Target mass production for inertial fusion energy

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

Executive Summary

Targets are the nexus of an IFE reactor. Targets contain the fusion fuel. They are where the driver energy is deposited and where the fusion output products emanate from to be collected by the chamber and blankets of the reactor. They are also the source of much waste (aka "ash"). Targets require high fabrication tolerance (~10 μm level), and large numbers if them are needed (~500,000/day/reactor). This makes the mass production of targets at an economically affordable price a central issue to be developed for IFE power plants.

Economic models of IFE target factories have been created for several target designs. These project target cost at a modest fraction of the target's energy value. Laboratory-scale prototyping of scalable target fabrication processes has been conducted with encouraging results. This work needs to be extended to all processes and scaled up in target throughput.

There are several development steps for the target supply for IFE reactors. These include: staged scale up of target production equipment to higher rates and injector velocities; integration of the various processes into an end-to-end target production and injection system and integration of targets to supply target injection and tracking systems with a driver beamline test facility. These steps are best conducted within the arena of a full IFE reactor development program.

Introduction

Typical inertial fusion energy (IFE) power plants will produce energy by repetitively directing energy onto a target containing the fusion fuel, causing ignition and burn. Ion beams, laser beams, and magnetic fields from pulsed power have all been considered as drivers for directing the energy onto the target. Each target is destroyed by the driver shot or pulse, and the subsequent fusion reaction, so targets must be produced and fueled at the shot rate of the plant driver. We refer to the economic fabrication and fueling of targets, as target mass production. *Economic* here means the cost of the target is a modest fraction of energy value that is produced by that target. Typical IFE power plants will utilize roughly 500,000 targets/day (~6 Hz) for ion or laser drive, and roughly 9000 targets/day (~0.1Hz) for magnetic compression. These rates plus many dimension tolerances on the target at the 10 μm level make target production a highly challenging issue for IFE.

This paper describes prior work we have done on target mass production. Recommended directions for future development of high throughput target manufacturing are also provided.

Target Mass Production

At present, fully in-specification targets (laser direct and indirect drive) are fabricated, DT filled and layered for individual ICF experiments. However, factories for the mass production of IFE targets do not exist, even at pilot scale. These current-day targets can, on average, cost thousands of dollars each. This is due to low quantities, constantly changing designs, fabrication equipment that emphasizes flexibility to accommodate new designs, and very thorough characterization of each target. To meet the low-cost economic requirements of IFE, an IFE target factory will require a paradigm shift to manufacturing a single target design using low-cost, high-throughput manufacturing techniques. Additionally, cost will need to be lowered by the use of large batch sizes for fabrication processes, and the statistical characterization of a small fraction (rather than 100%) of targets; to track production process parameter drift.

To estimate likely costs, factory models have been constructed utilizing experience from the chemical batch processing industry combined with in-house expertise at GA and LLNL, along with other industrial sources. This has been done for several target types: laser direct and indirect drive, heavy ion indirect drive, and magnetic compression drive; see Figure 1. These models considered likely manufacturing and assembly equipment types; factory build costs; personnel and operational costs; in-process volumes (etc.); and then amortized the integrated costs over the volume of targets produced. A conceptual layout of a target factory for laser direct drive targets is shown in Figure 2. The resulting predictions of estimated cost are shown in Table I. Studies like these should be conducted for today's target designs, such as wetted foam direct drive (Ref. 3), X-target ion drive (Ref. 4), and magLIF magnetic drive (Ref. 5 & 6).

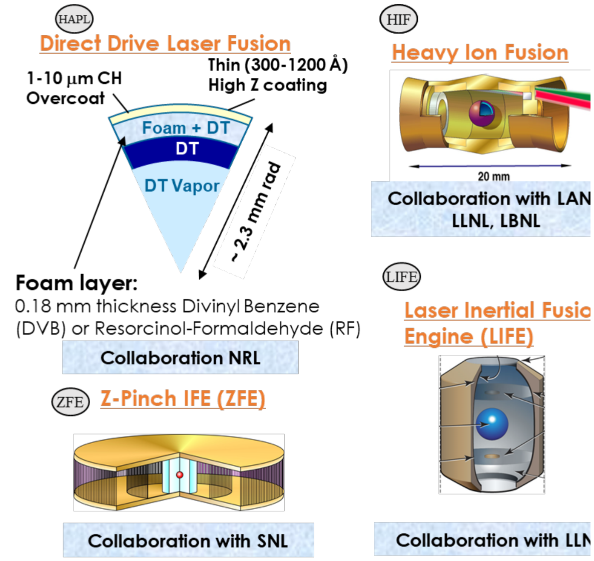

Figure 1: Target designs for which mass production cost models were made.

