IFE STAR

IFE-STAR Conference 2025

April 7 – 11
Breckenridge, CO

Program & Conference Abstracts

Supported by the U.S. Department of Energy's Office of Science, Fusion Energy Sciences Program.

IFE-STAR 2025 Conference

Organizing Committee

Liz Conrow, UR
Dustin Froula, UR
Tammy Ma, LLNL
Carmen Menoni, CSU

Program Committee

Javier Garay, UCSD
Brenda Garcia-Diaz, SRNL
Siegfried Glenzer, SLAC

Monday, April 7

Time	Name	Institution	Abstract Title
Session I		**Dustin Froula, Chairperson**	
8:30 AM	Jean Paul Allain	U.S. Department of Energy	Building Bridges: A Bold Vision for the DOE Fusion Energy Sciences Program
9:00 AM	Bassem El Dasher	Lawrence Livermore National Laboratory	History of IFE in the US: Half a Century of Vision
9:30 AM	Art Pak	Lawrence Livermore National Laboratory	Progress and Outlook of the Inertial Confinement Fusion Program at Lawrence Livermore National Laboratory
10:00 AM	Break		
Session II		**Rahul Shah, Chairperson**	
10:15 AM	Riccardo Betti	University of Rochester	Laser Direct-Drive Inertial Fusion Energy: Challenges and Opportunities
10:45 AM	Pravesh Patel	Focused Energy	Shock Ignition/Fast Ignition Overview
11:15 AM	Nathan Meezan	Pacific Fusion	Overview of Pulser-Driven Inertial Fusion Energy
11:45 AM	Tammy Ma	Lawrence Livermore National Laboratory	2022 Basic Research Needs Workshop on Inertial Fusion Energy (Update)
12:00 PM	Lunch Provided	Mentor/Mentee Lunch in Aspen Dining Room	
IFE Workshop		**Roger Falcone, Chairperson**	
1:30 PM	IFE Workshop I	Panel Participants	Rahul Shah, John Edwards, Kyle Peterson, Neil Alexander Connor Galloway, and Brenda Garcia-Diaz
3:00 PM	Break		
3:30 PM	IFE Workshop II	Panel Participants	Rahul Shah, John Edwards, Kyle Peterson, Neil Alexander Connor Galloway, and Brenda Garcia-Diaz
7:30 PM	Poster Session I		

Monday, April 7 – Poster Session I

Number	Author	Institution	Abstract Title
P-1	Andrew Nelson	Columbia University	Fusion Energy Week: Connecting Communities in the Pursuit of Fusion Energy
P-2	Archis Joglekar	Ergodic LLC	Optimal Bandwidth Spectra for Two Plasmon Decay Subject to Many Plasma Conditions
P-3	Arnaud Colaïtis	University of Rochester	A 3D AMR-ALE Framework for ICF and IFE Calculations
P-4			
P-5	Dan Haberberger	University of Rochester	FZP-Based High-Resolution Imprint Radiography
P-6	Danielle Brown	SLAC National Accelerator Laboratory	Resolving Species Contributions in CR-39 Multi-Ion Spectra Using Bayesian Inference
P-7	Elizabeth Grace	Lawrence Livermore National Laboratory	Single-Shot Diagnostics for Laser Produced Plasmas
P-8	Yasuhiko Sentoku	The University of Osaka	FIREX-NEO Project in ILE: Strategy to Demonstrate Fast Ignition by Upgraded GEKKO-XII and LFEX Lasers
P-9	Griffin Glenn	SLAC National Accelerator Laboratory	Laser-Driven Ion Acceleration from Pre-Expanded Converging H2O Microjets
P-10			
P-11	Jihoon Kim	Cornell University	Producing Arbitrarily Shaped IFE-Relevant Excimer Laser Pulses Using Stimulated Brillouin Compression
P-12	Aurelien Perron	Lawrence Livermore Naitonal Laboratory	Design of Complex High-Performance Materials for Extreme Environments
P-13	Clément Goyon	Lawrence Livermore National Laboratory	STARFIRE Hub Research Highlights and Path Forward
P-14	Dhrumir Patel	University of Rochester	Estimating Neutron Down-Scattered Ratio Through Neutron Time-of-Flight Data on OMEGA Direct-Drive Implosions
P-15	Patrick Poole	Lawrence Livermore National Laboratory	IFE Workforce Development at LLNL
P-16	Ramon Rodriguez-Lopez	Colorado State University	Amorphous Oxide Mixtures for $\lambda \leq 355$ nm Multilayer Dielectric Coatings
P-17	Bruce Remington	Lawrence Livermore National Laboratory	Hydrodynamic Instabilities in the Context of IFE
P-18	Daniel Hodge	Brigham Young University	Single-Shot 2D X-Ray Phase-Contrast Imaging and Phase Retrieval of Void-Shockwave Dynamics

P-19	Marco Garten	Lawrence Berkeley National Laboratory	Simulations of Ion Beam Focusing in Laser-Irradiated Hemisphere Targets
P-20	Maren Hatch	Sandia National Laboratories	The Impact of Surface Imperfections on High-Current-Density Conductors
P-21	McKenzie Leininger	Brigham Young University	Flat-Field Correction of Void Collapse Evolution Imaging
P-22	Koichi Masuda	EX-Fusion	Advancing XF-COLR: Innovations in Vacuum Systems, Adaptive Optics, Beam Steering, and Target Injection
P-23	Kurt-Julian Boehm	General Atomics	Progress Towards Target Flight-Tracking and On-The-Fly Engagement for an IFE Injection System
P-24	Ryan Lau	University of Colorado, Boulder	Nonlocal Thermal Transport Effects on Laser Propagation in MagLIF-Relevant Gaspipes on the NIF
P-25	Ryan Nedbailo	University of Texas, Austin	Proton Focusing and Heating of Warm Dense Matter at OMEGA-EP
P-26	Sheila Chauwinoir	Texas A&M University	Investigating Nonlinear Optical Phenomena for Robust Direct Drive Laser Fusion Design
P-27	Sophia Malko	Princeton Plasma Physics Laboratory	Detailed Benchmarking of the Nernst Effect in Magnetized HED Plasma
P-28	Stefano Faubel	SLAC National Accelerator Laboratory	Developing a Versatile Next-Generation Liquid Sheet Target for Studies in High Repetition Rate & High-Power Laser-Matter Interactions
P-29	Travis Hallam	Texas A&M University	High-Fidelity Neutronics Analysis for Inertial Confinement Fusion Concepts
P-30	Vijay Patel	University of California, Los Angeles	Eliminating Stimulated Raman Backscatter Through Induced Laser Bandwidth Concomitant from Forward Scatter
P-31	Kyle McMillen	University of Rochester	Gaussian Laser Beam Filamentation Influenced by Additional Smoothed Laser Beams

Tuesday, April 8

Time	Name	Institution	Abstract Title
Session I - Target Physics		**Tammy Ma, Chairperson**	
8:30 AM	Constantin Haefner	Fraunhofer ILT	Transforming Supply Chains: The Impact of Global Advancements in Laser Fusion Energy on the Photonics Market
9:15 AM	David Turnbull	University of Rochester	Plans to Demonstrate LPI Mitigation with a Broad-Bandwidth Laser Beam
9:35 AM	Camille Samulski	Los Alamos National Laboratory	Validating Los Alamos National Laboratory's xRage Common Model Framework for Polar Direct Drive Target Design
9:55 AM	Alison Christopherson	Xcimer Energy Incorporated	Advancing Two-Sided Inertial Fusion: Xcimer's Hybrid Drive and Target Design Roadmap
10:15 AM	Break		
Session II - Target Physics		**Nathan Meezan, Chairperson**	
10:40 AM	Darwin Ho	Lawrence Livermore National Laboratory	High-Yield Implosions Using DT Wetted Foam for Inertial Fusion Energy
11:00 AM	Xiaoxing Xia	Lawrence Livermore National Laboratory	Polar-Direct-Drive DT Wetted Foam Studies on the National Ignition Facility
11:20 AM	Warren McKenzie	HB11 Energy	HB11 Energy: Advances in Laser Boron Fusion Science and Engineering
11:40 AM	Marius Schollmeier	Marvel Fusion GmbH	First Experimental Evaluation of a 10-PW-Driven Nano Accelerator for IFE
12:00 PM	Lunch Provided		
2:00 PM	Teambuilding	Breckenridge Scavenger Hunt Meet in the coffee shop at Gravity Haus (605 S. Park Ave)	
7:00 PM	Dustin Froula	University of Rochester	IFE-STAR Ecosystem Overview
8:30 PM	Poster Session II		

Tuesday, April 8 – Poster Session II

Number	Author	Institution	Abstract Title
P-1	David Chesny	SpaceWave	Development of Solid-State Linear Transformer Drivers and Enhancing Fusion Energy Science Research in the Southeastern U.S.
P-2	Derek Mariscal	Lawrence Livermore National Laboratory	Advancing IFE Science Through Machine Learning and High-Repetition-Rate High-Energy-Density Experiments
P-3	Igor Golovkin	Prism Computational Sciences, Inc.	Radiation-Hydrodynamics Code HELIOS-CR: Improved Models for Dense Plasma Effects and IFE Simulations
P-4	John Marozas	University of Rochester	Broadband Laser Smoothing for ICF and IFE targets
P-5	Jonathan Brodrick	Pasteur Labs	Auto-Differentiation Powered Inverse Design Workflows on the Cloud
P-6	Justin Angus	Lawrence Livermore National Laboratory	An Implicit Particle Code for Fully Kinetic Simulations of Burning Plasmas
P-7			
P-8	Kirill Lezhnin	Princeton Plasma Physics Laboratory	Laser Ion Acceleration from Concave Targets: Focusing, Scaling, and Robustness
P-9	Kaikai Zhang	Amplitude Laser Inc.	Building Blocks of kJ Nanosecond and Picosecond Lasers for Fusion Research
P-10	Matthew Wolford	U.S. Naval Research Laboratory	Advances in Development of an Argon Fluoride (ArF) Laser Driver for Inertial Fusion Energy (IFE)
P-11	Zhenhuan Yi	Texas A&M University	Toward High Power Laser for Fusion: Stimulated Brillouin Scattering Modeling with Kinetic Analysis
P-12	Edward Moses	Longview Fusion Energy Systems	Longview Fusion Energy Systems: The Path from the NIF to Commercial Fusion Energy
P-13	Félicie Albert	Lawrence Livermore National Laboratory	The Jupiter Laser Facility: A Kilojoule-Class Laser for Producing and Exploring Extreme States of Matter
P-14	Jim Gaffney	Focused Energy	A Fusion Pilot Plant Design for Direct Drive IFE
P-15	Maggie Rivers	Princeton Plasma Physics Laboratory	Platform for High Resolution Proton Stopping Power Measurements in WDM
P-16	Richard Sandberg	Brigham Young University	Developing the Future Inertial Fusion Energy Workforce in the RISE IFE-STAR Hub
P-17	Daniel Casey	Lawrence Livermore National Laboratory	Understanding Implosion Physics Degradations to Advance IFE-Relevant Targets

P-18	Stephen Messing	Univesity of Illinois Urbana-Champaign	Absolute Gain-Coupling Coefficients for Stimulated Brillouin Scattering at 266 nm in Low-Pressure Gases
P-19	Pericles Farmakis	University of Rochester	Multidimensional Modeling of the Hybrid Shock Drive for Low-Adiabat Direct-Drive Fusion Experiments at the Omega Laser Facility
P-20	Raspberry Simpson	Lawrence Livermore National Laboratory	Investigation of Ion Focusing Using Structured Targets for Applications to Ion Fast Ignition
P-21	Levi Hancock	Brigham Young University	Nanostructure of Polymer Foams using 3D Ptycho-Tomography for Inertial Fusion Energy (IFE) Applications
P-22	Sabrina Silva	General Atomics	Advancing IFE Target Fabrication with Microencapsulate Dicyclopentadiene-Norbornene Foam Shells
P-23	Jaden Hoechstetter	Colorado State University	Angular Distribution of Ions Accelerated by Irradiation of Nanowire Arrays with Laser Pulses of Relativistic Intensity
P-24	Jesse Griff-McMahon	Princeton Plasma Physics Laboratory	Characterization of Proton Focusing from Hemispherical Targets
P-25	Jordan Lee	University of Oxford	Bayesian and Particle Swarm Approaches to Inertial Confinement Fusion Implosions
P-26	Kassie Moczulski	University of Rochester	Numerical Simulations of Laser-Driven Experiments of Ion Acceleration in Stochastic Magnetic Fields
P-27	Nashad Rahman	Colorado State University	Fabrication of Nanowire Array Strips for Characterizing Ion Acceleration in Relativistic Laser-Nanostructure Interactions
P-28	Oren Yang	University of California, San Diego	Neutron Production in Krypton on Deuterium Gas Puff Z-Pinches
P-29	Perry Samimy	University of California, San Diego	Experimental Study of Proton Heating in Proximally Structured Cu Foam Targets
P-30	Rusko Ruskov	University of Oxford	The Effect of Broad Laser Bandwidth on the Two-Plasmon Decay Instability and Its Connection to Turbulence
P-31	Heath Martin	University of Oxford	The Electrothermal Filamentation of Igniting Plasmas

Wednesday, April 9

Time	Name	Institution	Abstract Title
Session I - Target Technology		**Carmen Menoni, Chairperson**	
8:30 AM	George Larsen	Savannah River National Laboratory	Assessing the Impacts of IFE Target Materials on the D-T Fuel Cycle
9:15 AM	Holly Flynn	Savannah River National Laboratory	Process Modeling and the Development of a Real-Time Monitoring and Accountancy Open Framework for Fusion Energy
9:35 AM	Alex Somers	Savannah River National Laboratory	Effects of Target Protium Content on Steady-State Protium Removal and Isotope Rebalancing Distillation Column Operation
9:55 AM	Kazuki Matsuo	EX-Fusion	10Hz Laser Beam Steering and Illumination for Continuously Delivered Targets
10:15 AM	Break		
Session II - Target Technology		**John Edwards, Chairperson**	
10:40 AM	Abbas Nikroo	Lawrence Livermore National Laboratory	Target Fabrication: From Single Shot Ignition to Rep-Rated IFE
11:00 AM	Neil Alexander	General Atomics	Development of Fabrication Methods for Wetted Foam Targets
11:20 AM	Sourabh Saha	Georgia Institute of Technology	Fast and Accurate Printing of Nanoporous Foams for IFE Targets
11:40 AM	Arianna Gleason	SLAC National Accelerator Laboratory	Static & Dynamic Phase Contrast Imaging of Inertial Fusion Energy Foams at the Linac Coherent Light Source
12:00 PM	Lunch Provided		
2:00 PM	Teambuilding	Hike to see the Isak Heartstone troll (.7 miles) followed by happy hour at Breckenridge Brewery (600 S. Main St) Meet in the coffee shop at Gravity Haus (605 S. Park Ave)	
7:00 PM	Kramer Akli	U.S. Department of Energy	Hubs/Private Sector Engagement
8:30 PM	Poster Session III		

Wednesday, April 9 – Poster Session III

Number	Author	Institution	Abstract Title
P-1	Leland Ellison	Pacific Fusion	Current-Driven ICF Target Design with FLASH
P-2	Mario Manuel	General Atomics	High-Repetition-Rate Technology Development on GALADRIEL Relevant to the Inertial Fusion Energy Industry
P-3	Muhammad Fauzan Syahbana	The University of Osaka	High Spectral Resolution X-Ray Thomson Scattering Diagnostics in High Density D2 Plasma
P-4			
P-5	Sonya Dick	South Dakota School of Mines & Technology	A Framework to Measure the Viscosity of HED Materials via Hydrodynamic Instabilities
P-6	Varchas Gopalaswamy	University of Rochester	A Physics-Based Bayesian Optimization Framework for Direct-Drive Implosions on Rep-Rated Facilities
P-7	Wojciech Rozmus	University of Alberta	Theory of Thomson Scattering via Ray Tracing Simulations
P-8	Jorge Rocca	Colorado State University	Multi Mega-Electron Volt Ion Acceleration in Nanowire Arrays Irradiated with Laser Pulses of Relativistic Intensity for IFE Concepts
P-9	Justin Galbraith	Lawrence Livermore National Laboratory	LD-FIRST (Laser Driven Fusion Integration Research and Science Test Facility): Design, Progress, and Future Development Pathways
P-10	Alenna Streeter	Sydor Technologies	Plasma Electrode Pockels Cell Technology (PEPC) for Inertial Confinement Fusion Energy
P-11	Mackenzie Nelson	Lawrence Livermore National Laboratory	Techno-Economic Inertial Fusion Power Plant Design through the Integrated Process Model (“IPM”)
P-12	Wolfgang Theobald	Focused Energy	An Implosion Test Facility for Laser Direct-Drive IFE
P-13	Xiao Chen	Lawrence Livermore National Laboratory	Inference of Anomalous Thermal Transport Using Bayesian Optimization with Uncertainty Quantification in Plasma Boundary
P-14	Alexey Zheltikov	Texas A&M University	On Nondamaging Laser-Damage Risk Assessment
P-15	Mark Moffett	SpaceWave, LLC	Scalable Modular Solid State Switching for Pulsed Power Fusion Applications
P-16	Ivan Oleynik	University of South Florida	Exploring the HED Physics of Amorphous IFE Ablator Materials

P-17	Jhonnatan Gama	SLAC National Accelerator Laboratory	Laser-Driven Ion Acceleration in Overdense and Underdense Targets: a Field-Particle Correlation Perspective
P-18	John Kuczek	Los Alamos National Laboratory	xRAGE Modeling for Xcimer Target Design on OMEGA
P-19	Kevin Meaney	Los Alamos National Laboratory	Fusion Reaction History and the Physics of Burn Propagation
P-20	Timothy Johnson	Lawrence Livermore National Laboratory	Impact of Asymmetries and Mix on Burn-Up Fraction for IFE Relevant Implosions
P-21	William Trickey	University of Rochester	Multidimensional Simulations of Igniting Direct-Drive ICF Targets at 250 kJ Laser Energy
P-22	Widianto Moestopo	Lawrence Livermore National Laboratory	Fully Additively Manufactured Wetted Foam Capsule for Inertial Confinement Fusion
P-23	Yongfeng Lu	University of Nebraska-Lincoln	Two-Photon Polymerization and Coherent Anti-Stokes Raman Scattering Microscopy for Fusion Target Fabrication and Diagnostics
P-24	Abbey Armstrong	University of Rochester	Studying Biermann-Generated Magnetic Fields in a Cylindrically Convergent System
P-25	Ajitha Dharmasiri	Texas A&M University	Sculpted Laser Statistics as a Probe for ICF Laser-Beam Stability
P-26	Alex Pietrow	University of California, San Diego	Effects of rear surface degradation on TNSA protons for Fast Ignition
P-27	Anson Olive & Brianna Rivera	Texas A&M University	Applying Inertial Fusion Energy for Hydrogen Production
P-28	Audrey DeVault	Massachusetts Institute of Technology	Utilizing the OMEGA High-Resolution Velocimeter (OHRV) to Quantify Shock Front Non-Uniformities in Wetted Foams
P-29			
P-30	Christopher Schowenwaelder	Friedrich-Alexander University Erlangen-Nuremberg	Designing a D2 Wetted Foam Target Station
P-31	Edna Rebecca Toro Garza	SLAC National Accelerator Laboratory	Warm Dense Matter Conductivity Measurements Using Single-Shot THz Spectroscopy

Thursday, April 10

Time	Name	Institution	Abstract Title
Session I - Driver Development		**Brenda Garcia-Diaz, Chairperson**	
8:30 AM	Mike Campbell	MCM Consultants	Perspectives on Inertial Confinement Fusion (ICF) and Inertial Fusion Energy (IFE)- History, Opportunities and Challenges
9:15 AM	Trevor Cohen	Blue Laser fusion, Inc	Recent Progress for Commercializing IFE Based on a Novel High Efficiency 10 MJ Laser and High Gain Fuel Target
9:35 AM	Takashi Sekine	Hamamatsu Photonics K.K.	Initiatives to Realize Long-Term IFE Research in HAMAMATSU
9:55 AM	Alexei Sokolov	Texas A&M University	High-Power Laser Beam Combining via Molecular Coherence
10:15 AM	Break		
Session II - Driver Development		**Arthur Pak, Chairperson**	
10:40 AM	Jorge Rocca	Colorado State University	Colorado State University ALEPH Petawatt-Class Laser and Upgrade for the New ATLAS Facility
11:00 AM	Erhard Gaul	Marvel Fusion GmbH	Short Pulse Laser Development for Direct-Drive IFE
11:20 AM	Kaikai Zhang	Amplitude Laser Inc.	High Repetition Rate Nd:Glass Amplifier Module for kJ Lasers for Fusion Research
11:40 AM	Kavita Desai Kabelitz	University of Illinois Urbana-Champaign	Optically Pumped Amplifiers in Alkali-Rare Gas Excimers for Laser Fusion Energy
12:00 PM	Lunch Provided		
2:00 PM	Teambuilding	Walk to the BreckConnect Gondola and take the free ride to the top! Meet in the coffee shop at Gravity Haus (605 S. Park Ave)	
6:00 PM	Cocktails & Hors d 'Oeuvre Reception		
7:00 PM	Banquet and Trivia Night		

Friday, April 11

Time	Name	Institution	Abstract Title
Session I: Cross-Cutting Fields		**Jim Gaffney, Chairperson**	
8:30 AM	Kyle Peterson	Sandia National Laboratory	Mutually Beneficial Pulsed Power IFE Science and Technology Investments
8:50 AM	Adriaan Riet	Idaho National Laboratory	Supporting Fusion at Idaho National Laboratory
9:10 AM	Krish Bhutwala	Princeton Plasma Physics Laboratory	Preliminary Results on Proton Beam Focusing and Heating Using a Modular Target Approach
9:30 AM	Willow Martin	Stanford University	Characterizing Laser-Heated Polymer Foams with Simultaneous X-Ray Fluorescence Spectroscopy and Thomson Scattering at LCLS/MEC
9:50 AM	Break		
Session II: Cross-Cutting Fields		**Mingsheng Wei, Chairperson**	
10:20 AM	Vignesh Perumal	CAMINNO, Inc.	Generative Design and Digital Twins for Fusion Energy Targets and Components
10:40 AM	Jean-Luc Vay	Lawrence Berkeley National Laboratory	Progress of the FES SciDAC Project on Kinetic IFE Simulations at Multiscale with Exascale Technology (KISMET)
11:00 AM	Carlo Fiorina	Texas A&M University	Building an Open-Source Framework for the Design and Analysis of IFE Chamber and Blanket Systems
11:20 AM	Box Lunch Provided		
1:00 PM	Conference Ends	Thank you for joining us!	

Session Information
Followed by Detailed Abstracts

Monday, April 7

Time	Name	Institution	Abstract Title
Session I		**Dustin Froula, Chairperson**	
8:30 AM	Jean Paul Allain	U.S. Department of Energy	Building Bridges: A Bold Vision for the DOE Fusion Energy Sciences Program
9:00 AM	Bassem El Dasher	Lawrence Livermore National Laboratory	History of IFE in the US: Half a Century of Vision
9:30 AM	Art Pak	Lawrence Livermore National Laboratory	Progress and Outlook of the Inertial Confinement Fusion Program at Lawrence Livermore National Laboratory
10:00 AM	Break		
Session II		**Rahul Shah, Chairperson**	
10:15 AM	Riccardo Betti	University of Rochester	Laser Direct-Drive Inertial Fusion Energy: Challenges and Opportunities
10:45 AM	Pravesh Patel	Focused Energy	Shock Ignition/Fast Ignition Overview
11:15 AM	Nathan Meezan	Pacific Fusion	Overview of Pulser-Driven Inertial Fusion Energy
11:45 AM	Tammy Ma	Lawrence Livermore National Laboratory	2022 Basic Research Needs Workshop on Inertial Fusion Energy (Update)
12:00 PM	Lunch Provided	Mentor/Mentee Lunch in Aspen Dining Room	
IFE Workshop		**Roger Falcone, Chairperson**	
1:30 PM	IFE Workshop I	Panel Participants	Rahul Shah, John Edwards, Kyle Peterson, Neil Alexander Connor Galloway, and Brenda Garcia-Diaz
3:00 PM	Break		
3:30 PM	IFE Workshop II	Panel Participants	Rahul Shah, John Edwards, Kyle Peterson, Neil Alexander Connor Galloway, and Brenda Garcia-Diaz
7:30 PM	Poster Session I		

History of IFE in the US: Half a Century of Vision

B. El-Dasher
Lawrence Livermore National Laboratory
7000 East Ave
Livermore, CA 95020
eldasher2@llnl.gov

Since the initial conception of Inertial Confinement Fusion (ICF), ideas of how to harness and control this process to create Inertial Fusion Energy (IFE) power plants started to percolate. Multiple schemes have been proposed, studied, and evolved in varying degrees as to how mankind can repeatedly initiate nuclear fusion reactions by compressing and heating targets filled with fuel in a manner that can be used to harness that energy to produce electricity.

Various methods have been proposed for the compression drivers, and included using lasers, heavy ion beams, light (alpha particle) ion beams or large electrical currents to rapidly compress fuel pellets in both direct and indirect configurations. Multiple chamber concepts have been investigated to address the threat of the byproducts of fusion events, with a great amount of out-of-the-box thinking applied to protect the chamber materials. Additionally, virtually all these concepts rely on a blanket outside of the fusion chamber to breed the tritium component of the fuel. Here again various arrangements and original approaches to generate and extract the tritium, provide cooling from the nuclear heating, as well as address or compensate for the material damage have been studied. In some instances, the studies included the energy extraction/electricity generation loop.

In this talk, the history of these creative achievements in the United States is presented in brief, with a specific focus on the designs and concepts that have matured to the level of integrated design studies. Innovative solutions to challenging design problems will be called out to highlight the inventiveness of those who have laid the foundation of scientific and engineering work in the field.

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Progress and outlook of the Inertial Confinement Fusion Program at Lawrence Livermore National Laboratory*

A. Pak[1] , on behalf of the LLNL ICF program]
1 Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, Ca, 94550
Pak5@llnl.gov

Creating a controlled fusion reaction that produces more energy than supplied to initiate it (i.e. target gain >1) is a grand scientific challenge with broad societal implications [1,2]. A significant barrier for every approach pursuing this goal is to create plasma conditions which exceed Lawson's criteria[3], where the power of fusion self-heating exceeds all the power losses of the system, to the point where target gain >1 is achieved. After decades of research and technological advances the first laser indirect-drive inertial confinement fusion[4,5] experiment to meet the Lawson Criteria and achieve a target gain >1 was performed [6-8].

This talk will discuss the key scientific and technological advances that enabled fusion ignition. Additional, details will be given on key nuclear and x-ray observations used to identify the principal sources of fusion yield variability that can arise from variations in target quality and implosion drive asymmetry. Experimental observations have been evaluated within a semi-analytic framework to quantify the impact of degradations that limit the fusion energy production. The two main sources of degradations were found to be low mode implosion asymmetries and enhanced radiative loss from higher atomic number contaminants that mix into the reacting deuterium tritium plasma.

Initial findings from recent experiments seeking to increase target gain from ICF experiments will be presented. Details of current and future research directions within the ICF program will be given and contextualized with respect to the needs of Inertial Fusion Energy. Research areas of mutual interest and benefit towards achieving higher target gains will also be discussed.

*This work was performed under the auspices of the U.S. Department of Energy, Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

[1] National Research Council, Burning Plasma: Bringing a Star to Earth (The National Academies Press, Washington, DC, 2004).

[2] National Academies of Sciences, Engineering, and Medicine, Bringing Fusion to the U.S. Grid (The National Academies Press, Washington, DC, 2021).

[3] J. D. Lawson, Proceedings of the Physical Society. Section B 70, 6 (1957).

[4] Nuckolls. *et al*. Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) applications. *Nature* **239**, 139-142 (1972).

[5] J. Lindl, Development of the indirect-drive approach to inertial confinement fusion and the target physics basis for ignition and gain, Phys. Plasmas, **2**, 3933-4024 (1995)

[6] H. Abu-Shawareb, *et al.* Achievement of Target Gain Larger than Unity in an Inertial Fusion Experiment, Phys. Rev. Lett. **132**, 065102 (2024)

[7] A. L. Kritcher *et al*., Design of the first fusion experiment to achieve target energy gain G>1., Phys. Rev. E, **109**, 025204 (2024)

[8] A. Pak, *et al*., Observations and properties of the first laboratory fusion experiment to exceed a target gain of unity, Phys. Rev. E, **109**, 025203 (2024)

Laser direct-drive inertial fusion energy: challenges and opportunities

R. Betti

University of Rochester, Laboratory for Laser Energetics

The physics principles of laboratory-scale inertial confinement fusion (ICF) have been recently demonstrated in implosion experiments at the National Ignition Facility (NIF) using ~2 MJ of UV light with indirect drive. Direct drive experiments on the 30 kJ OMEGA laser have also made notable progress by demonstrating core conditions approaching the ignition threshold and gains ≈1 when hydrodynamically scaled to NIF energies. Direct drive couples significantly more energy to the target and can potentially achieve higher target gains than indirect drive by imploding greater fuel masses. Direct drive targets are simple and suitable for mass production. The full potential of direct drive can be realized with the new generation of ultra-broadband lasers or new laser technologies enabling the suppression of laser plasma instabilities, the achievement of highest ablation pressures and possibly the mitigation of hydrodynamic instabilities. Deep UV light and beam zooming are other laser advances that can dramatically improve the laser energy coupling to the target thereby reducing the laser energy and power requirements. Turning laser-driven implosions into an energy source relies on the expectations that the results from single shot experiments can be replicated at much higher repetition rates to produce high average power at relatively low cost. This requires the development of new types of lasers, mass production of suitable targets, accurate injection and tracking systems and new materials for the reactor chamber components and final optics. An overview of the current state of laser direct-drive research and prospects for providing economically viable energy with high availability will be discussed.

This material is based upon work supported by the Department of Energy (DOE) Office of Fusion Energy Sciences under Award Numbers DE-SC0022132, DE-SC0024456, DE-SC0024381, the STARFIRE collaboration and the DOE [National Nuclear Security Administration] University of Rochester "National Inertial Confinement Fusion Program" under Award Number DE-NA0004144.

Overview of Pulser-Driven Inertial Fusion Energy

N. B. Meezan[1]
[1]Pacific Fusion
6082 Stewart Avenue
Fremont, CA, 94583
nathan@pacificfusion.com

Growing demand for energy, increasing urgency for carbon-free power sources, and recent scientific advances[1-3] have catalyzed a national conversation regarding the most promising path to commercial fusion energy. The science basis for inertial fusion has advanced significantly in the last few years with the demonstration of ignition[2] and propagating burn[3] on the NIF. While a groundbreaking scientific demonstration, NIF is still far from overall Facility Gain (Q_f), defined as fusion energy output exceeding the energy stored by the driver. A more efficient, cost-effective, and scalable approach to inertial fusion is needed for commercial power production. In Pulser-Driven Inertial Fusion Energy (IFE), a fast pulsed power driver (risetime $\tau_{\mathrm{driver}} \approx 100$ ns) magnetically implodes a target to reach fusion conditions. The technical basis for pulser IFE stems from experiments demonstrating values of $P\tau$ on par with those obtained by laser ICF and tokamaks. The leading precedent was established on the Z facility at Sandia National Laboratories[4], where the Magnetized Liner Inertial Fusion (MagLIF) target concept[5] is the most explored in published literature. MagLIF has demonstrated the second-highest $P\tau$ of any fusion concept, below only laser-driven ICF and exceeding the highest tokamak $P\tau$ to date. This was achieved with a small fraction of the investment dedicated to tokamaks and laser ICF.

We discuss the advantages of pulser IFE and the challenges that must be overcome to demonstrate facility gain $Q_f > 1$ and to design a credible fusion power plant. Pulser IFE retains the main advantage of ICF: the large capital investment driver facility can flexibly drive a variety of inexpensive fusion targets, enabling rapid iteration and innovation. Electrical pulsers are low cost relative to lasers and are built out of highly modular components (capacitors, switches, and transmission lines) that do not require exotic materials to fabricate. Magnetic Drive schemes like MagLIF deliver a large fraction of the pulser energy to the fusion target and to the fusion fuel, and the established scaling laws[6] are more favorable than hydro-equivalent scaling. Large fuel masses (relative to laser targets) enable a pulser IFE system to achieve $Q_f > 1$ with fuel gain and burn-up fraction levels already demonstrated on the NIF. Challenges include designing and building ancillary systems for fuel magnetization and preheat that are cost-effective and consistent with commercial system requirements, in addition to many of the same material handling and system integration challenges faced by laser-IFE schemes. Pulser-Driven IFE is a compelling path towards commercialization. Realizing facility gain $Q_f > 1$ and a subsequent pilot plan at the pace laid out by the 2022 Bold Decadal Vision requires a vigorous program in science and engineering, with improved collaboration and increased engagement across the IFE ecosystem.

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Monday, April 7 – Poster Session I

Number	Author	Institution	Abstract Title
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P-2	Archis Joglekar	Ergodic LLC	Optimal Bandwidth Spectra for Two Plasmon Decay Subject to Many Plasma Conditions
P-3	Arnaud Colaïtis	University of Rochester	A 3D AMR-ALE Framework for ICF and IFE Calculations
P-4			
P-5	Dan Haberberger	University of Rochester	FZP-Based High-Resolution Imprint Radiography
P-6	Danielle Brown	SLAC National Accelerator Laboratory	Resolving Species Contributions in CR-39 Multi-Ion Spectra Using Bayesian Inference
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P-12	Aurelien Perron	Lawrence Livermore Naitonal Laboratory	Design of Complex High-Performance Materials for Extreme Environments
P-13	Clément Goyon	Lawrence Livermore National Laboratory	STARFIRE Hub Research Highlights and Path Forward
P-14	Dhrumir Patel	University of Rochester	Estimating Neutron Down-Scattered Ratio Through Neutron Time-of-Flight Data on OMEGA Direct-Drive Implosions
P-15	Patrick Poole	Lawrence Livermore National Laboratory	IFE Workforce Development at LLNL
P-16	Ramon Rodriguez-Lopez	Colorado State University	Amorphous Oxide Mixtures for $\lambda \leq 355$ nm Multilayer Dielectric Coatings
P-17	Bruce Remington	Lawrence Livermore National Laboratory	Hydrodynamic Instabilities in the Context of IFE
P-18	Daniel Hodge	Brigham Young University	Single-Shot 2D X-Ray Phase-Contrast Imaging and Phase Retrieval of Void-Shockwave Dynamics

P-19	Marco Garten	Lawrence Berkeley National Laboratory	Simulations of Ion Beam Focusing in Laser-Irradiated Hemisphere Targets
P-20	Maren Hatch	Sandia National Laboratories	The Impact of Surface Imperfections on High-Current-Density Conductors
P-21	McKenzie Leininger	Brigham Young University	Flat-Field Correction of Void Collapse Evolution Imaging
P-22	Koichi Masuda	EX-Fusion	Advancing XF-COLR: Innovations in Vacuum Systems, Adaptive Optics, Beam Steering, and Target Injection
P-23	Kurt-Julian Boehm	General Atomics	Progress Towards Target Flight-Tracking and On-The-Fly Engagement for an IFE Injection System
P-24	Ryan Lau	University of Colorado, Boulder	Nonlocal Thermal Transport Effects on Laser Propagation in MagLIF-Relevant Gaspipes on the NIF
P-25	Ryan Nedbailo	University of Texas, Austin	Proton Focusing and Heating of Warm Dense Matter at OMEGA-EP
P-26	Sheila Chauwinoir	Texas A&M University	Investigating Nonlinear Optical Phenomena for Robust Direct Drive Laser Fusion Design
P-27	Sophia Malko	Princeton Plasma Physics Laboratory	Detailed Benchmarking of the Nernst Effect in Magnetized HED Plasma
P-28	Stefano Faubel	SLAC National Accelerator Laboratory	Developing a Versatile Next-Generation Liquid Sheet Target for Studies in High Repetition Rate & High-Power Laser-Matter Interactions
P-29	Travis Hallam	Texas A&M University	High-Fidelity Neutronics Analysis for Inertial Confinement Fusion Concepts
P-30	Vijay Patel	University of California, Los Angeles	Eliminating Stimulated Raman Backscatter Through Induced Laser Bandwidth Concomitant from Forward Scatter
P-31	Kyle McMillen	University of Rochester	Gaussian Laser Beam Filamentation Influenced by Additional Smoothed Laser Beams

Fusion Energy Week: Connecting Communities in the Pursuit of Fusion Energy

A.O. Nelson[1], S. Diem[2], A. Dominguez[3]

1 Columbia University
2 University of Wisconsin, Madison
3 Princeton Plasma Physics Laboratory

In May 2024, the US Fusion Outreach Team hosted a first ever Fusion Energy Week, featuring over 60 community engagement events across the US, Europe and Oceania. The mission of Fusion Energy Week, which will henceforth be conducted annually, is to generate excitement for fusion energy by forging connections between communities and researchers working on the continued pursuit of a clean, safe and readily available energy alternative. This event celebrates all aspects of fusion energy, from inertial to magnetic confinement fusion, dedicated research to pop-culture and public to private engagement. The week itself features a selection of locally-organized and virtual events all organized by volunteers. As part of the work, sets of fusion trading cards, featuring artwork from graduate students and local artists, were developed to highlight the diversity of technological approaches and physics concepts that underpin the study of fusion energy. Lessons learned and future plans for expanded future events in support of this clean, safe, and robust energy alternative are presented. If you'd like to be part of Fusion Energy Week 2025, stop by and learn about how to get involved!

