Additive Manufacturing for Inertial Fusion Energy Target Production System

Alex Haid[1], Neil Alexander[1], Mike Farrell[1], Rick Olson[2], Mark Schmitt[2], Brian Haines[2], Cliff Thomas[3], Elijah Kemp[4], Brent Blue[4], Mike Campbell[3]

[1]General Atomics, San Diego, CA 92121
[2]Los Alamos National Laboratory, Los Alamos, New Mexico 87185
[3]Laboratory for Laser Energetics, University of Rochester, Rochester New York, 14623
[4]Lawrence Livermore National Laboratory, Livermore California, 94551

Contact Information: Alex.Haid@ga.com

Topic Area: Targets (including manufacture, injection, and survivability)

Executive Summary:

Additive manufacturing (AM) techniques have made rapid advancement over the last decade and are being developed to meet target needs of the ICF and HEDP community. AM has enabled several new experiments based on previously unavailable target designs [1, 2, 3]. Contributions of target components have demonstrated the viability and utility of AM for target fabrication purposes. A high-resolution AM technique called two photon polymerization (2PP), also known as two photon lithography (TPL), permits the direct-writing of structures providing design flexibility including materials, microstructures, and surface functionalization of pre-existing structures such as capsules. Moreover, 2PP is a technology that can simultaneously be scaled up in both physical dimension and production rate. Based on recent experience in fabricating target components via 2PP AM, we propose investigation into the high-throughput 2PP-based system options(s) that will meet the requirements of target design space exploration and development, system adaptability, and speed increases to meet the needs of an Inertial Fusion Energy (IFE) power plant.

Introduction

The fuel-supply system of an IFE power plant will need to continuously provide a stream of shootable ICF targets to the ICF reactor, and must in turn be supplied with certain raw materials and the deuterium-tritium fusion fuel. The 2PP AM technique is poised to provide the cost-effective (¢s/target) target fab solution for IFE that is needed to fabricate the anticipated complex target geometries. Indeed, both aspects of this challenge are critical. Not only are we looking towards 2PP AM to provide the necessary volume of targets, but we intend to exploit its capability to provide on-demand complexity and variability to reduce per-target cost by orders of magnitude from the current target technology and yield economic power generation.

Four focus areas to develop AM techniques are outlined below:

1. **Investigation of high-throughput solutions towards mass production**
2. **Development of 2PP AM materials needed for IFE target**s

3. **Demonstration of key targets of interest for IFE using 2PP AM**
4. **Demonstration of a closed loop 2PP AM fabrication system with feedback loops to a HEDP laser facility.**

High-Speed AM 2PP System Development

2PP is a laser-based technique that can create arbitrary 3D structures with sub-micron features via photo-initiated polymerization of a monomer by tightly focusing femtosecond laser pulses. The pulses are focused so the two-photon absorption cross section becomes important only where the intensity of the light is at its highest. The non-linear nature of two photon absorption allows for sub-diffraction limit printing of structures, as well as for the printing of such structures inside pre-existing transparent structures, such as the traditional plastic capsules used in ICF work today.

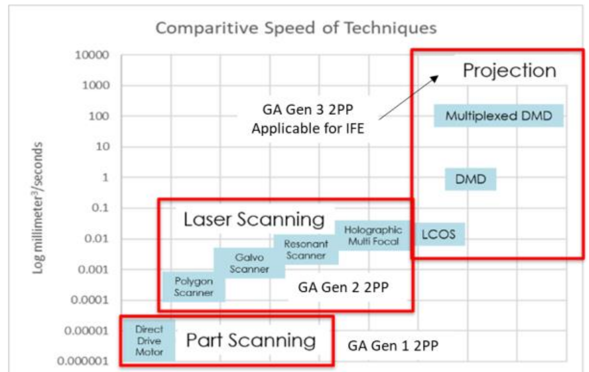

Figure 1: Comparative speed of 2PP fabrication techniques

To best realize these advantages, General Atomics (GA) has developed 2PP systems tailored specifically for target fabrication via part-scanning (Gen-1) and laser-scanning (Gen-2). An internally funded 3rd Generation system utilizing laser projection is under construction in CY2022, with each generation resulting in a multi order of magnitude increase in fabrication speed. GA's overarching goal for increased throughput aligns well with the estimated 500k – 1M targets/day requirement of IFE. A subsequent Gen-3.5 system could be designed and tailored specifically to meet IFE target fabrication needs. *A gen-4 system utilizing volumetric laser projection* [4] *could be envisioned but requires much more development for highly complex parts (e.g. designer foams).*

