for Applications and Science (ATLAS) laser facility.

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Heavy Ion Driven Inertial Fusion Energy

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Heavy-ion inertial fusion energy (HIF) offers an attractive path to fusion power by exploiting accelerator technology that is already proven at multi-megajoule beam energies, high reliability, and routinely high repetition rates. Heavy ion beams can deliver the required 1–10+ MJ to a millimeter-scale target in nanosecond pulses, achieving the high specific energy deposition $\approx 10^8$ J/g and intensity $\approx 10^{14}$ W/cm^2 needed for ignition and gain [1, 2]. Compared with laser driven IFE, accelerators can reach higher wall-plug efficiency, and avoid vulnerable optical elements by using magnetic focusing, which improves survivability in the fusion chamber environment. One can arrange the beam lines such that no beamline elements are in the line of sight of the capsule explosions. Beam physics strongly favors multi-GeV, singly charged heavy ions, which minimize current and emittance demands while matching ion range to target dimensions, and existing accelerator experience shows that such beams can be transported and focused within the stringent space-charge and phase-space limits. Both RF and induction linac options appear technically plausible, with induction linacs particularly well-matched to the required short, high-current pulses. A top development priority, cost reduction, is mainly an engineering challenge, rather than tied to physics barriers. Dedicated experiments and simulations aimed at beam quality (minimizing emittance growth), final-focus aberrations, and chamber/neutralization physics have so far shown promising results.

Vastar is commercializing heavy-ion inertial fusion energy by combining proven indirect-drive target physics from NIF with a high-efficiency (~50%) multi-beam induction accelerator delivering ~10 MJ to targets at 1–10 Hz, using a staged accelerator program that de-risks cost and performance and is designed for rapid replication of grid-scale plants.

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High-gain Laser Fusion Achieved by Heatwave-driven Fast Ignition for Inertial Fusion Energy

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We designed a high-gain laser fusion with a fast ignition (FI) scheme for the inertial fusion energy. A solid-sphere target which is robust to hydro instabilities can be utilized instead of a fragile shell target used in the central ignition. Following the implosion with precisely tailored laser pulses, the high-density fuel core will be heated immediately to the ignition temperature in 10 picoseconds by petawatt laser lights before the core plasma collapses. Achieving efficient laser fusion requires challenges: how to achieve the dense fuel core, how to efficiently deliver heating lasers through the corona plasma surrounding the fuel core, how to efficiently couple the heating laser energy into the fuel core plasma, and how to achieve high burn-up fraction of DT fuel. To address these challenges, our design employs 250 kJ of implosion laser energy and 30-40 kJ of heating laser energy, yielding about 15 MJ (gain ~ 50) of energy generated by the DT fusion reaction.

To deepen the understanding of heatwave-driven FI physics for a high-gain laser fusion, we have comprehensively studied the propagation, absorption, and energy transport processes of heating laser beams in imploding plasmas with a help of multi-dimensional kinetic plasma simulations, PICLS [1], which cooperates with Coulomb collisions, ionizations, radiations, and DT fusion reactions. We found that the efficient heating "heatwave" appears after forming the steepened absorption interface by extreme photon pressure of the heating laser [2]. The laser intensity required to drive the heatwave has been determined. The heatwave successfully delivers approximately 4 kJ of heating energy to the fuel core located about 100 μm from the interface. The energy accumulated in the core exceeds the ignition criteria in the proposed FI design, starting the DT fusion burn with power about 350 PW.

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Heavy Ion Fusion: Ready for Reconsideration?