Optimal bandwidth spectra for Two Plasmon Decay subject to many plasma conditions

A. S. Joglekar,[1, 2] R. K. Follett,[2] J. P. Palastro,[2] and D. H. Froula[2]
1 Ergodic LLC, Seattle, WA, 98103
archis@ergodic.io
2 Laboratory for Laser Energetics, University of Rochester, Rochester, NY, Zip

Previous work has shown that broadband lasers can mitigate laser plasma instabilities. Follett et. al considered various amplitude shapes (e.g. uniform, gaussian) and random phases, and showed that the mitigation can be predicted by determining the coherence time and that it is invariant with respect to the amplitude shape given the same coherence time. In this work, we explore whether optimal spectra (in both amplitude and phase) exist, what their characteristics are, and how well or poorly they mitigate the two plasmon instability in comparison to the previous approaches (e.g. uniform amplitude and random phase). We will discuss optimal spectra for realistic plasma parameters. The parameter space that is explored is given by –

$$2 \text{ keV} < T_e < 4 \text{ keV} \;||\; 200 \text{ um} < L_n < 600 \text{ um} \;||\; 10^{14} \text{ W/cm}^2 < I < 10^{15} \text{ W/cm}^2$$

To do this, we need to perform optimization of the slowly varying enveloped wave partial differential equations in a high-dimensional (O(100)) parameter space. This requires many iterations using gradient descent. We rewrite the LPSE solvers in a differentiable framework to make them amenable to performing gradient descent and to running on GPUs. Each of these are key enabling technologies for performing optimization of multi-dimensional PDEs in a high-dimensional parameter space.

This material is based upon work supported by the Department of Energy Office of Fusion Energy under Award Number(s) DE-SC0024863. This research used resources of the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231 using NERSC award FES-ERCAP0026741.

A 3D AMR-ALE framework for ICF and IFE calculations*

A. Colaïtis[1], S. Guisset[2], J. Breil[2], D. H. Froula[1]
1: Laboratory for Laser Energetics, 250 East River Rd, Rochester, NY 14623-1212
acol@lle.rochester.edu
2: CEA/CESTA, 15 Avenue des Sablières CS 60001, 33116 Le Barp cedex, France

Typical Inertial Confinement Fusion (ICF) and Inertial Fusion Energy (IFE) schemes involves processes occurring on a wide range of temporal and spatial scales. As new schemes for ICF and IFE emerge, their accurate simulation is crucial to explore the large parameter space of possible designs and to propose robust methods for fusion energy. Historically, ICF schemes have involved localized discontinuities such as shock waves and material interfaces, for which Lagrangian approaches were best suited for modeling. However, many of these high-speed flows are subject to the development of vorticity from hydrodynamics instabilities such as Rayleigh-Taylor. While Eulerian approaches are well suited to model vortical flows, Arbitrary-Lagrangian-Eulerian (ALE) methods were also developed to handle those within the Lagrangian framework. More recent IFE designs involve complex geometries, such as cones, double shells, asymmetric drives, spheres in cylinders, etc. Realistic simulation of these designs also requires including effects such as mispointing, drive imbalance, target and drive defects, etc. Many of these require 3-D modeling capabilities, and the meshing of these complex geometries was historically obtained using an unstructured grid framework. A more recent alternative is the use of Adaptive Mesh Refinement coupled to a Eulerian approach, to combine the strength of modeling flows with vorticity with the flexible nature of a mesh that adapts to the various scales, including shocks and material discontinuities. However, in most situations, even Euler-AMR approaches suffer from lower convergence rates than Lagrangian approaches for modeling discontinuities.

From these considerations, there is an interest in developing an ALE-AMR approach to combine the best of both methods. The goal is to benefit from the unstructured framework and accuracy in discontinuities of the Lagrangian approach, the ability to model vortical flows of the ALE approach, and to use AMR to adapt to the variety of scales. This last point is crucial in a 3-D framework, where computing costs quickly increase, and for which AMR could offer significant gains since mesh refinement/coarsening occurs along the 3 spatial dimensions. The adaptation of ALE to the AMR framework requires a rework of all the algorithms involved. Typical integrated modeling tools combine hydrodynamics, diffusion, radiation transport, laser tracing, alpha particle transport, magneto-hydrodynamics, etc. All of these various models should be made compatible with the nonconformal grids that emerge from the AMR framework, while retaining accuracy and properties of conservation (energy conservation, mass conservation, etc…). In addition, ALE rezoning techniques should be adapted to regularize meshes that contain inherent discontinuities introduced by variations in AMR depth.

In this presentation, we give a summary of recent developments in a 3D second-order cell-centered ALE-AMR framework for modeling of multimaterial flows. These algorithms are implemented in the Excession code in development at LLE. While this presentation focuses on multimaterial ALE-AMR hydrodynamics, Excession also implements a second-order cell-centered anisotropic diffusion operator, flux-limited and non-local heat transport, time-dependent multi-group radiation transport using tabulated NLTE opacities, two-temperature fluid model with multi-phase mixing closure and tabulated EOS, laser raytracing with collisional absorption, Langdon effect and Cross-Beam Energy Transfer, fusion reactions with alpha particle transport, and ideal magneto-hydrodynamics. Excession is intended to be shared within a restricted community to solve ICF and IFE challenges.

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FZP-based High-Resolution Imprint Radiography

D. Haberberger, A. Shvydky, R. C. Shah, D. Turnbull, D. H. Froula
University of Rochester
Laboratory for Laser Energetics
250 E River Rd, Rochester, NY 14623

Achieving inertial fusion energy means pushing towards implosions with higher gain and repetition rate. A large drive towards accomplishing this task is the development of new laser systems such as the fourth-generation laser for ultrabroadband experiments (FLUX) at the Laboratory for Laser Energetics. These new laser systems will need to address the many requirements for IFE including new mitigation strategies for laser imprint. In tandem, a new generation of diagnostics should be developed to access higher fidelity data to reduce uncertainty in the degree to which certain phenomena detrimentally affect implosions.

Up to this point, imprint measurements using pinholes[1] have achieved ≥8 µm spatial resolution necessitating a large acceleration of foils undergoing Raleigh-Taylor (RT) growth before useful measurements can be made. Even at these later times in the drive, a sizeable amount of the mode spectrum is smoothed over by the point-spread function of the imaging system. Achieving better spatial resolution will elucidate the dynamics of imprinting processes and ablative RT growth at smaller scales.

Deploying a Fresnel zone plate (FZP) for imprint measurements could improve the spatial resolution to around ~1 µm but must overcome two potential issues: chromatic aberration and multiple field-of-view's (FOVs).

Chromatic Aberration

FZP's are inherently chromatic and therefore require monochromatic backlighters to achieve high spatial resolution and contrast. Soft x-rays are required to achieve sufficient sensitivity to the small density modulations in imprint measurements. The generation of a soft monochromatic backlighter is challenging because the k-edge of low-Z materials is at a lower energy than their He-α line, and therefore can't be used as a spectral filter, which is commonly done at higher Z. However, the use of a backlighter material of Z with a filter material of Z+1 could be a successful combination to efficiently filter out the H-α line for imaging. Initial experiments on OMEGA EP have successfully shown the imaging of Al H-α at 1728 eV using Si as a filter to achieve 2 µm imaging resolution using an FZP.

Multiple FOV

To achieve multiple FOVs, a simple array of FZP's (as is done with pinholes) would require an infeasibly large detector to prevent the overlap of the 0^{th} orders with the 1^{st} orders in the image plane. To address this issue, a methodology has been developed to design a segmented multi-FZP using radial fragments (SMURF). In this design, an FZP is divided into sectors that are radially shifted to achieve accurate placement of multiple FOVs on an x-ray framing camera while simultaneously preventing overlap of the 0^{th} and 1^{st} orders. Results of the first testing of a SMURF on OMEGA will be presented.

*This material is supported under the IFE-COLoR grant GR534839 at the Laboratory of Laser Energetics.

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Resolving Species Contributions in CR-39 Multi-Ion Spectra using Bayesian Inference*

D. Brown,[1] M. Schollmeier,[2] and B. Gonzalez-Izquierdo[2]
[1]SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, Menlo Park, CA, 94025
[2]Marvel Fusion GmbH, Theresienhöhe 12, 80339 Munich, DE
danibrown@stanford.edu

CR-39 solid state nuclear track detectors have been the dominant tool for energetic particle detection for decades due to their high efficiency and ease of use. However, resolving individual species in multi-ion spectra remains challenging, particularly in laser-driven fusion experiments where α-particles from reactions like proton-boron and hydrogen isotope fusion are accompanied by high-background protons and carbons; in many current proton-boron fusion schemes, the background-to-signal ratio reaches 10^3, even in the best-case scenario. While CR-39 efficiently detects α-particles, accurately separating their contributions from the overlapping background is nontrivial.

A previous study applied a Monte Carlo-based approach to extract individual distributions from the multi-ion spectra discussed here.[1] We now present a Bayesian Inference framework using Markov Chain Monte Carlo (MCMC) sampling, which offers a probabilistic method of inferring the parameters of individual ion distributions from combined spectra. This approach improves species differentiation by significantly reducing user bias, accounting for parameter degeneracies, and providing rigorous uncertainty quantification and model validation. By solving the inverse problem of reconstructing individual signals from raw multi-ion spectra, this technique enhances the reliability of CR-39 fusion diagnostics for future experiments.

*This work conducted with data and support provided by Marvel Fusion GmbH, Munich, Germany.

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Single shot optical diagnostics for laser produced plasmas

Elizabeth Grace[1], A. Longman[1], G. Zeraouli[1,2], D. Attiyah[3], E. Welch[4], J. Clark[1], S. Maricle[1], A. Linder[1], N. Lemos[1], D. A. Mariscal[1], T. Ma[1], R. Trebino[5], S. Wilks[1], and M. P. Hill[1]
[1]Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore CA 94550 USA
grace11@llnl.gov
[2] Colorado State University, Isotope Dr, Fort Collins, CO 80524 USA
[3] University of California Irvine, Irvine, CA 92697 USA
[4] University of Nebraska Lincoln, 1400 R St, Lincoln, NE 68588 USA
[5] Georgia Institute of Technology 837 State St, Atlanta GA 30332 USA

High-intensity (>TW), short-pulse (<ps) laser systems are generating significant interest worldwide due to their numerous applications in science, technology, medicine and industry. These lasers are capable of generating secondary sources of electrons, ions, protons, neutrons, and x-rays, some of which may be used as a heating spark in fast ignition, and/or for multi-modal radiography, cancer treatment, and more.

At the heart of these applications is the laser-plasma that is initially produced by the high-intensity laser's interaction with the target matter. These plasmas range widely in spatial scales from microns to millimeters and their dynamics can evolve on femtosecond to nanosecond timescales. Due to the sensitivity with which the plasma properties depend on the incident laser system, and the downstream effects of this initial plasma on the subsequent secondary sources and physics applications, diagnostics that capture a robust picture of their temporal and spatial evolution on a single shot must be developed for and demonstrated on high-intensity, high-energy laser systems.

Studies of high-intensity-laser plasmas to-date have been limited by either temporal or spatial resolution, relying on scanning one variable, such as time or delay, to take a complete measurement. Such measurements that use multiple laser shots to form a complete measurement cannot reliably distinguish between changes due to shot-to-shot variations and changes due to the variable being scanned. To address this problem, this work discusses the development and implementation of single-shot diagnostics for laser-produced plasmas.

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FIREX-NEO Project in ILE – Strategy to Demonstrate Fast Ignition by Upgraded GEKKO-XII and LFEX Lasers

Y. Sentoku,[1] and FIREX-NEO team
[1]Institute of Laser Engineering, The University of Osaka, 2-6 Yamadaoka, Suita, Osaka, 565-0871
sentoku.yasuhiko.ile@osaka-u.ac.jp

Laser fusion has become an urgent issue for the establishment of high-efficiency schemes after the achievement of ignition at the National Ignition Facility (NIF) in the U.S. The NIF uses the central ignition scheme in which a thin shell containing the fusion fuel is simultaneously imploded and heated by X-rays emitted from a MJ laser heated gold hohlraum. The fast ignition (FI) scheme, on the other hand, separates the implosion and heating processes, and after forming a high-density core plasma, the core plasma is heated before being disassembled in picoseconds by a petawatt laser to achieve ignition burning. The key to success is how efficiently the heating laser delivers its energy to the core plasma.

We have performed basic experiments of laser fusion with GEKKO-XII and LFEX lasers and demonstrated the effectiveness of FI scheme[1]. In this FIREX experiment, GEKKO-XII lasers (4kJ/ns/2ω) imploded a solid ball, instead of a thin shell, to densities about 10 times of solid, and the core plasma was heated to an electron temperature of 2keV with a petawatt laser LFEX (1kJ/1ps). The total laser energies used in this experiment is about 5kJ. The efficient heating was achieved by the fast diffusion above the solid density from hot-dense plasma pumped by resistive heating driven by fast electron currents.

To deepen the understanding of FI physics and design a high-gain laser fusion with the FI scheme, 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, which cooperates with Coulomb collisions, ionizations, and radiation physics. We found that the efficient heating appears through the formation of steepened absorption interface by photon pressure of the heating laser light[2]. Our findings are the exact opposite of the conventional direction that the laser intensity of heating laser light should be reduced to optimize fast electron energy to a few MeV for efficient drag heating in the core, suggesting that the higher intensity lasers can heat core plasmas much more efficiently by entering “heatwaves” mode, see Fig. 1.

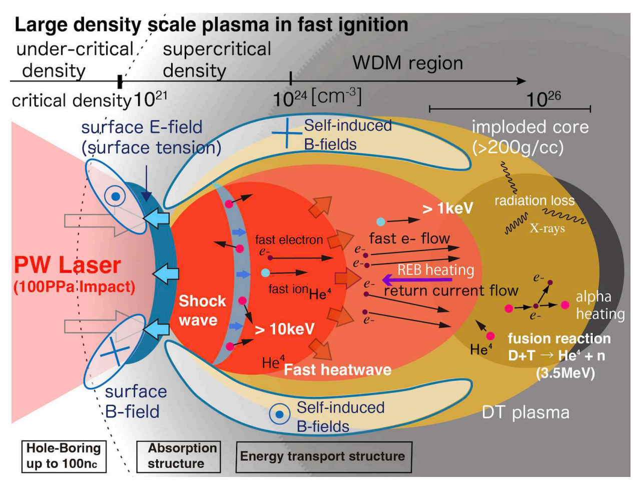

Fig. 1: Physics of fast ignition driven by PW laser

The ILE, Osaka has a plan to refine the GEKKO-XII and LFEX laser system in two years. The GEKKO-XII laser will be enhanced energy of 6 kJ (3ω) with a capability of highly accurate pulse profiles to implode a solid ball. The LFEX laser, of which energy will be increased to 3kJ, will have deformable mirrors to boost a focused intensity over 10^{20} W/cm^2. This presentation will show our strategy to demonstrate the fast ignition scheme with the efficient heating mode.

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Laser-driven ion acceleration from pre-expanded converging H_2O microjets*

G. D. Glenn,[1,2] D. P. DePonte,[1] S. Faubel,[1] J. Gama Vazquez,[1,2] R. Halifa Levi,[3] R. Hollinger,[4] G. Jain,[1,2] J. King,[4] C. A. J. Palmer,[5] P. Parsons,[5] I. Pomerantz,[3] S. Popa,[6] J. J. Rocca,[4] F. Treffert,[7] S. Wang,[4] S. Zahedpour Anaraki,[4] P. Zhang,[4] S. H. Glenzer,[1] and M. Gauthier[1]
1. SLAC National Accelerator Laboratory, Menlo Park, CA, USA
gdglenn@slac.stanford.edu
2. Stanford University, Stanford, CA, USA
3. Tel Aviv University, Tel Aviv, Israel
4. Colorado State University, CO, USA
5. Queen's University Belfast, Belfast, UK
6. ELI-NP, Bucharest, Romania
7. Lawrence Livermore National Laboratory, Livermore, CA, USA

Laser-driven ion sources exhibit a variety of features (such as MeV energies, high peak brightness, and ultra-high acceleration gradients) that make them compelling alternatives to conventional accelerators for applications in medicine, materials science, and fundamental physics. High-flux laser-driven ion beams operating at Hz-scale repetition rates also serve as a key driver technology for inertial fusion energy concepts based on ion fast ignition. A crucial research area for realizing these applications lies in optimizing both the peak proton energy and peak flux by accessing advanced acceleration mechanisms beyond target normal sheath acceleration (TNSA). Previous experiments using highly relativistic laser pulses irradiating targets pre-expanded to near-critical densities observed a twofold increase in peak proton energies as the laser penetrated the bulk of the target and accelerated protons at the moving relativistic critical density surface[1]. However, spatial jitter of the laser and target, as well as the sensitivity of this acceleration mechanism to small variations in initial conditions, hindered detailed experimental exploration of the acceleration mechanism.

In a recent LaserNetUS experiment using the ALEPH laser at Colorado State University (400 nm, 5 J, 50 fs, 0.5 Hz), we sought to explore advanced ion acceleration mechanisms in more detail using high repetition rate-compatible liquid water sheet jet targets[2] irradiated at relativistic laser intensities. Proton beams generated in the interactions were spectrally diagnosed using two Thomson parabola spectrometers, and a scintillator screen measured the proton beam spatial profile. When the laser was changed from s-polarization to p-polarization on target we observed an increase in the maximum proton energy to approximately 10 MeV, nearly double the peak energy obtained in prior experiments using s-polarization despite reduced on-target intensity. We also pre-expanded the liquid sheet using an independent laser pulse containing approximately 6 mJ at a series of delay times before the main pulse arrival. We observed a transition in ion beam pointing from the target normal to the laser forward direction with increasing pre-expansion, indicating possible relativistic transparency effects. We will present our initial results from this experiment as well as an outlook for an upcoming experiment at ELI Beamlines which will probe higher laser intensities and explore a larger region in phase space.

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Producing arbitrarily-shaped IFE-relevant excimer laser pulses using stimulated Brillouin compression

Jihoon Kim,[1,2] Polina Blinova,[1,2] and Gennady Shvets, [1,2]
[1] DOE IFE-STAR RISE-hub
771 Oval Drive
Fort Collins, CO, 80523
jk2628@cornell.edu
[2]Applied and Engineering Physics, Cornell University
142 Sciences Drive
Ithaca, NY, 14850

Attaining practical Inertial Fusion Energy (IFE) depends on how efficiently one can couple the driver (laser or ion) energy to the nuclear fusion fuel for compression and ignition. Stimulated Brillouin Scattering (SBS) provides a path to efficient compression of long, energetic pulses to IFE-relevant pulse durations and intensities. Produsing IFE-relevant pulse shapes, however, is an open challenge, even at the conceptual level. In this presentation, I will demonstrate that it is possible to obtain near-arbitrary final pulse shapes by providing an appropriate initial seed pulse. I will provide simple and intuitive expressions for "reverse-engineering" the initial seed shape and discuss physical limits determined by the prepulse and duration of the seed pulse.

Design of Complex High-Performance Materials for Extreme Environments

A. Perron, N. Ury, B. Bocklund, T. Voisin, and J. McKeown
Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA, 94550
perron1@llnl.gov

Fusion power plant first-wall materials must exhibit and maintain high performance under extreme conditions. For instance, properties required by first-wall materials include a high melting temperature and stability, low thermal expansion, large thermal conductivity, high strength, good thermal shock resistance, and low tritium retention. Also, the materials should maintain their properties under intense irradiation with neutrons and helium implantation (i.e., must not suffer strong radiation-induced embrittlement or other degradation).

Approximately 20 years ago, scientists started developing a new class of materials, commonly named high entropy alloys (HEAs), multi-principal element alloys, baseless alloys, or complex concentrated alloys. The initial idea driving the development of these alloys was to maximize the ideal entropy of mixing, resulting in the stabilization of single-phase solid-solution alloys of multi-principal-elements. HEAs can exhibit many attractive engineering properties, including high strength, strong fatigue-fracture resistance, high wear behavior, and excellent corrosion resistance at elevated temperatures. In addition, HEAs are attractive as radiation-resistant materials due to potential chemical-disorder- induced (1) slow energy dissipation (affecting radiation damage–defect production and recombination) and (2) enhanced point defect recombination via tailored interstitial defect cluster motion, which results in swelling resistance. The vast design space provided by HEAs holds potential for discovering new, promising alloys for first-wall fusion reactors.

Efforts at LLNL regarding the design of high performance HEAs for extreme environment will be presented. The LLNL's Materials Acceleration Platform (MAP) running on high-performance computers and handling CALPHAD-based, analytical and machine-learning models will be introduced to tackle the challenging task of screening and optimizing new alloys for multiple properties in a vast composition space. Among others, we will highlight the design of new refractory alloys targeting high yield strength and ductility at elevated temperatures with constraints on phase stability in a 10-element composition space. Finally, alloy design case studies using the Alloy Optimization Software (TAOS, https://softwarelicensing.llnl.gov/product/taos) – which is running on stand-alone computers and solving unconstrained and constrained optimization problems – will be presented with examples for structural material applications.

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STARFIRE hub research highlights and path forward

C. Goyon[1], N. Alexander[2], S. Banerjee[1], F. Beg[5], L. Bernstein[6], R. Betti[3], R. Deri[1], A. DeVault[7], B. El-Dasher[1], A. Eshun[1], W. Fenwick[1], C. Fiorina[8], J. Galbraith[1], M. Gatu-Johnson[7], C. Häfner[4], H, Hahn[9], D. Ho[1], Z. Hubka[1], O. Hurricane[1], T. Laurence[1], J. Lindl[1], S. MacLaren[1], M. Nelson[1], A. Pak[1], K. Peddicord[8], C. Santiago[1], D. Schaeffer[10], I. Tamer[1], W. Meier[1], X. Xia[1]
and T. Ma[1]
[1]Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550
goyon1@llnl.gov
[2]General Atomics, P.O. Box 85608, San Diego, California 92186-5608, USA
[3]Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA
[4]Fraunhofer Institute for Laser Technology ILT, Steinbachstraße 15, 52074 Aachen, Germany
[5]Center for Energy Research, University of California San Diego, La Jolla, California 92093, USA
[6]University of California Berkeley Department of Nuclear Engineering, Berkeley, CA 94720, USA
[7]Massachusetts Institute of Technology, Plasma Science and Fusion Center, Cambridge, MA 02139, USA
[8]Texas A&M Department of Nuclear Engineering, 125 Spence St., College Station, TX 77840
[9]The University of Oklahoma, Norman, OK 73019, USA
[10]University of California–Los Angeles Los Angeles, CA 90095, USA

Inertial Fusion Energy (IFE) research is building on the achievement of ignition at the National Ignition Facility and still requires significant advances to become viable. FES is supporting efforts in many different science areas, technology development efforts, infrastructure needs, private industry involvement, and workforce recruitment and development. In this talk, we will describe a multi-institution collaboration within this nascent ecosystem of innovation: the Science and Technology Accelerated Research for Fusion Innovation and Reactor Engineering (STARFIRE) program. We will describe the several key technical areas investigated under STARFIRE and highlights from this past year. We will present additive manufacturing techniques used for foam-target printing, studies of possible IFE target design limitations, diode pumped solid state lasers architecture, system plant design tools and recent outreach efforts such as the development of a six week undergraduate course. Then, we will describe the path forward for STARFIRE within the larger IFE ecosystem and work at LLNL to engage with partners from private companies, academia and other national laboratories, and to advance the current knowledge in IFE.

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Estimating Neutron Down-Scattered Ratio Through Neutron Time-of-Flight Data on OMEGA Direct-Drive Implosions

D. Patel[1,2], J.P. Knauer[2], R. Betti[1,2,3], B. Stanley[2], V. Gopalaswamy[2], A. Schwemmlein[2], M. J. Rosenberg[2], S.P. Regan[1,2]

[1]Department of Mechanical Engineering, University of Rochester, Rochester, NY 14627, USA
[2]Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623-1299, USA [3]Department of Physics and Astronomy, University of Rochester, NY 14627, USA

Corresponding Author Email: dpat@lle.rochester.edu

High gain implosions demanded by inertial fusion energy require high convergence and a robust fuel assembly. One crucial diagnostic tool for assessing implosion convergence and the state of fuel assembly is areal density measurement. For Deuterium-Tritium (DT) layered implosions, areal density diagnostics typically focus on detecting DT primary neutrons that are scattered— both elastically and inelastically—by the cold DT fuel surrounding the hot spot. Notably, scattered neutrons in the 10 to 12 MeV range, where elastic scattering predominates, present a particularly advantageous measurement choice. To be specific, the neutron down-scatter-ratio (DSR) —the ratio of total number of neutrons in the 10-to-12-MeV range to the total number of neutrons in the 13-to-15-MeV range (an approximation for DT primary neutrons) —can be used to infer areal-densities. Although the Magnetic Recoil Spectrometer [1] has been successfully employed on the OMEGA facility to measure DSR, conducting DSR assessments using neutron time-of-flight (nTOF) data poses significant challenges at the scale of OMEGA due to the very low areal densities, making this approach yet to be fully realized. In this work, we present a novel analysis of nTOF data for OMEGA DT-layered implosions to estimate the neutron DSR [2]. This measurement would deepen our understanding of OMEGA DT-layered implosions by augmenting the advances made in the 3D reconstruction [3] of the implosions.

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IFE Workforce Development at LLNL

P. L. Poole, Z. Liao, M. Albrecht, F. Graziani, T. Ma
Lawrence Livermore National Laboratory, Livermore CA 94550
poole11@llnl.gov

The realization of inertial fusion energy (IFE) power plants presents a transformative opportunity to meet global energy demands with a clean and sustainable solution. Achieving this vision requires not only technological advancements but also the development of a highly skilled workforce capable of designing, building, and operating these complex systems. While the National Ignition Facility (NIF) has demonstrated the physics principles of ignition, marking a critical milestone toward fusion energy, improvements both on NIF scales and the transition from experimental facilities to commercial-scale power plants will require a significant expansion of the workforce, with estimates suggesting tens of thousands of skilled professionals will be needed by the 2040–2050 timeframe. This workforce must encompass expertise in optical, nuclear, and systems engineering, as well as high-energy-density physics (HEDP), to address the unique challenges of IFE power plant development.

A coordinated approach to workforce expansion and training will be required for rapid advancement toward a fusion power plant. National facilities like NIF, in collaboration with academic institutions and private-sector demonstrator facilities, play a critical role in providing hands-on experience and fostering innovation in fusion research. Scaling these efforts will require increased support for recruitment, training, and curriculum development to ensure a robust pipeline of skilled professionals across a broad range of disciplines. By addressing these workforce challenges, the fusion community can accelerate progress toward the deployment of commercial fusion power plants, bringing this revolutionary energy source closer to reality.

Current workforce development efforts at LLNL target students from high school to post-graduate levels to build interest and momentum for progress in the short and long term. These initial IFE-focused programs are expanding upon successful broader efforts already at LLNL including the undergraduate and graduate summer research program, faculty sabbaticals and collaborations with academic institutions, HED and IFE curriculum development in partnership with research universities, and more. These efforts and the outlook for workforce development broadly will be discussed.

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Amorphous oxide mixtures for $\lambda \leq 355$ nm multilayer dielectric coatings

Ramon Rodriguez-Lopez[1], Maxwell Weiss[1], Aaron Davenport[1],
François Schiettekatte[2], Martin Chicoine[2] and Carmen S. Menoni[1,3]
[1] Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO 80523, USA
[2] University of Montreal, Montreal, Quebec H3T 1J4, Canada
[3] XUV Lasers Inc, Fort Collins, CO 80525, USA
r.rodriguezlopez@colostate.edu

The remarkable results of ignition from a laser-generated plasma obtained at the Lawrence Livermore National Lab National Ignition Facility (LLNL-NIF) in Dec. 2022[1] have spurred intense activity in both the public and private sectors to accelerate critical technologies that will enable the commercialization of inertial fusion energy. Several laser drivers are being considered and gaining traction for IFE. Among them are solid state near infrared lasers which are frequency tripled to generate 10's of kJ energy pulses at around λ ~350 nm [2] and excimer gas lasers which, by employing novel beam combining and pulse compression approaches, are projected to generate up to MJ-level pulses at λ=248 nm.[3] In either one of these laser architectures, interference coatings in key laser components play a paramount role in shaping the laser output energy, and the sustained reliable operation that will be required for IFE.

This paper describes the optical and structural properties of oxide mixtures of alloys based on HfO_2 mixed with SiO_2 and Al_2O_3 for ultraviolet coatings. These alloys are engineered as potential dielectric layers for laser wavelengths as short as λ=248 nm. The results of an extensive characterization of these materials will be presented to investigate pathways to extend the UV cutoff of the alloys to wavelengths of ~200 nm. In addition, laser damage studies were assessed to evaluate the long-term damage resistance of the coatings.

* This work is supported by the U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences, under Awards No. DE-SC0024882: IFE-STAR and SBIR DE-SC0023878.

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Hydrodynamic instabilities in the context of IFE*

Bruce A. Remington
Lawrence Livermore National Laboratory
remington2@llnl.gov

Depending on the specific approach to IFE, hydrodynamic instabilities may become important. Fortunately, much has been learned about hydrodynamic instabilities in the context of inertial confinement fusion (ICF), high energy density physics (HEDP), and astrophysical settings. Both experimental techniques and corresponding simulations have been developed, so realistic assessments can be made. A number of relevant articles have been written on the topic of RT instabilities in HED settings. [1-4] Looking forward, designs for IFE could be examined for sensitivities to hydrodynamic instabilities, and mitigation techniques explored.

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*This work conducted under the auspices…. If you do not have anything to credit, delete this line and the asterisk at the end of the title.

[1] A. Name, B. Name, and C. Name, “*Paper title,*” Journal name **Vol**, page (year). (Remove if no references.)
[2] A. Name and B. Name, Institution, personal communication (year). (Remove if no references.)

Single-Shot 2D X-Ray Phase-Contrast Imaging and Phase Retrieval of Void-Shockwave Dynamics

D. S. Hodge,[1] A. F. T. Leong,[2] K. Kurzer-Ogul,[3] S. Pandolfi,[4] D. S. Montgomery,[2] J. Shang,[3] H. Aluie,[3] S. Marchesini,[5] Y. Liu,[5] K. Li,[5] A. Sakdinawat,[5] E. Galtier,[5] B. Nagler,[5] H. J. Lee,[5] E. F. Cunningham,[5] T. E. Carver,[8] C. A. Bolme,[5] K. J. Ramos,[5] D. Khaghani,[5] P. M. Kozlowski,[2] R. L. Sandberg,[1] A. E. Gleason[5]
[1]Brigham Young University (BYU), Provo, UT, 84602
danielhodge42@gmail.com
[2]Los Alamos National Laboratory (LANL), Los Alamos, NM, 87545
[3]University of Rochester, Rochester, NY, 14623
[4]Sorbonne University, IMPMC, Paris, France, 75006
[5]SLAC National Accelerator Laboratory, 2575 Sand Hill Rd., Menlo Park, CA, 94025
[6]Stanford University, Stanford, CA, 94305

The National Ignition Facility (NIF) has exceeded scientific breakeven in multiple experiments, demonstrating the viability of inertial confinement fusion (ICF) and advancing the prospect of ICF-based powerplants. These breakthroughs bring humanity closer to achieving a sustainable, virtually limitless energy source capable of meeting global energy demands. Despite these successes, realizing practical ICF-based power plants requires optimizing energy yield, which is heavily influenced by the properties of the ablator materials used in fuel capsules. Voids in ablator materials are well known to degrade energy yield significantly by introducing hydrodynamic instabilities that lead to nonuniform compression. Therefore, characterizing ablator materials under dynamic conditions is crucial for understanding these nonlinear processes and developing strategies to mitigate or leverage them to improve energy yield. To analyze these dynamics and advance inertial fusion energy (IFE) science, we utilized the x-ray free-electron laser (XFEL) at the Matter in Extreme Conditions (MEC) instrument at the Linac Coherent Light Source (LCLS) to capture 2D x-ray phase-contrast (XPC) images of materials analogous to those used in ICF experiments. We intentionally incorporated a void as an ablator defect and subjected the sample to a long-pulse laser-driven shockwave to reach high-energy-density (HED) conditions. To correct the influence of the stochastic XFEL beam and enhance the quality of our XPC images, we applied a flat-field correction scheme using a combination of image registration and principal component analysis (PCA). This approach mitigates artifacts caused by variations in detector sensitivity and distortions in the optical path that are unrelated to the sample itself. To quantify the impact of voids during dynamic compression, we employed two established phase retrieval algorithms: the Contrast Transfer Function based on the fast Alternating Direction Method of Multipliers (CTF-fADMM) and the Projected Gradient Descent (PGD) method. These methods enabled us to extract phase information from complex, single-shot, multi-material dynamic flat-field corrected XPC images. We compared the retrieved phase outputs with simulations generated by xRAGE to assess similarities and discrepancies caused by the presence of a void. These comparisons provide valuable insights that could transform compression strategies and can contribute to refining parameters in existing models of void collapse.

Simulations of Ion Beam Focusing in Laser-Irradiated Hemisphere Targets

M. Garten[1], A. Kemp[2], A. Huebl[1], O. Shapoval[1], J. Ludwig[2], E. Zoni[1], R. Lehe[1], S. Wilks[2], and J.-L. Vay[1]
[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720
mgarten@lbl.gov
[2]Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA, 94551

As part of the 4-year, multi-institution DoE FES SciDAC project KISMET, *Kinetic IFE Simulations at Multiscale with Exascale Technology,* the thrust "Surface Physics" is focused on resolving the physics underlying laser-particle acceleration for proton-based Fast Ignition with unprecedented detail, where electrons and subsequently protons are accelerated and heated when a laser interacts with a high-density target.

Leveraging the ACM Gordon-Bell Prize-winning Particle-in-Cell (PIC) code WarpX, we present results from 2D numerical simulations of laser-irradiated hemisphere targets of various configurations. We explore the influence of laser-target coupling dynamics that occur on scales of femtoseconds and nanometers towards millimeter-scale plasma evolution for up to ~100 picoseconds, with a special emphasis on the generation and focusing behavior of 5-20 MeV ions. We report on lessons learned from algorithmic choices and resource-vs-resolution optimization considerations based on the observed conservation of energy and other physical quantities of interest.

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The impact of surface imperfections on high-current-density conductors*

M.W. Hatch,[1] T.J. Awe,[1] E.P. Yu,[1] B.T. Hutsel,[1] K. Tomlinson,[2]
1 Sandia National Laboratories, 1515 Eubank SE, Albuquerque, NM 87123
[mwhatch@sandia.gov]
2 General Atomics, 1515 Eubank SE, Albuquerque, NM 87123

The electrothermal instability (ETI) is a Joule heating-driven instability that instigates runaway heating on conductors driven to high current density, altering the 3D evolution of material expansion. Most metals include complex distributions of imperfections (voids, resistive inclusions) which seed ETI. To simplify comparison with modeling and theory, experiments examined growth of ETI from relatively void/inclusion free, 99.999% pure, diamond-turned, 1 mm-diameter aluminum rods, which are pulsed with 1 MA of current in 100 ns. Aluminum surfaces included a variety of deliberately machined and well-characterized perturbations, including 10-micron-scale quasi-hemispherical voids, or “engineered” defects (ED), and sinusoidal patterns of varying wavelength and amplitude. This talk will describe how the details of 2D and 3D surface perturbations drive instabilities, which will be compared to theoretical predictions and simulations.

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Flat-field correction of void collapse evolution imaging

M. Leininger,[1] D. S. Hodge,[1] R. L. Sandberg,[1] A. E. Gleason,[2] A. F. T. Leong,[3] K. Kurzer-Ogul,[4] S. Pandolfi,[5] D. S. Montgomery,[3] J. Shang,[4] H. Aluie,[4] S. Marchesini,[2] Y. Liu,[2] K. Li,[2] A. Sakdinawat,[2] E. Galtier,[2] B. Nagler,[2] H. J. Lee,[2] E. F. Cunningham,[2] T. E. Carver,[6] C. A. Bolme,[2] K. J. Ramos,[2] D. Khaghani,[2] P. M. Kozlowski[3]

[1] Brigham Young University (BYU), Provo, UT, 84602
leiningermc@gmail.com
[2] SLAC National Accelerator Laboratory, 2575 Sand Hill Rd., Menlo Park, CA, 94025
[3] Los Alamos National Laboratory (LANL), Los Alamos, NM, 87545
[4] University of Rochester, Rochester, NY, 14623
[5] Sorbonne University, IMPMC, Paris, France, 75006
[6] Stanford University, Stanford, CA, 94305

Inertial confinement fusion (ICF) has recently pulled ahead of other fusion methods due to the successful breakeven of the National Ignition Facility (NIF) in 2022. This has greatly improved the feasibility of using fusion as a near-unlimited source of clean energy; however, to meet the expected public demands of such an energy source, high-level efficiency and yield are required. One obstacle to achieving sufficient energy output is the presence of imperfections within the ablator material of the fusion capsules. These imperfections create hydrodynamic instabilities during shockwave compression, reducing yield. By developing methods to image, analyze, and simulate void collapse, we will better understand how these instabilities form and evolve over time, providing the knowledge required to reduce or account for ablator imperfections and improve the viability of ICF. Our aim is to experimentally image this void collapse at different stages, using 2D radiation hydrodynamic code (xRAGE) simulations as a model against which to compare our results. After creating void imperfections within materials analogous to those used for ICF, we used the x-ray free-electron laser (XFEL) at the Matter in Extreme Conditions (MEC) instrument at the Linac Coherent Light Source (LCLS) to both image and compress the samples via long-pulse laser-driven shockwaves. We obtained four separate 2D x-ray phase-contrast (XPC) images capturing various stages of void collapse within ablator-like material. We applied the flat-field correction methods of principal component analysis (PCA) and image alignment to reduce extraneous noise and artifacts in the images due to the shifting of the XFEL beam and variations in x-ray pulse energy. The flat-field corrected experimental images enabled us to validate the computational xRAGE model, as the matched features demonstrated its accuracy. In the future, these improved images can be used in phase retrieval algorithms to extract the phase and, correspondingly, the areal density. Taken together, this data furthers our understanding of the process of void collapse, allowing us to refine xRAGE parameters, better simulate the formation of hydrodynamic instabilities in fusion-relevant materials, and mitigate or leverage imperfections to achieve higher efficiency and yield in the ICF process.

Advancing XF-COLR: Innovations in Vacuum Systems, Adaptive Optics, Beam Steering, and Target Injection

[K. Masuda,[1] K. Matsuo,[1] H. Minato,[1] Y. Yoshimura,[1] K. Agatsuma,[1] Y. Hironaka,[1] M. Ishii,[1] R. Mori,[1] K. Urabe,[1] N. Kanmaki,[1] T. Sugimoto,[1] K. Sugita,[1] K. Sueda,[1] Y. Takagaki,[1] T. Chiba,[1] T. Mitsui,[1] N. Hayashi,[2] K. Ishii,[2] and Y.Mori,[1,2]]
[1]EX-Fusion Inc., Osaka, Japan
koichi_masuda@ex-fusion.com
[[2] The Graduate School for the Creation of New Photonics Industries (GPI), Hamamatsu, Japan]

To advance the continuous operation of the eX-Fusion Continuous Operation Laser Reactor (XF-COLR), EX-Fusion is developing key enabling technologies, including vacuum-integrated target injection, high-precision deformable mirrors (DMs), fast steering mirrors (FSMs), and high-frequency cryogenic target supply systems. These innovations aim to refine XF-COLR's high-repetition laser-plasma interaction capabilities and bridge the gap toward commercial laser fusion energy.