A few keys areas have been identified for development to get from planned CY22 GA Gen 3 2PP to Gen 3.5 2PP needed for IFE. For the most key components of the system, industry is steadily progressing towards equipment that will enhance throughput including higher-rep-rate high-energy femtosecond laser and spatial light modulators with faster switching times. Additional IFE-relevant 2PP laser system implementations needing development include:

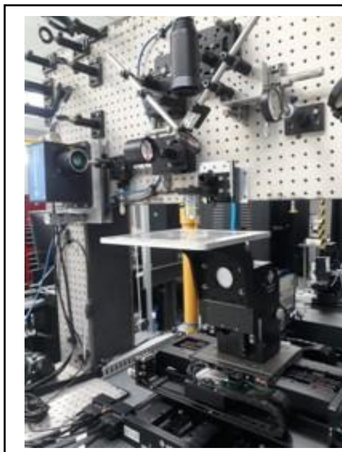
Figure 2: Image of GA-Built Gen-2 (Laser Scanning) 2PP System

- Parallelization of fabrication using multiplexed optics
- Large field of view & high numerical aperture final focusing optics
- High-speed axial optical translation of laser focus

- Tiled projectors
- Integrated microfluidics for high-speed target transfer
- In situ metrology and part characterization to cull out-of-spec targets

Photo Reactive Chemistry Development

The most commonly used materials with 2PP fabrication are acrylic polymers containing a photo-initiator that is sensitive to two-photon absorption. We propose to develop custom chemistries to investigate highly-sensitive photo-initiators for faster fabrication/high-resolution and low oxygen content/deuterated polymers for ICF applications. Additionally, with 2 Photon absorption, techniques could be developed for AM metals (e.g. Gold) and ceramics (e.g. SiO_2) with sub-micron features as well as multi-material printing for multi-component designs (i.e. indirect drive) and selective doping (laser plasma instability control). For IFE applications, the most pertinent 2PP material to develop would be a polymer that meets requirements for composition, mechanical properties, and survivability within an IFE reactor. More specifically, initial 2PP polymers are focused on:

- A low-oxygen-content carbon-hydrogen (CH)–based chemistry
- Deuteration and/or doped chemistry (e.g. halogens, metals)
- A polymer and structure that maintains mechanical robustness and survives an IFE reactor (i.e. simultaneous direct exposure to cryogenic temperature fluids and 800K reactor wall)
- Tailored permeability to liquid deuterium & tritium as well as other fluids

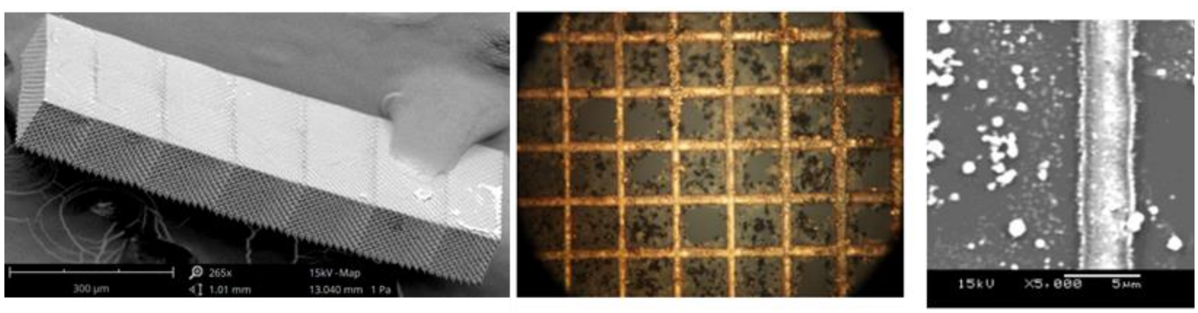

Figure 3: Prototype of a low oxygen content deuterated 2PP printed polymer (left) and of gold via multiphoton induced metal salt reduction (middle, right) fabricated at GA.