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Abstract

Research activities on heavy-ion fusion (HIF) were abandoned over a decade ago, and brought down to a crawl even earlier. It is easy to forget that in the 90's HIF was considered to be the top contender for developing inertial fusion energy (IFE). This is not surprising: accelerator technology is well-established, and the conversion efficiency from a wall plug to accelerated particles is hard to match, especially at the repetition rates required for IFE powerplants. Moreover, unlike most laser fusion schemes, HIF does not require any damageable optics. One of the often-cited reasons for abandoning HIF is its non-modular nature: testing even the most basic IFE components requires multi-km long induction accelerators. Compact high-gradient collective ion acceleration has the potential for drastic reduction of the driver size -- an important step towards modularity and compactness. I will describe the historical context for such schemes and describe the latest efforts in my group to improve them. In addition to driving future fusion power-plants, compact ion accelerators have many other exciting applications that I will describe. Those range from promising carbon ion radiation therapy in the short-bunch (FLASH) regime to testing space-bound electronics for deleterious effects from impinging high-energy ions.

Investigation of Ion Focusing using Structured Targets for Applications to Ion Fast Ignition

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Proton fast ignition is an alternative inertial confinement fusion scheme, which relies on using laser-accelerated protons of MeV energies to heat pre-compressed inertial confinement fusion pellet in order to relax driver energy and symmetry requirements while increasing fuel gain. [1] Petawatt-class, multi-picosecond short-pulse lasers, such as the National Ignition Facility-Advanced Radiographic Capability (NIF-ARC) laser, Orion laser facility and OMEGA-Extended Performance (EP) laser, which have been constructed over the last two decades, enable exciting opportunities to produce high-brightness, high-energy laser-driven proton sources which will be crucial for developing and investigating proton fast ignition platforms for inertial fusion energy. Laser-driven proton sources are typically spatially divergent (divergence angles ~ 20 degrees) therefore mechanisms to focus laser-driven proton sources are a crucial area of research to increase the efficiency of these sources for applications to proton isochoric heating and proton fast ignition fusion. This work investigates the use of structured targets such as hemispherical shaped foils and cones that can be used to focus the proton source to achieve a higher flux and thus increase focusing efficiency. In particular, we present a detailed parameter scan of the target design and laser parameters across at the Orion and OMEGA laser facilities in order to study the optimization of proton focusing for application to proton fast ignition in the multi-ps regime.

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FLARE: A new approach to Fast Ignition

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(1) *First Light Fusion*

This presentation introduces **FLARE (Fusion via Low-power Assembly and Rapid Excitation)**, a new concept developed by First Light Fusion to address longstanding challenges in inertial fusion. FLARE approaches inertial fusion through three key principles: (1) a novel target architecture that reduces driver power requirements whilst enabling higher energy gain; (2) low-power pulsed compression, which offers a simpler, lower-cost, and more efficient alternative to conventional high-power lasers; and (3) a liquid lithium pool reactor, designed to absorb neutrons, breed tritium, and shield structural components, thereby extending operational lifetime and improving both economic viability and engineering feasibility.

Together, these principles underpin an integrated, robust, and scalable system that offers a credible and economically viable pathway to inertial fusion energy.

Physics of Cone-in-Shell Implosions in OMEGA Experiments Studying Electron and Proton Fast Ignition

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Fast ignition has the potential of high fusion gains through the ignition of massive DT fuel assemblies. In the cone-in-shell target concept, a hollow cone provides a plasma-free path for a high-energy, high-intensity short-pulse laser to ignite the fuel. The cone is required to withstand a multi-gigabar external pressure at stagnation time, yet be transparent to multi-MeV fast electrons or protons generated by the high-intensity laser inside the cone.

A series of cone-in-shell core heating experiments have been performed on OMEGA laser at LLE in the past to study the electron fast-ignition scheme, while the proton fast-ignition experiments are currently underway. Low-adiabat, low-velocity implosions of massive surrogate plastic shells with a re-entrant golden cone were designed using two-dimensional DRACO [1] radiation hydrodynamics simulations. The implosion physics was verified using monochromatic 8-keV x-ray flash radiography [2] of the imploding plastic shells with a copper dopant. The measured optical density of the compressed plastic plasma and the times of peak compression and cone-tip breakout (measured in separate experiments) were in a good agreement with DRACO simulations. Images of the hot-electron induced Cu-Ka emission in the integrated core-heating electron fast-ignition experiments provided independent confirmation of the implosion hydrodynamics. Verified DRACO simulations have been used to design and optimize cone-in-shell implosions in the recent experiments, studying the proton fast-ignition scheme on OMEGA. These experiments study core heating by fast protons generated in the interaction of intense laser with a thin plastic partial hemisphere inside the cone. Harsh implosion environment affects proton generation. This is explained by the implosion plasma entering the cone interior after the cone-tip break-out (or through the open tip in the open-tip design) and plasma expansion at the interior cone and partial hemisphere surfaces by the radiative preheat, as predicted by DRACO simulations.