The vacuum-integrated target injection system has achieved a vacuum level of 0.3Pa, ensuring stable target delivery by mitigating air breakdown effects during laser irradiation. This lightweight aluminum chamber incorporates real-time monitoring and optimized sealing, with further refinements underway to enhance vacuum stability. Concurrently, adaptive optics for laser focusing are advancing through the development of a 3-inch, 37-channel deformable mirror (DM). Engineering improvements, including a newly designed holder achieving 625Hz resonance stability, address challenges related to stress-induced deformation and coating imperfections, enhancing reflectivity and durability through refined gold and dielectric multilayer coatings.

A 150mm two-axis fast steering mirror (FSM), designed for 10μm target-tracking accuracy at 30m, has demonstrated settling times of 66ms (Yaw) and 77ms (Pitch). Ongoing refinements focus on improving linearity and stability for precise high-repetition-rate laser alignment. In parallel, target injection technology is advancing toward a 10Hz cryogenic target supply system, featuring a custom high-precision mechanism that reduces mechanical friction and enhances reliability. Additionally, polymer-based cryogenic targets are under evaluation for mass production and long-term storage.

These developments are critical to achieving reliable, high-repetition fusion target engagement, laying the foundation for XF-COLR's transition from laboratory-scale experiments to a pilot-scale fusion demonstration. By integrating advanced optics, precision target tracking, and automated injection, EX-Fusion is accelerating the pathway to continuous laser fusion operation, reinforcing its position as a leader in commercial Inertial Fusion Energy (IFE) technology.

Progress towards Target Flight-Tracking and On-The-Fly Engagement for an IFE Injection System*

N.B. Alexander,[1] D. Appelt,[2] K.-J. Boehm,[1] A. Dautt-Silva,[1] R. Feru,[1,2] R. Kratz,[1] C. McGuffey,[1] A. Stobbs[1]

[1]General Atomics, 3550 General Atomics Court, San Diego, CA, 92121
Kurt.boehm@ga.com
[2]University of Texas at Austin, 2515 Speedway, Austin, TX, 78712

One approach to operate a rep-rated IFE fusion power plant is to launch fuel-filled capsules to the center of a reactor chamber (~5m radius) where they are hit on the fly by a set of laser beams. For a successful high-gain compression of this target, the needed alignment of the target to the incident laser beams is expected to be on the order of ~25um.

The goal of this work within the STARFIRE hub is to develop a benchtop system to demonstrate successful engagement of a spherical object moving at reactor-relevant velocities (≥50 m/s) using GA's GALADRIEL 1TW laser system. This will build upon the previously published[1] engagement work on spheres moving at 5 m/s. The system needs to integrate four main functions: accelerating a target (sphere), tracking the position of the target in time, predicting the position of the target in the chamber at shot time, making a small adjustment of the laser pointing a few milliseconds before the target flies through the center of the chamber and verifying the laser to target accuracy with which the laser beam hits the target.

An update on the selection of concepts and hardware along with the trade-offs considered in the selection is presented here.

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[Nonlocal Thermal Transport Effects on Laser Propagation in MagLIF-Relevant Gaspipes on NIF*]

[R.Y. Lau,[1] D.J. Strozzi,[2] A. Joglekar,[3] M. Sherlock,[2] W.A. Farmer,[2] Y. Shi,[1] J.R. Cary,[1]]
[[1]University of Colorado Boulder, 914 Broadway, Boulder, CO, 80302]
[Ryan.Lau@colorado.edu]
[[2]Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA, 94550]
[[3]Ergodic LLC, Seattle, WA, 98103]

We present simulations of heat flow relevant to gaspipe experiments on NIF to investigate kinetic effects on transport phenomena. These D2 and neopentane (C5H12) filled targets are used to study the laser preheat stage of a MagLIF scheme where an axial magnetic field is applied to the target[1]. Simulations were done with the radiation-MHD code Hydra[2] with a collision-dominated fluid model as well as the Schurtz[3] nonlocal electron conduction model. With nonlocal effects included the center of the gaspipe experienced increased temperatures due to inhibited radial heat flow and a faster laser propagation than without. Motivated for further study, we utilize Hydra to initialize plasma conditions for the Vlasov-Fokker-Planck K2 code[4]. Axial heat flow was well predicted by fluid models but the radial heat flow was found to be overpredicted by 150% in regions with the largest temperature gradient of D2 filled gaspipes. The Schurtz nonlocal electron conduction model was found to capture kinetic heat flow fairly well. We also present comparisons to a 2D analytic laser propagation model which includes laser absorption and heat conduction.

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Proton Focusing and Heating of Warm Dense Matter at OMEGA-EP

R. Nedbailo,[1,2] J. Griff-McMahon, [2] K. Lezhnin,[2] M. Rivers,[2] K. Bhutwala,[2] and S. Malko[2]
[1] The University of Texas at Austin, 2515 Speedway, Austin, TX 78712
[2] Princeton Plasma Physics Lab, 100 Stellarator Road, Princeton, NJ 08542-0451
ryan.nedbailo@utexas.edu

Over the past two decades, ample research has been directed at the proton-focusing capabilities of curved targets for inertial fusion energy and warm dense matter heating. It is well-established that hemispherical foils can effectively focus laser-driven proton beams. However, there are open questions regarding the optimal parameters for focusing as well as the exact location of the focused proton beam typically measured via mesh radiography. We present the results from an ongoing experimental effort to study proton focusing, with a particular focus on an campaign at OMEGA EP at the Laboratory for Laser Energetics. This campaign will investigate the proton-focusing and proton-heating capabilities of freestanding hemispherical targets with and without attached cones, using the kJ laser energies provided by OMEGA EP. Proton focusing will be measured using mesh radiography, while proton heating of warm dense matter will be characterized via streaked optical pyrometry and X-ray spectroscopy. As part of a broader effort to optimize proton focusing across high- and low-repetition-rate lasers, this campaign aims to determine whether the optimization of hemispherical and hemi-cone geometries scales effectively to higher laser energies. Successful outcomes could enhance OMEGA EP's proton heating platform for warm dense matter research and inform integrated studies on proton fast ignition.

Additionally, we will discuss an experiment proposed for OMEGA EP through LaserNetUS, which aims to develop a robust methodology for proton radiography of focusing electric fields of hemispherical targets. Side-on radiographs will be cross referenced to i) synthetic radiographs generated from extensive 2D particle-in-cell (PIC) simulations, and ii) results from on-axis mesh radiography data. Together, these measurements will establish a link between indirect virtual source characterization and direct physical source measurements. This combined data set will provide valuable insights to benchmark simulations and improve our understanding of proton focusing dynamics in structured targets in context of the proton fast ignition and isochoric heating warm dense matter. Looking ahead, we plan to extend this research by using plastic hemispherical targets instead of semi-cylindrical targets, offering direct measurements of focusing dynamics in a target geometry more directly applicable to proton fast ignition.

Investigating nonlinear optical phenomena for robust direct drive laser fusion design

Sheila Chauwinoir,[1] Ajithamithra Dharmasiri,[1] Zhenhuan Yi,[1] Alexei V. Sokolov,[1] Aleksei M. Zheltikov,[1] J. Gary Eden,[1,2] and Marlan O. Scully[1]

[1] Institute for Quantum Science and Engineering,
Department of Physics and Astronomy, Texas A&M University, College Station TX 77843
[2] Department of Electrical and Computer Engineering, University of Illinois, Urbana IL 61801

sheila.chauwinoir@tamu.edu

Direct drive laser fusion involves precise delivery of high-powered laser beams directly onto target samples.[1-3] Achieving the required intensity distribution at the target often necessitates intermediate nonlinear conversion processes, such as Raman and Brillouin scattering.[2,3] These nonlinear processes are highly sensitive to stochastic perturbations, especially in high-intensity regimes, where small fluctuations can grow nonlinearly, triggering extreme events such as rogue waves in solitons.[4,5] Rogue waves are unpredictable, localized intensity spikes, while solitons are self-reinforcing wave packets that maintain their shape due to balance of nonlinearity and dispersion. Although these phenomena can offer advantages in certain contexts, they also pose significant risks in laser inertial confinement fusion (ICF) systems. Amplified peak power pulses resulting from stochastic nonlinear dynamics can cause damage to optical components, impairing system performance and reliability.

Experimental analysis of such extreme events in high-power laser systems is challenging due to the rarity of their occurrence and the high cost of super-intense lasers and fragile optical components. To circumvent these limitations, we demonstrate a tabletop experimental platform to observe and characterize analogous phenomena in a controlled environment.[6] This system uses an ultrafast femtosecond laser coupled to a photonic crystal fiber (PCF), which provides a highly nonlinear and anomalously dispersive medium. Within the PCF, soliton formation and soliton self-frequency shift occur. This shifts the center wavelength of the input soliton from 800 nm to 1064 nm. These nonlinear processes provide a suitable framework to study extreme events, especially the formation of high-peak-power pulses.

In our study, we analyze millions of pulses before and after propagation through the PCF. Statistical analyses are conducted to identify the number of pulses with peak powers exceeding one, two, and more standard deviations from the mean. This allows us to determine the probability of extreme events and understand their characteristics. Additionally, we are implementing a theoretical framework to model the stochastic beam-instability dynamics of high-power laser fields for this analysis. Our results provide valuable insights into the dynamics of nonlinear optical systems, highlighting how stochastic fluctuations can seed instabilities that lead to extreme behavior. Our findings contribute to the development of predictive models and improved designs for safer and more efficient direct drive laser fusion technologies.

* This research was supported in part by the DOE Office of Science through the DOE Inertial Fusion Energy Science and Technology Accelerator Research (IFE-STAR) program (Grant # DE-SC0024882) and the Welch Foundation (Grants A-1801-20210327, A-1547, A-1261).

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Detailed benchmarking of the Nernst effect in magnetized HED plasma

S. Malko[1], C. Walsh[2], J. Griff-McMahon[1,3], C. Bruulsema[2], V. Valenzuela-Villaseca[3], D. B. Schaeffer[4], G. Fiksel[5], A. Hansen[6], A. Harvey-Thompson[6], D. Ruiz[6], M. Weis[6], C. Frank[7], A. Bose[7], and W. Fox[1,8]
[1]Princeton Plasma Physics Laboratory, Stellarator Rd.100, Princeton, NJ, 08540
smalko@pppl.gov
[2]Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550
[3]Princeton University. Princeton, NJ 08544
[4]Department of Physics & Astronomy, University of California–Los Angeles, 475 Portola Plaza, Los Angeles, CA 90095-1547
[5]Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109
[6]Sandia National Laboratories, Albuquerque, NM 87185
[7] Department of Physics and Astronomy, University of Delaware, 210 S College Ave, Newark, DE 19716
[8] University of Maryland, College Park, MD 20742

The Nernst effect plays a key role in magnetic flux transport in magnetized high energy density (HED) plasmas with high β and large temperature gradients. It is present in inertial confinement fusion plasmas and during the preheat phase of magnetized liner inertial fusion (MagLIF). The Nernst effect can lead to demagnetization of the fuel and heat flux suppression, affecting MagLIF's performance and efficiency[1]. Apart from magnetized IFE schemes, the Nernst effect can also influence self-generated magnetic fields in hohlraums[2], ablation fronts in directly driven ICF capsules[3] and ICF hotspots.

State-of-the-art extended magneto-hydrodynamic (MHD) and kinetic codes include the Nernst effect but differ in physics and implementation, resulting in many discrepancies. Detailed experimental benchmarking of these models is crucial for understanding and controlling magnetized plasma systems.

We report on a new experimental platform at the OMEGA laser facility to benchmark the Nernst effect in HED plasma by directly measuring Nernst velocity and plasma conditions. A laser beam heats an H2 gas jet to generate a plasma plume, which propagates parallel to an external magnetic field. Proton radiography, using 15 MeV and 3 MeV monoenergetic protons from a D3He implosion, measures magnetic field cavitation and advection velocity. Plasma parameters (ne, Te) and radial bulk flow speed are measured by 2ω optical both space and time-resolved Thomson scattering. The experimental results are compared with MHD GORGON simulations.

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. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

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Developing a versatile next-generation liquid sheet target for studies in high repetition rate & high-power laser-matter interactions*

S. Faubel[1]*, G. Jain[1], G. Glenn[1], S. Glenzer[1], M. Gauthier[1]

[1]*SLAC National Accelerator Laboratory*

**Corresponding author: stefanof@slac.stanford.edu*

Liquid sheet targets offer a variety of applications in inertial fusion energy when used with high repetition rate and high-power lasers. These include delivering accelerated ions for proton fast ignition schemes [1], neutron sources for plasma facing materials studies [2], and plasma mirrors for laser contrast enhancement [3]. Previous liquid sheet platforms can generate a replenishing liquid sheet target with thicknesses ranging from a few microns to hundreds of nanometers by driving water through a narrow channel made of etched Tungsten [2] or etched glass [4] pressed against a flat plate of the same material. We have built the next generation of this platform to improve the stability and surface flatness of the liquid sheet. As a result, we can now maintain a 6mm long, 1.5mm wide, sub-micron thick liquid sheet for hours of continuous laser firing at up to kHz repetition rate. Furthermore, we can reach a sheet surface flatness of λ/20 in local regions across the sheet. We have successfully fielded this target at the PW-class laser ALEPH in Fort Collins, and plan to field it again at ELI in Prague. We are pursuing a patent to license this technology to industry collaborators.

*This work conducted under the auspices of DOE Office of Science, Fusion Energy Science under FWP100182

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High-fidelity Neutronics Analysis for Inertial Confinement Fusion Concepts*

T. Hallam,[1] C. Fiorina[2] J. Galbraith[3]
[1]Texas A&M Department of Nuclear Engineering, 125 Spence St, College Station, TX, 77840
thallam@tamu.edu
[2]Texas A&M Department of Nuclear Engineering, 125 Spence St, College Station, TX, 77840
[3]Lawerance Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550

Abstract. A detailed prediction of neutron and gamma transport in inertial fusion energy systems is crucial to estimate damage to structural materials, heat deposition, and tritium breeding. This study develops a workflow for high-fidelity simulations to explore Inertial Confinement Fusion concepts. The workflow was validated using the HYLIFE-II conceptual reactor, introduced in 1991 by researchers at Lawrence Livermore National Laboratory (LLNL), due to its available verification data. HYLIFE-II employs a liquid wall of molten salt to mitigate neutron-induced damage while maintaining high tritium breeding efficiency. The workflow was then extended to LLNL's Laser Driven Fusion Integration Research and Science Test Facility (LD-FIRST), a newly proposed full-scale testbed for fusion energy concepts.

The proposed workflow utilizes a CAD-based model to generate a high-fidelity computational mesh for use in Monte Carlo neutron transport simulations, allowing mapping of neutron damage, energy deposition, and tritium breeding with higher accuracy than previously achieved. While previous models used one- or two-dimensional analyses to estimate the parameters of interest, this high-fidelity mapping enables three-dimensional visualizations, allowing for precise identification of areas with high neutron damage. It also provides insights into tritium breeding locations, helping to determine where tritium is being produced and identifying areas where additional breeding material can be added or removed to enhance production. The energy deposition data can be leveraged for thermal-hydraulic analysis to develop an efficient power removal system. Altogether, this work enables a more detailed analysis of the conceptual design and can be applied to evaluate other reactor concepts.

*This work was performed under the auspices of Lawrence Livermore National Laboratory through Subcontract No. B662528 under Master Agreement No. B658345. The funding was provided by the U.S. Department of Energy (DOE) under The Inertial Fusion Energy Science and Technology Accelerated Research (IFE-STAR) program.

Eliminating Stimulated Raman Backscatter through induced laser bandwidth concomitant from forward scatter

Vijay Patel, F. S. Tsung, E.P. Alves, B.W. Winjum, R. Lee, C. Joshi, and W. B. Mori
UCLA Department of Physics and Astronomy, 475 Portola Plaza, Los Angeles, CA 90095
vijayshane@physics.ucla.edu

Stimulated Raman Scattering (SRS) is a fundamental process within the nonlinear optics of plasmas. In SRS an incoming light wave scatters into a backward or forward light wave and a forward going plasma wave. Understanding and controlling SRS backscatter it is important for applications such as Inertial Fusion Energy (IFE) and Raman Amplification. SRS backscatter can limit the gain for indirect drive IFE by degrading drive symmetry and generating preheat. We show through OSIRIS simulations and envelope equations that SRS backscatter can in some cases be eliminated by the induced bandwidth from Stokes and anti-Stokes generation from the incident laser light scattering off the forward scatter generated (fast) plasmas wave (this can also be viewed as photon acceleration within a single wavelength of the fast wave. If the loss of pump energy occurs faster than SRS backscatter growth the backscatter can be prevented. We present examples where the fast wave is excited by an external driver and find the threshold value for the fast wave amplitude that eliminates backscatter. Preliminary results on the effects of ion motion and finite width lasers will also be presented.

*This work conducted under the auspices…. If you do not have anything to credit, delete this line and the asterisk at the end of the title.

A. Name, B. Name, and C. Name, "*Paper title,*" Journal name **Vol**, page (year). (Remove if no references.)
[2] A. Name and B. Name, Institution, personal communication (year). (Remove if no references.)

Gaussian Laser Beam Filamentation Influenced by Additional Smoothed Laser Beams

K.R. McMillen, J. Katz, J. Palastro, R.K. Follett, D. Turnbull, D.H. Froula, D.J. Haberberger, and J.L. Shaw
University of Rochester's Laboratory for Laser Energetics 250 E River Rd.
Rochester, NY 14623
kmcm@lle.rochester.edu

High-intensity laser propagation through plasmas is often limited by laser filamentation which can inhibit beam propagation, reduce the efficacy of laser-target coupling, and drive additional laser- plasma instabilities. Filamentation is typically thought of as a single-beam instability which arises due to non-uniformities in the laser intensity, phase front, or plasma density. However, we present experimental and simulation results showing the filamentation and the resulting beam spray of a Gaussian f/50 beam is enhanced by additional spatially and temporally smoothed laser beams. Our experiment utilizes the joint operation of the OMEGA 60 and OMEGA EP laser systems at the University of Rochester's Laboratory for Laser Energetics. In the experiment, an apodized 1ω short-pulse (1—100-ps) laser beam from OMEGA EP is coupled into a preheated plasma on the OMEGA 60 laser-plasma interaction platform. A gas-jet target is ionized and heated by 500 ps 3ω heater beams which use distributed phase plates (DPP) and smoothing by spectral dispersion (SSD). The resulting plasma conditions are determined via spatially-resolved Thomson scattering while the spray of the filamented short-pulse beam is recorded with a transmitted beam diagnostic. Results show significant amounts of spray of the short-pulse beam when propagating through the plasma while heater beams are on which remains unmitigated when SSD is turned on. In contrast, beam spray is reduced when the short-pulse beam propagates through the plasma after the heater beams have turned off and while at the same plasma conditions. Supporting 2D LPSE simulations indicate density fluctuations driven by overlapped DPP beams lead to enhanced filamentation seed levels which SSD on the order of ~1Å fails to mitigate.

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Numbers DE-NA0004144 and DE-SC0021057.

Tuesday, April 8

Time	Name	Institution	Abstract Title
Session I - Target Physics		**Tammy Ma, Chairperson**	
8:30 AM	Constantin Haefner	Fraunhofer ILT	Transforming Supply Chains: The Impact of Global Advancements in Laser Fusion Energy on the Photonics Market
9:15 AM	David Turnbull	University of Rochester	Plans to Demonstrate LPI Mitigation with a Broad-Bandwidth Laser Beam
9:35 AM	Camille Samulski	Los Alamos National Laboratory	Validating Los Alamos National Laboratory's xRage Common Model Framework for Polar Direct Drive Target Design
9:55 AM	Alison Christopherson	Xcimer Energy Incorporated	Advancing Two-Sided Inertial Fusion: Xcimer's Hybrid Drive and Target Design Roadmap
10:15 AM	Break		
Session II - Target Physics		**Nathan Meezan, Chairperson**	
10:40 AM	Darwin Ho	Lawrence Livermore National Laboratory	High-Yield Implosions Using DT Wetted Foam for Inertial Fusion Energy
11:00 AM	Xiaoxing Xia	Lawrence Livermore National Laboratory	Polar-Direct-Drive DT Wetted Foam Studies on the National Ignition Facility
11:20 AM	Warren McKenzie	HB11 Energy	HB11 Energy: Advances in Laser Boron Fusion Science and Engineering
11:40 AM	Marius Schollmeier	Marvel Fusion GmbH	First Experimental Evaluation of a 10-PW-Driven Nano Accelerator for IFE
12:00 PM	Lunch Provided		
2:00 PM	Teambuilding	Breckenridge Scavenger Hunt Meet in the coffee shop at Gravity Haus (605 S. Park Ave)	
7:00 PM	Dustin Froula	University of Rochester	IFE-STAR Ecosystem Overview
8:30 PM	Poster Session II		

Transforming Supply Chains: The Impact of Global Advancements in Laser Fusion Energy on the Photonics Market

Prof. Dr. Constantin Haefner
constantin.haefner@ilt.fraunhofer.de

Traditionally, fusion energy research has primarily been situated in the realm of basic science, focusing on understanding foundational plasma physics. However, the development of a first fusion power plant requires a clear transition from fundamental to applied research, focusing on technology transfer to industry. This transition presents significant opportunities for investors, researchers, and companies. A well-managed program to advance key technologies into a demonstration power plant is essential, supported by strategic collaborations among funding bodies, investors, research institutions, and industry.

Public and private investments are crucial for driving the risk buydown process, ensuring that advancements are backed by rigorous scientific research. Furthermore, a diversified and resilient supply chain is vital for achieving affordable fusion power plants and successfully commercializing fusion energy. The current reliance on single-source suppliers and specialized labs must evolve to foster a robust fusion industry capable of reducing costs and meeting future demands.

As the fusion energy market is still developing, converting key technologies into commercially viable products is imperative. Germany's Fusion 2040 Public-Private Partnership program funds industry, national laboratories, and university consortia to develop critical fusion technologies, particularly those related to laser systems, for commercialization and scaling. Additionally, identifying spillover technologies can generate early revenue and enhance supply chain development.

Engaging diverse stakeholders through strong risk-sharing mechanisms is essential to address long lead times and build the infrastructure for a sustainable energy future. By navigating these economic dynamics, fusion energy can emerge as a transformative force in the global energy landscape.

Plans to Demonstrate LPI Mitigation with a Broad-Bandwidth Laser Beam*

D. Turnbull,[1**] R. Boni,[1] T. Chapman,[2] T. Collins,[1] C. Dorrer,[1] D. H. Edgell,[1] R. K. Follett,[1] D. H. Froula,[1] D. Haberberger,[1] E. Hill,[1] R. Huff,[1] J. Katz,[1] P. Loiseau,[3] J. Marozas,[1] A. L. Milder,[1] C. Ruyer,[3] S. Sampat,[1] R. Shah,[1] A. Shvydky,[1] A. Solodov,[1] V. Tikhonchuk,[4,5] D. Weiner,[1] and J. Zuegel[1]
[1]University of Rochester Laboratory for Laser Energetics, Rochester, NY, USA
**turnbull@lle.rochester.edu
[2]Lawrence Livermore National Laboratory, Livermore, CA, USA
[3] CEA, DAM, DIF, F-91297 Arpajon, France
[4] Extreme Light Infrastructure ERIC, ELI-Beamlines Facility, Dolní Břežany, Czech Republic
[5] Centre Lasers Intenses et Applications, Université de Bordeaux–CNRS–CEA, Talence, France

Broad-bandwidth laser drivers are expected to enable a step-change in the performance of inertial confinement fusion implosions by mitigating laser-plasma instabilities and thereby significantly opening up the design space. Direct-drive implosions are particularly affected by crossed-beam energy transfer (CBET), the multibeam two-plasmon-decay instability (TPD), stimulated Raman side-scattering (SRSS) at long scale-lengths, and the Rayleigh-Taylor instability seeded by laser imprint. In modern indirect-drive implosions, stimulated Brillouin backscattering and filamentation are more relevant concerns.

We plan to investigate the impact of laser bandwidth on all of these instabilities and more using the fourth-generation laser for ultrabroadband experiments (FLUX). FLUX combines novel schemes for highly efficient optical parametric amplification of a spectrally incoherent source and broadband sum-frequency generation to deliver a high-energy ultraviolet beam with >1% fractional laser bandwidth. FLUX will be coupled into the OMEGA-60 target chamber to enable focused physics studies using various LPI platforms.

We will review plans for these platforms and the targeted results that we anticipate they will enable. In several cases, the platforms have already been activated, and narrowband results have been obtained. To study the multibeam TPD instability, an f/1.5 focusing capability is being developed in order to emulate a multibeam irradiation pattern with the single FLUX beam. FLUX experiments should begin this year.

*This material is based upon work supported by the Department of Energy [National Nuclear Security Administration] University of Rochester “National Inertial Confinement Fusion Program” under Award Number DE-NA0004144, and the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, under Award Number DE-SC0024863.

[Validating Los Alamos National Laboratory's xRage Common Model Framework for Polar Direct Drive Target Design *]

[C. Samulski[1] and J. Kline, [1]]
[1Los Alamos National Laboratory, Los Alamos, NM, 87545]
[csamulski@lanl.gov]

[The viability of an IFE fusion power plant requires target design, target manufacturing, laser design, and power plant operations to work as a single system. As we consider the individual components, trade-offs and hard choices based on technology will be made, and keeping these components as simple as possible will lead to the best chance of success. In this vein, we are evaluating polar laser direct drive of a spherically symmetric capsule at sufficiently large laser powers for maximal power production by neutron as a viable avenue for future high rep-rate experimental platforms. The work described here uses Los Alamos National Laboratory's xRage radiation hydrodynamics simulations code to evaluate such designs. Given the limited use of xRage for laser direct drive, we first utilized the LANL common model framework (CMF) to evaluate existing experimental laser direct drive data in order to benchmark our simulations. As we move forward, we continue to add experimental data to improve our models. Using the best settings based on data, we have designed preliminary polar direct drive capsules. In particular we are examining two configurations, the first uses a standard multibeam laser setup, and the second uses the planned high power, high-energy two-sided illumination by Xcimer. For these designs we use a shaped, time dependent energy profile. This presentation will cover both the common modeling used to benchmark our simulation choices, and the progress towards simple spherical capsule designs for IFE. This document has been provided release under the identifier LA-UR-25-21104.]

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Advancing Two-Sided Inertial Fusion: Xcimer's Hybrid Drive and Target Design Roadmap

Alison Christopherson[1], Cliff Thomas[2], Mark Schmitt[3], John Kuczek[3], John Kline[3], Camille Samulski[3], Tom Mehlhorn[4], David Montgomery[1,3], Bob Kirkwood[1], Pedro Velarde[5], Manuel Cotelo[5], Milan Holec[1], Kirk Flippo[1], Dan Barnak[2], Jonathon Davies[2], Mike Campbell[6], Neil Alexander[7], and Conner Galloway[1]

1. Xcimer Energy Inc, 10325 E 47th Ave, Denver, CO 80238
achristopherson@xcimer.net
2. Laboratory for Laser Energetics, 250 E River Rd, Rochester, NY, 14607
3. Los Alamos National Laboratory, Los Alamos, NM 87545
4. Mehlhorn Engineering Consulting Services, 17685 SW Pheasant Ln, Beaverton, OR 97003-4304
5. Instituto de Fusión Nuclear - Universidad Politécnica de Madrid, C. José Gutierrez Abascal, 2, 28006, Madrid, España
6. MCM Consultants, 17117 Tallow Tree Lane, San Diego CA 92127
7. General Atomics, 3550 General Atomics Ct. San Diego, CA 92121

Xcimer Energy Inc., founded in 2021, is developing a next-generation fusion reactor that leverages laser-driven inertial confinement fusion. Using a novel, cost-effective electron beam-pumped KrF laser system, Xcimer will produce high-energy, microsecond-long pulses and employ gas optics to deliver on-target pulses with up to 10 MJ energy within approximately 10 ns. Backed by significant funding—including a $9 million DOE Milestone award and $100 million in Series A financing—the company is constructing the Phoenix prototype facility to amplify a seed beam to ~1,000x its initial energy in a Stimulated Brillouin Scattering (SBS) gas cell, while preserving phase and operating below optics damage thresholds. Simultaneously, Xcimer is advancing a fusion pilot plant design based on the HY-LIFE concept[1], which features a FLiBe liquid curtain to protect the reactor chamber at 0.25–1 Hz repetition rates. The HY-LIFE approach is ideally suited for two-sided target irradiation, thereby simplifying the design of the FLiBe liquid jet system.

Xcimer's target design program is focused on developing concepts optimized for two-sided irradiation, including a recently published baseline hybrid drive design—developed in collaboration with the University of Rochester, Los Alamos National Laboratory, General Atomics, and Lawrence Livermore National Laboratory—that leverages a hohlraum to generate an x-ray–driven first shock for imprint mitigation, followed by directly driven compression for improved energy coupling[2]. This hybrid scheme also creates a plasma atmosphere in the first shock, enabling equatorial absorption of laser energy for enhanced symmetry. Additionally, the laser system's beam zooming capability allows the beam spot to dynamically adjust over time, opening new avenues for design innovation. In this talk, Xcimer's roadmap for advancing these two-sided target designs and managing their associated risks will be presented and discussed.

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High-yield implosions using DT wetted foam for inertial fusion energy (IFE)*

D. Ho,[1] A. Velikovich,[2] S. MacLaren,[1] P. Amendt,[1] J. Lindl,[1] and T. Ma[1 1]
Lawrence Livermore National Laboratory, Livermore, CA 94550
ho1@llnl.gov
[2] U.S. Naval Research Laboratory, Washington, DC 20375

IFE applications require high repetition rates, and capsules utilizing DT wetted foams offer an advantage over those using a DT ice layer, as the foam does not require a prolonged duration for β layering. However, wetted foam leads to significant yield degradation[1] due to several critical issues. (1) The C and O present in foams created by the 2PP process, or Si and O in chemically produced SiO_2 foams, absorb hard x-rays, which can penetrate conventional ablators, e.g., high-density carbon (HDC), Be, or CH. These x-rays preheat the foam, raise the adiabat, and, subsequently, reduce the areal density (ρR). The rate of preheating escalates with foam density. (2) As the burn progresses, the radiation loss is exacerbated by the foam material. (3) A DT- wetted foam has a higher vapor pressure, which further decreases ρR. (4) The turbulence created by shocks traversing the irregular foam structures can lead to under-compression,[2] particularly for high foam density.

To evaluate the performance of DT wetted-foam implosions, we use a HDC capsule with an outer radius (OR) of 1189 µm, which absorbs ~280 kJ of laser energy and is driven by an Au-lined DU hohlraum.[3] When the ice layer is replaced with a DT-wetted foam of 25 mg/cc density, the yield degradation is ~55% in 1D simulation. The primary cause of this yield degradation is the x-ray preheating of the wetted foam. However, this degradation can be mitigated by ~15% if an unlined-DU hohlraum is utilized to reduce the hard x-rays.[3] For a 50 mg/cc foam, ignition cannot be achieved. Generally, increasing the capsule size tends to reduce the yield degradation. For example, a Be capsule with an OR of 2340 µm absorbs 1.3 MJ of laser energy and achieves a 1D yield of 400 MJ. The extent of yield reduction varies between 20-80 %, depending on the O content, for a wetted foam at 25 mg/cc when driven by a Planckian radiation source. Therefore, it is essential to develop methods to readdress the significant yield degradation caused by the wetted foam.

We introduce two configurations of heavy ablators designed with a high concentration of mid- or high-Z materials to block hard x-rays. These heavy ablators optimize the trade-off between implosion velocity and ρR. The first configuration is the Pusher-Single Shell (PSS),[4,5] which employs a Be ablator with a 20 at.% of Mo or 6 at.% of W in the inner region. The concentration of Mo or W is graded, gradually decreasing toward the outer region to minimize the Rayleigh-Taylor instability (RTI). Experimental and theoretical studies at LLNL show that PSS is stable against RTI and can achieve a high ignition margin, e.g., a 1500 µm OR Be/W PSS absorbing 490 kJ of laser energy has a yield of 40 MJ. The yield degradation associated with wetted foam is notably reduced — 15% (20%) for 25 mg/cc (50 mg/cc) foam density. The W blocks almost all of the hard x-rays, resulting in minimal change to adiabat. Yield degradation primarily arises from enhanced radiation emitted by the foam material during the burn. While the W also reduces radiation leakage from the hotspot during burn, radiation trapping does not enhance performance, as the coupling between matter and radiation in the hotspot is weak. The second type of heavy ablator is the B_4C ablator blended with Ta, also featuring a graded concentration profile. B_4C has the advantage of possessing an amorphous structure. For foam density less than 50 mg/cc, the under-compression caused by turbulence is likely negligible, as indicated by numerical results.[2]

*This work conducted under the auspices of the U.S. DOE by LLNL under contract DEAC52-07NA27344

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Polar-direct-drive DT wetted foam studies on the National Ignition Facility*

X. Xia[1], G.E. Kemp[1], C.B. Yeamans[1], M. Hohenberger[1], S. Bhandarkar[1], B.E. Blue[1], T. M. Briggs[1], R.S. Craxton[2], L. Divol[1], M. Do[3], M. Farrell[3], A. Haid[3], B.M. Haines[4], S.A. MacLaren[1], P.W. McKenty[2], W.P. Moestopo[1], J. Oakdale[1], R.E. Olson[4], Y. Ping[1], M.J. Rosenberg[2], M.J. Schmitt[4], C. Thomas[2], H.D. Whitley[1], and K. Widmann[1]

1) Lawrence Livermore National Laboratory, Livermore, CA, 94550, USA
E-mail: xia7@llnl.gov
2) Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623, USA
3) General Atomics, San Diego, CA, 92121, USA
4) Los Alamos National Laboratory, Los Alamos, NM 87544, USA

Previous design studies have suggested that direct laser ablation of liquid deuterium-tritium (DT) wetted foam (WF) inertial confinement fusion (ICF) targets[1] could reach ignition on the National Ignition Facility (NIF) laser[2]. Despite the recent ignition success of the laser indirect-drive (LID) approach to ICF[3], the high laser-to-target coupling, the absence of ablator mix, and the lower in-flight aspect ratio of directly driven WF designs are anticipated to provide improved robustness to target imperfections and drive nonuniformities, even with the polar-direct-drive (PDD) geometry of NIF. Furthermore, the low target mass provides a favorable testing environment for high-fluence neutron exposure experiments and the liquid approach greatly reduces fielding time with respect to the current beta-layered ice designs. A multi-lab collaborative effort[4] is exploring the feasibility of PDD-WF designs for the envisioned implementation on the NIF, in particular (i) novel two-photon-polymerization (2PP) printed targets and (ii) cryogenic cooling through a large conductive fill tube attached to a traditional LID cold finger. We discuss recent experimental and modeling efforts to understand the potential risks and benefits associated with PDD-WF designs for ICF and inertial fusion energy schemes.

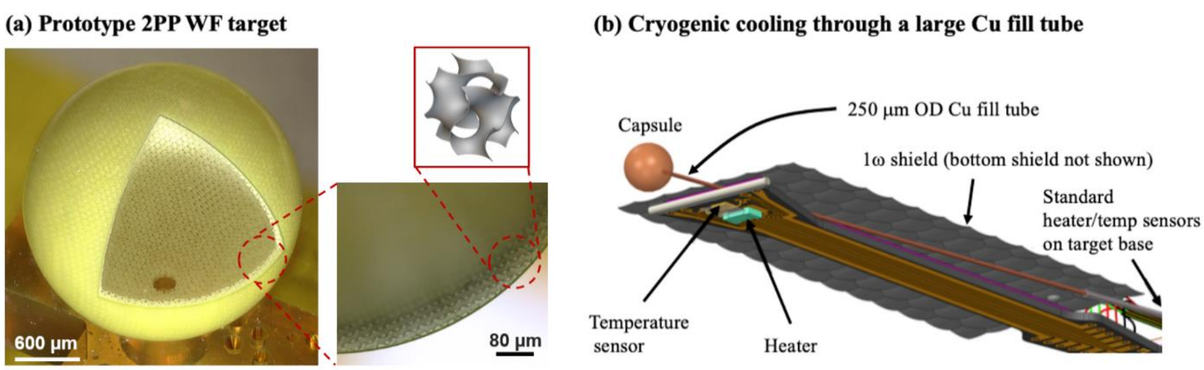

Figure 1: (a) Optical images of a prototype 2PP WF target. (b) Cryogenic cooling configuration for direct drive targets on NIF, enabled by conduction through a large Cu fill tube.

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HB11 Energy: Advances in laser boron fusion science and engineering

T. Mehlhorn, W. McKenzie
HB11 Energy, 101 Belgrave St, Manly Beach, NSW, 2095

HB11 Energy is pursuing clean energy based on the laser-driven fusion of proton-boron and non-DT alternate fuels.

It's a fuel physics program (1), led by an international team of theorists, experimentalists, and technologists, is pursuing opportunities for ignition and quantification of the burn space of laser-driven fusion for proton-boron and alternate fuels. It has also begun programs to commercialize two technologies in support of science and technology gaps for commercial laser-driven IFE; (2) high-efficiency laser systems and (3) micro-structured laser targets.

(1) HB11 Energy's fuel physics program is focused on the integration of newly understood kinetic and supra-thermal effects into simulation tools to be suitable for modeling of plasma at extreme conditions corresponding to the burn space of advanced fuels. One such project is its DOE-funded INFUSE project with the TriForce team at the University of Rochester, with additional projects planned with both Rochester and Los Alamos National Labs. HB11 Energy team has published many peer-reviewed articles that describe the proton-boron technical roadmap[1], map the proton-boron burn space, quantify the impact of non-thermal/suprathermal effects, show preliminary data on burn and proton ignition using high energy short pulse laser pulses[2], and communicate the results of recent international experiments.

