Enabling Advanced Ablator Materials for High-Gain Inertial Fusion Energy (IFE) Target Design

S. X. Hu[1,*], Y.-F. Lu[2], L. A. Collins[3], A. White[3], C.-K. Li[4], I. E. Golovkin[5], M. Gu[5], J. Peebles[1], V. V. Karasiev[1], S. Zhang[1], N. R. Shaffer[1], P. M. Nilson[1], D. Harding[1], M. S. Wei[1], S. P. Regan[1], V. N. Goncharov[1], E. M. Campbell[1], C. Deeney[1]

1. **1.** Laboratory for Laser Energetics, University of Rochester
2. **2.** Departments of Electrical and Computer Engineering, Mechanical and Materials Engineering, University of Nebraska-Lincoln
3. **3.** Los Alamos National Laboratory
4. **4.** Massachusetts Institute of Technology
5. **5.** Prism Computational Sciences

*Email: shu@lle.rochester.edu

I. Executive Summary

Designing and manufacturing advanced ablator materials, to have enhanced laser absorption and superior hydro-efficiency that can be verified by focused experiments and *first-principles* calculations, are critical to enable high-gain IFE target design.

II. Introduction

Laser direct-drive (LDD) is one of the most suitable schemes for inertial fusion energy (IFE) design, as it can couple at least twice more laser energy to the imploding shell than indirect drive [1]. Once cross-beam energy transfer (CBET) is mitigated by broad-band laser technologies or laser wavelength detuning, the laser coupling to target in LDD can be further enhanced by a factor of ~2. LDD relies on the absorption of laser energy by low-Z ablator materials/plasmas like polystyrene, beryllium, carbon, etc. The absorbed laser energy in coronal plasmas is transported to the ablation front mainly by electron thermal conduction. The efficiency of this process is termed the "hydro-efficiency" of the implosion, *i.e.,* a product of laser absorption and rocket efficiency. The more the kinetic energy of an imploding capsule, the larger margin for ignition and higher gain of IFE targets. Three things are fundamentally important to the success of IFE *via* the LDD scheme: (1). Getting most of the laser energy absorbed by ablator plasmas in the corona; (2). Obtaining the best hydro-efficiency to couple as large a fraction of laser energy as possible to the kinetic energy of the imploding capsule, which provides high ablation pressure to accelerate the shell; and (3) increasing ablation velocity to stabilize the Rayleigh-Taylor instability growth for better capsule integrity. There are several research directions to reach the above goals. Advanced laser technology such as broad-band laser can address issues such as increased absorption and reduced imprint [2]. A complimentary avenue is a target solution, *i.e.,* by designing and manufacturing advanced ablator materials to provide the above key ingredients for the success of high-gain IFE target designs. Target solution can address issues as imprint reduction and RT growth reduction. This white paper calls for investment in advancing target/material R&D within the IFE program.

III. Designing Advanced Ablator Materials for IFE

For the past three decades, the most common ablator material used for LDD fusion targets is polystyrene (CH) or glow-discharged polymer (GDP), even though other low-Z materials such as beryllium (Be) and high-density carbon (HDC) have long been considered for LDD designs. For cryogenic deuterium-tritium (DT) layered targets, the use of Be/HDC ablators requires the development of a fill tube for LDD, while CH/GDP can rely on permeation to fill targets. This practical reason has mostly limited the choice of ablator material for LDD fusion targets to CH/GDP even up to today, although in terms of considering laser absorption and hydro-efficiency CH/GDP is not the best because of their lower effective charge and thermal conductivity. Given the tremendous opportunity brought by a reinstalled IFE program in the US, it's time to utilize our computational, manufacturing, and experimental tools to design, fabricate, and verify advanced ablator materials for high-gain IFE targets.

For designing the best ablator material, one needs to first consider what materials can give the largest laser absorption without too much radiation loss in the *open* corona. The key parameter that determines laser absorption and radiation loss is the so-called *effective ion charge,* $Z_{eff} = \sum_i f_i Z_i^2 / \sum_i f_i Z_i$, with f_i and Z_i being the atomic fraction and ion charge of each element in a compound ablator material. Since the laser absorption in coronal plasmas *via* inverse bremsstrahlung scales as $\sim Z_{eff}^2$, ablator materials having moderately higher Z_{eff} than the current CH case ($Z_{eff} = 5.3$) would enhance laser absorption in LDD plasmas. Of course, this needs to be balanced with the consideration of radiation loss and DT-fuel preheat from the coronal plasmas, which also depend on Z_{eff}. We believe that a thorough study for the best balanced Z_{eff} through ablator material design is motivated and could lead to an optimal ablator for enhanced laser absorption for LDD. The other important factor for an optimal ablator is its superior thermal conduction thereby giving higher hydro-efficiency for LDD. Past experiments and