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Viscosity Measurements of Shock-compressed Epoxy

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Viscosity governs the momentum transport in a system and plays a crucial role in mixing and growth of hydrodynamic instabilities. Viscosity measurements in High Energy Density (HED) states are particularly important to accurately develop hydrodynamic models and to bridge the gap between simulations and experimental results of complex systems such as Inertial Confinement Fusion (ICF). We measured the dynamic viscosity of epoxy at high pressures (peak ~280 GPa) by tracing the motion of Stainless-Steel particles embedded in the target. The OMEGA-60 laser facility was utilized to generate shocks within a Stycast 1266 (epoxy, 1.1 g/cc) target, causing the displacement and deformation of spherical particles under the forces applied by the surrounding epoxy. Time-resolved X-ray radiography recorded the particle positions, 2D xRAGE simulations of the experiments were also used to calculate the fluid velocity and density. These measurements were used in determining the viscous and inviscid force contributions using a shock-particle forcing model. The forces thus obtained are used to calculate dynamic viscosity. Additionally, a Bayesian inference analysis of the force model was employed to reconstruct the particle displacement for given viscosity at a given range of input parameters. The integration of experimental data and simulation results yields valuable insights into the behavior of Epoxy under extreme conditions, offering essential data for various high-pressure applications. The viscosity of epoxy measured from this study ranges from $O(10^{-1}\text{-}10^{1})$ Pa.s.

Acknowledgment

The experiments were conducted at the Omega Laser Facility at the University of Rochester's Laboratory for Laser Energetics with the beam time through the Laboratory Basic Sciences (LBS) program. This work was supported by US DOE and NNSA under the joint HEDLP program under grant DE-SC0019329 and DE-NA0004134. Partial support from grants NSF PHY-2020249, DE-SC0020229 and DE-NA0003914 is also acknowledged.

High-Contrast Laser Interaction for Efficient Heating of Dense Plasma

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Inertial fusion energy (IFE) requires a target gain exceeding 100 relative to the input laser energy. Although ignition was demonstrated at the National Ignition Facility in 2022, the maximum gain achieved to date remains only 4, underscoring the need for more efficient ignition strategies. Fast ignition (FI) addresses this challenge by decoupling compression and heating, offering a viable path to high gain [1]. In FI, a relativistic electron beam (REB) generated by the heating laser must be efficiently transported and coupled to the fuel core. However, the large divergence angle and excessive mean energy of REBs have severely limited energy deposition efficiencies.

We present FI experiments employing a high-contrast heating laser to optimize REB generation and transport via two approaches: (a) structured targets that enhance laser absorption through internal reflections [2], and (b) cone geometry that aligns the Poynting vector toward the cone tip, promoting REB convergence [3]. A plasma mirror was employed to achieve ultra-high laser contrast ($>10^{12}$), preserving the solid-density target surface prior to main pulse arrival.

Experiments were conducted at the GXII–LFEX laser facility. REB properties were characterized using Cu tracer targets, in which K-alpha X-ray imaging provided both spatial distributions and energy spectra. Integrated implosion experiments were also performed, in which compressed plasma was subsequently heated by cone-focused REBs. A solid copper-oleate sphere was imploded by six GXII beams, and the high-contrast LFEX laser was injected through the cone to heat the compressed core. REB focusing via cone geometry yielded a 2.8-fold enhancement in heating efficiency relative to conventional unfocused REB heating. These results offer important design guidelines for next-generation facilities and targets in pursuit of high-gain laser fusion.