(2) HB11 Energy's laser program is pursuing high energy-efficiency low-cost laser technologies of use for both ICF and directed energy applications. This program has attracted Australian government co-investment through its Defence Trailblazer program. It plans to have the first generation of laser built and its experimental facility operational this year, which will be geared for fast-ignition research.

(3) Further, HB11 Energy is developing materials and micro-fabrication processes for the manufacture of micro structured targets to supply proprietary and academic fusion-related experiments at high power laser facilities. It delivered its first targets to external customers this year and is pursuing partnerships with laser facilities to open its capabilities to their users.

In this presentation we will highlight the most recent advances in burn physics, laser development, and target production, including their application for the wider IFE community.

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First experimental evaluation of a 10-PW-driven Nano Accelerator for IFE

Marius S. Schollmeier[1], D.E. Rivas[1], A. Fazzini[1], M.M. Günther[1], V. Scutelnic[1], A. Ailincutei[2], J.J. Bekx[1], G. Bleotu[4], C. Bild[1], C. Braganza[1], G. Bodini[1], A.F. Brodersen[1], A. Cavalli[1], O. Chalus[3], L. Chopinet[1], G, Cojocaru[4], J. D'Mello[1], I. Dancus[4], F. Deurvorst[1], C. Derycke[2], D. Doria[4], M. Ehrmanntraut[1], E. Gaul[1], D. Gengenbach[1], P. Ghenuche[4], D. Ghita[4], B. Gonzalez-Izquierdo[1], M. Gugiu[4], O. Juina[1], J. Jung[1], K. Kenney[1], S. Kumar[1], M. Martinez-Pacheco[1], I. Minguez Bacho[1], M. Nöth[1], N. Poetranto[1], G. Raj[1], E. Schork[1], M. Speicher[1], M. Stein[1], M. Talposi[4], A. Toma[4], M. Tosca[1,5], M. Touati[1], A. Ubarhande[1], L. Vasescu[4], H. Ruhl[1] and G. Korn[1]

[1]Marvel Fusion GmbH, Theresienhöhe 12, 80339 Munich, Germany
marius.schollmeier@marvelfusion.com
[2]Thales Systems Romania, 060071 Bucuresti, Romania
[3]Thales LAS France, 78990 Élancourt, France
[4]Extreme Light Infrastructure (ELI-NP), 30 Reactorului Street, 077125 Magurele, Romania
[5]ELI Beamlines Facility, The Extreme Light Infrastructure ERIC, Dolní Brežany 252 41, Czech Republic

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, an ultra-high-contrast ($<10^{-12}$ on ps timescales) and sub-100-fs duration with an efficiency nearing 100%. A large fraction of the absorbed energy is converted by this Nano Accelerator to high-current ion flows in a controlled manner[1]. The ion flow can then heat and potentially compress fusible material made of hydrogen, boron, deuterium and tritium[2,3] in close vicinity to IFE-relevant conditions.

In this contribution, we will present the first experimental demonstration of the Nano Accelerator driven by 10 PW laser pulses. Experiments were conducted with with HPLS laser at the Extreme Light Infrastructure for Nuclear Physics (ELI-NP) in Bucharest, Romania, which was operated at approximately 200 J of energy on target at a pulse duration of 23 fs. The original focusing geometry was modified[4] from F/60 to F/20 leading to intensities of 8×10^{20} W/cm^2 with a uniform focal spot volume of 20 µm FWHM and >200 µm length. The intense laser pulse was used to irradiate 100×100 µm^2 patches of highly aligned, high-aspect-ratio nanowires (length 20 µm, diameter 70 nm, pitch 800 nm). Monitoring the specularly reflected laser light and detecting ion emission via multiple Thomson Parabola & CR-39 spectrometers, we demonstrate an efficient laser power absorption capability of >5 PW and conversion to high energy ions nearing 30% efficiency, in line with theoretical expectations[5]. In addition, we show the possibility of tailoring the emitted ion spectra by varying the nanostructure parameters, which enables scaling and further optimization of the Nano Accelerator as a driver for IFE targets[1].

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Tuesday, April 8 – Poster Session II

Number	Author	Institution	Abstract Title
P-1	David Chesny	SpaceWave	Development of Solid-State Linear Transformer Drivers and Enhancing Fusion Energy Science Research in the Southeastern U.S.
P-2	Derek Mariscal	Lawrence Livermore National Laboratory	Advancing IFE Science Through Machine Learning and High-Repetition-Rate High-Energy-Density Experiments
P-3	Igor Golovkin	Prism Computational Sciences, Inc.	Radiation-Hydrodynamics Code HELIOS-CR: Improved Models for Dense Plasma Effects and IFE Simulations
P-4	John Marozas	University of Rochester	Broadband Laser Smoothing for ICF and IFE targets
P-5	Jonathan Brodrick	Pasteur Labs	Auto-Differentiation Powered Inverse Design Workflows on the Cloud
P-6	Justin Angus	Lawrence Livermore National Laboratory	An Implicit Particle Code for Fully Kinetic Simulations of Burning Plasmas
P-7			
P-8	Kirill Lezhnin	Princeton Plasma Physics Laboratory	Laser Ion Acceleration from Concave Targets: Focusing, Scaling, and Robustness
P-9	Kaikai Zhang	Amplitude Laser Inc.	Building Blocks of kJ Nanosecond and Picosecond Lasers for Fusion Research
P-10	Matthew Wolford	U.S. Naval Research Laboratory	Advances in Development of an Argon Fluoride (ArF) Laser Driver for Inertial Fusion Energy (IFE)
P-11	Zhenhuan Yi	Texas A&M University	Toward High Power Laser for Fusion: Stimulated Brillouin Scattering Modeling with Kinetic Analysis
P-12	Edward Moses	Longview Fusion Energy Systems	Longview Fusion Energy Systems: The Path from the NIF to Commercial Fusion Energy
P-13	Félicie Albert	Lawrence Livermore National Laboratory	The Jupiter Laser Facility: A Kilojoule-Class Laser for Producing and Exploring Extreme States of Matter
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P-15	Maggie Rivers	Princeton Plasma Physics Laboratory	Platform for High Resolution Proton Stopping Power Measurements in WDM
P-16	Richard Sandberg	Brigham Young University	Developing the Future Inertial Fusion Energy Workforce in the RISE IFE-STAR Hub
P-17	Daniel Casey	Lawrence Livermore National Laboratory	Understanding Implosion Physics Degradations to Advance IFE-Relevant Targets

P-18	Stephen Messing	Univesity of Illinois Urbana-Champaign	Absolute Gain-Coupling Coefficients for Stimulated Brillouin Scattering at 266 nm in Low-Pressure Gases
P-19	Pericles Farmakis	University of Rochester	Multidimensional Modeling of the Hybrid Shock Drive for Low-Adiabat Direct-Drive Fusion Experiments at the Omega Laser Facility
P-20	Raspberry Simpson	Lawrence Livermore National Laboratory	Investigation of Ion Focusing Using Structured Targets for Applications to Ion Fast Ignition
P-21	Levi Hancock	Brigham Young University	Nanostructure of Polymer Foams using 3D Ptycho-Tomography for Inertial Fusion Energy (IFE) Applications
P-22	Sabrina Silva	General Atomics	Advancing IFE Target Fabrication with Microencapsulate Dicyclopentadiene-Norbornene Foam Shells
P-23	Jaden Hoechstetter	Colorado State University	Angular Distribution of Ions Accelerated by Irradiation of Nanowire Arrays with Laser Pulses of Relativistic Intensity
P-24	Jesse Griff-McMahon	Princeton Plasma Physics Laboratory	Characterization of Proton Focusing from Hemispherical Targets
P-25	Jordan Lee	University of Oxford	Bayesian and Particle Swarm Approaches to Inertial Confinement Fusion Implosions
P-26	Kassie Moczulski	University of Rochester	Numerical Simulations of Laser-Driven Experiments of Ion Acceleration in Stochastic Magnetic Fields
P-27	Nashad Rahman	Colorado State University	Fabrication of Nanowire Array Strips for Characterizing Ion Acceleration in Relativistic Laser-Nanostructure Interactions
P-28	Oren Yang	University of California, San Diego	Neutron Production in Krypton on Deuterium Gas Puff Z-Pinches
P-29	Perry Samimy	University of California, San Diego	Experimental Study of Proton Heating in Proximally Structured Cu Foam Targets
P-30	Rusko Ruskov	University of Oxford	The Effect of Broad Laser Bandwidth on the Two-Plasmon Decay Instability and Its Connection to Turbulence
P-31	Heath Martin	University of Oxford	The Electrothermal Filamentation of Igniting Plasmas

Development of Solid-state Linear Transformer Drivers and Enhancing Fusion Energy Science Research in the Southeastern U.S.

D. L. Chesny,[1] G. Xu,[2] M. B. Moffett,[1] and K. Boehm[2]
[1]SpaceWave, Satellite Beach, FL, 32937
david.l.chesny@gmail.com
[2]University of Alabama in Huntsville, Huntsville, AL 35899

Using advancements in high-power solid-state switching (S3), we are closing technology gaps within S3 pulsed power drivers (PPDs) toward developing the future fusion-energy workforce in the Southeastern (SE) U.S. region. Our development of thyristor-based S3 PPD technology will be optimized for a range of state-of-the art experiments in high-energy density physics (HEDP) and inertial fusion energy (IFE), including experimental fusion reactors and enabling basic plasma sciences. Linear transformer drivers (LTDs) and Impedance-matched Marx Generators (IMGs) typically operate using triggered gas switches with limited electrode lifetimes and that are pressurized with harmful gases. Making LTDs and IMGs more robust and reliable for future fusion power plant operations can directly benefit from a transition to S3. This is an LTD/IMG technology gap solution that can be addressed now while experimental fusion reactors are still under development. In a wider application to basic plasma sciences around the country, S3 PPDs can optimize plasma formation of a coaxial plasma gun (CPG) for a more robust snowplow mode, which will reduce canting of the plasma sheath and increase the total gas consumption and ionization, which will maximize the plasma density and thus enable the resistive MHD environment for numerous applications.

We are fostering public-private partnerships between industry and academia to provide access and training for researchers and especially students in the SE U.S. to learn about and gain hands-on experience in HEDP/IFE-related research in order to gain the knowledge and experiment to access world-class user-facilities (e.g. NIF, Z-machine) and contribute to these areas of scientific and national interest. HEDP and IFE are areas of interest to the DOE with broad impacts in basic plasma science, fusion energy, and astrophysics. The proposed thyristor-switched LTD/IMG addresses technology gaps in high-efficiency and long lifetime PPDs for IFE. We are also addressing fusion workforce development in the SE U.S. by performing this type of HEDP research, which is a largely underrepresented region in fusion energy sciences. HEDP/IFE are currently being studied at NIF, Z-machine, and the Laboratory for Laser Energetics as well as at private fusion companies in the Pacific Northwest and Northeast US. However, accessing these facilities is competitive and requires years of prior experience and knowledge and the necessary equipment to gain that experience. Thus, our group's goal is to bridge the gap between the desire to perform HEDP/IFE plasma research and having the experience to contribute. As our successes grow, we will seek to collaborate with the existing world-class facilities and industry to provide pathways for rising investigators to gain access to their facilities.

We will present results from our first tests of an S3 LTD for a near term application toward a CPG basic energy science application. We will then scale this S3 LTD up to multiple parallel pulsed systems for achieving laboratory magnetic reconnection. The expansion of these state-of-the-art hardware techniques will include a transition to S3 IMG development and applications to fusion energy sciences.

The main objectives of the this work are to 1) study, test, and understand thyristor switch behavior when stacked for higher voltage and current operation, 2) develop an S3 LTD and IMG for 100 kA with low shot-to-shot timing jitter to demonstrate feasibility of the approach, and 3) conduct experimental and computational studies of CPGs in high current snowplow mode.

Advancing IFE Science through Machine Learning and High-Repetition-Rate High-Energy-Density Experiments

[D. A. Mariscal,[1] B. Z. Djordjević,[1] A. Sarkar,[1] G. Zeraouli,[2] and T. Ma[1]]
[1 Lawrence Livermore National Laboratory, Livermore, CA 94550
[mariscal2@llnl.gov]
[2 Colorado State University, Fort Collins, CO 80532]

Enabling High-Repetition-Rate Inertial Fusion Energy through Machine Learning and Advanced Diagnostics

The realization of high-repetition-rate (HRR) inertial fusion energy (IFE) systems requires addressing the challenges posed by the highly complex, nonlinear physics and drivers involved in creating and diagnosing high-energy-density (HED) conditions. Machine learning (ML) offers transformative potential to overcome these challenges by enabling real-time optimization, autonomous experimental control, and the development of scientific self-driving systems. This work outlines key areas where ML can be applied to accelerate progress in HRR IFE research and highlights the development of diagnostics and frameworks that deliver physics fidelity comparable to current state-of-the-art methods, while meeting the demands of HRR environments.

A critical component of this effort is the development of HRR-compatible diagnostics that maintain data fidelity while operating in the harsh environments created by pulsed, high-energy particles and photons. We have designed and demonstrated a range of HRR-capable diagnostics, including keV–MeV x-ray spectrometers, MeV electron spectrometers, and MeV ion spectrometers, which are now capable of collecting data at rates compatible with the multi-Hz systems in operation today. Synthetic modeling of diagnostics, in tandem with modeling of the physics of laser-plasma interactions, has also been employed to train ML algorithms for extracting key metrics such as source temperature, flux, and spectral shape—capabilities that will be vital for enabling self-driving experimental platforms.

Looking ahead, we discuss the needs of HRR HED and IFE experimental platforms, including the development of robust next-generation diagnostics and enhanced integration with ML-driven feedback loops. These capabilities will be essential as system complexity increases. These advancements will enable the transition from standalone diagnostics to fully integrated, autonomous systems capable of optimizing experimental conditions and advancing scientific understanding in real time, paving the way for the next generation of HRR IFE research.

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

I. Golovkin,[1] J. MacFarlane,[1] and M. Gu[1]
1 Prism Computational Sciences, Inc., 455 Science Dr., suite 140, Madison, WI 53711
golovkin@prism-cs.com

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. We will also discuss 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.

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Broadband Laser Smoothing for ICF and IFE targets*

J.A. Marozas, C. Dorrer, R.K. Follet, R. Huff, D. Haberberger, J.D. Zuegel, S.G. Demos, A. Pineau, R.C. Shah, A. Shvydky, W. Trickey, D. Weiner, A.L. Rigatti, N.D. Urban, K.L. Marshall, T.J.B. Collins, V.N. Goncharov, J.P. Palastro, and D.H. Froula
Laboratory for Laser Energetics, U. of Rochester, 250 East River Road, Rochester, NY, 14623
jimijam@lle.rochester.edu

Broadband laser sources offer laser–plasma instability (LPI) mitigation and faster laser-speckle smoothing that can outperform current smoothing systems. Broad bandwidth disrupts LPI growth via temporal incoherence and reduces nonlinear interaction intensity since the energy spreads across the wide spectrum. The broadband laser inherently reduces coherence time, and when coupled with dispersion, the time-averaged illumination smooths the random speckle field on an inertial confinement fusion (ICF) or inertial fusion energy (IFE) target, which consequently improves the compression uniformity, achieving higher compression and larger fusion yields. Smaller coherence time alone cannot reach adequate smoothing levels for nominal ICF/IFE target designs; therefore, future ICF/IFE facility upgrades require additional design implementations. This talk explores the requirements to achieve adequate smoothing levels that outperform current ICF smoothing systems and far-field spot-shape control and the flexibility they offer for on-shot reconfiguration of design choices. The broadband laser sources are compatible with the random continuous polarization[1,2] device that provides instantaneous polarization smoothing in all directions of far-field speckle modulation with optional far-field spot envelope control via random birefringence patterns, which is realizable in a variety of birefringent material properties. Simulation capabilities that emulate the far-field qualities will be discussed, as well as incorporating these properties and certain LPI mitigation advantages in multi-physics hydrodynamic simulations.

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Auto-Differentiation Powered Inverse Design Workflows on the Cloud

J P Brodrick[1], A S Joglekar[2,3,1], A J Crilly[4], A Lavin[1,3,5]
1 Pasteur Labs, 19 Morris Ave, Brooklyn, NY 11205, pasteurlabs.ai
jonathan.brodrick@simulation.science (Edinburgh, UK)
2 Ergodic LLC, Seattle, WA
3 Laboratory for Laser Energetics, University of Rochester, Rochester, NY
4 Imperial College, London, UK
5 Institute for Simulation Intelligence, 19 Morris Ave, Brooklyn, NY 11205

An underappreciated and more general-purpose outcome of the machine learning (ML) revolution is the ability to write high-level but hardware-accelerated numerical programs that support automatic differentiation. Automatic differentiation ("autodiff")—the computational backbone of all ML and artificial intelligence (AI)—enables the calculation of fast and accurate gradients with respect to input parameters in a single simulation.. The Pasteur platform[1] is autodiff-native to provide differentiable physics programming, targeting scientific workflows at industrial scale—for example, enabling high-dimensional (50+ parameters) inverse design powered by gradient-based multiphysics workflows. Purpose-built for industrial R&D, it provides a Python SDK and visual programming interface enabling scientists to implement or improve existing inverse design workflows through autodiff and accelerated hardware. Infrastructure challenges are taken care of (covering multi-cloud and hybrid setups), including remote execution, gradient calculation on accelerated cloud instances and interoperability with heterogeneous hardware. We present all these advantages in the context of inertial fusion applications, including optimisation of capsule design, pulse shape and laser bandwidth to increase neutron yield or minimise LPI. Simulation capability is provided by end-to-end auto-differentiable ADEPT[2,3] plasma transport code software along with the Pasteur production platform.

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An implicit particle code for fully kinetic simulations of burning plasmas*

J. Angus, W. Farmer, A. Friedman, Y. Fu, V. Geyko, D. Ghosh,
D. Grote, D. Larson, A. Link, J. Ludwig, J. Van De Wetering, G. Zimmerman

Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550

angus1@llnl.gov

A collisional particle-in-cell (PIC) algorithm based on modern implicit energy- and charge-conserving methods is developed for fully kinetic studies of burning plasma implosions. The implicit PIC method is ideally suited to study dense plasmas because 1) it can efficiently use time steps larger than the plasma period and grid cells larger than the Debye length, and 2) it can do so while maintaining *exact* energy and charge conservation. How the implicit solver works, and steps taken to implement the algorithm for axisymmetric geometries are discussed. The coulomb collision algorithm accounts for both cumulative small angle and single large angle events. The numerical algorithm also includes methods for Bremsstrahlung radiation emission, photon transport, and photon absorption. Finally, we discuss on-going work simulating burning implosion experiments on the NIF and implementing the algorithm in the GPU-capable WarpX particle code.

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Laser ion acceleration from concave targets: focusing, scaling, and robustness*

K.V. Lezhnin[1,†], V. Ospina-Bohórquez[2], K. Bhutwala[1], J. Griff-McMahon[1,3], X. Vaisseau[2], T. Bauer[2], R. Nedbailo[4], M. Rivers[1], W. Fox[1,3], I. D. Kaganovich[1], S. Malko[1]
[1]Princeton Plasma Physics Laboratory, 100 Stellarator Rd, Princeton, NJ 08540
[2]Focused Energy Inc., 11525-B Stonehollow Dr Suite 200, Austin, TX 78758
[3]Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544
[4]Department of Physics, University of Texas at Austin, 2515 Speedway, Austin, TX 78712
[†]klezhnin@pppl.gov

Proton fast ignition (pFI) is one of the promising approaches for achieving fusion energy. pFI employs separate lasers for target compression and heating, potentially enhancing the control over both stages. Achieving this requires precise focusing of energetic proton beams and high laser-to-proton energy conversion efficiency for effective target heating. It is widely recognized that laser ion acceleration from concave targets may satisfy the requirements for pFI. However, despite decades of theoretical and experimental exploration, the parameters of deliverable proton beams and their controllability still need improvement to meet the pFI requirements.

To bridge this gap, experimental studies investigating laser-driven proton acceleration and focusing by concave targets are underway at the CSU ALEPH laser facility (30 J, 40 fs), with future experiments planned to cover a wider range of laser and target parameters. To support the experimental campaign, we perform a numerical study of laser-driven proton acceleration and focusing using hemisphere targets. We use the radiation hydrodynamic code FLASH to estimate the parameters of preplasma and the fully kinetic relativistic Particle-In-Cell code EPOCH to simulate laser-driven proton acceleration. We assess the role of target geometry, characterize the proton focusing characteristics, and evaluate robustness concerning factors such as laser pointing stability and finite laser contrast. We also discuss whether the findings for short-pulse lasers (<100 fs) apply to intermediate pulse durations (~1 ps).

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Building blocks of kJ nanosecond and picosecond lasers for fusion research

Stéphane BRANLY[1], Florian MOLLICA[1], Franck FALCOZ[1], Kaikai Zhang[1,2,*], Antoine COURJAUD[1], and Pierre-Mary PAUL[1]
1. Amplitude Laser Group, 2 rue du Bois Chaland, Lisses, 91090, FR
2. Amplitude Laser Inc., 406 S Hillview Dr, Milpitas, CA 95035
*kaikai.zhang@amplitude-laser.com

In this work, we present laser systems under development, leveraging 20 years of accumulated expertise in high energy and high power lasers. Built on the heritage of petawatt-class lasers where pulse contrasts routinely exceed 10^{11}, this modular system integrates subsystems optimized for performance and reliability, representing one promising pathway for IFE.

This presentation will focus on some key building blocks of the laser systems under development. The synchronization subsystem, derived from accelerator applications, achieves femtosecond precision. Our second-generation OPCPA seeder, evolved from more than a decade of experience with industrial pump lasers and modern technological advances, provides enhanced temporal contrast and pulse shaping capabilities. Our nanosecond DPSS frontend pushes the limits of pulse energy and laser power with advanced thermal management. The pseudo active mirror disk amplifier module (PAMDAM) heads are capable of delivering over 200 J per pulse at 0.1 Hz in a single beam. Development is ongoing for larger PAMDAM heads to achieve the kJ energy level.

A sophisticated laser command-control software system forms the backbone of the platform, offering comprehensive control, monitoring, and safeguarding. Integrated datalogging is particularly beneficial for improving fusion research at high repetition rates, and a machine learning framework under development promises further optimization of system performance. These features are instrumental in enabling high-repetition-rate ignition and compression beamlet operations, thereby boosting experimental throughput and contributing to the foundational technology for future demonstration plants.

Recognizing that future IFE implementations will require industrial-scale laser production, our extensive experience in manufacturing thousands of ultrafast lasers for the medical market is now informing the scalable production of kJ-class systems. Key lessons from medical laser production such as modular manufacturing, stringent quality control, and supply chain optimization are directly applicable to achieving the reliability and scalability required for IFE lasers.

Advances in Development of an Argon Fluoride (ArF) Laser Driver for Inertial Fusion Energy (IFE)*

M.F. Wolford, and M. C. Myers
U.S. Naval Research Laboratory, 4555 Overlook Ave., SW Washington, DC 20375
Matthew.f.wolford.civ@us.navy.mil

Recently, the U.S. Naval Research Laboratory utilizing a low energy argon fluoride (193 nanometer) seed laser increased the yield of the Electra ArF laser to a record 237 Joules. The enhancement was due to coupling the low energy (<0.5 J, ~15 nanosecond) seed laser beam to a plano-parallel optical configuration. This configuration allows an increased extraction time of the ArF gain medium provided by 140 nanosecond pulse length generated with 500 keV counter propagating electron beams. The technical presentation will be focused on why this optical configuration laser technology is available to ArF lasers and not as practical for the electron beam pumped angularly multiplexed krypton fluoride lasers.[1] High yield ArF lasers have required improvements in cathodes (electron beam emission at higher current densities than previously used regularly), hibachi design (lower gain media pressure allowing less interception and higher efficiency of electron beam transport into the gain medium) and other key aspects including the role of amplified spontaneous emission (ASE) of preserving the created gain media which will be discussed in the presentation. These inherent characteristics along with the modular nature of the ArF laser driver development presents a path for rapid advancement and the ability to transition the technology quickly from the laboratory to the building stage of reliable, efficient, durable laser driver needed for successful inertial fusion energy (IFE).

The potential of the electron beam pumped argon fluoride laser for a IFE laser driver has been discussed elsewhere.[2] Briefly, the short wavelength at 193 nm allows greater direct drive coupling to the expected target materials utilized for IFE. In addition, the short wavelength creates a higher absorption pressure on the target for the same number of photons as opposed to longer wavelengths. The higher pressure for the same laser intensity is an advantage for deleterious process such as laser plasma instabilities (LPI) and increases the target design space to allow thicker targets, which are less susceptible to hydro-instabilities. Another important aspect is the broad bandwidth native to argon fluoride laser, which means a photon field of photons within the laser are dispersed in energy. The dispersion of photon energy in the ArF laser field will allow mitigation of laser plasma instabilities relative to a singular discrete energy photon field which is the 'typical' photon field for lasers. These target physics aspects and the prospective wall plug efficiency of 10%[2], modular nature, reliable pulsed power technology, ability for zooming, tracking the laser beam diameter to the target diameter during compression, and laser beam smoothing potential for argon fluoride electron beam lasers offers opportunities of substantial advancement for IFE laser drivers.

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Toward High Power Laser for Fusion: Stimulated Brillouin Scattering Modeling with Kinetic Analysis

Zhenhuan Yi,[1] Muzzamal Iqbal Shaukat,[1] Barnabas Kim,[1] Alexei V. Sokolov,[1] Aleksei M. Zheltikov,[1] J. Gary Eden[2] and Marlan O. Scully[1]
1 Institute for Quantum Science and Engineering and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843-4242, USA
2 Department of Electrical and Computer Engineering, University of Illinois, Urbana, IL 61801, USA

The recent scientific break-even in the inertial fusion experiment,[1] in 2022, has opened a new era and stimulated a new wave of focused research and investment in commercial fusion energy via the laser driven inertial confined fusion approach. High power ultraviolet laser is a key driver, which requires both high energy flux and short temporal duration.[2] Both experiments and simulations put the laser power in the petawatt range, which demands multi-mega-joule, nanosecond pulses for effective fuel burning.[3] While stimulated Brillouin scattering (SBS) is a potential source of laser optics damage in the solid-state system used in NIF,[1] it is the key mechanism for pulse compression in all-gas excimer laser system pursued in the RISE hub. Reported new experimental results of SBS gain for various gas media indicate an elaborate model is needed from both engineering and theoretical interests.[4]

The Bhatnagar-Gross-Krook (BGK) model provides a simplified yet effective framework for analyzing kinetic processes.[5] While the model by Averbakh et al. includes local fluctuations of gas density, velocity and temperatures of both external and internal degrees of freedom, we further investigate the impact of velocity-dependent relaxation time on the SBS gain by comparing the BGK relaxation representation of the collision integral that yields the correct moment equations. Our results demonstrate that accounting for velocity-dependent relaxation leads to significant modifications in the gain spectrum. These findings offer new insights into kinetic effects and provide a potential new parameter for the engineering effort to optimize SBS gain of high-power laser system for laser fusion.

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Longview Fusion Energy Systems: The Path from NIF to Commercial Fusion Energy

Edward Moses,[1]

[1] Longview Fusion Energy Systems, 1075 Sherry Way, Livermore, CA, 94550
ed.moses@longviewfusion.com

On December 5, 2022, at the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory (LLNL), fusion with energy gain was demonstrated [1]. This has been repeated several times, confirming the physics basis for fusion power production using the indirect drive target illumination approach.

Longview Fusion Energy Systems is founded on using this approach, eliminating the need to build an intermediate physics demonstration facility to prove fusion performance. This will enable directly building a Market Entry Power Plant (MEP). The MEP design, initially conceptualized in the LIFE program at LLNL [2-4], was developed and reviewed with eight major U.S. utilities, key industrial partners, and experts in fusion physics and technology. It is a self-consistent in terms of technology availability, performance, operability, and commercially competitive economics. The MEP is being designed with Longview's engineering and construction partner, Fluor, an international leader in innovative engineering solutions in the energy sector. The MEP is designed to generate 1600 MWt (thermal) and 440 MWe (electrical) of carbon-free and safe power. It will have a primary purpose to show the path to (i) cost-competitive electricity for residential, transportation, hyperscale and exaflop computation, and industry and (ii) the same for thermal chemical and thermal electrochemical production of carbon-free commodities such as synfuels, ammonia, and hydrogen and can be used for water desalination. The MEP is designed to be highly modular with extensive use of factory-built 'plug-and-play' technology subsystems. The MEP will serve as the template for deploying high-availability fusion power plants in the 500 MWe to 1500 MWe operating range in the U.S. and worldwide.

Several key advances must be made to enable this commercialization plan. To reach these performance goals and be cost competitive in the commercial market requires the fusion gain to ~15 to close both the power loop and fuel cycle, and ~30 for 440MWe power production. Operating the lasers at higher energy than the NIF and increasing the holhraum efficiency through advanced target configurations, laser temporal and bandwidth tuning, and other modifications project these performance capabilities. In addition, several key technologies must be commercialized for competitive performance of Longview Power Plants. These include operating the laser and target injector at 10-15 Hz rep rate with a laser wall plug efficiency of ~15%. Use of Diode-Pumped Solid-State Lasers, or DPSSLs [5] are projected to meet these requirements. In addition, the laser capital cost and the target operating costs must be improved significantly. Collaboration with several industrial companies in the diode and optics communities predict laser costs and performance consistent with the requirements of the MEP. Simplified functional designs and mass production techniques of targets have been studied and are also projected to meet these goals.

Many of the challenges of deploying the MEP, including tritium systems, have common cause among the IFE community. Longview will collaborate with the DOE, national labs, industrial partners, and with IFE private companies in pursuit of optimizing the path to commercial fusion energy.

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The Jupiter Laser Facility: a kilojoule-class laser for producing and exploring extreme states of matter*

Félicie Albert, D. Alessi, A. Barry, C. Boutsikakis, D. Cloyne, R. Costa, R. Cross, T. Dumbacher, B. Fischer, E. Gower, M. Jamison, E. Johnson, G. Khorsand, J. Larregui, A. Linder, S. Maricle, M. Marsh, A. Stappleton, B. Stuart, N. Vanartsdalen, J. Vite, K. Zoromski
Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA, 94550, USA
Albert6@llnl.gov

This presentation will discuss enabling capabilities for experiments related to discovery science and inertial fusion energy as well as the user program at LLNL's Jupiter Laser Facility (JLF). The facility has just completed a 4-year long refurbishment and is welcoming users back through the LaserNetUS network. In addition to scientific discovery, JLF has historically served as a steppingstone to larger experiments at the NIF and OMEGA lasers, supporting the development of new platforms and diagnostics for inertial confinement fusion science and applications.

JLF has multiple laser platforms: Titan, Janus TA1, and COMET. Titan's two-beam system is composed of a nanosecond, kilojoule long-pulse beam and a short- pulse beam with 1 to 10 ps pulses and energies up to 300 J, depending on pulse duration, and these beams can be used together or independently. JLF's Janus system has two independent beams, each of which can produce 1 kJ at 1.053 µm with pulse lengths from 1 to 20 ns. The system fires approximately every 30 minutes and offers frequency doubling, as well as a variety of pulse shapes. COMET's flexible configuration, which was designed primarily to generate laboratory x-rays, offers uncompressed pulse lengths from 500 ps to 6 ns, compressed pulses down to 0.5 ps, and beam energies up to 10 J.

After an overview of the facility and its scientific impact and achievements, the presentation will focus on our user program and how it can help support the IFE-STAR ecosystem.

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A Pilot Fusion Plant Design for Direct Drive IFE

Jim A Gaffney[1], Stefano Atzeni[1], Matthias Brönner[1], Debbie Callahan[1], Gilles Cheriaux[1], Arnaud Debayle[1], Doug Hammond[1], Maximilian Hartmann[1], Markus Hesse[1], Javier Honrubia[1], Patrick Lutz[1], Alfonso Mateo[1], Adrian McFarland[1], Linh Nguyen[1], Valeria Ospina[1], Clément Paradis[1], Prav Patel[1], Manolo Perlado[1], Markus Roth[1], Gabriel Schaumann[1], Martin Sokol[1], Wolfgang Theobald[1]

[1] Focused Energy, Inc
1808 El Camino Real
Redwood City, CA 94063

Focused Energy aims to design and build a successful fusion pilot plant (FPP) in the shortest time possible while controlling risk and costs. To achieve this goal we will pursue a series of subscale experiments and facilities, including our Implosion Test Facility [Theobald et al., this conference], that culminate in the integration of all fusion reactor technologies and the demonstration of engineering gain at the FPP. Core FPP milestones will include ignition and high gain from direct-drive implosions at 10Hz, the maturation of all reactor technologies to tech readiness level 8, and the validation of direct-drive IFE as a commercially viable fusion energy concept.

We have developed a preconceptual design for our FPP based on a down-scaling of a commercially viable first-of-a-kind (FOAK) reactor, accounting for bold technology and manufacturing developments over the next 10 years. In this talk we will present our preconceptual design, discuss the core design decisions, and describe our strategy to derisk the key technologies required. Finally, we will present our fully integrated computer aided engineering (CAE) approach to increase the fidelity of our design and to continually assimilate data from our R&D programs.

Platform for high resolution proton stopping power measurements in WDM*

M. Rivers,[1] K. Bhutwala,[1] R. Nedbailo,[1,2] W. Cayzac,[3] R. Hollinger,[4] F. Kraus,[1] A. Huerta,[5] J. I. Apinaniz,[5] C. Salgado López,[5] C. Sanchez,[5,6] D. Tolfiño,[5,6] X. Vaisseau,[7] M. Bailly-Grandvaux,[8] A. Kononov,[9] A. White,[10] S. Hu,[11] S. Hansen,[9] L. Wegert,[12] P. Neumayer,[12] R. Fedosejevs,[13] J. Rocca,[4] L. Volpe,[5,6] and S. Malko,[1]

[1]Princeton Plasma Physics Lab, Princeton, NJ 08540
mrivers@pppl.gov
[2]Center for High Energy Density Sciences, The University of Texas at Austin, Austin, TX 78712
[3]CEA, DAM, DIF, F-91297, Arpajon, France
[4]Colorado State University, Fort Collins, CO, 80523
[5]Centro de Laseres Pulsados (CLPU), E-37185 Villamayor, Salamanca, Spain
[6]Universidad Politécnica de Madrid, 28040 Madrid, Spain
[7]Focused Energy GmbH, 64293 Darmstadt, Germany
[8]Center for Energy Research, University of California San Diego, La Jolla, CA 92093
[9]Sandia National Laboratories, Albuquerque, NM 87123
[10]Los Alamos National Laboratory, Los Alamos, NM 87545
[11]Laboratory for Laser Energetics, University of Rochester, Rochester, NY 14623
[12]GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[13]University of Alberta, Department of Electrical and Computing Engineering, Edmonton, Alberta T6G 2V4

Warm Dense Matter (WDM) is a complex plasma state in which electrons are non-ideal (moderate coupling $\Gamma > 0.1$) and degenerate ($\Theta < 10$). These plasma parameters are relevant to high energy density and inertial fusion energy plasmas and can aid in understanding processes like alpha particle deposition for inertial confinement fusion [1]. The modeling of ion stopping power in WDM is particularly challenging, leading to discrepancies of up to 30% between models. This highlights a need for more experimental data to benchmark simulation codes.

Our group has demonstrated a high repetition rate platform for studying proton stopping power in WDM and performed measurements at low velocity projectile ratios $v_p/v_{th} \sim 3\text{-}10$ [2]. Protons are generated using a high intensity laser interacting with a solid target and are subsequently shaped into pencil-like, narrow-band beams of 0.5-1 MeV with 100-200 ps time spread by using a compact magnet-based energy selector [3]. These protons propagate through a WDM sample created by irradiating a thin carbon foil with a fs-laser. Our proposed research aims to fill data gaps in the parameter space to create comprehensive benchmarking for candidate models by using an upgraded platform at the CSU ALEPH laser facility. Experiments will produce hundreds of measurements for velocity projectile ratios $v_p/v_{th} = 6 \pm 2$, 8 ± 1, and 10 ± 1, which will improve statistical analysis and bridge the data gap to higher v_p/v_{th}. Simultaneous characterization of the WDM using Streaked Optical Pyrometry and XUV imaging measure sample conditions ($T_e \sim 15\text{-}20$ eV) required for the desired v_p/v_{th} ratio. Here we will discuss the recent results from our LaserNetUS Cycle 4 experiment at the CSU ALEPH facility, demonstrating successful energy bandwidth selection of protons. Further platform design changes to overcome and existing challenges will also be discussed.

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Developing the future inertial fusion energy workforce in the RISE IFE-STAR Hub

Richard L. Sandberg,[1] Gennady Shvets,[2] Arianna Gleason,[3] Siegfried Glenzer,[4] Carmen S. Menoni[5]
1 Department of Physics and Astronomy, Brigham Young University, Provo, UT 84653
rsandberg@byu.edu
2 Applied and Engineering Physics, Cornell University, Ithaca, NY 14850
3 SLAC National Accelerator Laboratory, Stanford University, Menlo Park, CA 94025
4 Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, CO 80523

With the great excitement about the fusion ignition results at the National ignition Facility (NIF), there is great need to rapidly increase the number of qualified scientists, engineers, and technicians in the workforce. The promise of Inertial Fusion Energy (IFE) as a potential for a sustainable, limitless energy source will not be realizable without a strategic and concerted effort to train the next generation fusion workforce. For this reason, the IFE-STAR RISE Hub is exposing students to fusion research at universities, private companies, and National laboratories. We are training post-doctoral researcher, graduate, and undergraduate students as well as performing outreach to high school students. In this poster, we will discuss our efforts to create a pipeline for training students in IFE related areas that expands from K-12 to undergraduate to post-doctoral education.

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Understanding Implosion Physics Degradations to Advance IFE-Relevant targets*

D. T. Casey,[1] T. M. Johnson,[1] S. Davidovits, [1] C. Weber[1]
[1]Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, USA
casey21@llnl.gov

Lawson's criterion has been exceeded in Inertial Confinement Fusion (ICF) experiments at the National Ignition Facility (NIF) and target gain greater than unity (G > 1) has been demonstrated.[1] Demonstrating ignition in the laboratory was a grand scientific challenge and yet harnessing that fusion energy will be yet another grand engineering challenge on the road to fusion power production via Inertial Fusion Energy (IFE).

