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Title: Three-dimensional ultrafast X-ray visualization of laser-driven wetted foam targets in implosions and planar geometry to develop low-cost, rep-rated IFE targetry

A. Gleason[1,2], S. Glenzer[1], M. Stadermann[3] , B. Kozioziemski[3], S. X. Hu[4], V. Goncharov[4], D. Montgomery[5], A. Leong[5], J. Kline[5], K. Flippo[5]
1- SLAC National Accelerator Laboratory
2- Stanford University
3- Lawrence Livermore National Laboratory
4- Laboratory for Laser Energetics
5- Los Alamos National Laboratory

Topical areas covered: *Targets; Target physics & design; Diagnostics*

Executive Summary

Recent technical discussions around deployable inertial fusion energy (IFE) test-platforms for future, pilot power plant(s) center around reasonable and cost-effective repetition-rates, of order 10 Hz. Targetry, Target Protection Systems and diagnostics to monitor performance (e.g., target delivery, laser parameters, etc.) all need to be realized and optimized for a 10 Hz repetition-rate. This is at the heart of the technical challenge our community faces. In this whitepaper, we outline a series of studies in metal foam and wetted foam samples, coupled with a design for an implosion (converging symmetric shock) and planar-shock experiment at the Matter in Extreme Conditions (MEC) instrument and the MEC-Upgrade at SLAC, in coordinating with efforts on other foam targets pursued at LLE and LLNL. These studies will be designed to address critical, technical aspects of high rep-rate targetry by testing foam performance in a direct-drive design and leverage the state-of-the-art, rep-rated laser and X-ray diagnostics available now and in the future with the MEC-U and LCLS.

Introduction

IFE is a possible clean energy solution needed to address aspects of climate change. The physics understanding for IFE arises out of the inertial confinement fusion (ICF) concept associated with the nuclear weapons stockpile stewardship programs (e.g., Norreys et al., 2020). Achieving ignition and propagating thermonuclear burn via ICF is one of the primary goals of the U.S. Department of Energy. Very recent success in sustained net-energy gain was achieved at the National Ignition Facility (NIF), where a burning plasma was obtained as the primary source of heat in the plasma -- needed to enable high energy gain (Zylstra et al., 2022). This tremendous success was due in large part to the exquisite target design and quality, perfected and optimized over decades for best results in an indirect-drive (Hohlraum-geometry) with an HDC + fill tube capsule. However, as we consider the 10 Hz rep-rated needs of an IFE test-platform for a future pilot plant, this indirect-drive with HDC capsule may not be cost effective (estimated cost required at few pennies per target). Foam targets and in particular, liquid deuterium-tritium (DT) wetted polymer foams in a direct-drive geometry have been gaining traction in the community as a path forward toward ignition and burn (e.g., Sacks and Darling, 1987; Olson et al., 2016; Goncharov et al., 2020; Olson et al., 2021). Simulations have suggested that a wetted foam target will ignite at a NIF-scale laser facility in a direct-drive geometry (e.g., Collins, 2005). A wetted foam target design may have technical/performance benefits and, perhaps in the future, can be optimized for mass production/cost-effectiveness. These benefits include: 1) higher laser absorption allowing a thicker shell and greater stability, 2) capability to mitigate hydrodynamic instabilities – meaning the foam microstructure itself could be tuned to mitigate instabilities arising from beam imbalance or imprint structure, 3) polymer foams could eventually be 3-D printed/additively manufactured in a way that achieves the cost-requirement for an IFE test-platform.

Approach

We propose a holistic approach to investigate the design and optimization of foam and wetted-DT foam targetry, examining the foam performance in a direct-drive implosion and planar shock geometries, to support IFE. Experiments would include a systematic study of low-Z/polymer foam microstructures, building off of, and in collaboration with, current work at the NIF, General Atomics and LLE (e.g., see white paper submission from V. Goncharov on Advanced Targets). Polymer and low-Z foams developed use in ICF science have historically been made through bulk chemical processes, but newer strategies include 3D printing platforms as well. One parameter of interest is the minimum pore size that still allows wicking of the DT. Other foam physical parameters – pore size distribution, wetting angle between particles, polymer composition, dopants, impurities, pore wall thickness, and density can all influence stability and strength of the foam (e.g., Geng et al., 2021), and therefore also influence the wetted DT foam performance during a compression process. In the ramp up to MEC-U completion, the intention is to perform studies to improve the fabrication of foams and porous structures in an iterative process between data-feedback via experiment-to-foam fabricator at existing facilities (e.g., MEC, LCLS, LLE, LLNL).