In the HAPL program (Ref. 7), laboratory-scale demonstrations of the manufacturing processes for the laser direct drive target were undertaken. This included foam capsule formation by micro-encapsulation using coaxial nozzles, followed by curing of the foam capsules in rotary contactors (drums); overcoating the foam capsule with PVP via interfacial condensation chemical reaction; further overcoating with glow discharge polymer (GDP) using a GDP roto-coater specifically designed to be scalable to IFE volume; solvent extraction from the foam capsule by super-critical CO_2 drying; sputter coating a thin Au/Pd layer on top of the overcoats; target filling via permeation; and target fuel layering in a cryogenic fluidized bed. By the time activity ceased, foam capsules were being made with 75% yield. The overcoats were being made leak tight, although this required ~15 μm thickness rather than the desired 5 μm. The Au/Pd sputter coat had sufficient permeability for filling and sufficient IR reflectivity to protect the target from chamber thermal radiation. Finally, the cryogenic fluidized bed had been successfully operated at cryogenic temperature with empty targets, the outer surface of which remained within the roughness specifications. Some of these developments are shown in Figure 3. Further details on foam capsule production and layering are provided in companion white papers.

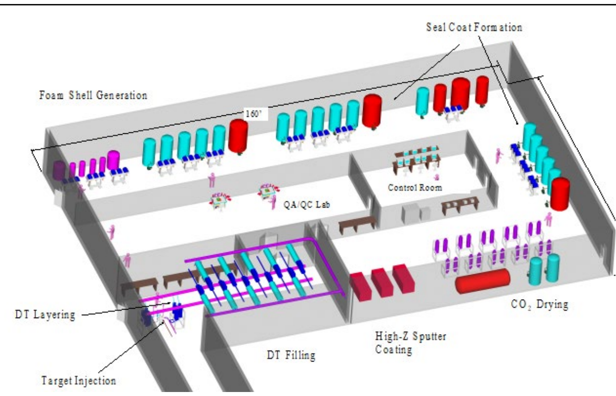

Figure 2: Layout for laser direct drive fusion target factory.

To support indirect drive targets, development was started on using swaging of lead (Pb) to form hohlraum parts. Swaging is used in the mass manufacture of air rifle pellets. Laboratory scale swaging of half hohlraums showed ~10 µm level repeatability (1 standard deviation), Ref.: 8, see Figure 4. This indicates suitability of the swaging process, but development of the technique at high throughput is still required.

Table 1: Estimated cost of targets from Figure 1 per factory economic models, Ref.: 1 & 2.

IFE Concept	Target Design	Target Yield (MJ)	Cost/target for 1000 MW(e)	% of E-value
Direct Drive Laser Fusion	Direct drive foam capsule	~400	$0.17	~6
HIF	Indirect drive distributed radiator	~400	$0.41	~14
ZFE	Dynamic hohlraum	~3000	$2.90	~13
LIFE	Indirect drive Pb rugby hohlraum	~132	~$0.30	~30

Some targets required mechanical assembly. A robotics target assembly system was built at General Atomics. For cone-in-shell targets, the system assembled 80% of target with the cone tip centered to the capsule sphere within +/- 10 µm, see Ref. 8 & 9, and Figure 5. The assembly rate was one every several minutes. The type of robotics was picked for flexibility to be adaptable to many types to target assembly task. Additionally, robotic assembly is used for several ICF target assembly tasks (Ref. 10 & 11). Automated machinery dedicated to one task will be able to operate at higher rates.