One of the central questions facing an IFE reactor system is whether inertial fusion targets can produce significant energy gain, reliably, cheaply, and rapidly when integrated with the full reactor system. Ignition experiments from the NIF have shown a sensitivity to enhanced radiation losses induced by impurities from the capsule shell material mixing into the burning fusion fuel (mix) and implosion asymmetries because both effects compete with fusion heating. The maximum target gain in ICF depends on a competition between fusion heating and losses (from expansion, radiation, and conduction). It is therefore critical to assess how these issues might impact hypothetical IFE power systems.

In this talk, we will discuss ongoing work using HYDRA simulations, simplified rocket-piston models, AI-driven tools, and experimental data on the NIF to understand the degradations in high-gain IFE implosions. Additionally, we will overview the development of neural network-based tools for fast 3D postshot modeling and their potential to accelerate data analysis and system design. Currently, experiments are being proposed at OMEGA to test these models and explore IFE-relevant concepts, such as decoupling heating and compression, compensating for asymmetry, and interaction of IFE-specific features with pre-existing asymmetries. The end goal is to understand how ongoing experiments at the NIF can inform high gain fusion power systems.

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Absolute Gain-Coupling Coefficients for Stimulated Brillouin Scattering at 266 nm in Low-Pressure Gases

Stephen Messing*,[1] Thomas Reboli,[1] Andrey Mironov,[1,2] Conner Galloway,[2] John Gjevre,[3] Robert Fedosejevs,[3] and J. Gary Eden,[1]
[1]Department of Electrical and Computer Engineering, University of Illinois, 306 N. Wright St., Urbana, IL, 61801, USA
[2]Xcimer Energy, Inc., 10325 E. 47th Ave., Denver, CO, 80238, USA
[3]Electrical and Computer Engineering, University of Alberta, Edmonton, Alberta, Canada TG6 1H9
*messing5@illinois.edu

KrF excimer lasers are under consideration as drivers for laser fusion energy due to their ability to generate high energy UV radiation without significant concern for efficient cooling of the system or damage to the gain medium. However, for KrF laser fusion drivers to be realized, it will likely be necessary to scale the output to much higher peak intensities. Low-pressure Brillouin amplifiers have potential to compress high energy long excimer laser pulses to nanosecond durations (increasing peak intensity) with very high energy transfer efficiency. Additionally, low-pressure Brillouin amplifiers are desirable as they exhibit higher laser breakdown thresholds and minimize aberrations introduced to the beam profile. Previous work on SBS in gases has concentrated on high pressures ($p \geq 10$ atm) where hydrodynamic theory models have proven effective. Hydrodynamic models are expected to break down at low pressures, and instead kinetic models are expected to give more accurate predictions and different scaling laws for gain versus pressure. Nevertheless, some of the predictions given by kinetic models have yet to be confirmed experimentally. We present here measurements of the Brillouin gain spectra and peak gain-coupling coefficients compared to the kinetic theory model of Averbahk et al.[1] These measurements were performed by counterpropagating two frequency-quadrupled Nd:YAG pulses at a 5 mrad crossing angle in a gas cell containing up to 6 atm of the sample gas. The frequency detuning between pump and seed laser pulses was adjusted within a ±10 GHz range while measuring the incident and amplified seed pulse energies. Gain-coupling coefficients were directly calculated from the relative gain of the seed using interaction lengths calculated from a beam path simulation that intersects two pulses at the specified crossing angle. The peak gain-coupling coefficients for Ar and Kr are shown as a function of pressure in Fig. 1 along with the coefficients predicted by hydrodynamic and kinetic theory models. The data acquired to date and the results of modeling studies will be presented.

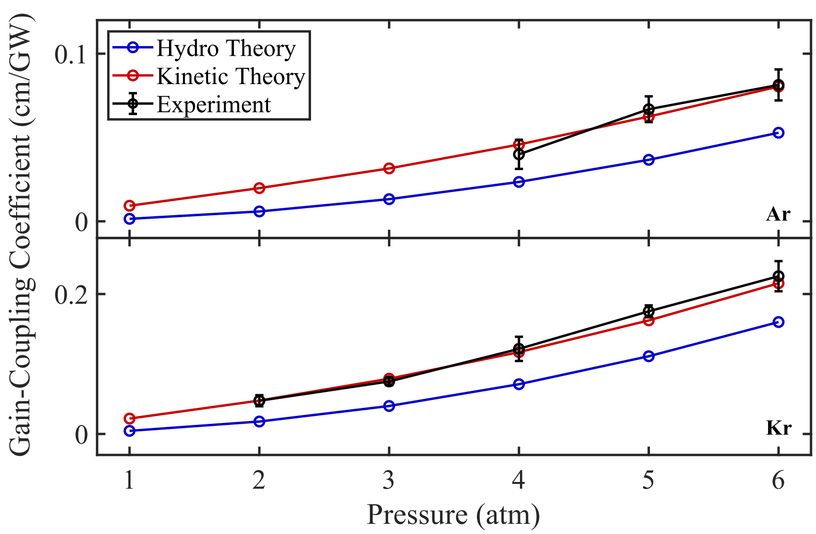

Fig. 1. The Brillouin gain-coupling coefficients for Ar (top), and Kr (bottom) as a function of cell pressure.

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Multidimensional Modeling of the Hybrid Shock Drive for Low-Adiabat Direct-Drive Fusion Experiments at the Omega Laser Facility

P.S. Farmakis, L. Ceurvorst, R. Betti, V. Gopalaswamy, C.A. Thomas, D. Cao, and A. Lees Laboratory for Laser Energetics, U. of Rochester

Recent advances in multidimensional modeling of the hybrid shock drive (HSD) platform for low-adiabat spherical implosions at the 60-beam Omega Laser Facility indicate that HSD is capable of mitigating laser imprint. During the early stages of the implosion of directly driven (LDD) cryogenic targets, imprint imparts high ℓ-mode perturbations which are not effectively smoothed by the still forming conduction zone. These unstable Rayleigh–Taylor modes grow rapidly with convergence, limiting current target designs on OMEGA at high adiabats ($\alpha > 4$). The mechanism that allows the HSD to suppress early imprint involves the conversion of the laser picket into x rays by means of a high-Z converter foil, which fully envelops the cryogenic target and is offset by a foam cushion. The x-ray burst drives a smooth initial shock into the target, which allows enough time for the conduction zone to expand before the target is directly illuminated by the laser, thereby also mitigating imprint at later times. Results of multidimensional simulations show that the imploding shell of a high- performance HSD target at a low adiabat ($\alpha \simeq 2$) is free from high ℓ-mode perturbations coming from the laser system, while its LDD counterpart does not survive the high ℓ-mode feedthrough. From these results, HSD appears to be a promising platform for high yield and ρR at low adiabats. Analysis of recent experiments on OMEGA EP and on the OMEGA-60, currently underway, will inform the next steps in modeling and in further optimization of the HSD platform. This material is based upon work supported by the Department of Energy [National Nuclear Security Administration] University of Rochester "National Inertial Confinement Fusion Program" under Award Number DE-NA0004144 and the DOE Office of Science under Award DE-SC0024381.

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

Raspberry Simpson[1], Drew Higginson[1], Tom Hodge[2], Mathieu Bailly-Grandvaux[3], Derek Mariscal[1], Elijah Kemp[1], Scott Wilks[1], Andreas Kemp[1], Jaya Sicard[1], Max Tabak[1], Ronnie Shepherd[1], William Riedel[1], Elizabeth Grace[1], Marius Millot[1], and Steve MacLaren[1]

1. *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
E-mail: simpson56@llnl.gov
2. *Orion Laser Facility, Aldermaston UK*
3. *Center for Energy Research, UC San Diego, San Diego CA 92093, USA*

Corresponding Author: simpson56@llnl.gov

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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Nanostructure of Polymer Foams using 3D Ptycho-tomography for Inertial Fusion Energy (IFE) Applications

Levi Hancock
Brigham Young University, Provo, UT, 84602
levijh1@gmail.com
Stanford Linear Accelerator Center, 2575 Sand Hill Rd, Menlo Park, CA 94025

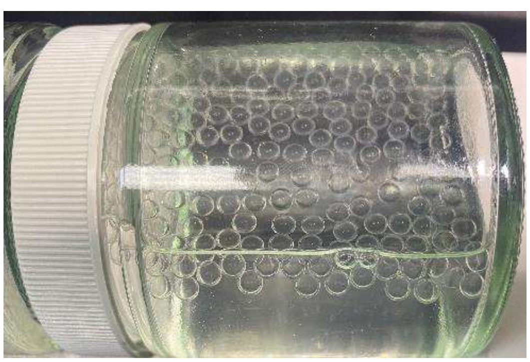
Contemporary designs of fuel capsules for laser-based fusion targets used in Inertial Fusion Energy (IFE) make use of polymer foams with nanostructure that increase the energy gain of fusion reactions. The lack of high-resolution characterization of pre-implosion micro- to nanostructure and models of these polymer foams, however, is hindering much needed progress in fuel capsule design/optimization. Utilizing the unique capabilities of an X-ray Free Electron Laser (XFEL), like total coherence and brilliance, and the Ptychographic X-ray computed tomography (PXCT) imaging technique, we reconstruct a 3D model of electron density of an IFE polymer foam material. We calculate quantitative information about the foam, such as localized density and variability of the wall thickness, which we then compare to fabrication specifications of the polymer foam. These comparisons inform further improvements in modeling and fabrication of polymer foams to improve future IFE experiments.

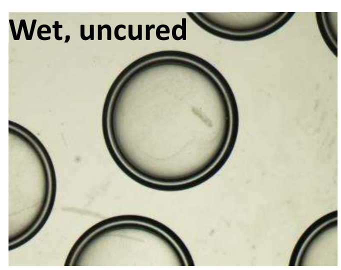
Advancing IFE Target Fabrication with Microencapsulated Dicyclopentadiene-Norbornene Foam Shells

S. Silva, V. Shiu, W. Sweet, F. Elsner, and N. Alexander
General Atomics, 3550 General Atomics Ct. San Diego, CA 92121
Sabrina.silva@ga.com

Future inertial fusion energy (IFE) power plants depend on the realization of cost effective, mass-produced targets. Foam shells for wetted foam IFE targets must achieve low densities (<50 mg/cc expected) to limit radiation cooling from higher Z elements from the foam mixed into the fuel hot spot, so as to still permit ignition. Thus, foam materials comprised of solely carbon (C) and hydrogen (H) atoms are better than those that also contain nitrogen or oxygen. Additional desirable properties for IFE foam shell targets include small pore sizes (<1 μm) and high mechanical strength. Previous works involving resorcinol formaldehyde and divinylbenzene foam shells have only achieved densities >50mg/cc. Oxygen (O) atoms retained within resorcinol formaldehyde's foam structure are also undesirable. While this issue is not observed in divinylbenzene, its foam shells exhibit pore sizes >1 μm, which complicates the application of smooth overcoats required for target fabrication. Thus, we have sought a new foam system compatible with micro-encapsulation for production of foam shells. After a literature search, we decided to pursue making foam shells via microencapsulation using dicyclopentadiene and norbornene.

In this work for the RISE hub of DOE's IFE-STAR program, we report the development of IFE foam shell targets made from dicyclopentadiene and norbornene (DCPD/NB). DCPD/NB and are solely comprised of C and H atoms. Using the microencapsulation technique, we have fabricated initial DCPD/NB foam shells that have nominal 25 mg/cc densities and fine pore sizes (<<1 μm), shown in the images below. We are currently improving the curing, solvent exchange, and supercritical drying steps in our shell fabrication process with goals to improve shell quality and fabrication yield. The work discussed herein supports a priority research objective for target fabrication included in DOE's Basic Research Needs for IFE workshop report.





Φ ~3500 μm
Wall ~350 μm

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Angular Distribution of Ions Accelerated by Irradiation of Nanowire Arrays with Laser Pulses of Relativistic Intensity

Jaden Hoechstetter,[1] Nashad Rahman,[1] Sina Zahedpour Anaraki,[2] Jim King,[2] M. Gabriela Capeluto, [2,3] Logan Byers,[1,2] Russell Meziere Jr., [4] Malik Carter, [4] Ping Zhang, [2] Reed Hollinger,[2] Shoujun Wang,[2] Alex Meadows,[2] Vyacheslav Shlypatsev,[2] Jorge Rocca[1,2]

[1]Physics Department, Colorado State University, Fort Collins, CO USA 80523
j.hoechstetter@colostate.edu
[2]Electrical and Computer Engineering Department, Colorado State University Fort Collins, CO USA 80523
[3]Departamento de Física, Universidad de Buenos Aires-IFIBA, 1428 Buenos Aires, Argentina 1428
[4]Department of Physics, Morehouse College, Atlanta, GA USA 30314

Laser-irradiated nanowire arrays act as micro-accelerators of high energy ions that can induce nuclear fusion reactions, producing high energy neutrons[1] and alpha particles[2]. Ions are accelerated by different mechanisms which include acceleration in the electric field of a space charge sheath that develops at the target surface, a well-studied mechanism known as transverse normal sheet acceleration (TNSA), radiation pressure, and other mechanisms which relative contributions depend on the conditions. In all cases ions are accelerated in the target normal direction. Here, we studied the angular distribution and flux of ions accelerated from CH_2 and Nickel nanowires and experimentally observed a significant amount of ions accelerated in the radial direction, in accordance to our previous prediction based on simulations[3]. This new form of radial TNSA accelerates ion within the target itself, allowing the energy to be deposited by collisions in the surrounding target material, where they can locally drive nuclear reactions. The results are relevant to applications that include new fusion energy schemes.

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Characterization of Proton Focusing from Hemispherical Targets

J. Griff-McMahon,[1] X. Vaisseau,[2] W. Fox,[3] K. Lezhnin,[4] K. Bhutwala,[4] M. Rivers,[4] V. Ospina-Bohorquez,[3] R. Nedbailo,[5] T. Bauer,[3] and S. Malko[4]
[1]Princeton University, 4 Ivy Ln, Princeton, NJ 08544
jgriffmc@pppl.gov
[2]Focused Energy, San Francisco Bay Area, CA
[3]University of Maryland, 8279 Paint Branch Dr, College Park, MD 20740
[4]Princeton Plasma Physics Laboratory, 100 Stellarator Rd, Princeton, NJ 08540
[5]University of Texas, 110 Inner Campus Drive, Austin, TX 78712

Tightly focused proton beams with high-energy-density are an essential ingredient to several applications including heating to warm dense matter and proton fast ignition (PFI). In this scheme of inertial confinement fusion (ICF), the compression and heating stages are largely decoupled: ns-duration lasers compress the fuel capsule, and a ps-duration proton beam heats it to ignition temperatures. PFI has gained recent interest due to the potential for higher fusion efficiency and weaker symmetry requirements than conventional hotspot ignition. Focused beams of protons are commonly generated through target normal sheath acceleration of a hemispherical curved foil so that protons are accelerated inwards, towards the geometric center of the hemisphere. However, there are still several open questions on basic characteristics of the beam such as the beam focus location and beam focal spot size.

Here, we conducted LaserNetUS high-rep-rate experiment at the ALEPH laser at Colorado State University to provide a first systematic characterization of the focusing dynamics of a proton beam generated from hemispherical foils of various diameters. The gold hemispherical foils were irradiated with a 25 J, 30 fs laser pulse to produce a proton beam. Mesh radiography was used to characterize the focusing behavior of the generated proton beams. A mesh placed after the proton focus encodes a mesh shadow on the beam and is used to infer the beam focus location based on the mesh magnification on the detector. The focus location of the proton beam is measured to be upstream of the hemi geometric center and dependent on the distance from the target to the mesh; the focus location moves towards the hemi geometric center as the mesh is moved further away. This trend suggests either (1) there is a beam-mesh interaction that curves the beam such as significant mesh charging or (2) the beam is still evolving at the mesh locations. The dependence of the beam pointing and divergence on the hemi diameter, mesh distance, and proton energy are also explored. The experimental data is used to benchmark EPOCH PIC simulations.

Bayesian and Particle Swarm Approaches to Inertial Confinement Fusion Implosions

J. J. Lee,[1] D. Coope,[2,3] J. Refern,[3] [1] R. Paddock, and P. Norreys[3]
[1]University of Oxford, Parks Rd, Oxford, Oxfordshire, OX1 3PU
Jordan.lee@physics.ox.ac.uk
[2]Central Laser Facility, STFC Rutherford Appleton Laboratory, Didcot, Oxfordshire, OX11 0QX
[J]John Adams Institute for Accelerator Science, Keble Road, Oxford, Oxfordshire, OX1 3RH

Central to the success of inertial confinement fusion (ICF) implosions is the optimisation of target configurations and laser drive profiles. However, this optimisation presents a formidable challenge due to the complex, high-dimensional nature of the design space, where numerous parameters influence implosion performance. This paper presents the development of general-purpose Bayesian optimisation and particle swarm optimisation (PSO) packages and their application to the optimisation of ICF implosions. Specifically, the optimisation of wetted-foam target designs and isochoric fuel assemblies for fast ignition (FI) ICF are presented. Wetted-foam targets are of particular interest due to the control they provide over hydrodynamic properties of the implosion, providing a method of improving implosion quality by mitigating performance-degrading instabilities. The optimisation process explores fusion performance in a regime robust to instabilities and benchmarks our results against previous optimisation efforts, showcasing the advantages of Bayesian and PSO methods over traditional approaches. Additionally, these optimisation tools are applied to isochoric fuel assemblies for FI, a concept that separates the compression and ignition phases to enhance fusion yield. These findings demonstrate the significant improvement of implosion designs when utilising these optimisation techniques and highlight the potential of Bayesian optimisation and PSO to advance ICF target design, paving the way for more efficient and effective fusion energy research.

Numerical simulations of laser-driven experiments of ion acceleration in stochastic magnetic fields.

K. Moczulski[1], H. Wen[1], T. Campbell[2], A. Scopatz[1], C. A. J. Palmer[3], A. F. A. Bott[2], C.D. Arrowsmith[2], K. A. Beyer[4], A. Blazevic[5], V. Bagnoud[5], S. Feister[6], J. Halliday[2], O. Karnbach[2], M. Metternich[5], H. Nazary[7], P. Nuemater[5], A. Reyes[1], E. C. Hansen[1], D. Schumacher[5], C. Spindloe[8], S. Sarkar[2], A.R. Bell[2], R. Bingham[8], F. Miniati[2], A.A. Schekochihin[2], B. Reville[4], D.Q. Lamb[10], G. Gregori[2], P. Tzeferacos[1]

[1]University of Rochester, Rochester, New York 14627, USA

[2]University of Oxford, Oxford, OX1 3PU, United Kingdom
[3]Queens University Belfast, Belfast, BT7 1NN, United Kingdom
[4]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany
[5]GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany
[6]California State University Channel Islands, Camarillo, California, 93012, USA
[7]Technische Universität Darmstadt, D-64289 Darmstadt, Germany
[8]STFC Rutherford Appleton Laboratory, Didcot, OX11 0QX, United Kingdom
[9]Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany
[10]University of Chicago, Chicago, IL 60637, USA

We present numerical simulations used to interpret laser-driven plasma experiments at the GSI Helmholtz Centre for Heavy Ion Research. The mechanisms by which non-thermal particles are accelerated, in astrophysical environments e.g., the solar wind, supernova remnants, and gamma ray bursts, is a topic of intense study. When shocks are present the primary acceleration mechanism is believed to be first-order Fermi, which accelerates particles as they cross a shock. Second-order Fermi acceleration can also contribute, utilizing magnetic mirrors for particle energization. Despite this mechanism being less efficient, the ubiquity of magnetized turbulence in the universe necessitates its consideration. Another acceleration mechanism is the lower-hybrid drift instability, arising from gradients of both density and magnetic field, which produce lower-hybrid waves with an electric field which energizes particles as they cross these waves. With the combination of high-powered laser systems and particle accelerators it is possible to study the mechanisms behind cosmic-ray acceleration in the laboratory. In this work, we combine experimental results and high-fidelity three-dimensional simulations to estimate the efficiency of ion acceleration in a weakly magnetized interaction region. We validate the FLASH MHD code with experimental results and use OSIRIS particle-in-cell (PIC) code to verify the initial formation of the interaction region, showing good agreement between codes and experimental results. We find that the plasma conditions in the experiment are conducive to the lower-hybrid drift instability, yielding an increase in energy of approximately 264 keV for 242 MeV calcium ions.

Fabrication of nanowire array strips for characterizing ion acceleration in relativistic laser-nanostructure interactions.

Nashad Rahman[1], Jaden Hoechstetter[1], Sina Zahedpour Anaraki[2], Jim King[2], M. Gabriela Capeluto[2,3], Ping Zhang[2], Reed Hollinger[2], Shoujun Wang[2], Alex Meadows[2], Vyacheslav Shlypatsev[2], Jorge Rocca[1,2]

Nashad.Rahman@colostate.edu

[1]*Physics Department, Colorado State University, Fort Collins, CO USA*
[2]*Electrical and Computer Engineering Department, Colorado State University Fort Collins, CO USA*
[3]*Departamento de Física, Universidad de Buenos Aires-IFIBA, 1428 Buenos Aires, Argentina*

Nanostructures can efficiently couple intensive laser energy into matter, resulting in extreme energy densities [1]. Experiments and simulations have demonstrated that the interaction of intense, high contrast, femtosecond laser pulses with high aspect ratio nanostructures can accelerate ions to multi-MeV energies, leading to nuclear fusion. An initial demonstration of D-D fusion reactions resulted from intense laser irradiation of arrays of aligned CD2 nanowires, which accelerated deuterons to MeV energies. Development of new nanostructured targets is essential to increasing laser energy absorption efficiency and for characterization of the interaction,
Here, we discuss the fabrication and characterization of strips of nanostructures to be used in experiments designed to measure the angular distribution of the accelerated ions. Strips of nickel and CH2 Nanowires 10 micrometers in width were fabricated using electroplating of metals and heated extrusion of polymers. Using UV lithography, nanowires can be grown only in designated regions of a target to form strips. New methods of nanowire fabrication involve two photon polymerization, which allows for more organized arrays of nanowires were demonstrated. These nanowire strips were successfully uses in experiments, the results of which will be presented in an accompanying poster.

Acknowledgements: U.S. Department of Energy (DOE), Office of Science, Fusion Energy Sciences, Award No. DE-SC0024882: IFE-STAR, using facilities supported by LaserNet US, DOE grant US DE- SC0021246.

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Neutron Production in Krypton on Deuterium Gas Puff Z-Pinches

O. Yang,[1] R. Beattie-Rossberg,[1] K. Inzunza,[1] A. Shah,[1] H. U. Rahman,[2] E. Ruskov,[2] A. E. Youmans,[3] D. P. Higginson,[3] and F. N. Beg[1]
[1]University of California, San Diego, 9500 Gilman Dr, La Jolla, CA 92093
oryang@ucsd.edu
[2]Magneto Inertial Fusion Technologies, Inc., 2600 Walnut Ave suite a, Tustin, CA 92780
[3]Lawrance Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550

Z-Pinches are a well studied fusion concept[1] that have exhibited prohibitive challenges in the past. Developments in driver technology and load designs, however, have led to renewed interest in the concept for fusion energy applications. One such technology is the linear transformer driver (LTD) which allows for Z-pinch devices to have a smaller footprint and operate at lower voltages than the traditional Marx generators. Utilizing this technology with the gas-puff staged Z-pinch load, experiments studying fusion have been carried out on the CESZAR LTD at UCSD[2]. CESZAR is an LTD capable of delivering 500 kA in 160 ns to a load in vacuum. The experiments presented here focus on Krypton liner on Deuterium target gas puff implosions.

The primary diagnostic for these experiments was a LaBr neutron activation detector, part of the PANDA-FES diagnostic suite developed at Lawrence Livermore National Laboratory[3]. Neutrons produced in the pinch activate the ^{79}Br and ^{89}Y in the detector, and their decay is measured by a scintillator and photo multiplier tube. This gives the fluence of neutrons from the pinch, which can be used to determine the total yield from the shot. Typical yields on CESZAR with Krypton on Deuterium are in the range of 10^6-10^8 neutrons. Adjusting the density of deuterium in the target, which can be done through adjustments to the plenum pressure, leads to changes in the resulting yield. Results of these adjustments will be presented here.

Along with neutron yield measurements, X-ray diodes, XUV framing cameras, and Schlieren imaging are used for diagnosing the pinch. X-ray diodes give a sense of relative x-ray yields and the time of peak compression. XUV images and schlieren images provide time gated images of the pinch during the implosion, which give information about stability, implosion velocity, and implosion radius. While the ultimate goal is high neutron yields, it is important that the pinch is stable so that it can be repeated and burn a larger fraction of the fuel. Images of the pinches are presented alongside neutron yields in this poster.

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Experimental Study of Proton Heating in Proximally Structured Cu Foam Targets*

P. Samimy,[1] C. McGuffey,[2] M. Bailly-Grandvaux,[1] J. Kim,[1] S. Bolaños,[1] and F. N. Beg[1]
[1]Center for Energy Research, University of California, San Diego, 3183 Matthews Ln, La Jolla, CA 92093
[2]General Atomics, 3550 General Atomics Ct, San Diego, CA 92121
psamimy@ucsd.edu

In conventional inertial confinement fusion (ICF), laser pulses are used to simultaneously compress, heat, and finally ignite a fuel capsule triggering a self-sustained thermonuclear burn.[1] Now the goal is to increase gain so that inertial fusion energy (IFE) becomes economically viable. Fast Ignition (FI) is an advanced ICF scheme that offers higher gains than conventional methods by using separate sets of compression and ignition beams to reduce laser energy and symmetry requirements.[2] Proton beams are particularly well suited to heating the compressed fuel because they can be tightly focused and provide a high rate of energy deposition with minimal transport instabilities.[3,4] Despite the resulting interest that has recently developed in the IFE community surrounding proton-driven FI (PFI), many aspects of proton acceleration, transport, and energy deposition are still not yet fully understood.

In support of addressing this knowledge gap, a PFI experiment was conducted at the Institute for Laser Engineering to study proton heating in proximally structured Cu foam targets. The protons were accelerated by irradiating a curved C foil (R300 µm, 1 µm thick) with the LFEX laser (~1 kJ on target, 1.5 ps, 1053 nm, I >2×10^{19} W/cm^2). The foil was located 500 µm from the tip of an open gold cone, where the focused proton beam was delivered to a Cu foam cylinder (1 mm L, 250 µm ϕ, 1.1 g/cm^3). A HOPG x-ray spectrometer and three proton/electron spectrometers measured the energy spectra with and without the cylinder. When included, the 8.048 keV copper K_α emission was visualized using two narrow-band Spherical Crystal Imagers mounted orthogonal to and above the LFEX axis. Several proximal structure geometries of varying complexity were tested to evaluate their relative effects.

The free-standing foil yielded 11% laser coupling efficiency, but adding the extra focusing cone mass reduced this to 0.6% causing decreased proton yield and maximum energy. The proton spectra were further analyzed to reveal that the $\rho\tau=0.11$ g/cm^2 cylinder absorbed 93% of the proton energy. Particle-in-cell simulations of the proton and electron beams interacting with the Cu foam, incorporating new stopping power models, showed that both species heated the foam. Work is also in progress to estimate the cylinder temperature by comparing simulated x-ray emission spectra from the PrismSpect atomic code with experimental measurements. Results will be presented at the conference.

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*In collaboration with H. Habara, S. Noma, T. Ohtsuki, A. Tsujii, K. Yahata, Y. Yoshida, Y. Uematsu, S. Nakaguchi, A. Morace, A. Yogo, H. Nagatomo, K. Tanaka, Y. Arikawa, S. Fujioka, H. Shiraga, (ILE, OSAKA UNIV)

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The effect of broad laser bandwidth on the two-plasmon decay instability and its connection to turbulence

Rusko T. Ruskov[1]
[1]Department of Physics, Atomic and Laser Physics sub-Department, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom
rusko.ruskov@physics.ox.ac.uk

Broad-bandwidth laser technology has attracted considerable interest for its high potential impact on direct-drive ICF. Large enough laser bandwidth is expected to lead to substantial suppression of the deleterious parametric instabilities occurring in the coronal plasma, thereby unlocking the ablation pressures required for IFE-relevant gains. Therefore, detailed understanding of the effects of laser bandwidth on the various instabilities is paramount.

From a theoretical point of view the complications arise from the fact that such a problem can be statistically nonlinear and statistically inhomogeneous, even in a uniform plasma during the linear stage of the instability. Recent techniques developed to tackle similar problems in a magnetic confinement as well as geophysical contexts, are applied to the two plasmon decay instability (TPD).

We derive a dispersion relation for it valid under laser fields with arbitrary power spectra. When investing the effects of temporal incoherence, growth rates are shown to be more sensitive to the laser spectral shape, rather than the coherence time. Laser bandwidth is also seen to broaden the range of plasma waves generated by two plasmon decay, making the absolute modes accessible in regions further away from the quarter critical density[1]. The resulting spectra show good agreement with LPSE simulations.

These results are extended to the non-linearly saturated regime of TPD. The turbulent plasma state excited by the instability significantly modifies the nature of the interaction. A renormalized theory of TPD which takes the turbulent background into account is developed. We will discuss its implications on the instability saturation levels (and hence hot electron production) and their dependence on laser bandwidth.

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The electrothermal filamentation of igniting plasmas

H. Martin,[1] R. W. Paddock,[1] M. W. von der Leyen,[1] V. Eliseev,[1,2,3] R. T. Ruskov,[1] R. Timmis,[1] J. J. Lee,[1] A. James,[1] and P. A. Norreys[1,4]
Heath.martin@univ.ox.ac.uk
[1]Department of Physics, Atomic and Laser Physics sub-department, Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom
[2]IBM Research Europe, The Hartree Centre, Daresbury Laboratory, Keckwick Lane, Warrington WA4 4AD, United Kingdom
[3]Wrexham University, Mold Rd, Wrexham LL11 2AW, United Kingdom
[4]John Adams Institute for Accelerator Science, Denys Wilkinson Building, University of Oxford, Keble Road OX1 3RH, United Kingdom

Dense, hot plasmas are susceptible to the electrothermal instability[1,2]: a collisional process which permits temperature perturbations in electron currents to grow. We show that linearizing a system comprised of two opposing currents and a mobile ion background as three distinct fluids yields unstable modes with rapid growth rates (~10^13 s−1) for wavenumbers below a threshold kth. An analytical threshold condition is derived, this being surpassed for typical hot-spot and shell parameters. Particle-in-cell simulations successfully benchmark the predicted growth rates and threshold behavior. Electrothermal filamentation within the shell will produce magnetic fields, which is known to impact the burn wave propagation into the cold fuel[3,4] and resulting burn dynamics.

The electrothermal instability is driven by a flux of hot electrons and fusion alphas into the shell. A computational model capable of capturing kinetic electrons and fusion alphas is being developed to characterize this current and capture other electron kinetic effects potentially relevant to ignition and burn propagation.

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Wednesday, April 9

Time	Name	Institution	Abstract Title
Session I - Target Technology		**Carmen Menoni, Chairperson**	
8:30 AM	George Larsen	Savannah River National Laboratory	Assessing the Impacts of IFE Target Materials on the D-T Fuel Cycle
9:15 AM	Holly Flynn	Savannah River National Laboratory	Process Modeling and the Development of a Real-Time Monitoring and Accountancy Open Framework for Fusion Energy
9:35 AM	Alex Somers	Savannah River National Laboratory	Effects of Target Protium Content on Steady-State Protium Removal and Isotope Rebalancing Distillation Column Operation
9:55 AM	Kazuki Matsuo	EX-Fusion	10Hz Laser Beam Steering and Illumination for Continuously Delivered Targets
10:15 AM	Break		
Session II - Target Technology		**John Edwards, Chairperson**	
10:40 AM	Abbas Nikroo	Lawrence Livermore National Laboratory	Target Fabrication: From Single Shot Ignition to Rep-Rated IFE
11:00 AM	Neil Alexander	General Atomics	Development of Fabrication Methods for Wetted Foam Targets
11:20 AM	Sourabh Saha	Georgia Institute of Technology	Fast and Accurate Printing of Nanoporous Foams for IFE Targets
11:40 AM	Arianna Gleason	SLAC National Accelerator Laboratory	Static & Dynamic Phase Contrast Imaging of Inertial Fusion Energy Foams at the Linac Coherent Light Source
12:00 PM	Lunch Provided		
2:00 PM	Teambuilding	Hike to see the Isak Heartstone troll (.7 miles) followed by happy hour at Breckenridge Brewery (600 S. Main St) Meet in the coffee shop at Gravity Haus (605 S. Park Ave)	
7:00 PM	Kramer Akli	U.S. Department of Energy	Hubs/Private Sector Engagement
8:30 PM	Poster Session III		

Assessing the Impacts of IFE Target Materials on the D-T Fuel Cycle

George Larsen, Brenda Garcia-Diaz, Alex Somers, Arron Rowell, Collin Malone, Holly Flynn
Savannah River National Laboratory
george.larsen@srnl.doe.gov

The development of a sustainable deuterium-tritium (D-T) fuel cycle for inertial confinement fusion energy (IFE) poses unique challenges and opportunities. Two key features distinguish an IFE fuel cycle from other fusion approaches: a larger high burn-up fraction and compression of a target comprising non-fuel elements. Consequently, the presence of significant non-D-T target material and isotopic impurities such as protium in the target polymers leads to impurity flows that can be comparable to or even significantly exceed the flow of unburned fuel.

For a sustainable fuel cycle, it is essential to quickly separate and efficiently process these impurities to recover tritium incorporated within the stream. The fuel processing plant must then blend this recovered D-T with tritium extracted from breeding materials to create new targets, thereby closing the fuel cycle. This involves pressurizing, storing, and transferring the gases to a fuel fabrication facility to produce enough targets to meet a fuel injection rate of approximately 1-20 Hz.

Additionally, the fuel cycle must effectively address the clean-up of target debris following each fusion event. As highlighted by research from Lawrence Livermore National Laboratory (LLNL) and others, target debris can significantly impact reactor components and complicate the tritium recovery process. Integrating debris management strategies into the fuel cycle is crucial for minimizing contamination and maintaining operational efficiency. Techniques for debris mitigation and removal must be developed and optimized to ensure the longevity and safety of the IFE system.

The target preparation process significantly impacts fuel cycle design and exemplifies the unique demands IFE places on tritium processing systems. IFE fuel cycle research at SRNL underscores the importance of integrating D-T fuel cycle management with target design, plasma physics, and debris clean-up strategies in the co-design of an IFE facility. This holistic approach is crucial for addressing the specific challenges of IFE and ensuring the sustainability of its fuel cycle

Process Modeling and the Development of a Real-Time Monitoring and Accountancy Open Framework for Fusion Energy

Holly B. Flynn[1], Larry M. Deschaine[1], William E. Gilbraith[1], Robert J. Lascola[1], Collin A. Malone[1], George K. Larsen[1], Paul A. Rowell[1], Houston H. Smith[1], and Alex D. Somers[1]
Savannah River National Laboratory, SRNL, Aiken, SC, 29808-0001
*holly.flynn@srnl.doe.gov

The fuel cycle for a commercial fusion plant will need to operate continuously while both breeding and consuming tritium with only occasional interruptions for maintenance. Current DT fuel cycles for defense applications or pre-pilot fusion devices (e.g., JET, ITER, etc.) have only operated on a non-continuous/batch basis. Current measurement approaches are not designed for the real-time accountancy required for a continuously operating fusion fuel cycle that will have a dynamically changing tritium inventory. The Tritium Facilities at the Savannah River Site (SRS), which have a relatively stable tritium inventory, accounts for a full physical inventory of tritium in their systems every two years. SRS is required under DOE Order 474.2 to demonstrate 95% confidence that there is not more than 1% error in the accuracy of the accountancy every year and be able to generate accurate physical inventories in under 24 hours. These requirements will be challenging for commercial fusion due to the integrated system complexity of a fusion fuel cycle that needs to consider the losses from burn-up, permeation into and through materials, and gains through breeding. This talk provides an overview of SRNL's efforts with process modeling and the foundations of a tritium accountancy framework, emphasizing potential differences between IFE and MFE.

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* This work was produced by Battelle Savannah River Alliance, LLC under Contract No. 89303321CEM000080 with the U.S. Department of Energy

Effects of Target Protium Content on Steady-State Protium Removal and Isotope Rebalancing Distillation Column Operation

Alex D. Somers[1], P. Arron Rowell [1], Collin Malone[1], Holly B. Flynn[1], George K. Larsen[1]
Savannah River National Laboratory, SRNL, Aiken, SC, 29808-0001
alex.somers@srnl.doe.gov

Target design and material selection varies among inertial fusion energy concepts. Polymers have been proposed as a viable target encapsulation material and will introduce additional protium content in the fuel cycle. Increased protium content in fusion exhaust streams will require additional isotope separation capacity within the fuel cycle to ensure sufficiently detritiated protium waste streams. Deuteration of polymer targets can mitigate the introduction of excess protium but with the tradeoff of increased fabrication cost per target. Technology selection for isotope separation will depend on the requisite separation efficiencies and flow rates to mitigate protium content in the target and ensure reliable delivery of pure deuterium-tritium fuel to the fueling system, both of which are necessary for the viability of inertial fusion energy. This work presents a preliminary design optimization study for a continuously operated cryogenic distillation column for protium removal and isotope rebalancing. In the case where dueterated polymers are implemented, this column serves as an isotope rebalancing column. The work was performed using the CryOgenic Distillation For Isotopic Separation of Hydrogen (CODFISH) code developed at Savannah River National Laboratory. Effects of the protium content in targets on the design and operating parameters of a steady-state protium removal column are presented.