Demonstration of Specific IFE Targets

Demonstration of high-throughput fabrication of specific target designs will be needed to commission and qualify 2PP AM for IFE. GA has successfully demonstrated fabrication of various targets including planar microtube arrays [5], compound parabolic concentrators [6], and low-density foam hemispheres [7]. In particular, GA demonstrations of hollow foam spheres with solid-density skin layers have generated interest in 2PP as a viable technique for fabrication of wetted foam targets [8]. Wetted foam targets are an attractive candidate for IFE, and GA 2PP–related developments could focus on demonstrating scaled-up fabrication to 500k-1M wetted foam targets per

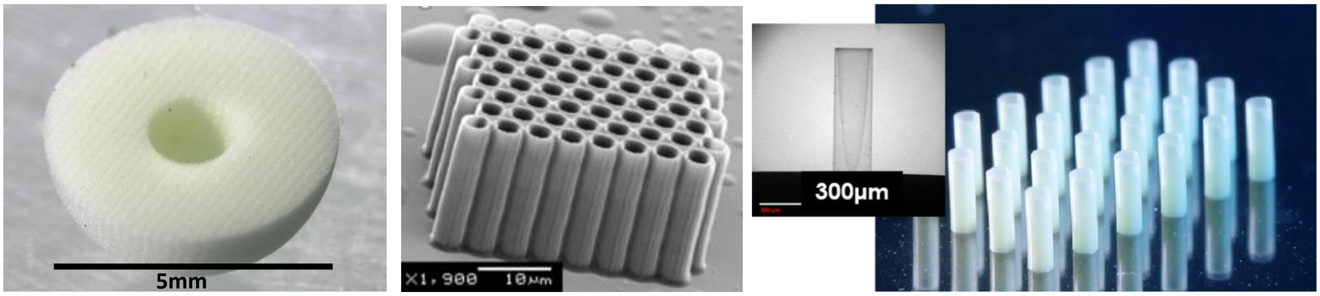

Figure 4: Targets produced at GA via 2PP including multi-shell PDD foam cushions (left), microtube plasma lenses for enhanced TNSA proton generation (middle), and compound parabolic concentrators for MeV X-Ray generation (right) with precision batch fabrication.

day. Concurrently to throughput scale-up development, efforts should also focus on proof-of-concept demonstration (*not necessarily at 500k-1M/day)* of various IFE targets with varying degrees of complexity to be shot at existing laser facilities and newly developed high-rep-rate facilities. Near term AM wetted foam prototype to be shot at NIF/OMEGA will be used to demonstrate key parameters (ablation rates, gain, etc.) as well as characterization of key target specifications including variations in foam thickness/density, out-of-roundness, roughness, pore-size.

Three AM approaches are being considered by GA researchers to produce wetted foam style targets. The first method is to print a foam shell for traditional plastic layer coating. The second is to print the inner foam layer and a solid density outer layer for DT vapor retention. The third method is to take a pre-existing capsule (PAMS, GDP, glass) and print a foam layer on the interior surface of the capsule.