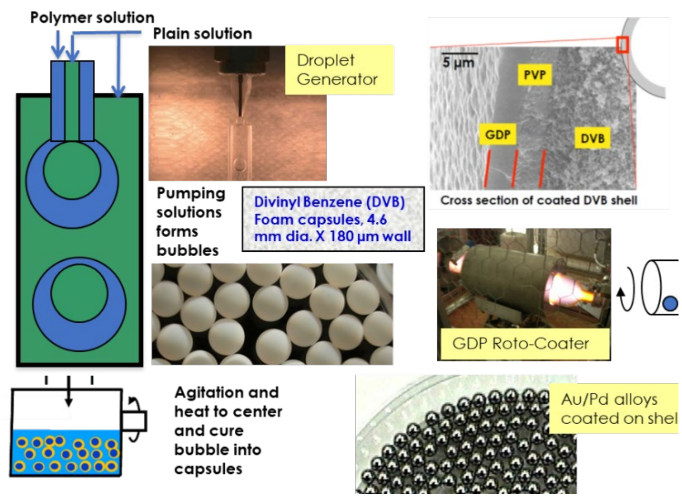

Figure 3: Examples of development of laboratory scale manufacturing processes for laser driven direct drive target in the HAPL program.

Target fabrication also includes precision metrology. For IFE, it needs to involve rapid automated inspection systems for the target parts and assemblies. This will be especially true in the beginning stages of IFE, when the process yields are not likely to be extremely high. That is, in the beginning, a 99% yield process is not required, and a 55% yield would be sufficient provided there are methods to quickly find and remove parts that are out of tolerance. The low volume and mass of these parts means that the material lost will not lead to a significant expense The added expense will only be the “time on machine” of the fabrication process. Development of such automated metrology and handling equipment and processes naturally needs to happen as part of

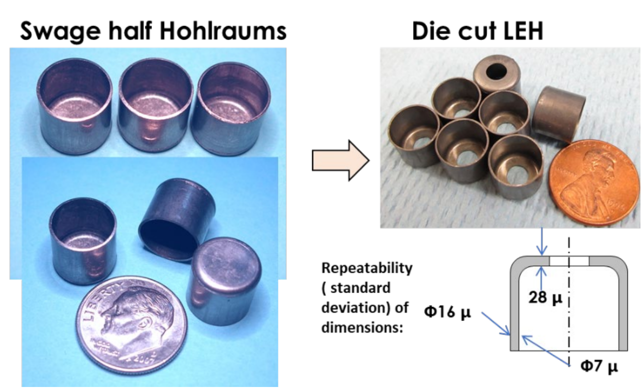

Figure 4: Swaged lead (Pb) half hohlraums.

mass fabrication strategies. Tolerances for IFE targets will likely be similar to current-day targets that are planned for ignition, with surface finish requirements often at the nanometer level, and a few tenths of a percent for many parameters. This is a significant challenge that should not be underestimated.

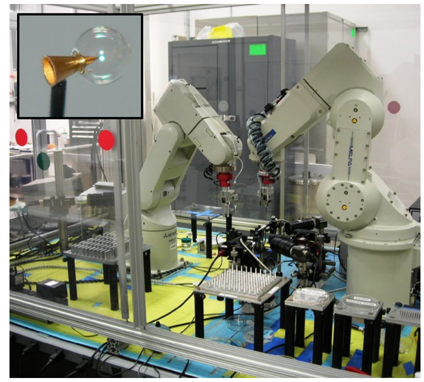

Figure 5: Robotic target assembly has been demonstrated with cone-in-shell targets at modest assembly rate.

Today, while studying ICF implosions at the most powerful laser systems, metrology of targets and target components is key to understanding underlying Physics. With the capsule being one of the most sensitive components to the success of the ICF experiments, a significant portion of the production time and effort is allocated to several precision measurements. The inspection and selection of mandrels onto which some of the ablators are grown in subsequent steps has already been automated with the main objective to reduce operator involvement of a highly repetitive process (see figure 6). Using machine vision learning and image recognition algorithms, optical inspection systems have been developed as part of GA's capsule fabrication capabilities that can image capsules at a rate of 1 per minute, classify surface defects observed in these images, and make an autonomous decision whether a capsule is suitable for production or not [Ref 12]. These types of systems will need to be developed for other on-line quality assurance processes and will need to demonstrate reliable operation at the required throughput.