Previous work from this team has focused on X-ray imaging with X-ray Free electron lasers (XFELs). In particular, coherent diffractive imaging (CDI) has emerged in the last decade as a promising high-resolution lens-less imaging approach for characterizing a wide variety of materials – with significant technical progress through source, algorithm and imaging methodologies (e.g., Xiong et al., 2014). CDI techniques are pushing spatial resolution to 5 nm and can provide accurate phase projections to yield detailed quantitative 2D and 3D reconstructions with a resolution that is not limited by imaging optics. Recent efforts at LCLS are enabling a new nanoscale imaging instrument based on a ptychographic method for the collection of static, high resolution 2D and 3D images, down to 10s nm resolution, e.g., could be used in support of ICF and IFE capsule or sample inspection/studies (Fig. 1). Preliminary efforts at LCLS have inspected Cu-foam from LLNL with unprecedented 30 nm resolution over a few μm^3 volume providing 2D and partial 3D reconstructions. Future work is focusing on single-shot ptychographic methods to provide 2D or 3D image reconstructions without the need to raster or scan the sample. This would open up the possibility to perform 2D and 3D imaging in situ, during dynamic compression events. At MEC, near-field propagation-based phase contrast imaging (PCI) and Talbot-CDI proved very successful in measuring 2D void collapse in ICF-ablator materials to 200 GPa. These images of a single collapsing void with sub-micron spatial resolution and picosecond temporal resolution will allow us to study high pressure (several Mbar) shock interaction for insights on hot spots and instability mitigation in a single void. These data are being compared with 2D xRAGE simulations (courtesy D. Montgomery, LANL) for 1:1 physics model comparisons. In addition, the Talbot-CDI method, which can reconstruct the actual wavefront and be applied to reconstruct the image of a shocked sample, i.e., the wavefront after the sample interaction, results in a novel single-shot imaging technique. Prior campaigns on single void collapse have leveraged the LCLS pulse train and UXI cameras to measure a shock traversing a single void in a single sample (Hodge et al., 2021).

Though this previous work has only focused on the material response surrounding a single void, this has enabled us to steadily develop the techniques, capabilities and workforce needed to examine the properties and behavior of complex materials during the implosion phase of an IFE target. With these techniques now established and opportunities to benchmark physics models in the simplest, single-void case, we are poised to build complexity in the sample microstructure and move from single- to few- to many-pores sample designs -- ultimately to experimentally visualize the 3D response of a wetted foam during compression.

We envision a series of experiments at MEC and MEC-U, complimented by state-of-the-art radiation-hydrodynamic modeling, to systematically assess the effect of tuned wetted foam microstructure on the implosion or planar shock compression processes. The plan would include compression studies on both foam-only (i.e., without liquid hydrogen fill) and truly wetted foams with liquid fill. The intent is to examine behavior over a time, which would start with compression of the wetted foams, then include wetted foam-to-liquid only mix out to hot spot formation timescales. Based on these experiments our goal would be to optimize the target design for best performance in an IFE test-platform. The microstructure will be varied using chemical and 3D printing processes (e.g., pore density, pore size distribution, polymer composition, etc.) in collaboration with LLE, LLNL, LANL, and GA. Using CDI, static 2D and 3D X-ray images of these wetted foams will be collected to establish pre-shock microstructure and examine wetting angle between pores as a function of process/fabrication type. A selection of these foam samples can then be prepared for dynamic compression experiments. In order to determine high fidelity 2D and 3D density reconstructions of these wetted foams during the passage of single or multiple shocks, we will leverage the coherent properties of the LCLS beam with a tailored temporal X-ray pulse structure over 100 ns. A 8-pulse train of X-rays, each with femtosecond pulse widths, delivered in tunable pattern with 350 ps to several or 10s of ns intervals, will probe the temporal evolution of the dynamically compressed wetted foam target.