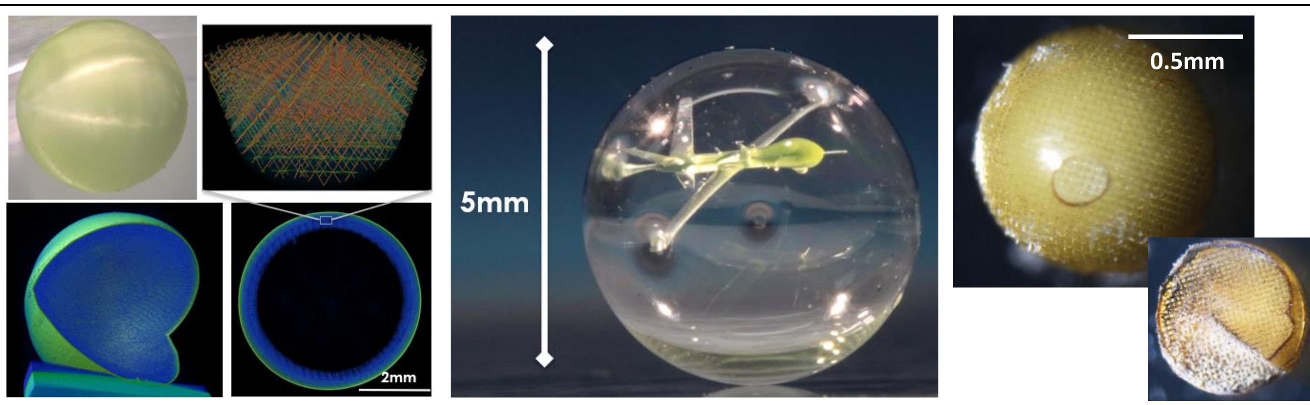

Figure 5: GA developments towards "foam in capsule" fabrication including 2PP printing of inner foam and exterior solid density layer (left), 2PP printing of arbitrary structure in a PAMS capsule (middle), 2PP printing of a foam in GDP capsule for CY22 shot campaign (right).

In addition to already specified variants of wetted capsules, 2PP AM can enable designs that are beyond the capability of other techniques due to the exacting control over features at micron/submicron scale. An example is highly reproducible production of the exact same foam microstructure for every target, thus eliminating a stochastic variation seen in traditional foam chemistry fabrication. Other examples include advanced wetted foam target designs, such as gradient foam densities to mitigate

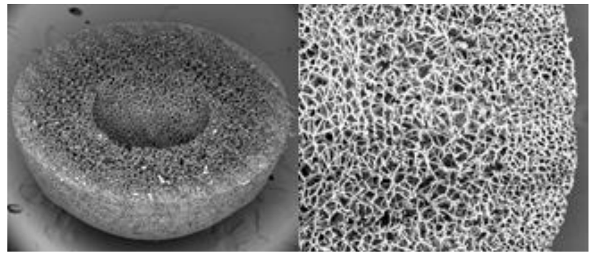

Figure 6: Micrographs of a 2PP AM foam hemisphere with a defined density gradient

hydrodynamic instabilities, engineered foam structures to control the wicking location of liquid fuel via spatially defined capillary action [9], and features that are tailored to the specific laser profile on the capsule (i.e. spatially variant foam layer thickness depending on location where driver laser beam hits the target). Finally, the 2PP AM technique is well suited to rapid changes in wetted foam target designs for a variety of laser facilities differences, as well as variations with the drivers themselves.

Beyond wetted foam target concepts, 2PP AM is readily applicable to several other target designs and geometric forms proposed by the scientific community for an IFE power plant. For example, 2PP AM can be used to rapidly produce diagnostic targets and other consumable diagnostics that require periodic replacement within an IFE reactor. For indirect drive or fast ignition fusion targets that require multiple components, 2PP could be used to precision-print target components directly together, thus eliminating assembly steps. With advances in multi-material printing, 2PP AM could be used to directly print entire multicomponent assemblies.

Pilot a closed loop IFE-AM Platform

Prior to construction of laser drivers with suitable rep-rates for IFE, many of the requisite technologies can be piloted at already constructed HEDP high rep-rate laser facilities. At high rep-rates, diagnostic information as well as variations in the driver will be collected at exponentially higher rates allowing for faster experimental iteration [10]. In the context of IFE, the faster data collection combined with a responsive target fabrication system (i.e., change target diameter or foam thickness “on the fly”) will allow for faster optimization towards parameters needed for IFE, as well as more stable, continuous operation of an IFE reactor. IFE would benefit from a closed-loop target fabrication system connected with feedback loops to diagnostics, driver, data analysis, and predictive simulations. The system could be driven wholly via artificial intelligence or machine learning.

2PP AM is beneficial in this context, in that changes to target design can be implemented rapidly compared to other fabrication techniques, so the entire fabrication cycle is short enough that it can engage within the high rep-rate feedback loop. Furthermore, in-situ metrology during fabrication has been demonstrated at LLNL [11] as an input to fabrication/target-selection and potentially the driver parameters. A study on high throughput closed-loop 2PP AM system design options is proposed incorporating options such as feedback loops and autonomous operation. A prototype system could be built and evaluated at a LaserNetUS rep-rated facility.

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