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Inertial Fusion Energy and its potential for acceleration

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For several decades, it was commonly said that fusion energy is 50 years away, and coincidentally, it always will be. Artificial intelligence and "thinking machines" were typically viewed the same way, at least until very recently. Since the future tends to arrive ahead of schedule---and when you least expect it---this talk discusses the potential of inertial fusion energy, its many challenges, and reasons for recalibrating all previous predictions.

Acknowledgement

This work was supported by the U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences, under Award No. DE-SC0024863: IFE-STAR.

Conceptual design for a European High Power Laser Fusion Research Facility

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On behalf of HiPER+ community

HiPER+
EUROPEAN LASER FUSION ENERGY

The demonstration of ignition and follwing progress at the National Ignition Facility validated inertial fusion as a viable approach to Inertial Fusion Energy (IFE) and triggered initiatives and significant investments worldwide. In Europe, the HiPER+ initiative began around 2020 as a bottom-up proposal emerging from the academic community [1]. The initiative focuses on the study of the direct drive approach to inertial fusion, considered the most promising route towards energy due to its higher efficiency and better compatibility with the high repetition rates required for a power plant [2].

Recently, HiPER+ has been endorsed by EUROfusion under the HiPER+RF project [3], funded for the period 2026–2027. The project brings together 30 research groups from 12 European countries thus assembling the vast majority of the European laser–plasma and IFE community. At present, Europe lacks a civilian laser-driven fusion infrastructure. The main goal of HiPER+RF is therefore to address this strategic gap by developing a conceptual design for the next-generation laser fusion research facility, based on direct drive, thus strengthening Europe's position in the global fusion landscape.

The project will address advanced laser architectures, scalable target fabrication and injection solutions, materials for future reactors, breeding issues, and state-of-the-art diagnostics suitable for reactor-relevant environments. The proposed facility will be designed to achieve ignition and progress toward high-gain regimes. HiPER+RF builds upon the legacy of the original HiPER project and subsequent European initiatives, bringing together leading research institutions and major European laser facilities. It will promote collaboration with industrial partners and fusion start-ups, trying to get the needed support from policymakers to enter the ESFRI Roadmap.

This talk will provide an overview of the HiPER+RF project, highlighting its scientific goals, key technological challenges, and its contribution to the development of a European strategy for inertial fusion energy.

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[1] D.Batani, *et al.* "Future for Inertial Fusion Energy in Europe: a Roadmap" HPLSE, 11, e83 (2023)
[3] Eurofusion Enabling Research Project CfP-FSD-AWP26-ENR-01 "Conceptual design for a European High Power Laser Fusion Research Facility" (HiPER+RF)

Revisiting the Physics of Collisional Suppression of Hot Electron Generation by Two-Plasmon Decay Using Kinetic Simulations

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The mitigation of hot electron generation by laser—plasma instabilities is a key consideration in the development of next-generation laser drivers for inertial confinement fusion and high-energy-density–physics experiments. At the high laser intensities these applications require, electron plasma wave instabilities including two-plasmon decay (TPD) can generate copious hot electrons, leading to undesirable laser absorption and target preheat. While simulations using different methods and algorithms agree that collisions increase the threshold intensity for TPD and suppress above-threshold hot electron generation, they disagree on the strength of the suppressive effect. Using fully-kinetic particle-in-cell (PIC) simulations with state-of-the-art algorithms for improved energy conservation, we revisit the collisional suppression of hot electron generation by TPD. Simulations performed using the open-source PIC code WarpX with these improved algorithms indicate greater collisional suppression of above-threshold hot electron generation than other modeling. One driver of this discrepancy is differing evolution of the plasma density profile, which affects the growth of convective TPD. Simulations with both WarpX and the wave-based code LPSE predict sensitivity of the density profile to the physics and numerics of energy deposition, including energy conservation, damping, and kinetic effects. This work demonstrates that accurate modeling of the density profile evolution – which is sometimes neglected in simulations – is critical to predicting hot electron generation by TPD. Furthermore, it suggests intentional density profile modification as a potential strategy for mitigating hot electron preheat.