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* This work was produced by Battelle Savannah River Alliance, LLC under Contract No. 89303321CEM000080 with the U.S. Department of Energy

10Hz Laser Beam Steering and Illumination for Continuously Delivered Targets

K. Matsuo,[1] H. Minato,[1] Y. Yoshimura,[1] K. Agatsuma,[1] Y. Hironaka,[1] M. Ishii,[1] R. Mori,[1] K. Urabe,[1] N. Kanmaki,[1] T. Sugimoto,[1] K. Sugita,[1] K. Sueda,[1] Y. Takagaki,[1] T. Chiba,[1] T. Mitsui,[1] N. Hayashi,[2] K. Ishii,[2] and Y.Mori,[1,2]
[1]EX-Fusion Inc., Osaka, Japan
kazuki_matuso@ex-fusion.com
[2] The Graduate School for the Creation of New Photonics Industries (GPI), Hamamatsu, Japan

To realize commercial laser-driven Inertial Fusion Energy (IFE), EX-Fusion has developed the eX-Fusion Continuous Operation Laser Reactor (XF-COLR) in Hamamatsu, Japan. This private fusion research facility integrates high-repetition-rate target injection and multi-beam laser systems, addressing key challenges for scalable fusion power plants.

The facility is designed to replicate critical aspects of the fusion process through two laser systems: an Implosion-Mimic Laser, a four-beam system at 0.53 µm, currently delivering 0.7 J per 9 ns pulse at 10 Hz, simulating fuel compression, and a Heating-Mimic Laser, a two-beam system at 0.8 µm, currently delivering 2 TW (0.2 J/100 fs) at 10 Hz, mimicking fast heating for ignition. Additionally, the facility includes a 10-Hz free-fall bead pellet injector, capable of delivering 1-mm stainless steel pellets, supporting high-energy-density plasma experiments. Advanced X-ray pinhole imaging diagnostics enable plasma temperature measurements.

EX-Fusion has successfully demonstrated 10-Hz laser tracking and illumination of free-falling targets, achieving 200 µm horizontal and 56 µm vertical tracking accuracy, marking a major step toward reactor-scale fusion target engagement. To further advance IFE development, XF-COLR will undergo significant upgrades in FY2025, including an increase in Implosion-Mimic Laser energy to 4 J per 7 ns pulse at 10 Hz for enhanced compression simulations and an upgrade of the Heating-Mimic Laser to 10 TW (0.6 J/60 fs) at 10 Hz, improving fast ignition research. These enhancements will bridge the gap between laboratory-scale experiments and reactor-scale fusion feasibility, providing a unique testbed for repetitive high-power laser-plasma interactions.

Building on these advancements, EX-Fusion aims to improve laser tracking precision to below 50 µm for reactor-scale accuracy, automate target injection and laser alignment for continuous operation, and transition from XF-COLR's experimental phase to a pilot-scale fusion energy demonstration. Leveraging diode-pumped laser technology and high-throughput ignition systems, EX-Fusion is positioning itself as a global leader in the development of commercial laser fusion energy.

Target fabrication: From Single Shot Ignition to Rep-Rated IFE*

A. Nikroo, S. Bhandarkar, W. Moestopo, J. Oakdale, M. Stadermann and X. Xia
Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA, USA 95550

Central in the achievement of ignition at NIF was the focused effort over the last two decades in precision target engineering and scientific R&D, production and cryogenic fielding along with associated metrology at nm levels on mm size objects for the “single shot” ICF program. In this talk we will discuss the highlights of such developments particularly as they relate to the challenge of doing the same for IFE at a rate of 106 higher where a properly fueled target of required quality and fabrication rate compatible with the rest of the plant will again be a critical part of the picture. We will also discuss various current and planned developmental efforts in IFE target fabrication at LLNL using a number of innovative approaches as well as tapping into the lessons learned from NIF, all ideally with close partnership with other labs and entities, to address some of the critical path items towards such a target supply to accelerate realization of IFE needs.

LLNL-PROC-872405

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Development of fabrication methods for wetted foam targets*

N. Alexander, J. Williams, W. Sweet, S. Silva, V. Shiu F. Elsner, A. Haid, M. Jaris and M. Do
General Atomics, 3550 General Atomics Ct, San Diego, CA, 92121
Neil.Alexander@ga.com

Production of wetted foam capsules for inertial fusion energy (IFE) is priority research opportunity listed in the DOE Basic Research Needs for IFE workshop report[1]. A wetted foam target typically consists of or includes a spherical polymer shell with a layer of low-density polymer foam just inside the shell. The foam layer would be used to wick in and create a layer of liquid DT filling the foam. Lower density foams are wanted in this application since the carbon and other high atomic number elements in the foam are mixed with the DT increasing radiative losses in DT fuel during the implosion of the target making ignition of the target more difficult. Polymer with just carbon and hydrogen (or deuterium) are preferred over those that also contain some oxygen or nitrogen for this same reason. Faster filling of liquid DT via wicking into a foam shell (10's of seconds expected) would greatly lower tritium inventory of the IFE DT target fill system compared to kg tritium quantities that would be required for permeation gas filling targets[2].

We are developing spherical foam shells with density ≤50mg/cm^3. Two different approaches to the manufacture of these shells are being pursued: microencapsulation and additive manufacturing via two photon polymerization (2PP). We report on our progress towards making the low-density foam shells by these two approaches. We outline the design of micro-projection-2PP printer for IFE (STARFIRE). We have microencapsulated dicyclopentadiene/norbornene (DCPD/NB) foam shells at 25mg/cm^3 (RISE). This is a pure CH chemistry. We have taken some of these foam shells through solvent exchange and critical point drying steps and continue to work to improve quality and fabrication yield. We have developed techniques to microencapsulate our GACH pure CH or CD foam. In the previously available cast or cast and machine techniques, GACH foam has been made in billets with density from 5 to 200 mg/cm^3 and submicron pore size[3]. We have made microencapsulated GACH foam shells with a nominal density of 15 and 25mg/cm^3, diameters of 3 to 4 mm and wall thicknesses of ~100 to 200 µm. We continue to improve wall uniformity and drying processes for these foam shells.

Methods for deterministic symmetry control in micro-encapsulated capsules/foam shells will also be outlined.

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[1] REPORT OF THE FUSION ENERGY SCIENCES 2022 BASIC RESEARCH NEEDS WORKSHOP ON INERTIAL FUSION ENERGY, https://science.osti.gov/-/media/fes/pdf/workshop-reports/2023/IFE-Basic-Research-Needs-Final-Report.pdf
[2] Schwendt et al, Fusion Sci. &Tech. 43:2, March 2003, 217-229, DOI: 10.13182/FST03-A262
[3] M. J.-E. Manuel, et al, Matter and Radiation ant Extremes 6, 206904 (2021), https://doi.org/10.1063/5.0025374

Fast and Accurate Printing of Nanoporous Foams for IFE Targets*

Golnaz Aminaltojjari,[1] Sourabh K. Saha[1]

[1]George W. Woodruff School of Mechanical Engineering,
Georgia Institute of Technology, 801 Ferst Drive, Atlanta, GA 30332, USA.

Email: ssaha8@gatech.edu

Scalable and affordable manufacturing of targets is a key technological hurdle that must be overcome to achieve economically viable inertial fusion energy (IFE). For fusion to be economically competitive, targets must be produced at a fraction of the current cost and at much higher speeds. Toward this goal, the aim of our project is to generate the processing science for a scalable additive manufacturing (AM) approach to produce spherical shell and wetted-foam capsule targets. Spherical wetted-foam capsules are being considered for future IFE targets because the foam layer can allow for easier and cost-effective filling and layering of the liquid DT fuel through wetting. Despite the existing knowhow for producing these capsules, today's manufacturing technologies cannot satisfy the needs for IFE due to their extremely poor production rate and cost. For example, the cost of fusion targets must be reduced from more than tens of thousands of dollars to less than a dollar. Such a massive improvement will require novel target manufacturing technologies that are inherently scalable while simultaneously capable of achieving the extreme precision of current techniques. Here, we present our recent work in developing the desired target manufacturing capability based on nanoscale AM.

Nanoscale AM based on two-photon polymerization (2PP) can achieve the extreme precision required for IFE targets due to its ability to print complex 3D structures with building blocks as small as 100 nm[1]. 2PP uses focused light beams to cure photopolymer material with nanoscale precision. One of the key advantages of AM for target manufacturing is its ability to produce complex yet deterministic geometries for the double-layered spherical foam targets. Furthermore, AM can enable high-yield target designs with precise sphericities and gradients in foam density. However, current forms of 2PP have limitations that make them unsuitable for producing fusion targets. For IFE-relevant wetted-foam targets, the foam must have pores smaller than about 1 µm and a density about 1/20th that of bulk material, which is on the order of 50 mg/cc. These combinations have neither been achieved in 2PP foams in the past, nor are they achievable with current 2PP processing knowhow due to the density versus pore size tradeoff inherent to deterministic foams. A key limitation is that at submicron pore sizes, stochastic defects emerge within the pores due to excessive uncontrolled printing. It is generally considered that these defects originate from the proximity effects, but their origins are not well understood.

In our work, we have investigated the origins of proximity effects by performing 2PP with various custom-made photopolymer feedstock materials. Through experiments, we demonstrate that the proximity effects arise from the spatio-temporal dynamics of the photopolymerization termination reactions. We also demonstrate how these dynamics can be controlled to minimize the proximity effects by tuning the composition of the photoresist. This knowledge was then applied to print exemplary foam structures with 250 – 400 nm pore wall thickness and 1-5 µm pore sizes at five times higher speeds than past demonstrations. To contextualize this improvement for IFE, we will also present our proposed AM-based target manufacturing technology development roadmap for economically viable IFE[2].

*This work conducted under the auspices of the U.S. Department of Energy, under the Early Career Research Program (grant number DE-SC0025461) from the Office of Fusion Energy Sciences.

[1] S.K. Saha, et al., "*Scalable submicrometer additive manufacturing,*" Science **Vol. 366**, pp. 105-109 (2019).
[2] S.K. Saha, "*Additively manufactured nanoporous foam targets for economically viable inertial fusion energy*," Societal Impacts **Vol. 3**, p. 100029 (2024).

Static & Dynamic Phase Contrast Imaging of Inertial Fusion Energy Foams at the Linac Coherent Light Source

A. Gleason[1] & R. Sandberg[2]
[1]SLAC National Accelerator Laboratory, 2575 Sand Hill Rd., Menlo Park, CA 94025
[2]Brigham Young University, Provo, UT 84602
ariannag@stanford.edu; rsandberg@byu.edu

Foams can be fabricated with tailored physical characteristics -- initial density, dimensions, micro/nanostructure and chemical composition, which can all be designed for a given application. Precision manufactured foams play a central role in experiments envisioned for delivering nuclear fuel in future inertial fusion energy (IFE) power plant concepts. A possible way to increase fusion yield in IFE is to use foams wetted with deuterium and tritium (D/T) fuel inside the capsule. However, these novel foam materials are not well studied or understood. Questions remain regarding their dynamic response, equation of state and influence of starting nanostructure on seeding hydrodynamic instabilities and fuel mix. Critical benchmarking experiments are needed to for strategic implementation in IFE schemes, such that dynamic behavior can be accurately modeled in radiation hydrodynamic codes. As part of the IFE-STAR RISE Hub, our team at Brigham Young University, SLAC National Accelerator Laboratory and collaborators at LANL, UC San Diego, and LLNL have been studying 3D printed polymer foams at the Linac Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory.

We imaged IFE foams with 3D static x-ray ptychographic-tomography on several types of samples, including copper nanofoams, aerogels and two-photon polymerized foams. These images provide information about nanometer scale densities and chemical composition. Additionally, we have performed single shot, ultrafast x-ray imaging of laser-driven shock-wave interactions with voids in capsule ablator surrogates and in foams at the LCLS Matter in Extreme Conditions (MEC) instrument. As we compare our ultrafast x-ray images with xRAGE hydrodynamic code simulations, we can better understand these materials for future IFE applications.

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*This work conducted under the auspices…. If you do not have anything to credit, delete this line and the asterisk at the end of the title.

[1] A. Name, B. Name, and C. Name, "*Paper title,*" Journal name **Vol**, page (year). (Remove if no references.)
[2] A. Name and B. Name, Institution, personal communication (year). (Remove if no references.)

Wednesday, April 9 – Poster Session III

Number	Author	Institution	Abstract Title
P-1	Leland Ellison	Pacific Fusion	Current-Driven ICF Target Design with FLASH
P-2	Mario Manuel	General Atomics	High-Repetition-Rate Technology Development on GALADRIEL Relevant to the Inertial Fusion Energy Industry
P-3	Muhammad Fauzan Syahbana	The University of Osaka	High Spectral Resolution X-Ray Thomson Scattering Diagnostics in High Density D2 Plasma
P-4			
P-5	Sonya Dick	South Dakota School of Mines & Technology	A Framework to Measure the Viscosity of HED Materials via Hydrodynamic Instabilities
P-6	Varchas Gopalaswamy	University of Rochester	A Physics-Based Bayesian Optimization Framework for Direct-Drive Implosions on Rep-Rated Facilities
P-7	Wojciech Rozmus	University of Alberta	Theory of Thomson Scattering via Ray Tracing Simulations
P-8	Jorge Rocca	Colorado State University	Multi Mega-Electron Volt Ion Acceleration in Nanowire Arrays Irradiated with Laser Pulses of Relativistic Intensity for IFE Concepts
P-9	Justin Galbraith	Lawrence Livermore National Laboratory	LD-FIRST (Laser Driven Fusion Integration Research and Science Test Facility): Design, Progress, and Future Development Pathways
P-10	Alenna Streeter	Sydor Technologies	Plasma Electrode Pockels Cell Technology (PEPC) for Inertial Confinement Fusion Energy
P-11	Mackenzie Nelson	Lawrence Livermore National Laboratory	Techno-Economic Inertial Fusion Power Plant Design through the Integrated Process Model (“IPM”)
P-12	Wolfgang Theobald	Focused Energy	An Implosion Test Facility for Laser Direct-Drive IFE
P-13	Xiao Chen	Lawrence Livermore National Laboratory	Inference of Anomalous Thermal Transport Using Bayesian Optimization with Uncertainty Quantification in Plasma Boundary
P-14	Alexey Zheltikov	Texas A&M University	On Nondamaging Laser-Damage Risk Assessment
P-15	Mark Moffett	SpaceWave, LLC	Scalable Modular Solid State Switching for Pulsed Power Fusion Applications
P-16	Ivan Oleynik	University of South Florida	Exploring the HED Physics of Amorphous IFE Ablator Materials

P-17	Jhonnatan Gama	SLAC National Accelerator Laboratory	Laser-Driven Ion Acceleration in Overdense and Underdense Targets: a Field-Particle Correlation Perspective
P-18	John Kuczek	Los Alamos National Laboratory	xRAGE Modeling for Xcimer Target Design on OMEGA
P-19	Kevin Meaney	Los Alamos National Laboratory	Fusion Reaction History and the Physics of Burn Propagation
P-20	Timothy Johnson	Lawrence Livermore National Laboratory	Impact of Asymmetries and Mix on Burn-Up Fraction for IFE Relevant Implosions
P-21	William Trickey	University of Rochester	Multidimensional Simulations of Igniting Direct-Drive ICF Targets at 250 kJ Laser Energy
P-22	Widianto Moestopo	Lawrence Livermore National Laboratory	Fully Additively Manufactured Wetted Foam Capsule for Inertial Confinement Fusion
P-23	Yongfeng Lu	University of Nebraska-Lincoln	Two-Photon Polymerization and Coherent Anti-Stokes Raman Scattering Microscopy for Fusion Target Fabrication and Diagnostics
P-24	Abbey Armstrong	University of Rochester	Studying Biermann-Generated Magnetic Fields in a Cylindrically Convergent System
P-25	Ajitha Dharmasiri	Texas A&M University	Sculpted Laser Statistics as a Probe for ICF Laser-Beam Stability
P-26	Alex Pietrow	University of California, San Diego	Effects of rear surface degradation on TNSA protons for Fast Ignition
P-27	Anson Olive & Brianna Rivera	Texas A&M University	Applying Inertial Fusion Energy for Hydrogen Production
P-28	Audrey DeVault	Massachusetts Institute of Technology	Utilizing the OMEGA High-Resolution Velocimeter (OHRV) to Quantify Shock Front Non-Uniformities in Wetted Foams
P-29			
P-30	Christopher Schowenwaelder	Friedrich-Alexander University Erlangen-Nuremberg	Designing a D2 Wetted Foam Target Station
P-31	Edna Rebecca Toro Garza	SLAC National Accelerator Laboratory	Warm Dense Matter Conductivity Measurements Using Single-Shot THz Spectroscopy

Current-Driven ICF Target Design with FLASH

C. Leland Ellison[1]
1. Pacific Fusion, 6082 Stewart Ave, Fremont, CA 94538
lee@pacificfusion.com

Multidimensional radiation hydrodynamics codes have been instrumental to progress in inertial confinement fusion, including achievement of ignition at NIF and achieving Lawson triple products on Z that exceed tokamak records. To date, the most heavily exercised and validated codes for designing targets at world-leading ICF facilities are exclusively developed and accessed at national laboratories. For the private sector to seize the commercial prospects of inertial fusion energy, a widely available, validated ICF target design code is necessary.

To meet this need for current-driven ICF, Pacific Fusion has chosen to partner with the Flash Center at the University of Rochester to co-develop FLASH. FLASH is 3D Eulerian AMR code with resistive and extended MHD, multigroup radiation diffusion, and tabular material properties. In recent work, we have successfully improved and validated FLASH for modeling high performing current-driven ICF targets, including matching thermonuclear burn metrics of high performing MagLIF experiments at Z and demonstrating good agreement with HYDRA in published studies of scaling MagLIF to ignition regimes. In this presentation, I will review improvements and validation benchmarks and discuss FLASH's suitability as an ICF target design tool.

High-repetition-rate Technology Development on GALADRIEL Relevant to the Inertial Fusion Energy Industry

M. J.-E. Manuel,[1] G. W. Collins IV,[1] A. Keller,[1] J. H. Nicolau,[2] S. Buczek[1,2], J. Ramirez,[2] D. Dahlke,[2] N. Sabouri,[2] B. Sammuli[1], R. Nazikian[1], N. Alexander[1]
[1] General Atomics, 3550 General Atomics Ct, San Diego, CA, 92121
manuelm@fusion.gat.com
[2] University of California at San Diego, 9500 Gilman Drive, San Diego, CA 92093

Most point designs for laser-based inertial fusion energy (IFE) require operation at rates of ~0.1-10 Hz, yet many diagnostics and target-fielding strategies implemented at present high-power-laser facilities require breaking vacuum between shots to exchange film-media, replace a stalked target, etc. This experimental paradigm must change as our community seeks to build an IFE-based fusion power plant. The General Atomics (GA) LAboratory for Developing Rep-rated Instrumentation and Experiments with Lasers (GALADRIEL) facility [1] will serve as a platform for this change, providing a test bed to enable rapid development and testing of rep-rated technologies required to address questions in Engineering Science relevant to IFE. The ~1TW system (~25fs, ~25mJ) has been commissioned and routinely runs experiments at 1Hz, though the laser is capable of 10Hz operation. All experimental data is stored using the MOngoDB Repository for Information and Archiving (MORIA) system [2], a custom-developed database framework designed specifically for high-rep-rate laser experiments. The database is fully queryable and leverages an organizational strategy that shifts data hierarchy from a shot-based to a diagnostic-based approach in order to increase archival and retrieval efficiency to handle large amounts of data.

The modest size of this facility allows users to focus on outstanding questions in Engineering Science; including targetry, diagnostics, environmental and materials studies, analysis and machine learning (ML) algorithm development, as well as feedback control systems. A review of system capabilities will be given, including example experiments in the areas of advanced pulse-shaping techniques at the femtosecond-scale, ML-based pulse-shaping control algorithms, Bayesian optimization of MeV electron production from a laser-wakefield accelerator, and automated delivery of complex targets using a tape-drive system. Future projects for tracking and engaging spherical targets will be briefly discussed.

*This work is supported through internal research and development funds at General Atomics with database development efforts supported by the Department of Energy Office of Science through grant DE-SC0025083.

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[2] M. J.-E. Manuel et al., "*A customizable data management framework for high-repetition-rate high-energy-density science,*" Rev. Sci. Instr. **95**, 093532 (2024).

High Spectral Resolution X-ray Thomson Scattering Diagnostics in High Density D_2 Plasma

M. F. Syahbana[1], S. Fujioka[1], M. Koenig[2], T. Pikuz[1], J-Y. Dun[1], Y. Karaki[1], F. Perez[2], B. Albertazzi[2], F. Delahaye[3], G. Gregori[4], R. Takizawa[1], K. F. F. Law[1], J. Hernandez[1], X. Han[1], H. Matsubara[1], R. Akematsu[1], R. Omura[1], Z. Zhong[1], Y. Gong[1], et. al.

[1] Institute of Laser Engineering, The University of Osaka, 2-6 Yamada-oka, Suita, Osaka, Japan, 565-0871
u636621e@ecs.osaka-u.ac.jp
[2] LULI, École Polytechnique, Route de Saclay, Palaiseau, France, 91128
[3] Observatoire de Paris, Sorbonne University, 61 Avenue de l'Observatoire, Paris, France, 75014
[4] Department of Physics, University of Oxford, Parks Road, Oxford, United Kingdom, OX1 3PU

The significance of high-energy-density science experiments, particularly in laboratory astrophysics and laser fusion research, lies in their ability to validate numerical simulations through controlled plasma measurements. However, accurately measuring temperature and density in fast, microscopic, and transient laser-produced plasmas remains challenging, often necessitating reliance on simulations, which limits experimental validation capabilities. Previous work has demonstrated the potential of X-ray Thomson Scattering for dense plasma measurements[1,2], but traditional implementations face limitations in signal-to-noise ratio.

We are now trying to implement a new diagnostics system of X-ray polycapillary optics in X-ray Thomson Scattering (XRTS) diagnostics at the GEKKO-LFEX laser facility. Traditional XRTS measurements suffer from low signal-to-noise ratios due to small scattering cross-sections and it requires placing X-ray sources close to the target ($\approx 1\ mm$), potentially disturbing plasma conditions, just to get proper signals. Our new approach will employ two polycapillary systems: Polycapillary-A for collection of scattered X-ray and Polycapillary-B for maintaining non-invasive probing by allowing greater source-target separation ($\approx 100\ mm$) while preserving source brightness. The experimental setup utilizes six GEKKO-XII laser beams ($200\ \text{J}, 0.53\ \mu\text{m}, 1\ \text{ns}$) and LFEX-generated CuKα X-rays ($8.05\ \text{keV}$) optimized for the $7 - 8$ keV spectral range where polycapillary transmission peaks.

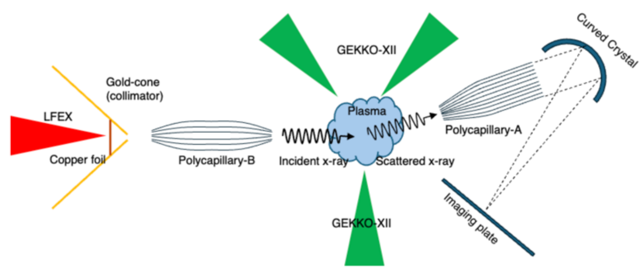

Fig 1. XRTS setup

The diagnostic system design is optimized through comprehensive numerical calculations, particularly focusing on X-ray ray-tracing simulations for the dual polycapillary configuration. We will use spherically bent Quartz crystals to analyze scattered X-rays, focusing them onto an imaging plate detector for high-resolution spectral measurements. Numerical simulations will be used to optimize the spectrometer design, from quartz crystal dimension, collection geometry, and energy range, to achieve high spectral resolution. This improved diagnostic system will allow us to measure plasma conditions across a broader range of densities and temperatures.

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A Framework to Measure the Viscosity of HED Materials via Hydrodynamic Instabilities

S. Dick,[1] T. Perez,[2] R. Smith,[3] J. Wicks[4], and E. Johnsen[5]
[1]South Dakota School of Mines & Technology, 501 E St Joseph St, Rapid City, SD, 57701
Sonya.Dick@sdsmt.edu
[2]Carnegie Science, 5251 Broad Branch Rd NW, Washington, DC, 20015
[3]Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA, 94550
[4]Johns Hopkins University, Baltimore, MD, 21218
[5]University of Michigan, Ann Arbor, MI, 500 S State St, Ann Arbor, MI, 48109

The properties of high-energy-density (HED) materials are difficult to measure due to the extreme conditions under which they exist. Understanding transport properties—such as viscosity—is crucial for accurately modeling and simulating HED flows. In this work, we employ a numerical framework to study hydrodynamic instabilities relevant to HED materials. By combining these simulations with experimental data, we can constrain the viscosity of HED materials.

The growth of hydrodynamic instabilities—including the Richtmyer-Meshkov Instability (RMI) and the Rayleigh-Taylor Instability (RTI)—as well as the decay of a corrugated shock, is highly dependent on a material's viscosity. A recent campaign established an upper bound on the viscosity of plastically deforming MgO shocked to 180 GPa[1]. In this work, experiments were conducted at the OMEGA laser facility, where a perturbed epoxy-MgO interface was shocked and RMI growth was measured via VISAR. To simulate these experiments, we used an in-house hydrodynamic code that solves the compressible Navier-Stokes equations using a five-equation model with a stiffened equation of state. Strain-rate-dependent viscosity was implemented at the shock front following the Grady law. Hydrodynamic simulations were performed for different values of MgO viscosity, and comparison with the VISAR results provided an upper bound of approximately 10^2 Pa·s.

In this presentation, we discuss improvements to this campaign and explore how the approach can be extended to study the viscosity of other HED materials. We present preliminary work on designing laser-driven hydrodynamic instability experiments to measure the viscosity of HED plasmas. The relatively low viscosity expected for plasmas, as predicted by the Braginskii model[2], poses several experimental challenges. To explore these challenges, we apply a linear theoretical framework to the Rayleigh-Taylor instability under conditions anticipated to be achievable at a laser facility.

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A Physics-Based Bayesian Optimization Framework for Direct-Drive Implosions on Rep-Rated Facilities

V. Gopalaswamy, R. Ejaz, A. Lees, R. Betti

Finding the optimal implosion design for inertial confinement fusion experiments requires an exhaustive search of the vast design parameter space. This is clearly infeasible on current facilities with O(10) shots per year, but will remain so even on the best-case rep-rated research facilities capable of ~ 100 shots per week. Taking full advantage of the enhanced capabilities of rep-rated facilities requires the development of advanced optimization schemes. Schemes that have no prior knowledge of ICF experiments avoid assumptions about ICF physics, but may require an unfeasibly large optimization budget. Recently, a Bayesian Optimization framework that factorizes the parameter space into five parts was developed for OMEGA simulations and experiments [1]. This algorithm was shown to be able to optimize a pulse shape for a given target within 500 samples, making it viable for the optimization budget of rep-rated facilities. However, as presented in [1] the algorithm is not suited for direct application to rep-rated facilities. Additionally, the budget for optimizing both target and pulse shape is O(10,000), which could be challenging for the assumed shot rate. We show here how this framework can be adapted for use on rep-rated facilities, and how the framework can be improved with deep learning acquisition functions to further reduce the budget to fully optimize the pulse shape and target with the expected optimization budget in a completely automated manner, thereby making full use of future rep-rated facilities.

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Theory of Thomson Scattering via Ray Tracing Simulations

W. Rozmus,[1] D. E. Carleton,[1] J. Myatt,[2] E. Rettich[1]
C. Bruulsema[3], G.F. Swadling[3], A. Milder[4], J.P. Palastro[4], D.H. Froula[4]

[1] Department of Physics, University of Alberta, Edmonton, Alberta T6G 2E1, Canada
wrozmus@ualberta.ca
[2] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB T6G 1H9, Canada
[3] Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[4] Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA

Thomson scattering (TS) is a well-established diagnostic technique for laboratory plasmas. This work presents recent advancements in TS interpretation, enabling measurements of local magnetic fields, accounting for induced emission in the subthreshold regime of scattering instabilities, and introducing a novel approach to fitting TS spectra using ray tracing simulations.

Due to the small scattering cross-section, high probe beam intensities (~10^{14} W/cm^2) are often required to enhance the signal-to-noise ratio. At such intensities, the probe can amplify electron density fluctuations in the subthreshold regime of parametric instabilities or induce nonzero convective gain for stimulated Raman (SRS) and Brillouin scattering (SBS) within the TS volume in inhomogeneous plasmas [1]. We applied a ray tracing code to generate TS spectra in stable plasmas, incorporating modified particle noise and spatial variations in plasma parameters. In the weak-probe, small-gradient limit, our method recovers standard TS cross-section results.

Our approach has been validated in several plasma experiments. Notably, we reproduced TS spectra in laser-driven counter-streaming plasma experiments [2] in the nonlinear regime of ion-Weibel instability. The analysis revealed strong density modulations due to current filaments and explained multi-resonant structures in electron plasma wave spectra, attributed to density inhomogeneity and nonzero side-scatter SRS gain. Additionally, we inferred large magnetic fields (~100 T).

I will discuss the application of ray tracing methods for routine TS analysis of ICF related plasmas.

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Multi Mega-electron volt ion acceleration in nanowire arrays irradiated with laser pulses of relativistic intensity for IFE concepts*

Jorge J. Rocca [1,2], Jadon Hoechstetter[2], Nashad Rahman[2], Maria Gabriela Capeluto[1,3],Sina Anaraki Zahedpour[1], Jim King[1], Reed Hollinger[1], Shoujun Wang[1], Ping Zhang,[1] and V.N. Shlyaptsev[1]

[1]Electrical and Computer Engineering Department, Colorado State University Fort Collins, CO
[2]Physics Department, Colorado State University, Fort Collins, CO
[3]Department of Physics, University of Buenos Aires, Buenos Aires, Argentina
Jorge.Rocca@colostate.edu

Laser-irradiated nanowire arrays act as efficient micro-accelerators in which the laser energy can be nearly totally absorbed and efficiently converted into kinetic energy of high energy ions to induce nuclear fusion reactions, producing high energy neutrons[1] and alpha particles[2]. This platform is of interest for new fusion energy schemes and for neutron source development. Of particular interest is the energy spectrum and angular distribution of accelerated protons, and the fraction of laser energy converted into ion kinetic energy.

Here we present results of the measurement of accelerated ions in polyethylene (CH_2) and nickel nanowire array targets irradiated with ultrahigh contrast laser femtosecond pulses from the Petawatt-class laser ALEPH. An array of seven Thomson parabola ion spectrometers and CR-39 ion detectors were placed at different angles respect to the target normal. The results are compared with those obtained irradiating flat solid targets from the same materials. We demonstrate that while in flat targets ions are accelerated predominantly in the laser forward and backward direction by the well know mechanism of transverse normal sheet acceleration (TNSA), in nanowire arrays ions are also accelerated radially along the target plane. This radial acceleration is shown to result from the formation of a charge sheet surrounding each of the nanowires. The observation of this new in-target plane ion acceleration mechanism is in agreement with our earlier prediction using 3-D particle-in-cell simulations[3]. This new form of radial ion acceleration that occurs within the target itself locally drives nuclear reactions. The results are relevant to new fusion energy schemes.

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LD-FIRST (Laser Driven Fusion Integration Research and Science Test Facility) – Design Progress and Future Development Pathways

J. Galbraith[1], M. Albrecht[1], R. Deri[1], M. Dunne[2], J. Edwards[1], B. El Dasher[1], C. Fiorina[4], B. Garcia-Diaz[3], C. Goyon[1], T. Hallam[4], T. Lynch[1], T. Ma[1], J. McCarrick[1], W. Meier[1], M. Nelson[1], A. Pak[1], P. Poole[1], I. Tamer[1], V. Tang[1], J. Williams[1]
[1]Lawrence Livermore National Laboratory, 7000 East Ave., Livermore, CA 94550
galbraith4@llnl.gov
[2]SLAC National Accelerator Laboratory, 2575 Sand Hill Rd., Menlo Park, CA 94025
[3]Savannah River National Laboratory, Savannah River Site, Aiken, SC 29808
[4]Texas A&M Department of Nuclear Engineering, 125 Spence St., College Station, TX 77840

The latest design of a Laser Driven Fusion Integration Research and Science Test Facility (LD-FIRST) will be presented, reflecting critical efforts toward advancing inertial fusion energy (IFE) through both the STARFIRE Hub and the greater IFE-STAR collaborative ecosystem. LD-FIRST is envisioned as a comprehensive community testbed that will integrate and test critical technologies across both Inertial Fusion Energy (IFE) and Magnetic Fusion Energy (MFE) concepts. The mission for LD-FIRST was recently vetted by a FESAC subcommittee on facilities and "deemed important and worthy of support by [DOE] FES."[1] An associated whitepaper was submitted and collaborative workshops held, solidifying a community vision for LD-FIRST and including representation from over 120 participants spanning 20 institutions.[2]

LD-FIRST harnesses decades of research and technology, modernizing insights from the LLNL Laser Inertial Fusion Energy (LIFE) study and building on the groundbreaking achievement of fusion ignition at the National Ignition Facility (NIF). LD-FIRST is designed to operate with deuterium-tritium fuel, targeting plant-relevant neutron outputs at 14.1 MeV. This capability will enable extensive materials and performance testing of fusion blankets and fuel cycle systems, including tritium breeding and recovery.

LD-FIRST will serve as an accelerated testbed for various blanket concept modules relevant to both IFE and MFE, utilizing the unique point source nature of Inertial Confinement Fusion (ICF) and adjustable irradiation fluxes based on proximity to target chamber center. We anticipate achieving yearly displacements-per-atom (DPA) of 10 or higher for meter-scale objects, even at target yields of just 10 MJ per laser shot (with NIF having already demonstrated a yield of 5.2 MJ as of 2024), contingent upon LD-FIRST attaining a repetition rate of ~10 Hz.

Currently in the pre-conceptual design phase, LD-FIRST is leveraging LLNL's Integrated Process Model (IPM) to optimize its design. The IPM incorporates over 100 user input parameters and conducts a self-consistent techno-economic assessment of facility architecture, informed and validated by NIF experiments.

To realize LD-FIRST, we recognize the importance of robust partnerships across the IFE, MFE, and ICF communities, and between public and private sectors and supply chain vendors. These collaborations will be essential in defining the detailed design and development pathways for LD-FIRST. This will not only enhance the United States' leadership in fusion science but also contribute significantly to achieving fusion commercialization and ensuring energy security. As such, we are particularly interested in partnering with others within the IFE-STAR ecosystem and eagerly seek out your input, feedback, and suggestions.

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LLNL-ABS-872247

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Plasma Electrode Pockels Cell Technology (PEPC) for Inertial Confinement Fusion Energy

Alenna Streeter[1*], Samuel Agnello[2], Luke Bernier[1], Gary Butterfield[1], Noah Carrier[2], Bryan Chan[1], Jerry Chung[1], Robert Chung[1], Yoram Fisher[1], Rick Frisicano[1], Matthew Zelazny[1], Avery Maynard[1], David Garand[1], Kyle Gibney[2], Jeff Hettrick[2], Elizabeth Hill[2], Brian Kruschwitz[2], Gary Mitchell[2], David Nelson[2], Amy Rigatti[2], Gary Wagner[2], Troy Walker[2], and Jon Zuegel[2]

[1]*Sydor Technologies;*
[2]*Laboratory for Laser Energetics;*

**Corresponding author: alenna.streeter@sydortechnologies.com*

The Plasma Electrode Pockels Cell (PEPC) is a key enabling technology towards successful Inertial Confinement Fusion (ICF) and eventually viable laser-based fusion energy. Each PEPC system acts as an optical switch for high-energy, large aperture multi-pass amplifiers, and can additionally perform as a retro-reflection protection device to prevent beam remnants from propagating to sensitive laser system components.

Sydor Technologies has been awarded a Small Business Innovation Research (SBIR) Phase II grant funded by the Department of Energy Office of Fusion Energy Sciences (DOE-FES) with the University of Rochester's Laboratory for Laser Energetics (LLE) to commercialize a mid- scale version of the PEPC well suited to support high-power, high-energy laser systems and future Inertial Fusion Energy needs. Switching speeds of less than 70 ns (1-99%) and spatially averaged contrast exceeding 1000:1 across the 23 cm square aperture allow for more compact, efficient amplification cavities such as those found in LLE's Fourth generation Laser for Ultra-broadband eXperiments (FLUX) laser system [1].

This poster will detail the mPEPC design and how it addresses the unique challenges high- energy laser facilities must face. A top-level assessment of the technology and next steps towards commercialization will also be presented.

This project is supported by a DOE Phase II SBIR, DE-SC0023913.

Keywords: Electro-Optic, Pockels Cell, Inertial Confinement Fusion, Optics, Lasers

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Techno-Economic Inertial Fusion Power Plant Design through the Integrated Process Model (“IPM”) *

[Mackenzie Nelson and Justin Galbraith]
[Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA, 94550]
[nelson275@llnl.gov]

An integrated process model (“IPM”) was developed with the purpose of analysis and modeling of inertial fusion energy (“IFE”) power plant designs. This model considers technical inputs surrounding a diode pumped solid state laser (“DPSSL”) indirect-drive IFE plant, combined with economic analysis in the form of capital costs related to all aspects of the design, development and construction. This model also considers the annual anticipated operating and maintenance expense of an IFE plant. Using this model, IFE plant designs may be developed for a first-of-a-kind IFE plant, second-of-a-kind IFE plant, or Nth [10^{th}]-of-a-kind IFE plant. This model is used for down-selection and optimization of plant design criteria and for analysis of trade-offs of various IFE DPSSL plant design components. This poster will provide an overview of the IPM, its uses and capabilities, as well as an analysis of proposed demonstration facilities and plant designs. One such demonstration facility, “LD-FIRST”, is proposed to fulfill a critical need in realizing fusion power, which would serve as a full-scale community testbed for essential technologies across IFE and magnetic fusion energy concepts. Proposed designs are informed by technical and economic analyses and trade studies, advancing the work initiated by W. R. Meier et. al[1] on IFE plant system modeling. The future of systems modeling and additional capabilities planned for the IPM will be showcased as well.