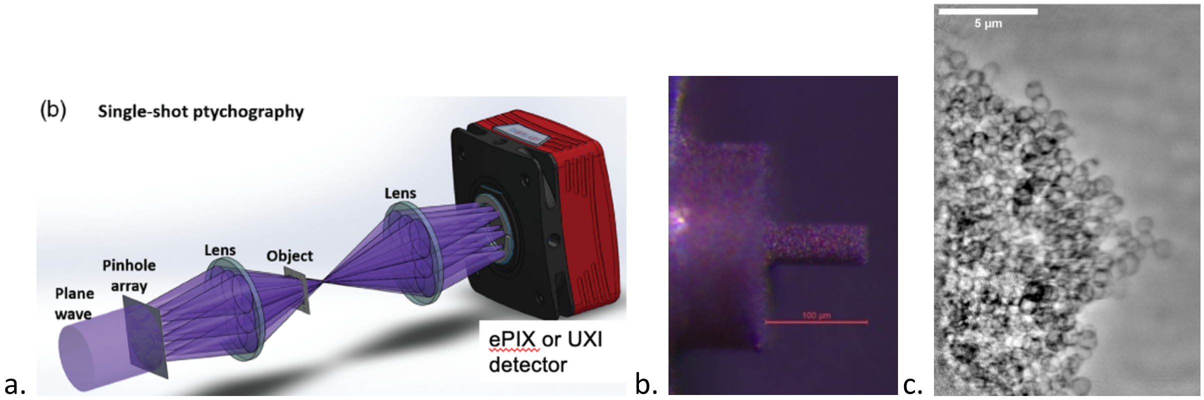

Fig. 1. a) Modified from Sidorenko and Cohen, 2016. Experimental schematic of possible single-shot ptychography setup using a pinhole array to enable 2D or 3D reconstructions with the LCLS X-ray beam where the X-ray laser axis is fixed. b) Optical microscope image of nano Cu foam from LLNL used in ICF sample construction. c) Reconstructed image of Cu nano foam in (b) from 2021 using ptychography at LCLS. We envision using this same technique in a tomo-ptychographic X-ray imaging geometry for single-shot diffraction and 2D and 3D samples reconstructions during dynamic compression.

In a separate experimental configuration, the beams can also be split and steered to generate a stereo- to tomographic perspective of the compression event (up to 8 unique views). For each beam, the diffraction image to then be reconstructed by iterative phase retrieval algorithms should be recorded on gated detectors, building off the current technology of the hCMOS-UXI and/or ePIX-Delta platforms. This imaging approach should be deployed in concert with a suite of additional diagnostics available at the facility: high resolution imaging alcove at an 8 meter for maximum spatial resolution, wide- and small angle scattering, velocimetry, streaked optical pyrometry, and X-ray Thomson scattering. There would be two main compression geometries deployed for this work: planar and converging. The simpler, planar shock compression is well-established at the current MEC facility (e.g., Gleason et al. 2015), however as part of the MEC-U long pulse laser upgrade, we would aim to achieve compression states in the wetted foam to 600 GPa and use carefully tailored drive profiles over several 10s of ns. In addition to this we would design a converging shock geometry in an implosion-style experiment steering the upgraded long-pulse laser to deliver 6-beams on target in a symmetric design. These experimental results can provide critical information for rad-hydro simulations of wetted foam targets at LLE and elsewhere, which will enable reliable IFE target designs.

	Parameter	**Significance**	**Design Requirement**
X-ray diagnostics	Peak flux	Temporal Resolution	1e12 ph/pulse at 12-25 keV in 10 femtoseconds
	Transverse coherence	Object size and spatial resolution	larger samples now possible, from nanoparticles to of order 100s um^3 with spatial resolution to 10s nm
	Bandwidth	Quantitative image interpretation, diffraction	~50 eV, for CDI: reconstruction convergence now more robust
	Pulse structure	continuity of images during single event	8-pulse train, tunable structure in 350ps increments
	Target interaction geometry	achieve 3D reconstructions	8-unique views via split and delay
Shock driver parameters	Energy	maximize compression states achieved	4 kJ, 3*w*
	Pulse duration	sustain compression	60 ns, pulse shaping capability
	Target interaction geometry	versatility in compression style	planar or 6-beam symmetric & convergent
	Spot size	uniformity of imprint & maximize compression states achieved	variable, 0.5 to 2.5 mm

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