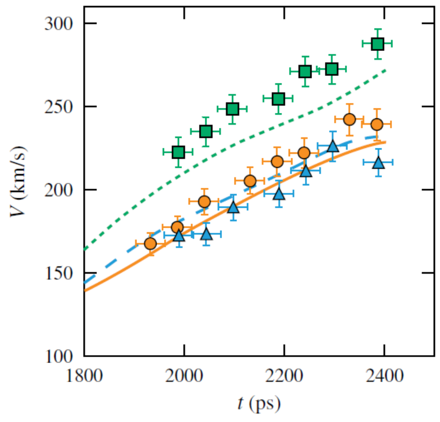

Figure 1. Comparison of the calculated (curves) and measured velocities of the shells averaged over 200 ps (symbols) in CH (orange solid line and circles), C (blue dashed line and triangles), and Be (green dotted line and squares) ablators [3].

simulations have showed that the key quantity controlling this is the ratio of average ion mass to ion charge, i.e., $< A >/< Z > = \sum_i f_i\, M_i/\sum_i f_i\, Z_i$. The higher this ratio becomes, the larger fraction of laser energy can be coupled to the imploding capsule. Figure 1 shows the proof-of-principle experiments, in which the larger $< A >/< Z > = 2.25$ of Beryllium leads to the highest implosion velocity measured on OMEGA with the same laser pulse and mass-equivalent targets [3], while this ratio is 1.86 and 2.0 for CH and HDC, respectively. Based on this observation, tritium is a valuable material to consider for advanced target designs, since it achieves the highest possible $<A>/<Z> = 3$. Lastly, one wishes to have a high ablation velocity to stabilize RT growth in LDD implosions [4], for which low-density foam would serve for this purpose as simulations already suggested [5]. In fact, ablation velocity scales inversely to the ablator material density; Thus, low-density foam will give higher ablation velocity, thereby leading to reduced RT growth.

Given all of the above arguments and the practical consideration to avoid the difficulty/cost of DT-layered targets, we tend to take the wetted foam approach [6] for IFE. For the ablator part, we propose to use *tritium-wetted CHON-foam with certain Si-/mid-Z-doping*, in which we will design the proper fraction of each element to have moderately-high value of Z_{eff} and larger $< A >/< Z >$. Note that the CHON foam can be made with the additive manufacturing technique (discussed next), in which a certain fraction of Si and other mid-Z elements can be added into the CHON resin. For the inner foam portion holding the liquid DT fuel, researches will be directed to eliminate O, N from the resin (if possible) and to lower the C fraction to an acceptable level for reducing the unavoidable radiation loss in hot spot (due to carbon ions).

IV. Additive Manufacturing of Designed Advanced Ablator Materials

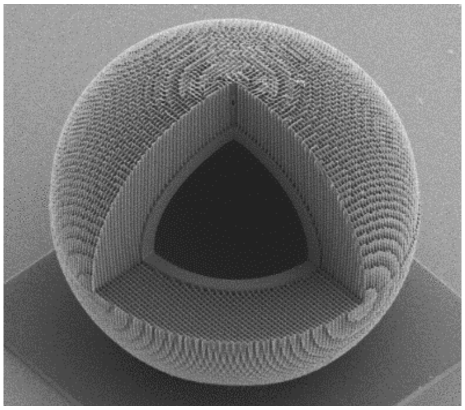

Figure 2. An example of a foam target with a solid shell inside. The external diameter is 860 µm, a shell

Two-photon-polymerization (TPP) is a laser-driven direct-write technology for fabrication of precision micro-scale components (µm to mm-scale) with nanoscale resolutions. IFE targets, including low-density foam targets, can be fabricated by direct laser writing using TPP. The basic target structures are comprised of log-pile-like microstructure with overall dimensions over 1 mm, a resolution of ~100 nm, and a nominal density of ~100 mg/cm^3 or less. The microstructures can be customized by manual programming of the laser scanning paths. With stitching or slower scanning using a piezo stage, the overall sizes can be extended to centimeter ranges. The main challenge in fabricating the foam targets comes in maintaining dimensional and structural stability during TPP post-processing particularly during development, drying and release from the substrate [7]. Figure 2 shows an example of a foam target with a solid shell inside, fabricated by the TPP process. Researches on how to fill (wet) such foam targets with liquid DT and pure tritium will also be needed.

Mid-Z nanoparticles can be doped into the resin used for the TPP process. Note that some mid-Z nanoparticles are commercially available. If not, a mid-Z solid target (e.g., Al and Si) can be placed in a liquid (such as water). A femtosecond laser can be used to ablate the target to generate a plasma. When the plasma is cooled in the liquid, nano-sized particles of the same mid-Z material will be formed. A centrifuge will be used to separate the nanoparticles according to the particle size. The nanoparticles will be processed using a surfactant to avoid clustering. The particles will then be mixed in a TPP resin. The density and size of the nanoparticles mixed in the resin will be tuned to avoid light scattering so that the TPP accuracy and structural integrity will not be affected.