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LLNL-ABS-2002329

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An Implosion Test Facility for Laser Direct-Drive IFE

W. Theobald,[1,2] D. Callahan,[1] S. Atzeni,[1] M. Brönner,[1,3] G. Cheriaux,[1] A. Debayle,[1] J. Gaffney,[1] D. Hammond,[1] J. Honrubia,[1,4] A. MacFarland,[1] A. Mateo,[1,4] K. L. Nguyen,[1] V. Ospina-Bohórquez,[1] C. Paradis,[1,5] P. K. Patel,[1] M. Roth,[1,3] G. Schaumann,[1,3] M. Sokol,[1] and X. Vaisseau[1]

[1]Focused Energy Inc., 1808 El Camino Real, Redwood City, CA, 94063, USA and Focused Energy GmbH, Im Tiefen See 45, 64293 Darmstadt, Germany
wolfgang.theobald@focused-energy.world
[2]Department of Mechanical Engineering, University of Rochester, Rochester, NY, 14627, USA
[3]Technische Universität Darmstadt, Department of Physics, Darmstadt, Germany
[4]ETSI Aeronáutica y del Espacio, Universidad Politécnica de Madrid, Madrid, Spain
[5]Pulsed Light Technologies GmbH, Lagerhofstraße 4, 04103 Leipzig, Germany

Experiments on the National Ignition Facility (NIF) have demonstrated the viability of laser-based inertial fusion by achieving ignition and target net energy gain.[1] Major scientific and technical challenges remain, however, to progress to a commercial fusion power plant. Scientific challenges include developing and testing new target designs that are capable of significantly higher fusion gains than achieved so far on the NIF and exhibiting improved robustness in drive symmetry and in target quality. Technical challenges specific to inertial fusion energy (IFE) include developing high repetition rate, energy efficient, low-cost laser drivers, mass produced low-cost targets, precision target injection and tracking, diagnostics, and operations at high shot rates. This will require a high degree of automation in controls systems, diagnostics, and data interpretation.

While our company is working on a conceptual design of a fusion pilot plant with the goal of net energy production through high gain direct-drive inertial confinement fusion (ICF) implosions operating at a high repetition rate (~10 Hz), we propose along the path to build a sub-scale implosion test facility (ITF) to de-risk scientific and technical challenges.

ITF would have an intermediate repetition rate of about a shot per minute to test and optimize direct-drive IFE concepts and to demonstrate key IFE technologies. The use of liquid-cooled amplifier beamlines capable of firing hundreds of shots per day would enable rapid exploration and optimization of target designs over large parameter spaces. An initial concept of ITF is laid out that would combine symmetrically configured, 351-nm wavelength long-pulse compression lasers with a pulse duration of up to 10 ns for sufficient illumination uniformity on the implosion capsule. The concept for the long-pulse compression lasers includes the operation of beam zooming and broad spectral bandwidth for the mitigation of laser-plasma instabilities, the optimization of laser energy coupling, and an improved laser illumination uniformity. Additional short-pulse laser capability is considered to support advanced direct-drive ICF approaches.

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Inference of anomalous thermal transport using Bayesian optimization with uncertainty quantification in plasma boundary*

Yichen Fu, Xiao Chen, Benjamin Dudson, Maxim Umansky, Filippo Scotti, Thomas Rognlien
Lawrence Livermore National Laboratory, Livermore, California 94550, USA
chen73@llnl.gov

UEDGE is a fluid-based code simulating the edge of fusion plasma developed in LLNL. Inferring anomalous transport coefficients in UEDGE is crucial for complementing sparse data, enabling comprehensive interpretation of plasma behavior and accurate prediction under given conditions. In this work, we utilize heat flux at the divertor plate, infra-red camera image, and bolometer data experimentally measured from DIII-D tokamak. Transport coefficients in UEDGE require high spatial resolution for accurately prediction, which makes it computationally expensive to infer. A reduced-order UEDGE is used in this work. To further alleviate the computational burden, we developed an integrated workflow using Batch Bayesian Optimization, which is a global optimization method suitable for computationally expensive objective. In the workflow, transport coefficients are inferred by minimizing a loss function on HPC that utilizes a local Gaussian Process approximation to accelerate the optimization process through parallel updates of the acquisition function. We demonstrate this framework by discussing various radiation constraints and inference metrics, considering both model and data uncertainties for the assimilation of DIII-D data into our UEDGE model. The code is implemented within the UETOOLs (UEDGE toolkit).

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On nondamaging laser-damage risk assessment

Aleksei M. Zheltikov,[1] Carmen S. Menoni,[2] Alexei V. Sokolov,[1] Zhenhuan Yi,[1]
Jorge J. Rocca,[2] J. Gary Eden,[1,3] and Marlan O. Scully[1]

[1] IQSE, Dept. Physics and Astronomy, Texas A&M University, College Station TX

[2] Department of Electrical and Computer Engineering, Colorado State University, Fort Collins, Colorado

[3] Department of Electrical and Computer Engineering, University of Illinois, Urbana IL

zheltikov@tamu.edu

The existing laser-damage tests for optical components for high-power laser beamlines are based on procedures that induce a laser damage in a tested sample as their central element. Specifically, in standardized procedures for laser-damage threshold characterization,[1] approved by the International Organization for Standardization (ISO), the probability of laser-induced damage and the number of pulses until the laser damage are measured as functions of the laser fluence in a series of experiments in which each site within a test pattern in a tested sample is irradiated with a single laser pulse (1-on-1 test) or a sequence of *S* laser pulses with a preset fluence (*S*-on-1 test). While such standard protocols provide valuable information on laser-induced damage, they are not optimal for the characterization of optical components for ultrahigh-intensity or ultrahigh-energy laser facilities, including laser sources for extreme-light science[2,3] and systems for laser fusion.[4,5]

Here, we present a formal framework and identify the class of physical settings in which the risks of laser-induced damage can be quantified in a nondamaging way, i.e., without damaging the tested components. We show that, with the parameters of the laser driver adjusted in such a way that laser-damage events are rare, the multipulse laser damage probability can be expressed in closed form as a function of the laser fluence and the signal-to-noise-ratio of the laser driver. Whenever these solutions can be extended to include an adequate model of laser-damage-assisting light-induced material modifications, e.g., phenomenologically or via the existing theoretical frameworks of laser-driven ionization in solids,[6,7] the risks of laser damage can be evaluated without damaging tests but based solely on suitable prior data on the statistics of the laser driver and the properties of light-induced material modifications. With the rare-event statistics of laser-induced damage found in the class of generalized extreme-value distributions,[8] nondamaging laser-damage risk assessment is categorized as an extreme-event prediction problem, falling into the same class of problems as the prediction of maximum sea levels, extreme floods, rainfall accumulation, rogue waves, anomalous data traffic, and catastrophic wildfires. As a demonstration of its descriptive power, this approach is shown to provide an accurate fit for the multipulse laser-damage data for dielectric multilayer coatings[9,10] designed for high-power laser beamlines, including laser beamlines for IFE applications.

* This research was supported in part by the DOE Office of Science through the DOE Inertial Fusion Energy Science and Technology Accelerator Research (IFE-STAR) program (Grant # DE-SC0024882).

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Scalable Modular Solid State Switching for Pulsed Power Fusion Applications

Mark B. Moffett, David L. Chesny
SpaceWave, LLC Satellite Beach, FL 32937
mbedfordm@gmail.com

Scalability for modular solid state switches enables custom designed and built switches for a defined load and application. The benefit of solid state switches over traditional spark gaps is apparent in both efficiency and precision timing. Precision timing between two or more distinct pulsed power systems requires solid state switches in order to achieve high repeatability and reliability for microsecond time constraints involved with fusion energy applications. High energy discharges within controllable microseconds of one another enables new methods to be developed as primary plasma energy sources or secondary plasma energy injectors into various fusion techniques. For the example case here, two separate circuits are discharged to produce a plasma and magnetic field effect. The capacitor discharges are 3kv at 55uF and 3kv at 360uF, respectively. The plasma's theoretical resistance is 0.5 ohms with an added 3 ohms of buffer resistance and the load of the magnetic field has a resistance of 3 ohms. Based on these energy and load definitions, a switch can be designed to withstand these loads within a conservative margin, ensuring a reliable and robust switch with low losses and precision timing. This work showcases a modularity technique that enables the building of any number of solid state switches within a system to be robust for a defined load limit while also enabling microsecond precision control of discharging the respective loads. This work is in conjunction with University of Alabama, Huntsville with application in spacecraft propulsion and fusion energy science*.

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Exploring the HED physics of amorphous IFE ablator materials

I.I. Oleynik,[1] and S.J. Tracy,[2]
[1]University of South Florida, ISA2019, Tampa, FL 33620
oleynik@usf.edu
[2]Carnegie Institution of Washington, 5241 Broad Branch Road, NW
Washington, DC 20015- 1305

Developing next-generation ablator target materials is a key research priority in IFE. The goal is to enhance target performance metrics beyond the current gold standard—high-density carbon (HDC)—by introducing new ablators that are efficient, cost-effective, and scalable. HDC ablators suffer from instabilities seeded by material microstructures. Amorphous ablators can mitigate the effects of crystalline grain microstructures by suppressing inhomogeneities in the shock front while significantly reducing the fuel adiabat.

Promising next-generation ablator materials include amorphous carbon (a-C) and boron carbide (B_4C). These materials exhibit a desirable array of characteristics suitable for IFE, including low atomic mass, high density, uniform density distribution, chemical resistance, and mechanical durability.

In this presentation, we describe our advances in investigating the HED properties of amorphous ablator materials through experiments at Omega EP and the European XFEL, as well as billion-atom, quantum-accurate molecular dynamics (MD) simulations on the first DOE exascale supercomputer, Frontier. We specifically focus on the equation of state (EOS) across a wide range of pressure-temperature conditions and the phase diagram, particularly potential crystallization regions, constraining the melting line, and determining the transition into the liquid phase along the Hugoniot. Additionally, we investigate the planarity of the shock front and the potential appearance of shock front roughness at varying shock strengths.

Our experiments and predictive MD simulations provide a solid foundation for high-gain IFE designs using amorphous IFE targets.

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Laser-driven ion acceleration in overdense and underdense targets: a field-particle correlation perspective

[J. Gama,[1,2] F. Fiuza,[3] S. Glenzer,[2] and A. Kemp[4]]
[1 Physics Department, Stanford University , CA 94305]
[jgamav@slac.stanford.edu]
[2 High Energy Density Science Division, SLAC National Accelerator Laboratory, CA 94025]
[3 Instituto de Plasmas e Fusão Nuclear, Insituto Superior Técnico, Lisbon 1049–001]
[4 Lawrence Livermore National Laboratory, CA 94550, USA]

Particle acceleration is a central topic in laser-plasma interactions. There has been a significant effort in understanding how to optimize the generation of highly energetic particle beams for applications such as fusion energy, medical imaging and therapy, and laboratory astrophysics. A wide variety of energization processes have been identified in laser-driven particle acceleration, but understanding the transition between them remains a challenge. In this work we explore the use of the field-particle correlation analysis to identify a particular, locally-occurring energization process using PIC simulations data from short pulse interactions with overdense and relativistically underdense plasmas. The expected characteristic signatures in momentum-space of TNSA and RTF-RPA are compared and discussed.

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xRAGE modeling for Xcimer target design on OMEGA*

J. Kuczek,[1] A. Christopherson,[2] J. Davies,[3] J. Kline,[1] D. Montgomery,[2] C. Samulski,[1] C. Thomas[3]
1 Los Alamos National Lab, MS 1087, Los Alamos, NM, 87544
jkuczek@lanl.gov
2 Xcimer Energy Inc., 10325 E 47th Avenue, Denver, CO, 80238
3 Laboratory for Laster Energetics, 250 E River Road, Rochester, NY, 14623

Xcimer and Los Alamos National Laboratory (LANL) are jointly developing baffled hohlraum models to optimize performance in both hybrid and indirect-drive inertial confinement fusion (ICF) experiments. A two-sided target concept[1] has been introduced through collaboration between Xcimer and the Laboratory for Laser Energetics. While theoretical and simulation studies are important in refining these designs, experimental validation is essential to assess their viability.

Scaling down the baffled hohlraum concept for experiments on OMEGA provides an opportunity to investigate the physics of this baffle design concept and help validate simulation models. Rather than employing standard polar drive, laser beams will target the baffle, enabling a direct assessment of the cavity's ability to reach the predicted X-ray temperatures. While some degree of radiation trapping is anticipated, verifying both X-ray generation within the cavity and the corresponding shock pressures is crucial. This work presents simulation results using the radiation-hydrodynamics code xRAGE[2] for the proposed OMEGA experiments, including synthetic diagnostic predictions. Preliminary xRAGE simulations indicate that radiation temperatures of approximately 100 eV can be achieved using a 6 kJ, 1 ns laser pulse.

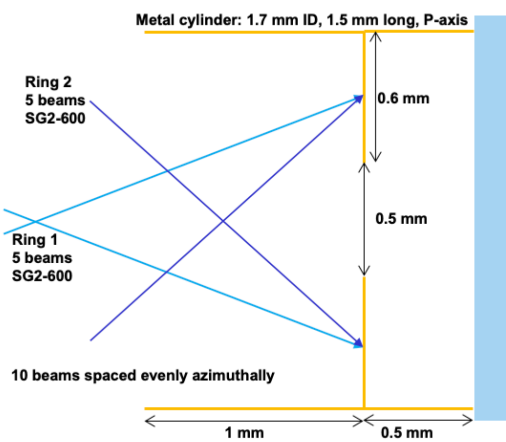

Figure 1: OMEGA halfraum with baffles

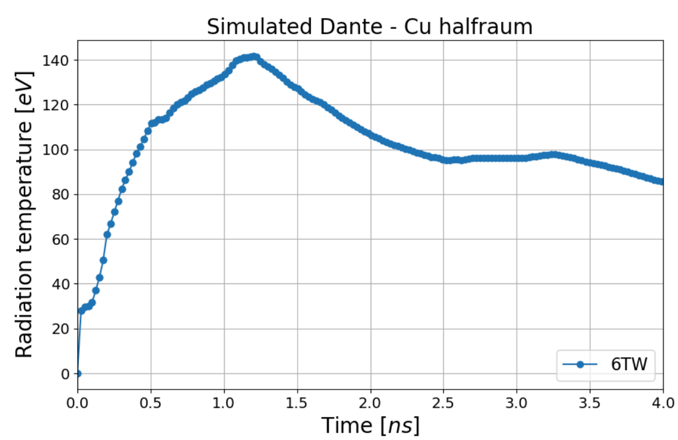

Figure 2: xRAGE simulation results for OMEGA design

* This work was performed by the Los Alamos National Laboratory, operated by Triad National Security, LLC for the National Nuclear Security Administration (NNSA) of U.S. Department of Energy (DOE) under Contract No. 89233218CNA000001.

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Fusion reaction history and the physics of burn propagation

K.D. Meaney[1], R. Dwyer[1,2], Y. Kim[1], H. Geppert-Kleinrath[1], B. Haines[1], W. Daughton[1], D. Schlossberg[3]
[1]Los Alamos National Laboratory, Los Alamos NM, 87545
[2]University of Rochester Laboratory for Laser Energetics, 250 E. River Rd, Rochester, NY 14623
[3]Lawerence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550
meaney@lanl.gov

For a high gain ICF concept one must propagate the fusion burn from an initial spark – such as the cryogenic layers on National Ignition Facility (NIF) implosions. The specific dynamics and details of how that fusion burn propagates sets what gains can be achieved and how they scale, which is of high interest to IFE concepts. However, the dynamics of the propagating burn are extremely quick – with the whole fusion burn occurring on the order of ~100 ps with specific processes – such as mass ablation or fusion driven temperature runaway – evolving on 10s of picoseconds time scale. Los Alamos has developed ultrafast fusion reaction history diagnostics able to observe the evolution of fusion burn and has started benchmarking and excluding various models of fusion propagation based on the measurements of igniting NIF implosions. These measurements allow unprecedented insight into the fundamental process of fusion burn propagation. The implications of such measurements for various ICF concepts and the potential for similar such measurements on future IFE facilities will be discussed.

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Impact of asymmetries and mix on burn-up fraction for IFE relevant implosions

T. M. Johnson[1], D. T. Casey[1], S. Davidovits[1], C. Weber[1]
[1]Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA 94550
johnson445@llnl.gov

Inertial confinement fusion (ICF) implosions for power production need to be robust. Degradations from sources such as asymmetries or high-Z mix need to be understood and considered for an economical power plant. In this work, the impact of asymmetries and mix on burn-up fraction are studied for inertial fusion energy (IFE) scale implosions. First, a high gain indirectly driven capsule design is developed. This design is subsequently degraded with mix and drive asymmetries. The results show an increased tolerance to mode-1 asymmetries for robustly burning capsules. In particular, the higher rhoR side of the asymmetric implosion produces more fusion yield than the equivalent half of a symmetric implosion. Simulations of mode-2 asymmetries similarly show increased robustness at high gain. Work is ongoing to assess the role of asymmetry in limiting gain and the impact of ablator mix into the ice layer on the overall burn-up fraction. LLNL-ABS-2002456

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*This work conducted under the auspices…. If you do not have anything to credit, delete this line and the asterisk at the end of the title.

[1] A. Name, B. Name, and C. Name, "*Paper title,*" Journal name **Vol**, page (year). (Remove if no references.)
[2] A. Name and B. Name, Institution, personal communication (year). (Remove if no references.)

Multi-dimensional simulations of igniting direct-drive ICF targets at 250 kJ laser energy

W. Trickey, D. Cao, T.J.B. Collins, R.K. Follett, D.H. Froula, V.N. Goncharov, R.C. Shah, D. Turnbull, A. Shvydky
Laboratory for Laser Energetics, U. Rochester

After the recent achievement of ignition at the Nation Ignition Facility (NIF), the time is now opportune to consider the physics requirements next-generation Inertial Confinement Fusion (ICF) laser facilities. The performance of present laser direct-drive experiments degraded by laser-plasma interactions (LPI) which act to scatter energy away from the plasma and reduce the ablation pressure. Ablation pressure is a key metric in the performance of ICF implosions[1], thus reducing LPI is crucial requirement for next- generation laser technologies. Recent efforts in modelling LPI[2] show that the addition of bandwidth to the laser radiation should raise the thresholds for LPI and, with the addition of focal-spot zooming, will raise drive pressures well above 200 Mbar. With a driver capable of such performance, it is possible that ignition conditions could be achieved under direct-drive at more moderate (200 – 300 kJ) laser energies. We present a number of multi-dimensional simulations that explore the stability of such targets to laser and target nonuniformities.

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 and by the Office of Science, Fusion Energy Sciences, under Award No. DE-SC0024863:

Fully additively manufactured wetted foam capsule for inertial confinement fusion

Widianto P. Moestopo,[1] Jean-Baptiste Forien,[1] Jim Sater,[1] Tim R. Prisk,[1] Travis M. Briggs,[1] G. Elijah Kemp,[1] Montu Sharma,[2] Claudia Shuldberg,[2] Jay Crippen,[2] Xia,[1] and James S. Oakdale[1]

[1]Lawrence Livermore National Laboratory, Livermore, CA, USA 94550
[2]General Atomics, Target Fabrication, San Diego, CA, USA 92121
Email: moestopo1@llnl.gov

As the societal need for more sustainable sources of energy increases, the recent demonstration of the first-ever fusion ignition in a laboratory has renewed interests in scaling up the inertial confinement fusion (ICF) technology for commercial energy generation. To address the technological gap that exists in mass-producing high quality ICF fuel capsules, we demonstrate the fabrication and testing of fully additively manufactured (AM) foam-lined capsules using a commercial two-photon lithography machine. We will present our recent advancements in improving printing speed and printing foam lining inside our capsules, and we will discuss results from metrology and foam wetting experiments. AM foam capsules were fielded for polar-direct drive experiments on the National Ignition Facility, and we will discuss the unique design considerations involved. The capabilities enabled by our process will shorten the turnaround time between each target design iteration and enable the exploration of more complex physical interactions between the laser, capsule, and fuel.

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Two-photon polymerization and coherent anti-Stokes Raman scattering microscopy for fusion target fabrication and diagnostics

Y.F. Lu[1*], Xi Huang[1], P.Z. Li[1], H.Y. Dong[1], Mark Bonino[2], Sarah A. Muller[2], Dale Guy[2], Dustin Froula[2], Sean P. Regan[2], David R. Harding[2]

[1]Department of Electrical and Computer Engineering, University of Nebraska-Lincoln (UNL), NE 68588-0511, United States

[2]University of Rochester-Laboratory for Laser Energetics (LLE), 250 E. River Rd, NY 14623, United States

Laser-direct-drive (LDD) inertial confinement fusion (ICF) relies on the implosion of a spherical-shell target containing a thermonuclear fuel layer of cryogenic deuterium–tritium (DT). Achieving successful fusion requires a highly uniform and symmetrical implosion of the target, driven by lasers that compress the DT fuel to temperatures exceeding 100 million degrees. However, small perturbations—such as nanoscale pits, voids, or contaminants on the target—can amplify instability growth, ultimately leading to ignition failure. Recent advancements in target manufacturing, particularly through two-photon polymerization (TPP), have introduced new possibilities for designing and fabricating fusion targets with exceptional precision. TPP, the most accurate three-dimensional (3D) printing technique, utilizes a femtosecond (fs) laser in combination with laser scanners to create complex structures with resolutions below 100 nm. This technique enables the fabrication of delicate structures spanning 1D to 3D dimensions and µm to cm scales. Over the past several years, we have developed practical TPP-based approaches to fabricating various ICF target components, including low-density foams, plastic capsules, ablators, target filling tubes, and plasma lenses. These structures are precisely engineered with controlled geometries, profiles, and surface qualities to minimize printing defects. Through our recent work in TPP, we systematically studied radical diffusion behaviors during the printing process, providing fundamental insights into achieving ultra-smooth target surfaces without printing defects. Additionally, by introducing a novel one-way printing approach into TPP, we have significantly optimized the trade-off between fabrication time and surface smoothness, enhancing the efficiency and quality of fusion target production.

At the same time, assessing the quality of fusion targets before ignition experiments is also critical, requiring a comprehensive evaluation of surface imperfections, internal defects, and the distribution of DT fuel ice at cryogenic temperatures. For example, voids within the target shell, typically hundreds of nanometers in size, are large enough to distort laser beams and potentially cause ignition failure. Through years' work, broadband coherent anti-Stokes Raman scattering (CARS) microscopy built at UNL has demonstrated its potential to offer 3D topographical maps of the elemental composition of hydrogen (H) and deuterium (D) loaded fusion targets at cryogenic temperature (~11K). Moreover, our recent developed narrowband CARS microscopy has significantly improved imaging resolution and signal-to-noise ratios compared to previously used broadband CARS microscopy. The key advantage of narrowband CARS lies in its efficient Stokes laser power: while broadband CARS can utilize only ~60 mW of Stokes power spread across a wide spectral range, narrowband CARS, equipped with a new laser system, can deliver tens of milliwatts of Stokes power at a specific wavelength, greatly boosting the CARS signals. This newly built narrowband CARS is currently being integrated into cryo-CARS imaging system, which aims to deliver enhanced imaging performance for studying hydrogen isotope HD distributions at cryogenic temperatures within fusion targets.

*Yongfeng Lu, E-mail: ylu2@unl.edu, Tel: 402-617-3509

Studying Biermann-Generated Magnetic Fields in a Cylindrically Convergent System.

[A. Armstrong, [1, 2] J. Sauppe,[2] J. Sauppe,[2] H. Li,[2] E. Merritt,[2] A. Reyes,[1] E. Hansen,[1] P. Tzeferacos,[1,2]
[1]University of Rochester
[2]Los Alamos National Laboratory

Theoretical work suggests that magnetic fields may be self-generated in inertial confinement fusion implosions [1, 2, 3], however diagnosing such systems remains a challenge. In contrast, cylindrical implosions retain the effects of convergence while allowing direct diagnostic access to the interior of the target by viewing down the axis of the system. Los Alamos National Laboratory has a long history of success studying hydrodynamic instability [Rayleigh-Taylor (RT), Richtmyer-Meshkov (RM), and Bell-Plesset effect] growth in convergent systems using such platforms [4]. Such instabilities can generate magnetic fields via the Biermann Battery mechanism [5], and when paired with the flux compression of a convergent system the latter can be amplified. To date, Los Alamos National Laboratory's cylindrical implosion platform has not been designed for accessing physical regimes where Biermann battery can operate effectively and is not dominated by resistive diffusion. When magnetic fields are of dynamical import, the growth rates of RT [6] and RM [7] instabilities can change. Using the existing cylindrical implosion platform as a starting point, we present 2D FLASH simulations that transform the platform into one that can viably study Biermann generated fields in a convergent geometry. This work supplies the foundations for future experimental campaigns, which can in turn be used for code validation.

LA-UR-24-32159

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Sculpted laser statistics as a probe for ICF laser-beam stability

Ajithamithra Dharmasiri,[1] Sheila Chauwinoir,[1] Zhenhuan Yi,[1] Alexei V. Sokolov,[1] Aleksei M. Zheltikov,[1] J. Gary Eden,[1,2] and Marlan O. Scully[1]

[1] IQSE, Department of Physics and Astronomy, Texas A&M University, College Station TX 77843
[2] Department of Electrical and Computer Engineering, University of Illinois, Urbana IL 61801

ajithamithra@tamu.edu

Laser facilities for laser-driven inertial confinement fusion (ICF) operate with extreme-energy laser beams produced by combining the outputs of multiple powerful laser sources.[1-3] Typical levels of peak powers in such beams are many orders of magnitude higher than the critical power of self-focusing not only in solid-state materials, but also in atmospheric-pressure gases. Laser beams at this level of peak powers are prone to self-focusing, modulation instabilities (MIs), and beam filamentation. An unchecked intensity buildup in such beam evolution scenarios causes a damage of optical components in laser beamlines. Multiple filamentation, on the other hand, tends to break beam symmetry, making beam-symmetry-sensitive laser – target interaction settings, such as those needed for ICF,[1-3] difficult to implement.

Because of inevitable field intensity fluctuations within manifolds of laser beams in ICF laser beamlines, the beam-combined laser field is inevitably, intrinsically stochastic. While deterministic laser beams maintain their stability as long as their peak power and field intensity are kept below the respective self-focusing and MI thresholds, stochastic laser beams tend to exhibit instabilities over large pulse samples even when their parameters nominally meet deterministic beam-stability criteria.[4] Beam-stability analysis for such fields thus has to deal with beam statistics and needs to be performed within an adequate statistical framework.

In this work, we demonstrate that the stochastic beam-instability dynamics of high-power laser field waveforms, including the laser pulses used for laser-driven ICF, can be scaled down in laser power and studied in laboratory-scale laser experiments. Moreover, we present an experimental setup that implements this idea. At the heart of this experiment is a laser statistics generator that delivers laser pulses whose statistics is tailored as needed for scaled-down experimental studies of ICF-related laser-field instabilities. Tailored statistics generation in our experiments is based on a cascade of nonlinear processes in a highly nonlinear optical fiber and an Nd: YAG amplifier, which transform the statistics of input Ti: sapphire laser pulses, yielding laser fields with desirable statistical properties. A special focus at this stage of work is on experimental studies of how the wavelength-shifting soliton dynamics in a nonlinearity- and dispersion-managed optical fiber transforms the statistics of laser pulses.

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Effects of rear surface degradation on TNSA protons for Fast Ignition

A. Pietrow[1], S. C. Wilks[2], A. J. Kemp[2], D. P. Higginson[2], M. Tabak[2], S. MacLaren[2], J. D. Ludwig[2], M. Bailly-Grandvaux[1], J. Kim[1], and F. N. Beg[1]
[1]Center for Energy Research, UC San Diego, La Jolla, CA 92093
[2]Lawrence Livermore National Laboratory (LLNL), Livermore, CA 94550
apietrow@ucsd.edu

Ignition through conventional inertial confinement fusion (ICF) has been demonstrated at the National Ignition Facility (NIF), achieving energy gains exceeding 2. This milestone has sparked discussion within the Inertial Fusion Energy (IFE) community about designing a practical IFE power plant. Achieving net energy output requires DT fuel capsule implosions with gains exceeding 100 at a 10 Hz repetition rate. However, conventional ICF, particularly the indirect-drive approach, faces challenges such as high implosion velocity and low laser-to-X-ray conversion and burn efficiencies. These limitations have driven interest in alternative ICF schemes like fast ignition (FI), which reduces symmetry requirements by decoupling compression and ignition phases and uses high-intensity, short-pulse (SP) driven electron or proton beams to ignite fuel [1,2]. A key challenge for proton FI, however, includes the preheating of the proton-generating foil by X-rays from the capsule implosion during compression, degrading the foil's rear surface and hindering SP-accelerated ions for ignition.

When an intense short-pulse (SP) laser, with an intensity exceeding 10^{18} W/cm^2 and a pulse duration on the order of picoseconds, irradiates the surface of a thin foil (<100 μm), it accelerates electrons to relativistic energies. These electrons generate strong electrostatic fields at the rear surface of the foil which subsequently accelerate ions to multi-MeV energies. This process, known as target normal sheath acceleration (TNSA) [3,4], is a widely studied mechanism for ion acceleration. The accelerated ions predominantly originate from a sub-micron layer of hydrocarbons or contaminants present on the foil's rear surface. Using Particle-in-Cell (PIC) simulations, we analyze the conversion efficiency and energy distribution of accelerated ions [5]. This particular study investigates the impact of finite (i.e., non-uniform) rear-surface density profiles—arising from effects such as laser pre-pulses or radiative heating of the foil—on the ion spectrum generated by TNSA.

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Applying Inertial Fusion Energy for Hydrogen Production*

A. Olive[1] and B. Gouteyron[1]
[1]Texas A&M University Department of Nuclear Engineering, 125 Spence St, College Station, TX
ansolive@tamu.edu

One current challenge in the fusion industry is the scope to which fusion energy is often confined. Fusion is often relegated to being a power source good for little else other than being a strong producer of base load power. This is a challenge our project aims to solve, allowing fusion to be used to produce cheap, green hydrogen, which can be utilized in many different sectors that are looking at using hydrogen as an alternative fuel source. Because of the high temperatures that fusion reactors produce, it becomes relatively easy to produce hydrogen via electrolysis, but using fusion reactors for this purpose produces unique considerations for the longevity of the design of the reactor used.

The material challenges are addressed by considering a modified HYLIFE-II reactor design that incorporates a molten salt blanket composed of FLiBe, used both to enhance heat conduction to the electrolyzer and protect the reactor from neutron damage that would require the operation to frequently replace the reactor walls. In addition to incorporating the electrolyzer instead of a traditional secondary loop used to boil water, the walls were also modified to be composed of advanced high-temperature materials, such as Hastelloy N and oxide dispersion-strengthened steel, which were selected for their superior corrosion resistance, mechanical integrity, and low neutron activation.

To verify the results of the preliminary survey of existing literature and basic calculations, software programs will be used to obtain more accurate results. Neutronic and heat deposit calculations will be performed using OpenMC, which will verify the rate of heat deposition into the FLiBe. Coreform Cubit will also be utilized to create detailed meshes of the reactor geometry that can be examined closely to understand the neutronics and heat deposition factors over every part of the reactor. Then, using the temperature of the FLiBe salt and known efficiencies of commonly used heat exchangers for molten salt reactors (MSRs), an optimization problem can be conducted to find a design with the highest hydrogen production and lowest neutron damage to the vessel. Judging from previous papers on this reactor design, it is likely that secondary outlet temperatures of 690 K are easily achievable and could be even higher if high-efficiency heat exchangers, such as shell-and-tube heat exchangers, are used[1].

The upfront cost of constructing a HYLIFE-II inertial confinement fusion reactor estimates the costs for two different designs. In a 1993 study, the upfront construction costs for these HYLIFE-II fusion power plant designs were estimated at $2.166 billion for a 940 MW reactor and $2.825 billion for an enhanced 1934 MW version[2]. The energy cost for these reactors was calculated at 6.5 cents per kWh for the 940 MW model and 4.5 cents per kWh for the enhanced version. Given that hydrogen production via PEM electrolysis requires approximately 39.4 to 50 kWh per kilogram[3], the cost to produce 1 kg of hydrogen with the HYLIFE-II reactor would be approximately $5.27 for the 940 MW reactor and $3.65for the enhanced version. To produce consistency, all the costs in this section have been adjusted to the value of the dollar for the 2022 calendar year[4]. These costs line up well with the current cost of green hydrogen, which is approximately $5 per kilogram[5].

*This work was conducted under the auspices of the Texas A&M Department of Nuclear Engineering.

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Applying Inertial Fusion Energy for Hydrogen Production*

A. Olive[1] and B. Gouteyron[1]
[1]Texas A&M University Department of Nuclear Engineering, 125 Spence St, College Station, TX
brianna_rivera@tamu.edu

One current challenge in the fusion industry is the scope to which it is often confined. Fusion is often relegated to being a power source good for little else other than being a strong producer of base load power. This is a challenge our project aims to solve, allowing fusion to be used to produce cheap, green hydrogen, which can be utilized in many different sectors that are looking at using hydrogen as an alternative fuel source. Because of the high temperatures that fusion reactors produce, it is easier to produce hydrogen via electrolysis but also produces unique considerations for the longevity of the design of the reactor used.

One of the ways we addressed the material challenges was by considering a modified HYLIFE-II reactor design that incorporates a molten salt blanket composed of FLiBe, used both to enhance heat conduction to the electrolyzer and protect the reactor from neutron damage that would require the design to frequently replace the reactor walls. In addition to incorporating the electrolyzer instead of a traditional secondary loop used to boil water, we also use advanced high-temperature materials, such as Hastelloy N and oxide dispersion-strengthened steel, which were selected for their superior corrosion resistance, mechanical integrity, and low neutron activation.

To verify the results of this preliminary survey of existing literature and basic calculations, several software programs will be used to obtain more accurate results. Neutronic and heat deposit calculations will be performed using OpenMC, which will help verify the rate of heat deposition into the electrolyzer and therefore the quantity of hydrogen able to be produced on an annual basis.

Judging from previous papers on this reactor design, it is likely that secondary outlet temperatures of 690 K are easily achievable and could be even higher if high-efficiency heat exchangers, such as shell-and-tube heat exchangers, are used[1]. Additionally, in a 1993 study, the upfront construction costs for a HYLIFE-II fusion power plant were estimated at $2.166 billion for a 940 MW reactor and $2.825 billion for an enhanced 1934 MW version[2]. The energy cost for these reactors was calculated at 6.5 cents per kWh for the 940 MW model and 4.5 cents per kWh for the enhanced version. Given that hydrogen production via PEM electrolysis requires approximately 39.4 to 50 kWh per kilogram[3], the cost to produce 1 kg of hydrogen with the HYLIFE-II reactor would be approximately $2.60 ($5.27 in 2022 dollars) for the 940 MW reactor and $1.80 ($3.65 in 2022 dollars[4]) for the enhanced version. These costs line up well with the current cost of clean hydrogen according to the DOE, resulting in a cost of around $5/kg[5].

*This work was conducted under the auspices of the Texas A&M Department of Nuclear Engineering.

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Utilizing the OMEGA High-Resolution Velocimeter (OHRV) to Quantify Shock Front Non-Uniformities in Wetted Foams*

A. DeVault[1,A], M. Millot[2], M. Gatu Johnson[1], S. Ali[2], R. Nora[2], P. Celliers[2], S. A. Maclaren[2], Xiaoxing Xia[2], J.A. Frenje[1]

[1]*Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, MA 02139*
A) Corresponding Author Email: devault@mit.edu
[2]*Lawrence Livermore National Laboratory, Livermore, CA 94550*

Foams printed using 2-Photon Polymerization (2PP) and wetted with liquid fuel provide a promising new target platform for understanding target degradation mechanisms in inertial confinement fusion (ICF) implosions. These wetted foam targets are less expensive and easier to produce than solid ice layered targets, enabling more rapid fielding of dense-fuel implosions. Radiation hydrodynamic simulations of polar direct drive wetted foams have shown increased laser-target coupling, increased fusion yield, and reliable ignition [1]. Experimental characterization of wetted foams to benchmark these simulations and better understand the target platform is vital. Using OMEGA's Capseed Campaign platform, planar shock fronts were propagated through DD-wetted foams, and their nonuniformities were diagnosed with the OHRV. By varying pore structures, densities, and thicknesses the shock-front nonuniformities and hydrodynamic instabilities seeded by various wetted foam samples were quantified and characterized. The results of this work are used to motivate further experiments to provide a more complete understanding of whether wetted foams may prove to be a tunable platform for investigating hydrodynamic instabilities in ICF implosions.

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Designing a D2 wetted foam target station

C. Schoenwaelder[1,2], C. Brown[1], M. Gauthier[1], A. Gleason[1], N. Hartley[1], M. Ikeya[1], W. Wilson[1,3], X. Xia[4], S. H. Glenzer[1]

[1]SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA, 94025
[2]Friedrich-Alexander University Erlangen-Nuremberg, Hugenottenplatz 6, Erlangen, 91054
[3]Stanford University, 450 Jane Stanford Way, Stanford, CA, 94305
[4] Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA, 94550
schchris@slac.stanford.edu

We report the design and development of a cryogenic liquid foam target testing station at the SLAC National Accelerator Laboratory for future use in high-energy density science and IFE relevant experiments at the Linac Coherent Light Source (LCLS). This platform incorporates a range of foam target designs, wetted with cryogenic deuterium (D_2), to investigate the wicking process and enable precise control over target density profiles with homogeneous liquid distribution. The cryogenic system is engineered to maintain the liquid D_2 at temperatures below 20 K, with precise thermal management to maintain structural integrity. The testing station provides a unique capability to study D_2 ice formation, either through controlled processes or via rapid exposure to vacuum, leading to evaporative cooling and subsequent freezing. This platform lays the groundwork for the development of a versatile, rep-rated cryogenic D_2 wetted foam target system for integration into next-generation IFE experiments. By advancing cryogenic targetry, this testing station serves as a critical tool for probing the fundamental properties of matter under extreme conditions, supporting the progression of high-energy-density science and fusion energy research.

Warm Dense Matter Conductivity Measurements using single-shot THz spectroscopy

E. R. Toro* [1 2] **, M. Ikeya**[1]**, T. Held**[3]**, E. Sung**[1]**, B. Rethfeld**[3] **, M. Z. Mo**[1]**, and S. Glenzer**[1]**, and B. Ofori-Okai**[1]

[1]SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, CA 94025
etorogar@stanford.edu
[2]Department of Mechanical Engineering, Stanford University, Stanford, CA 94305
[3] Department of Physics and Research Center OPTIMAS, University of Kaiserslautern, Germany 67663

Understanding WDM is critical for optimizing Inertial Confinement Fusion trajectory and modeling planetary dynamos. However, predicting WDM properties remains difficult due to the combination of non-trivial degeneracy and strong Coulomb coupling. While state-of-the-art computational tools are in development for predicting the transport properties of materials at WDM conditions, experimental data needed to validate such models is limited.