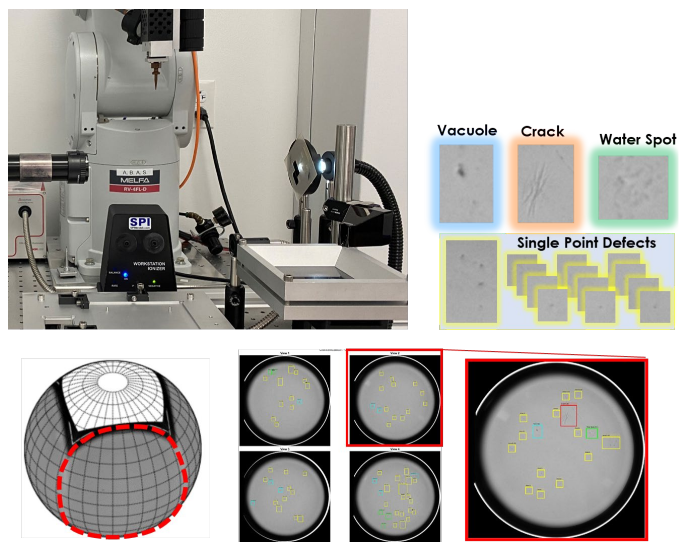

Figure 6: A robot arm is used to pick shells out of a tray, take four images of the shells surface, detect and classify surface features and determine the quality of the shell. System has been in production at GA, inspecting 100's of shells per month.

After the feasibility of IFE has been demonstrated, outsourcing of target production to entities that are best suited to do the manufacturing should take place. As we work towards manufacturing for power plants, we must engage manufacturing sources. By the time of power plant operations, there must be a team with multiple members having the required expertise in target technology and in manufacturing methodologies.

Key Metrics

Target cost should be a modest fraction of the energy value of the target. Typically, this equates to target costs of less than a few tens of cents. The target production rate must be at least that of reactor shot rate. Often this is ~500,000 targets/day for beam driven targets and ~9000 targets/day for magnetic compression driven targets. Targets should meet design tolerances. Tolerances of many parameters can be at a few tenths of a percent level.

Principal steps to demonstrating the target supply for IFE

We put forward the following pathway as a guide for developing each IFE target type that is to be carried forward. Note that depending on the type of target, some of these steps may have already been done, may not be required, or may be applicable to more than one approach.

- Identify target design(s) for the demonstration plant and target production systems.
- Iterate with the target designers and experimentalists to adjust target design for enhanced manufacturability.
- Establish required manufacturing tolerances for targets through a combination of simulation and experimentation (e.g., experimental shots of single targets on NIF) to guide and iterate with developmental effort in this area.
- Develop and build subscale mass-production prototypes of the target manufacturing processes.
- Develop the apparatus to retrieve cryogenic targets from fuel-layering system and load them into the cryogenic target injector.
- Integrate most mass-production processes together in a prototype target factory capable of supplying the requisite targets to the demonstration power plant; for some subsets of components (e.g., hohlraums) outsource as appropriate to begin development of the industrial partnerships that will be needed for economical manufacturing of a commercial power plant target supply.
- Demonstrate at an IFE Demo plant, (or, if appropriate to be done prior to that, at a subscale target research facility) the capability to inject, track, and engage targets at the required repetition rate and accuracy. This must be consistent with wider target and power plant survivability requirements which may be dependent on IFE approach and plant design. Separately, take measurements on NIF to quantify alignment tolerances for ignition.
- Supply targets and prototype target layering (DT fuel layer) equipment to a full-scale IFE beamline test facility that includes an injection and tracking engineering prototype. Ideally this would include ability to load cryogenic layered targets into the injector, and a surrogate of a target chamber whose inner wall can be heated to reactor relevant temperatures (e.g., an ovenized vacuum flight tube). This, along with appropriate diagnostics, could allow characterization of the target condition after transit through an environment similar to an IFE reactor.
- Having demonstrated the above principal steps to a target supply for IFE, demonstrate the ability to provide, inject, track, engage, and ignite targets with high (>99%) reliability; demonstrate long-term subsystem reliability for the full-scale commercial power plant environment

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