With the further development in IFE, net energy gain will be pursued as the ultimate goal. Low-cost (< $1 per target) manufacturing of wetted foam targets with large quantities (~1 million targets per day) will be a critical step to enable commercial usage of IFE. The supporting technologies are being explored. We have proposed a roadmap to reach the goal by combining established techniques, including laser interference 3D lithography to fabricate low-density foams, microstamping to form hemispherical foam structures, and Origami folding of hemispherical foam structures to form spherical foam targets. Infrastructures will be established to enable this manufacturing capability.

V. Investigating HED properties of Designed Ablator Materials with First-Principles Calculations and Focused Experiments

To understand the HED properties of the designed advanced ablator materials (AAM), we plan to carry out first-principles calculations of equation-of-state, opacity, and thermal conductivities by using density-functional-theory (DFT) based quantum molecular-dynamics (QMD), like what we did for deuterium [8] and CH [9] in a wide range of plasma conditions relevant to ICF. For high-temperature regimes, we can extend the QMD simulations with the recently-developed mixed-DFT method [10]. The emissivity and opacity of the designed AAM in the low-density and high-temperature regimes will be tabulated by Prism's OPACEOS code [11] and/or by REODP code [12]. These calculated material properties (FPEOS, FP-opacity, and DFT-based conductivity model) will be first validated with focused experiments. These experimentally benchmarked tables and models will be used by radiation-hydrodynamics codes for IFE target designs.

Focused experiments to study the designed ablator materials at ICF conditions will include: (a). Shock Hugoniot measurements [13] to benchmark the FPEOS table; (b). Trajectory experiments to measure the expected superior hydro-efficiency and large laser absorption for comparison with code predictions [14]; and (c) Rayleigh-Taylor instability measurements to verify the high ablation velocity and the stabilization of RT growth, by using cone-in-shell platform [15,16] developed at both OMEGA and NIF. The findings of these focused experiments will feed back to the material designs for optimization. At the end, we expect to identify optimal ablator materials - *tritium-wetted CHON-foam with certain Si-/mid-Z doping* – with a specific fraction of each element, for integrated implosion experiments on OMEGA and NIF.

VI. Enabling IFE Target Designs with Integrated Simulation and Implosion Experiments

Finally, we will use 1D/2D/3D rad-hydro-codes to design IFE targets by using the identified and optimized ablator material: *tritium-wetted CHON-foam with certain Si-/mid-Z doping.* Such IFE targets will be using wetted foam: the inner part will have hydro-carbon-only foam (with minimized carbon concentration) wetted by liquid DT fuel, while the outer part uses the identified ablator material, i.e., *tritium-wetted CHON-foam with certain Si-/mid-Z doping.* Integrated implosion experiments with these wetted foam targets will be performed to verify the designed ignition and fusion energy gain.

References

1. R. Betti and O. A. Hurricane, Nat. Phys. **12**, 435–448 (2016).
2. R. K. Follett *et al.,* Phys. Plasmas **26**, 062111 (2019).
3. D. T. Michel *et al.,* Phys. Rev. Lett. **111**, 245005 (2013).
4. V. A. Smalyuk, S. X. Hu, V. N. Goncharov et al., Phys. Rev. Lett. **101**, 025002 (2008).
5. S. X. Hu *et al*., Phys. Plasmas **25**, 082710 (2018).
6. R. E. Olson *et al.,* Phys. Rev. Lett. **117**, 245001 (2016)
7. O. Stein, Y. Liu, J. Streit, J. H. Campbell, Y.F. Lu, Y. Aglitskiy, and N. Petta, Fusion Sci Tech. **73**, 153-165(2018)
8. S. X. Hu et al., Phys. Rev. Lett. **104**, 235003 (2010); Phys. Rev. B **84**, 224109 (2011); Phys. Rev. E **89**, 043105 (2014); Phys. Rev. E **90**, 033111 (2014).
9. S. X. Hu *et al*., **92**, 043104 (2015); Phys. Plasmas **23**, 042704 (2016); Phys. Rev. B **96**, 144203 (2017).
10. A. J. White and L. A. Collins, Phys. Rev. Lett. **125**, 055002 (2020)
11. J. J. MacFarlane, I. E. Golovkin, P. R. Woodruff, JQSRT **99**, 381 (2006).
12. G. Miloshevsky and A. Hassanein, Phys. Rev. E **92**, 033109 (2015).
13. C. A. McCoy, S. X. Hu, M. C. Marshall *et al*., Phys. Rev. B **102**, 184102 (2020).
14. S. X. Hu, V. A. Smalyuk, V. N. Goncharov *et al*., Phys. Rev. Lett. **101**, 055002 (2008).
15. V. A. Smalyuk, S. X. Hu, J. D. Hager *et al*., Phys. Rev. Lett. **103**, 105001 (2009).
16. V. A. Smalyuk, D. T. Casey, D. S. Clark *et al.,* Phys. Rev. Lett. **112**, 185003 (2014).