Here, we present near-zero-frequency (DC) electrical conductivity measurements of warm dense copper determined by THz spectroscopy [1-3]. Copper thin films were heated using intense laser pulses to WDM conditions and probed using single-cycle THz pulses. Combining the measured conductivities with temperature estimates based on the Two-Temperature model [4], the results of these measurements are compared with theoretical predictions and previous experimental measurements [5-8]. This represents an important step towards benchmark high precision experimental data, which is essential to provide critical tests of computational methods, including DFT.

This work is supported by the DOE Office of Science, Fusion Energy Science under FWP 100182, FWP 100866, and by the DOE LDRD program at SLAC National Accelerator Laboratory, under contract DE-AC02-76SF00515 as part of the Panofsky Fellowship awarded to BKOO.

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Thursday, April 10

Time	Name	Institution	Abstract Title
Session I - Driver Development		**Brenda Garcia-Diaz, Chairperson**	
8:30 AM	Mike Campbell	MCM Consultants	Perspectives on Inertial Confinement Fusion (ICF) and Inertial Fusion Energy (IFE)- History, Opportunities and Challenges
9:15 AM	Trevor Cohen	Blue Laser fusion, Inc	Recent Progress for Commercializing IFE Based on a Novel High Efficiency 10 MJ Laser and High Gain Fuel Target
9:35 AM	Takashi Sekine	Hamamatsu Photonics K.K.	Initiatives to Realize Long-Term IFE Research in HAMAMATSU
9:55 AM	Alexei Sokolov	Texas A&M University	High-Power Laser Beam Combining via Molecular Coherence
10:15 AM	Break		
Session II - Driver Development		**Arthur Pak, Chairperson**	
10:40 AM	Jorge Rocca	Colorado State University	Colorado State University ALEPH Petawatt-Class Laser and Upgrade for the New ATLAS Facility
11:00 AM	Erhard Gaul	Marvel Fusion GmbH	Short Pulse Laser Development for Direct-Drive IFE
11:20 AM	Kaikai Zhang	Amplitude Laser Inc.	High Repetition Rate Nd:Glass Amplifier Module for kJ Lasers for Fusion Research
11:40 AM	Kavita Desai Kabelitz	University of Illinois Urbana-Champaign	Optically Pumped Amplifiers in Alkali-Rare Gas Excimers for Laser Fusion Energy
12:00 PM	Lunch Provided		
2:00 PM	Teambuilding	Walk to the BreckConnect Gondola and take the free ride to the top! Meet in the coffee shop at Gravity Haus (605 S. Park Ave)	
6:00 PM	Cocktails & Hors d 'Oeuvre Reception		
7:00 PM	Banquet and Trivia Night		

Perspectives on Inertial Confinement Fusion (ICF) and Inertial Fusion Energy (IFE)- History, Opportunities and Challenges

Dr Mike Campbell[1]

[1] MCM Consultants,17117 Tallow Tree Lane, San Diego, CA 92127,
mike.campbell.sd8@gmail.com

Abstract
The need to decarbonize central power production and the recent demonstration of fusion ignition and scientific gain greater than 1 at the National Ignition facility has renewed interest in Inertial Fusion Energy (IFE). The presentation will give a brief history of ICF, summarize the present state of fusion physics, and the challenges and opportunities for a program focused on IFE.

Recent progress for commercializing IFE based on a novel high efficiency 10 MJ laser and high gain fuel target*

T. Cohen[a], J. Mance[a], S. Gandrothula[a], K. Arai[b], F. S. Carcoba[b], H. Ohta[a], P. M. Pattison[a], P. Rudy[a], N. Svadlenak[a], C. Smith[a], R. Fukuda[a], S. Iizuka[a], Y. Ohara[a], K. Tsubakimoto[c], R. Adhikari[b], S. Nakamura[a]
[a]Blue Laser Fusion Inc., 6950 Hollister Ave., Goleta, CA, USA 93117
tcohen@bluelaserfusion.com
[b]The Division of Physics, Mathematics and Astronomy, California Institute of Technology, 1200 E California Blvd., Pasadena, CA, USA 91125;
[c]Institute of Laser Engineering, Osaka University, Suita, Osaka, 565-0871 Japan

Blue Laser Fusion (BLF) is commercializing a laser technology capable of enabling the world's first clean, on-demand, renewable inertial fusion energy (IFE) generation. The BLF IFE laser platform enables a high efficiency 10 MJ laser at 4 Hz coupled to a high gain fusion fuel target to generate energy. We present recent progress, in collaboration with Caltech as well as Osaka University, on the modular pulsed laser system, including performance of CW and pulsed laser energy storage in a large-scale optical enhancement cavity (OEC), injected with a coherent beam combined (CBC) fiber amplified laser system. The pulsed OEC is a Fabry Perot cavity that is designed to store large amounts of energy within the 2-mirror cavity by carefully timing the round-trip time of the intracavity laser pulse with the injection laser, resulting in phase matching and stacking of the laser pulses. Through the combination of multiple CBC + OEC laser modules, the architecture can deliver high pulse energy and broad spectral width on aggregate, with high spatial beam quality, appropriate polarization and precise temporal tuning optimized for direct drive IFE with a high gain fuel target. We will also describe technical challenges with the system and our development roadmap, including the progression from 1.5 to 15 to 150m cavity lengths and increases to the injection laser pulsed power.

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Initiatives to realize long-term IFE research in HAMAMATSU

T. Sekine,[1] T. Morita,[1] N. Kageyama,[1] Y. Hatano,[1] M. Kamei,[2] K. Suzuki,[1] Y. Muramatsu,[1] T. Hiraiwa,[1] T. Fujita,[1] Y. Takeuchi,[1] K. Ikeda,[1] N. Akiyama,[1] N. Ichikawa,[1] A. Oba,[1] H. Huang,[1] Y. Zheng,[1] Y. Ikeya,[1] S. Okawara,[3] T. Kitajima,[2] T. Kuhara,[2] K. Torii,[3] T. Nagakura,[3] T. Miyake,[3] M. Aranami,[3] K. Kaneko,[3] A. Iwashita,[3] H. Suzuki,[2] K. Morita,[2] T. Oda,[2] Y. Miyamoto,[2] D. Hori,[2] J. Ebihara,[2] N. Akikusa,[3] K. Makino,[1] Y. Tamaoki,[1] Y. Kato,[1] H. Fujiwara,[1] Y. Ueda,[1] and T. Kawashima[1]

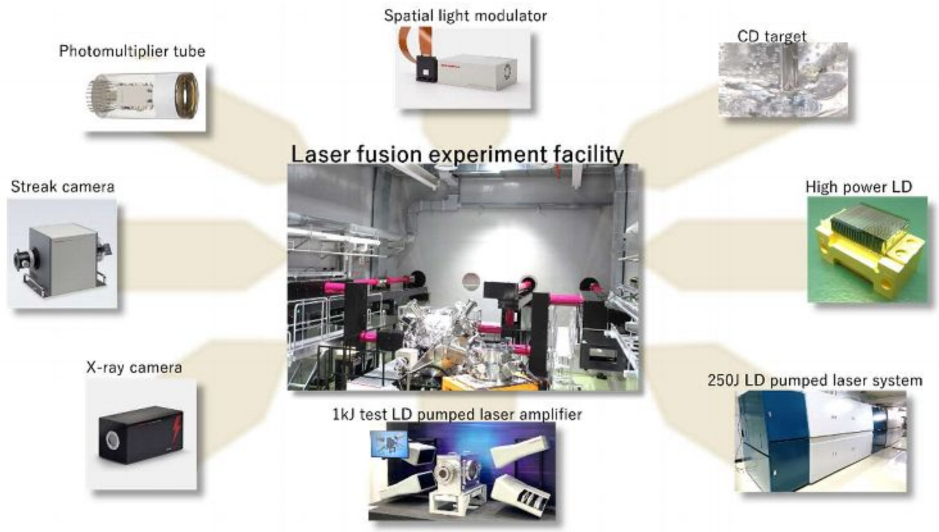
1 Central Research Laboratory, Hamamatsu Photonics K.K., 5000 Hirakuchi, Hamana-ku, Hamamatsu, Shizuoka, 434-8601, Japan

t-sekine@crl.hpk.co.jp

2 Laser Division, Hamamatsu Photonics K.K., 1-8-3, Shinmiyakoda, Hamana-ku, Hamamatsu, Shizuoka, 431-2103, Japan

3 Solid State Division, Hamamatsu Photonics K.K., 1126-1 Ichino-cho, Chuo-ku, Hamamatsu, Shizuoka, 435-8558, Japan

Hamamatsu Photonics K.K. has been conducting research and development for over 30 years to realize laser fusion technologies. In particular, we have demonstrated world-class performance in high-power laser diodes(LD) and repetitive high-energy LD pumped solid-state lasers[1-]. We are also working on R&D of technology to mass-producible and cost-effective deuterated polystyrene targets (shells and beads) for use in laser fusion experiments with high precision. Furthermore, our unique products such as streak cameras, X-ray cameras and photomultiplier tubes for neutron detection are already used in cutting-edge laser fusion research around the world. In addition, to our knowledge, we are the only private company that owns a laser fusion experiment facility with a total area of 885 m^2, including a 1.2m thick concrete shielded laboratory. Currently, we are engaging in experiments aiming for an output of 250 J at 10 Hz with an LD-pumped Yb:YAG laser, while also in development of high-power LDs and laser amplifiers technologies to realize a 1kJ-class LD-pumped solid-state laser. In this presentation, we will report on our latest experimental results and our long-term efforts in IFE.



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High-power laser beam combining via molecular coherence*

Alexei V. Sokolov,[1] Aleksei M. Zheltikov,[1] Zhenhuan Yi,[1] J. Gary Eden[2] and Marlan O. Scully[1]
1 Institute for Quantum Science and Engineering and Department of Physics and Astronomy,
Texas A&M University, College Station, TX 77843-4242, USA
2 Department of Electrical and Computer Engineering, University of Illinois, Urbana, IL 61801, USA

Laser-driven nuclear fusion holds promise to supply mankind with ample clean energy for hundreds and thousands of years to come. The recent scientific break-even demonstration[1] has produced a renewed wave of excitement for the inertial confinement fusion (ICF), and while that particular experiment[2] utilized the indirect drive approach mediated by x-ray production in a hohlraum, the direct-drive scheme[3] can boost the overall efficiency of the system. In the direct drive approach, where ultraviolet laser beams, supplied for example by advanced excimer laser systems, illuminate the fusion capsule directly, the requirements for the laser beam quality and controllability are particularly high. Moreover, since the typical laser power exceeds solid-state damage thresholds, beam combining, focusing, and pulse compression need to be done through nonlinear processes in gases. In particular, one promising scheme relies on combining multiple excimer-laser beams, with simultaneous beam-profile shaping and clean-up, through stimulated Raman scattering (SRS) in a molecular gas.

Gas-phase SRS beam combining and Raman beam cleanup (RBC) have been extensively studied in the past[4-6] and remain a hot topic and an area of active research. We approach this topic from the viewpoint of a broader area of molecular coherence phenomena. Quantum coherence corresponds to a situation where atoms or molecules of a sample are prepared in a coherent superposition of eigenstates[7]. High degree of coherence can lead to remarkable results, and is a central feature of multiple techniques. Atomic coherence has been used in electromagnetically induced transparency and lasing without inversion. Molecular coherence enables a variety of applications, including, for example, a technique termed molecular modulation, which produces a coherent optical bandwidth spanning infrared, visible, and ultraviolet spectral regions, allowing arbitrary ultrafast space- and time-tailored sub-cycle optical field synthesis[8]. The use of molecular coherence for the purpose of combining high-power laser beams through stimulated Raman scattering -- a technique adopted by the laser-fusion community -- is another remarkable example. It's enabled by a remarkable feature of SRS where the wave-vector of the driven molecular coherence is essentially arbitrary. In this presentation we will review recent ideas and advances in this arena.

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Colorado State University ALEPH Petawatt-class laser and upgrade for the new ATLAS facility*

Shoujun Wang, Yong Wang[1], Reed Hollinger[1], Sina Anaraki Zahedpour[1], Jim King[1], Ping Zhang,[1] Fernando Tomasel[1], Aaron Davenport[1], Vladimir Chvykov[1], Carmen S. Menoni[1], and Jorge J. Rocca[1,2]

[1]Electrical and Computer Engineering Department, Colorado State University Fort Collins, CO
[2]Physics Department, Colorado State University, Fort Collins, CO
Jorge.Rocca@colostate.edu

The ALEPH (Advanced Laser for Extreme Photonics) at Colorado State University (CSU) is a λ= 800 nm high repetition rate Petawatt-class Titanium Sapphire femtosecond laser that was developed in-house. It generates 0.85 PW pulses of 30 fs duration at repetition rates up to 3.3 Hz (burst mode)[1]. ALEPH also enables experiments requiring ultra-high contrast (> 1×10^{12}) operating in second harmonic mode. ALEPH has performed 40 LaserNet US user experiments to-date. Many of these experiments are in Inertial Fusion Energy (IFE) relevant areas. These, and other experiments performed by the local team, include proton and deuteron acceleration, ion stopping power, D-D fusion, neutron generation, and X-ray radiography. ALEPH is also a tool for the research conducted at the IFE-STAR hubs, including RISE, and for the FIRE collaboratives.

An upgrade of ALEPH is underway. In a public/private partnership with Marvel Fusion CSU is constructing a new building to house the new ATLAS facility. This facility will combine the upgraded ALEPH with two Petawatt lasers constructed by Marvel Fusion. ATLAS will have multiple target chambers and will be accessible to external users thought LaserNet US.

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Short pulse laser development for direct drive IFE

E. W. Gaul*[1], P. Fischer [1], G. Bodini [1], J. Jung [a], F. Bucksteggе [2], Ch. Aleshire [2], P. Jhetre[2], O. Naranjo [2], M. Krüger [1], M. Martinez-Pacheco [1], A. Meadows[3], A. Moshova[1], M. Speicher[3], J. H. Buss [1], A. Schmalz [2], M. Schollmeier [1], H. Ruhl [1], G. Korn [1]

[1]Marvel Fusion GmbH, Theresienhöhe 12, 80339 Munich, Germany
Erhard.gaul@marvelfusion.com
[2]Pulsed Light Technology GmbH, Lagerhofstraße 4, 04103 Leipzig, Germany
[3]Marvel Fusion Inc, Fort Collins, USA

Ultrafast lasers provide a unique path to couple energy efficiently and fast into matter. Absorption of such high-power laser pulses has been proposed as an efficient path to couple energy into nanostructure targets [1,2]. At sufficient laser intensity the electrons are expelled via the ponderomotive force and subsequent Coulomb forces within the ionized nanostructure accelerate ions well into the MeV range[3]. This process effectively couples large amounts of the laser energy to the ions and enables new possibilities for IFE concepts[4,5,6].

We develop diode pumped solid state Petawatt Lasers (>100 J, <100 fs) for 10 Hz operation with emphasis on achieving an overall wall-plug efficiency approaching 10%, while reaching a high temporal pre-pulse contrast $>10^{-10}$:1at a timescale of a few picoseconds, and while keeping the overall design compact for future scaling.

The laser system is based on optical parametric chirped pulse amplification (OPCPA) and subsequent broadband amplification in Neodymium doped glass. Here the OPCPA output delivers joule-class pulse with tailored spectrum to pre-compensate the gain narrowing of the laser glass or a combination of laser glasses. Such systems have been demonstrated to exceed petawatt peak powers[7]. Replacement of flashlamp with diode pumping technology is the dominant step to higher efficiency but can further be improved by better spatial and temporal gain overlap, better energy extraction, and better compressor efficiency. The latter is mostly due to multilayer dielectric gratings[8]. The final output will be frequency doubled for target isolation and contrast improvement.

Two such lasers will be installed at the Advanced Technology Lasers for Application and Science (ATLAS) facility at the Foothills Campus of the Colorado State University (CSU) in Fort Collins. Synchronization to femtosecond precision between two laser and third petawatt laser provided by CSU will enable a multitude of fusion relevant experiments.

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High repetition rate Nd:glass amplifier module for kJ lasers for fusion research

Stéphane BRANLY[1], Florian MOLLICA[1], Franck FALCOZ[1], Kaikai Zhang[1,2,*], Antoine COURJAUD[1], and Pierre-Mary PAUL[1]
1. Amplitude Laser Group, 2 rue du Bois Chaland, Lisses, 91090, FR
2. Amplitude Laser Inc., 406 S Hillview Dr, Milpitas, CA 95035
*kaikai.zhang@amplitude-laser.com

Research on laser fusion explores multiple strategies to achieve fusion gain, and a key challenge is delivering several megajoules of energy through multiple beamlines while ensuring uniform concentration on the target. Additionally, the spectral and temporal characteristics of these beamlines require a broad bandwidth and the capability to reach at least the kilojoule energy level. Finally, the laser technology must achieve high wall-plug efficiency to be viable for power plant operation.

Nd:glass is one of the preferred gain materials for such kJ-class beamlines due to its extensive use in high-energy laser facilities such as NIF, Laser Megajoule, and Omega. It also offers the potential for diode-pumping, which improves wall-plug efficiency and increases repetition rates by mitigating heat deposition in the gain medium.

Amplitude has developed a new concept, PAMDAM (Pseudo Active Mirror Disk Amplifier Module) technology, featuring liquid-cooled multidisks pumped with flashlamps. This efficient cooling technology has already been successfully integrated into pump lasers delivering 70 J at 10 Hz based on Nd:YAG and 100 J at 0.1 Hz based on Nd:glass.

As part of the THRILL European project, Amplitude is now developing a PAMDAM laser head based on Nd:glass, designed for kJ-class energy extraction at 0.1 Hz with flashlamp pumping. We will review the key characterizations of this laser head relevant to kJ lasers operating in both the nanosecond and picosecond regimes. Since this technology is compatible with diode pumping, this development represents a critical step toward realizing kJ lasers operating at 10 Hz for Inertial Fusion Energy applications.

Optically Pumped Amplifiers in Alkali-Rare Gas Excimers for Laser Fusion Energy

Kavita Desai Kabelitz,*[1] Stephen Messing,[1] and J. Gary Eden[1,2]
[1]Laboratory for Optical Physics and Engineering, Department of Electrical and Computer Engineering, 306 N. Wright St., Urbana, IL, 61801, USA
[2]Hagler Institute for Advanced Study, Texas A&M University, College Station, TX 77843
*kvdesai2@illinois.edu

In the pursuit of technological development for laser fusion energy (LFE), several laser gain media for the optical driver are currently under investigation. Specifically, the engineering of high-power amplifiers is being considered with a focus on excimer laser drivers. Unlike solid-state materials, excimer laser gain media cannot be permanently damaged by high optical field intensities and exhibit superior thermal properties that allow for efficient heat dissipation. As a result, high pulse energies can be extracted from a single aperture, as opposed to the 192 beams required for NIF. There are several excimer molecules being explored for high energy laser systems including, but not limited to, the rare gas halides and the alkali-rare gas molecules. In rare gas-halide systems, the rare gas atom is excited by an electron beam and the lowest-excited (bound) state of the rare gas-halide molecule is populated through a "harpooning" reaction. Subsequent emission occurs on a bound-to-free transition, producing photons with energies of ~5 eV for KrF and ~6.4 eV for ArF, and these systems can be amplified through nonlinear optical processes. KrF excimer lasers have a quantum efficiency of ~50% whereas the e-beam pumped systems developed to date have a wall-plug efficiency of ~7%. On the other hand, the alkali-rare gas excimers are optically excited through photoassociation on a free-free transition and emit on the lowest lying alkali atomic transitions (D lines) in the near infrared, resulting in quantum efficiencies >90%. For example, in the KXe molecule, emission occurs at ~769.9 nm and the excitation band wavelengths are shown below in Fig. 1. The critical point to be made is that this family of gas/vapor lasers are amenable to diode laser pumping which offers the potential for wall plug efficiencies well beyond those currently available with the rare gas-halide lasers. This characteristic is crucial to making an economical reactor as any increase in efficiency could drastically reduce the cost of power generated. In addition to higher efficiency, alkali-rare gas amplifiers produce near diffraction limited beams that can be used to clean up poor quality beams or as a brightness converter for fusion schemes considering using diode laser drivers. For direct-drive fusion, where the beam profile incident on the target is critical to achieving uniform compression, alkali-rare gas amplifiers could purify the beam before a specific phase profile is imparted onto the driving beam. The experimental results obtained to date for alkali-rare gas excimer amplifiers will be presented.

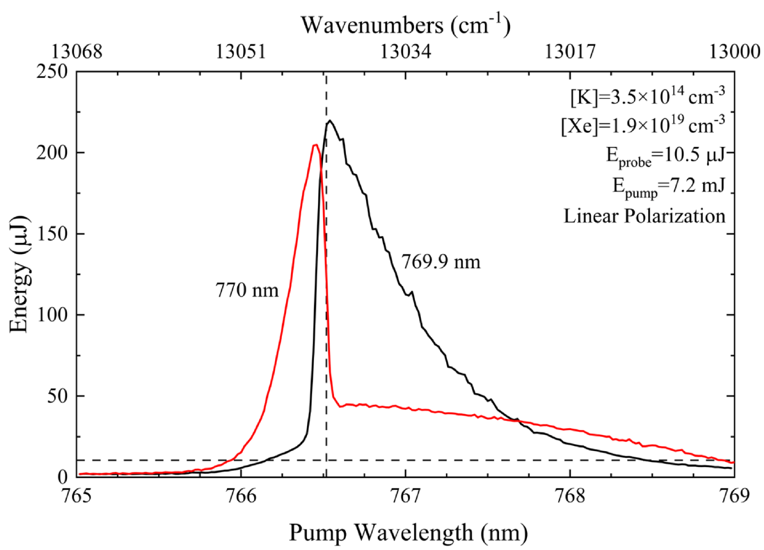

Figure 1: KXe laser excitation spectra for two different probe wavelengths: 770 nm (red) and the K D_1 line (black curve). Note that the gain bandwidth for this laser is >3 nm. The vertical and horizontal dashed lines represent the K D_2 line and the initial probe energy respectively.

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Friday, April 11

Time	Name	Institution	Abstract Title
Session I: Cross-Cutting Fields		**Jim Gaffney, Chairperson**	
8:30 AM	Kyle Peterson	Sandia National Laboratory	Mutually Beneficial Pulsed Power IFE Science and Technology Investments
8:50 AM	Adriaan Riet	Idaho National Laboratory	Supporting Fusion at Idaho National Laboratory
9:10 AM	Krish Bhutwala	Princeton Plasma Physics Laboratory	Preliminary Results on Proton Beam Focusing and Heating Using a Modular Target Approach
9:30 AM	Willow Martin	Stanford University	Characterizing Laser-Heated Polymer Foams with Simultaneous X-Ray Fluorescence Spectroscopy and Thomson Scattering at LCLS/MEC
9:50 AM	Break		
Session II: Cross-Cutting Fields		**Mingsheng Wei, Chairperson**	
10:20 AM	Vignesh Perumal	CAMINNO, Inc.	Generative Design and Digital Twins for Fusion Energy Targets and Components
10:40 AM	Jean-Luc Vay	Lawrence Berkeley National Laboratory	Progress of the FES SciDAC Project on Kinetic IFE Simulations at Multiscale with Exascale Technology (KISMET)
11:00 AM	Carlo Fiorina	Texas A&M University	Building an Open-Source Framework for the Design and Analysis of IFE Chamber and Blanket Systems
11:20 AM	Box Lunch Provided		
1:00 PM	Conference Ends	Thank you for joining us!	

Mutually Beneficial Pulsed Power IFE Science and Technology Investments

K.J. Peterson[1], Kate Bell[1], Mike Cuneo[1], Josh Leckbee[1], Matt Gomez[1], Greg Rochau[1]

kpeters@sandia.gov.
[1]Sandia National Laboratories, PO Box 5800, Albuquerque, NM, 87185

Pulsed power technology has proven to be an effective and economical way to compress energy in both space and time to produce short, high power electrical pulses that are useful for a wide range of applications. The U.S. Department of Energy (DOE) has employed pulsed power technology for decades for weapon effects simulations, thermonuclear fusion, and other science supporting stockpile stewardship. The unique high energy density conditions and/or radiation outputs that can be created in the laboratory using pulsed power provide important data in support of annual nuclear stockpile assessments and the qualification/certification of nuclear weapon modernization programs.

Pulsed power drivers are also an attractive approach for IFE since they can efficiently couple a significant fraction (5-10%) of the driver energy to a magnetically driven fusion target. Furthermore, magnetically driven pulsed power fusion targets have already demonstrated high Lawson criteria ($P\boldsymbol{\tau}$) performance, second only to the National Ignition Facility, with only modest investment in recent years. Detailed simulations and well-established scaling predictions suggest high fusion gain is obtainable with pulsed power drivers that deliver 8-10X the power and energy as Sandia's Z machine today.

Significant technical challenges remain to demonstrate high gain magnetically driven fusion and commercialize it. Demonstrating high gain magnetically driven fusion is the first step and a common goal of both the National Labs and the private fusion energy sector. This talk will focus on pulsed power science and technology investments being made and planned that will not only advance efforts to ultimately achieve a laboratory high yield fusion capability needed for stockpile stewardship, but also accelerate commercial fusion energy efforts. This includes plans to double the energy and power of the Z facility in the same facility infrastructure that exists today.

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

Supporting Fusion at Idaho National Laboratory*

Adriaan A. Riet,[1] Thomas Fuerst[1] Pierre-Clement Simon[1]
1Idaho National Laboratory, 1955 Fremont Ave, Idaho Falls, Idaho, 83402
adriaan.riet@inl.gov

The Fusion Safety Program at Idaho National Laboratory has supported efforts to develop magnetic and inertial confinement fusion energy devices for commercial energy power development since 1979. In addition to our DOE less than hazard category 3 tritium handling facility STAR, we also have unique capabilities such as an adaptation of the severe accident code MELCOR developed specifically for fusion, and integrated modeling capabilities using the MOOSE Finite Element Code.

In this presentation, we cover our unique experimental capabilities for investigating tritium sorption, solubility and permeation. We discuss unique experiments, such as the Tritium Plasma Experiment, the Tritium Extraction eXperiment, and the Tritium Gas Absorption Permeation experiment. We discuss the molten salt handling capabilities at STAR. We also show the application of MELCOR-TMAP to predict engineering scale plant conditions during normal and accident conditions, such as a Loss-of-Vacuum Accident. We detail additional functionality recently added into MELCOR to enhance tritium modeling capabilities. Finally, we demonstrate high-fidelity modeling capabilities found within the open-source MOOSE finite element framework as well as fuel-cycle modeling using TMAP8.

*This work conducted in support of the Department of Energy Fusion Energy Sciences Program

Preliminary Results on Proton Beam Focusing and Heating using a Modular Target Approach *

K. Bhutwala[1ⱡ], X. Vaisseau[2], W. Theobald[2], V. Ospina-Bohorquez[2], K. Lezhnin[1], J. Griff-McMahon[1], R. Nedbailo[3,1], M. Rivers[1], M. Bailly-Grandvaux[4], C. McGuffey[5], G. Schaumann[2], S. Klein[6], N. Kabadi[7], P. Nilson[7], F.N. Beg[4] and S. Malko[1]

[1] Princeton Plasma Physics Laboratory, Princeton, NJ 08540
[2] Focused Energy, Inc., Redwood City, CA 94063
[3]Center for High Energy Density Sciences, The University of Texas at Austin, Austin, TX 78712
[4] University of California San Diego, La Jolla, CA 92093
[5] General Atomics, San Diego, CA 92121
[6] University of Michigan Ann Arbor, Ann Arbor, MI 48109
[7] Laboratory for Laser Energetics, Rochester, NY 14623
ⱡ corresponding author: kbhutwal@pppl.gov

Since their discovery near the turn of the century, laser-driven proton beams have proven valuable in high energy density science applications. Despite their ultra-short bunch duration (<100 ps), they have high intensities and are focusable through target design, making them especially effective in warm dense matter generation [1] and inertial confinement fusion [2]. Research has so far shown that focusing may be accomplished using hemispherical ("hemi") thin-foil targets and enhanced by attaching cone structures [3]. Whereas most research has investigated partial hemi targets, preliminary simulations reveal that full hemi targets may offer better focusing characteristics with or without attached cones. Additionally, few experimental studies overall have sought to optimize the focusing dynamics from structured targets. We present the preliminary analysis from an experiment conducted on the OMEGA-EP laser assessing the focusing and heating capabilities of proton beams using a *modular target approach* for full hemi with added cone structures. For each modular structured target, proton focal characteristics were measured using mesh radiography [3], and the temperature evolution of proton-heated Cu disk samples was measured using streaked optical pyrometry and x-ray spectrometry. As part of a larger campaign to optimize proton focusing, this experiment would ascertain the energy-scaling properties of proton focusing to OMEGA-EP's kJ-class lasers.

* This work was conducted under the auspices of the Department of Energy through PPPL Laboratory Directed Research and Development: "Proton transport and stopping power in Warm Dense Matter" and FES High Energy Density Laboratory Plasma Science Program award "Ion stopping power in Warm Dense Matter" (Award Number DE-SC0024542).

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Characterizing Laser-Heated Polymer Foams with Simultaneous X-ray Fluorescence Spectroscopy and Thomson Scattering at LCLS/MEC

W. Martin[12], M. MacDonald[3], L.B. Fletcher[1], J. Nilsen[3], A. Gleason[1], S. Glenzer[1], H. Bellenbaum[4], T. Döppner[3], R. Falcone[5], S. Faubel[1], T.D. Gawne[4], L. Hancock[6], N. Hartley[1], M.L. Herbert[7], G. Jain[1], K.D. Kabelitz[8], D. Kraus[7], A.L. Garcia[4], A. Kritcher[3], O.L. Landen[3], J. Ripps[7], S. Schumacher[7], E.R. Toro[1]

willowm@slac.stanford.edu

[1]SLAC National Accelerator Laboratory
[2]Stanford University
[3]Lawrence Livermore National Laboratory
[4]Helmholtz Zentrum Dresden-Rossend
[5]University of California Berkely
[6]Bringham Young University
[7]University of Rostock
[8]University of Illinois Urbana Champaign

Inertial Fusion Energy (IFE) research aims to revolutionize energy production. Advancing this field requires precise data on materials under extreme conditions. Here, we present the first results and next steps in our experimental campaign designed to enhance IFE research through absolute measurements of the equation of state of polymer foams driven to high energy density (HED) states. During our recent experiment at LCLS utilizing the MEC short-pulse laser, we isochorically heat polymer foam samples and probe them with highly coherent x-rays. We obtain forward and backward x-ray Thomson scattering (XRTS) spectra and simultaneously perform complementary measurements via x-ray fluorescence spectroscopy (XFS) from dopant Co atoms in the foam. We aim to make high-precision measurements of density, temperature, and ionization state populations. These measurements will provide benchmark data at HED conditions, crucial for improving atomic models in atomic kinetic and radiation codes.

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Generative design and digital twins for Fusion Energy targets and components*

V. Perumal,[1] A. Stein,[1] A. Manikandan,[1,2] and R. Frye[1]
[1]CAMINNO, Inc., 2778 Agua Fria Street, Santa Fe, NM, 87507
vignesh@caminno.energy

Commercialization of fusion power plants requires advanced design and engineering capabilities. Currently, the complexity of the design and the complexity of the manufacturing process are treated separately. This is because our work is limited by the separation of the existing digital tools and the processing capability of the human mind. This disconnected approach leads to sequential, sometimes, repeated work leading to an increase in project costs and extending timelines.

One of the principal cost drivers in the IFE system is the target. There is considerable effort to design targets that will be manufactured at scale with the requisite uniformity. Recent advances with wetted-foam targets show that they naturally develop a shell which makes them suitable for mass production[1]. These offer several advantages, including simplicity in target production (suitable for mass production for inertial fusion energy), absence of the fill tube (leading to a more-symmetric implosion), and lower sensitivity to both laser imprint and physics uncertainty in shock interaction. There are now many methods for making foam targets, although one that stands out as not only scalable but also optimizable is the 2-photon polymerization[2]. However, the stochasticity of the AM outcomes currently makes this an unreliable process for mass manufacturing.

In this work, we present a multi-objective design optimization and digital twin algorithm that employs scientific ML-based process modeling. Our algorithm couples scientific AI-based physics models that simulate structural, thermal, fluidic, and electromagnetic physics & manufacturing processes with experimental manufacturing data for targets and other fusion components. The ML models are used as surrogates in a gradient-based multidisciplinary design optimization technique and can be used to expedite exploration for ideal target design. The algorithm achieves computational efficiency by replacing standard numerical solvers with their ML surrogates having similar accuracy. These surrogates can capture scale transitions in a computationally inexpensive framework compared to hierarchical scale transition approaches using high-fidelity simulations. This enables the creation of a manufacturing digital twin that can predict the different manufacturing outcomes in near real-time. AM surrogate models for manufacturing are necessary for fast and accurate computation - to take the data in from the manufacturing process, compute the required quality metrics, predict the probable future thermal and mechanical histories of the part, recommend the design changes required to ensure the performance criteria is satisfied by the finished component, and relay it back to the AM machine. Extension of this approach to other IFE applications are also discussed.

* This work is conducted under the auspices of the DOE-SBIR grant (DE-SC0024852) and the NMSBA assistance program in collaboration with LANL.

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IFE STAR

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Progress of the FES SciDAC project on Kinetic IFE Simulations at Multiscale with Exascale Technology (KISMET)

J.-L. Vay[1], A. Almgren[1], J. R. Angus[2], A. Formenti[1], M. Garten[1], B. Geveci[4], D. Ghosh[2], D. Grote[2], A. Huebl[1], R. Jambunathan[1], A. Kemp[2], R. Lehe[1], A. Myers[1], J. Palastro[3], A. Riedman[2], O. Shapoval[1], K. Weichman[3], J. Van De Wetering[2], S. Wilks[2], A. Yenpure[4], W. Zhang[1], E. Zoni[1]
[1]Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720
jlvay@lbl.gov
[2]Lawrence Livermore National Laboratory, 7000 East Ave, Livermore, CA, 94551
[3]Laboratory for Laser Energetics, University of Rochester, 250 East River Rd, Rochester, NY, 14623
[4]Kitware, Inc., 1712 ROUTE 9, Halfmoon, NY, 12065

The path towards a future IFE Fusion Pilot Plant (FPP) requires further improvement of the modeling tools, as recognized by the IFE community in the 2023 IFE Basic Research Needs (BRN) report. Importantly, the BRN report emphasized the need to (a) develop computational tools "capable of simulating kinetic effects in thermal and magnetized plasmas," (b) "accurately model and enable control of Laser-Plasma Instabilities (LPI) in IFE-relevant regimes," (c) "take advantage of and spur emerging technologies (*exascale computing*,..)," and (d) "develop modern simulation tools that leverage heterogeneous hardware to accelerate the path towards reliable IFE designs".

In response to these needs, the 4-year, multi-institution FES SciDAC project KISMET is leveraging the Particle-In-Cell (PIC) code WarpX, developed under the auspices of the US DOE Exascale Computing Project, and only PIC code awarded the ACM Gordon Bell Prize for outstanding achievement in high-performance computing (in 2022). Through further development and use of this next-generation capability for simulating kinetic effects in IFE-relevant thermal plasmas, the goal is to advance the understanding of the impact of kinetic effects on critical stages of IFE target physics – from the driver-target coupling to the compression and burn stages. The project is organized along 4 physics thrusts: (1) low-density plasma physics, (2) laser absorption and transport, (3) proton-driven fast ignition, (4) hotspot physics; and 2 computational thrusts: (5) algorithms and high-performance computing, (6) scalable data analysis & visualization.

We will present progress of the project, including: (a) study & mitigation of laser-plasma instabilities, (b) efficient modeling of proton-based fast ignition [1], (c) implementation of energy-conserving implicit PIC for simulating dense IFE-relevant plasmas, (d) energy-preserving coupling of explicit Particle-In-Cell with Monte Carlo Collisions [2], (e) an efficient GPU parallelization strategy for binary collisions in Particle-In-Cell plasma simulations [3].

*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 Fusion Energy Sciences, Scientific Discovery through Advanced Computing (SciDAC) program.

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Building an open-source framework for the design and analysis of IFE chamber and blanket systems

C. Fiorina,[1] N. Habtemariam[1], E. Cervi[2], B. Earley[3], K. Flippo[3]
1 Texas A&M University, Department of Nuclear Engineering
College Station, TX 77843-3133, USA
carlo.fiorina@tamu.edu
2 Argonne National Laboratory, Lemont, IL, 60439
3 Xcimer Energy, Redwood City, CA 94065

While some fundamental aspects of Inertial Fusion Energy (IFE) remain unresolved, achieving the deployment schedule for pilot and commercial plants outlined in the DOE's Bold Decadal Vision also requires initiating the engineering design of IFE chambers and blanket systems. However, IFE developers today face a challenge in that the necessary modeling and simulation tools are currently unavailable or not fully adequate.

Fortunately, collaborative efforts within the nuclear engineering community in the US and Europe have already laid a robust foundation through the development of a new set of tools based on OpenFOAM. OpenFOAM is arguably the most widely used open-source CFD toolbox worldwide, with an estimated user base of approximately 10,000. Its adoption within the fusion community continues to grow, as evidenced by the Fusion Energy Reactor Models Integrator (FERMI) project at ORNL and the numerous publications available in the open literature. Contributions from both the fission and fusion communities have further enhanced OpenFOAM's capabilities with: deterministic solvers for neutron transport; porous-medium solvers, often used for fission reactor cores, that can be used in IFE designs to achieve reasonable compute time for complex geometries like pebble-bed blankets; advanced nonlinear thermal-mechanics capabilities, including irradiation creep, embrittlement and swelling that can be used for detailed simulations of first-wall and structures; coupling capabilities through the Functional Mock-Up Interface international standard, and through the preCICE framework. Additionally, the authors of this abstract have provided OpenFOAM with tailored gas dynamics capabilities, including enhanced shock-capturing schemes, the use of non-ideal equations of state, and multiphase capabilities for simulating ablation or jet splashing. They have also implemented ray-tracing capabilities to evaluate ablation depth through the chamber.

This presentation introduces the challenges of chamber and blanket designs in IFE concepts, provides an overview of the status of modeling and simulation in the field, and details how the OpenFOAM framework is enabling scientific discovery and engineering design of IFE systems.