This material is based upon work supported by the KISMET collaboration, a project of the U.S. Department of Energy, Office of Science, Office of Advanced Scientific Computing Research and Office of High Energy Physics, Scientific Discovery through Advanced Computing (SciDAC) program, and by the U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences, under Award No. DE-SC0024863: IFE-STAR.

Theoretical model for laser propagation via relativistically induced transparency and the transition to hole boring

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Physics of high-intensity laser propagation in plasmas is fundamental to various applications such as laser-driven particle acceleration and inertial fusion. Relativistic laser light exceeding 10^{18}W/cm^2 can propagate in plasmas with densities above the critical density n_c due to the relativistic effect called the relativistically-induced transparency (RIT) [1, 2] by which the critical density is upshifted to γn_c. While theoretical expressions for the group velocity in the RIT regime have been discussed [3, 4], there is no comprehensive formula that describes the propagation velocity and transition density to the hole-boring (HB) regime observed in particle-in-cell (PIC) simulations.

In this study, we derive a theoretical expression for the group velocity of relativistic laser light in near-critical plasmas. Using 1D PIC simulations, we examined the pulse-front structure in the RIT regime and during the transition to HB which occurs in inhomogeneous-density plasmas. In the RIT regime, the laser pulse loses energy by accelerating ions at the pulse front. Consequently, the propagation velocity becomes slower than that predicted by the conventional group velocity. We derived a modified group velocity taking into account the energy dissipation. The transition density at which the laser switches from RIT to HB becomes lower than γn_c due to momentum transfer to ions, as captured by our model. The theoretical results show an excellent agreement with the 1D PIC simulations.

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Experimental study of resistively focused relativistic electrons for EFI

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Electron fast ignition (EFI) is a promising approach to achieving high gain in inertial confinement fusion. It reduces driver and symmetry requirements compared to conventional central hot spot ignition by separating the compression and ignition phases. Short pulse (sub-picosecond) lasers incident on solid targets generate energetic electrons which can then ignite a fuel capsule pre-compressed by nanosecond lasers. The short pulse laser energy is coupled very efficiently into electrons; however, they experience a large angular divergence in the solid material, making it challenging to deposit their energy into the limited hotspot volume. Resistive focusing via self-generated magnetic fields has been demonstrated as a viable electron collimation technique wherein a resistivity gradient in the material drives strong azimuthal fields (on the order of kiloteslas based on particle-in-cell simulations). In this work we present results from an experimental campaign conducted at the Apollon and Titan laser facilities (at 20fs and 0.5ps pulse durations respectively) for studying the resistive focusing of MeV electrons. We make simultaneous measurements of the electron angular-dependent energy distributions and spectroscopic measurements that help infer temperature gradients in coaxial wire targets with a radial resistivity gradient. The inferred temperature can help constrain resistivity gradients in the target as calculated from collisional PIC codes iteratively with the measured escaping electron energy distributions. This can help shed light on the heating mechanisms in the target which generate resistivity gradients driving electron collimation for EFI, and help to improve the predictive capability of EFI design codes.

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First demonstration of an additively manufactured wetted foam direct-drive inertial confinement fusion target on the National Ignition Facility

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Experiment N250316-001 marked the first demonstration of a layered direct-drive inertial confinement fusion (ICF) target on the National Ignition Facility (NIF) laser. The target consisted of a $\varnothing 3\,mm$ plastic capsule with a $15\,\mu m$ thick shell and a $120\,\mu m$ thick foam layer ($70\,mg/cc$), both of which were additively manufactured using two-photon polymerization (2PP). The shell and foam were fabricated concurrently in a single print, representing the fourth such target fielded at NIF. The foam layer was constructed as four concentric icosphere surfaces composed of solid-density struts (approximately $\varnothing 6\,\mu m \times 30\,\mu m$ in length), designed to wick liquid deuterium throughout the structure. This formed a wetted foam (WF) layer on the interior surface of the capsule, surrounding a central vapor region that forms the hot spot. Cryogenic cooling of the target was achieved via conduction through a $\varnothing 250\,\mu m$ copper fill-tube, which was integrated into a flange printed with the capsule. The target was cooled to $\sim 28\,K$, resulting in coexisting liquid and vapor deuterium phases with densities of $\sim 150\,mg/cc$ and $\sim 6\,mg/cc$, respectively.

The capsule was irradiated with an $850\,kJ$, $300\,TW$, $4\,ns$ laser drive using a polar direct drive (PDD) pointing configuration. Preliminary nuclear performance data aligned with preshot radiation-hydrodynamics predictions from HYDRA simulations, providing validation for early modeling studies that suggested robust ignition could be achievable with such designs on the NIF platform. Additively manufactured PDD-WF targets are being developed as next-generation, igniting, low-mass neutron sources for survivability experiments as part of NIF's National Security Applications Program [Phys. Plasmas **32**, 022702 (2025)]. These targets offer advantages in fieldability compared to current laser indirect drive (LID) beta-layered ice designs. Furthermore, this work is advancing capsule manufacturing technologies under consideration for liquid-layered LID ICF and inertial fusion energy (IFE) concepts, providing valuable insights into scalable production techniques for future applications.

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Indirect-drive wetted foam implosions at the National Ignition Facility*

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Liquid deuterium-tritium fuel supported by a spherical foam layer is currently the leading approach to solving the fuel layering problem for inertial fusion energy (IFE). Simplifying the fueling process for capsules and minimizing the fueling time will be essential to limit the tritium inventory necessary for IFE power plant operation. To scale to ~10 Hz repetition rates, both the foam layer and the capsule ablator must be amenable to mass manufacturing techniques, pointing to an advantage for additively manufactured foams such as those produced by two-photon-polymerization (2PP).

Models of fusion performance for implosions using wetted foam fuel layers predict degradations to ignition margin and gain from both radiative losses and reduced compressibility versus pure DT (ice) layers. However, very little data exists to validate these simulations, and none in the self-heating regime. We are planning to execute a pair of ignition-scale indirect-drive implosions on the NIF identical in all aspects except for the fuel layer. The wetted foam version of the implosion will use a foam layer printed directly onto the capsule inner surface via a process adapting 2PP to thick indirect-drive CH ablators. Comparison between the ice and liquid layer implosions allows for both direct inference of compression reduction and radiation losses from the data and constraints on simulations of these degradation mechanisms. We will describe the design of the experiments, the fabrication of the foam layer, and the predictions of performance for both types of layers. We will also describe several experiments carried out at the Omega Laser to investigate wetted foam microphysics during the first shock of the NIF implosion.

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2026 Innovative Concepts
for Inertial Fusion Energy

A Brief Literature Review of Heavy Ion Fusion for Energy Applications

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Fusion energy is often discussed as a possible long term source of clean electricity, but there are still many scientific and engineering challenges that limit practical use. One approach that continues to receive attention is heavy ion fusion, which is studied within the broader field of inertial confinement fusion. This abstract presents a short literature review of heavy ion fusion and related concepts using published sources that discuss target compression, ion stopping power, beam transport, and ignition challenges.

This review focuses on a few major topics that appear in current workshop discussions, especially ion stopping power and transport, hydrodynamic implosions, ion fast ignition, and heavy ion fusion. Published work suggests that heavy ion beams are of interest because they may offer good driver efficiency and controlled energy deposition in fusion targets. At the same time, the literature also shows that important challenges remain, including target design, implosion symmetry, beam focusing, and the difficulty of achieving conditions suitable for ignition and energy gain.

This work does not present original experimental or computational results. Instead, it summarizes a small set of accessible review and policy sources in order to better understand why heavy ion fusion remains scientifically important and what limitations still affect its future as an energy technology. The goal is to give a student level overview of the field and to connect one area of fusion physics to broader questions about future energy systems.

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Optimizing laser-driven ion sources for applications to ion fast ignition

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Our collaboration has been studying the physics underpinning ion fast ignition as an alternative fusion energy scheme. We have performed a series of experiments across a range of laser facilities, in pursuit of ion fast ignition relevant studies.

Initially, a series of laser and targetry optimisation and scaling experiments were conducted on the Orion laser at AWE. Orion provided the platform for a detailed experimental parameter scan to investigate the ion generating and focusing target design, using cone-in-shell geometries, in detail. Targets were primarily CD hemisphere foils and gold focusing cone assemblies. High quality spatial profile and spectral data were collected via ion diagnostics and Cu k-alpha imaging. Results showed strongly chromatic, but well focused ion beams, including significant deuterium ion acceleration. Findings informed experiments performed on Omega EP, Omega 60 and integrated shot days, extending to NIF-ARC shots to study ion focussing targets in the multi-kJ, multi-ps regime.

Beyond optimising the ion source outputs, another key consideration is how the cone in shell components impact the implosion dynamics. Experiments studying implosion dynamics using cone-in shell geometries have been performed on Omega. Simulations of these experiments have well replicated the dynamics, and these is good agreement between experimental and synthetic data from diagnostics. This provides a computational platform for further exploration and optimisation of the target geometry parameter space. Further work is planned for both Omega and NIF.

Magnetic Collimation of Relativistic Electron Beams through Resistivity Gradients

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In the electron fast ignition (EFI) approach to inertial confinement fusion [1], a relativistic electron beam (REB) deposits energy into the core of relatively cold, isochoric fuel assembly, sparking ignition and burn. The electrons are accelerated by short-pulse lasers and must travel from the critical density into the center of the compressed fuel (typically a few hundred microns). Short-pulse laser energy can be efficiently (~60%)[2] coupled into the REB. However, the resulting beam suffers from wide angular spread, making it difficult to focus the beam and deposit the energy into the small volume of the hotspot at a distance. One proposed solution is to collimate the beam through self-generated magnetic fields. Such fields can be formed using resistivity gradients in the background material [3] and potentially improve electron collimation [4]. In this work we report on simulations in support of an experimental campaign at the OMEGA EP laser facility to study fast electron transport and demonstrate resistive collimation in a well-characterized solid-density background material. Hybrid particle-in-cell (PIC) simulations of fast electron transport through various guiding channels show that collimation performance is sensitive to how the background temperature and resistivity evolve during the pulse, as well as the details of the injected electron spectrum. The OMEGA EP laser facility delivers up to ~1 kJ laser energy to target with pulse lengths between 0.7 – 10 ps. The experiment is diagnosed through time-resolved and time-integrated K-shell spectroscopy, including 1D spatially-resolved spectroscopy at the rear surface, and electron spectroscopy at multiple exit angles. The study aims to enhance understanding of field growth and improve predictive capability in modeling.

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Shock propagation in cryogenic deuterium-wetted foams

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Abstract. We present high-resolution X-ray imaging measurements of shock wave propagation through foams that have been wicked with liquid deuterium at 25K. The Titan laser facility at Lawrence Livermore National Laboratory delivered a 150-J, 600 fs short-pulse laser beam to drive a Cu K-alpha X-ray backlighter source at 8 keV providing X-ray phase-contrast images with 100 picosecond temporal resolution and 20-micron spatial resolution. A second long-pulse laser beam smoothed with a 600-micron continuous phase plate drives the shock wave through a plastic ablator into the wetted foam. Our measurements provide new results on the shock speed and the shock uniformity for various types of foam structures revealing a path towards approaching the uniformity achieved in a pure deuterium liquid. The data further visualize the mixing of foam material with the liquid behind the shock, providing important benchmark data for hydrodynamic simulations of laser-driven fusion targets for inertial fusion energy.

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