An automated IFE Target Factory based the "Lab-on-Chip" format

Laboratory for Laser Energetics
University of Rochester
D. R. Harding

Executive Summary – A "cradle-to-grave" concept for making DT-wetted-foam targets that was developed for the High Average Power Laser (HAPL) IFE program is described. [1, 2] The premise of this concept is that the highest target quality and production yield is achieved by making targets individually where they can be monitored through each phase of production; and that this can be done economically by eliminating human or robotic involvement by using a combination of microfluidics and programmable electrostatics in a miniaturized "Lab-on-Chip" configuration. This methodology provides in-situ real-time quality control and can be massively duplicated to provide the needed daily target throughput. Proof-of-concept experiments for many of the critical technologies that are needed to make this a credible proposal were validated over a 12 year period that produced 6 PhD theses.

1. Introduction

The economic viability of an IFE power plant will depend primary on the operating costs and, by extension, the following aspects of the target's design: the cost to manufacture an estimated 1 million targets per day; the targets' yield (and the repeatability of that yield); damage to the chamber and optics from the implosion products; and complexity of managing target debris and radiological issues.

Experiences from ICF experiments can instruct us of the challenges to manufacturing high-neutron-producing targets. These targets cost ~$8K to $30K for plastic shells and plastic-coated foam shells, respectively (excluding the cryogenic handling and tritium costs). These targets are made in multi-step, batch processes that require 3 to 6 months to complete, and the variability in quality requires that each target be characterized at each step. Efforts to improve the targets' quality for the ICF program, and to scale-up the process for the HAPL program, have had limited successes.

The manufacturing process proposed here (and investigated earlier) is a different paradigm to that used for the ICF program. The philosophy is to reduce (ideally eliminate) the need for humans and robots to select "acceptable" targets from a large batch and then transport them to the next step in the process (which adds risks to damaging the fragile target). It is deemed more efficient to make a target with a 99.999% certainty (6-sigma) that it is acceptable than it is to screen and select targets from a large batch. The crux for this concept is the existence of a mechanism that can rapidly, and with high certainty, accomplish this task in a small volume that then can be massively cloned. The methodology proposed used microfluidics and programmable electric fields in a miniaturized "lab-on-chip" format. Experiments showed that it was possible to make a target in <10 min., in a small volume (10x10x1 cm^3), and with a high degree of precision by using dielectrophoretic forces that provide converging feedback control. (The demonstration described did not complete the final step in this process of removing the fluids used to make the target- the HAPL program ended before this could be done.) The second part of this proposal involved filling the capsule with cryogenic DT in a single automated process. That was

demonstrated using deuterium. Included in the earlier work was an evaluation of the survivability of the target when it is injected into a target chamber that involved experiments and calculations. Not included in this proposal are details for injecting the target into the chamber and tracking its path. The viability of most of the individual steps in this process was demonstrated in 6 PhD thesis and numerous publications and presentations. These will be discussed in later sections.

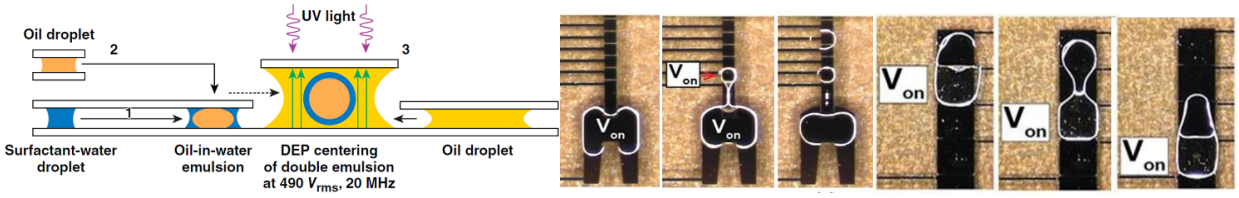
The proposed target design is a foam shell that supports a liquid DT layer and is overcoated with a thin condensed noble-gas layer, if needed, to seal the liquid in the target (i.e. neon, argon, xenon). The condensed gas overcoat helps protect the capsule from the thermal load (radiative from the chamber walls and conductive from the residual gas in the chamber) as is transits the chamber, if needed.

2. Manufacturing process

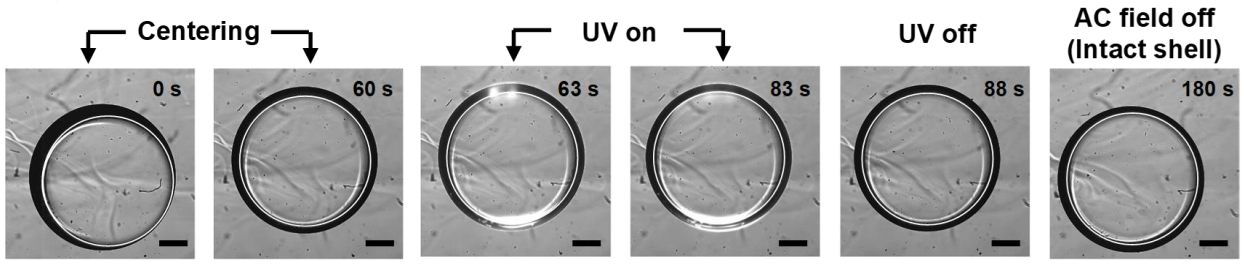
Making the foam shell This task has two parts: First, making the oil-water-oil emulsion that is the precursor for the shell; second, converting the emulsion into a bilayer sphere where the outer shell layer contains the chemicals to make the foam structure and the inner sphere establishes the target's internal dimension and the spherical shape, and then converting the outer shell layer into a rigid foam. The first part is done using either of two methods to extract three fluid droplets from separate reservoirs - each with the correct volume - and then combine them into an encapsulated double emulsion: one method uses electrodes patterned onto a substrate and by switching the voltage between these electrodes the resulting spatial change in the electric field drags the liquid droplet along the surface to different locations where separate operations are performed (using either a dielectrophoretic and electrowetting-on-a-dielectric force - depending on the dielectric constant and conductivity of the liquid). [3, 6] see **Figure 1**. The other method uses the Rayleigh-Plateau force that develops in co-propagating and intersecting fluid streams in a microfluidic device. [7 - 10]

The next step is to combine the droplets and move them to a larger volume (using either electric fields or converging fluid streams). [11, 12] There the dielectrophoretic force from an external electric field forms the liquid emulsion into a concentric bilayer spherical shell where the organic precursors in the outer layer are photopolymerized to form a free standing shell – in ~3 minutes. [12, 13]

The final step to making the shell is to remove the fluids from the foam and the inside of the shell using a continuous automated process. This concept is the least developed and is a prime topic for further investigation. The design proposed uses counter-flowing fluids in a serpentine microfluidic channel to create a turbulent boundary layer around the target that will maximize diffusion rates. This replaced the solvents used to make the shell with a low-surface-energy solvent that can evaporate without collapsing the foam structure under surface tension forces. [9] It may be necessary to use supercritical drying methods to remove the final solvent depending upon the fragility of the foam structure. If so, implementing this process in a continuous flow geometry is a topic for further research.



(i) (ii) (iii)



(iv)

Figure 1. Method for making a foam target in a "Lab-on-Chip" format: (i) schematic showing the process; (ii) example of droplets being formed; (iii) example of a double emulsion being moved to a volume to be made into a shell; and (iv) sequence of images showing how the shell is made spherical and concentric, and then photopolymerized.

Fueling the foam shell Current cryogenic ICF experiments add deuterium-tritium fuel to the target either by diffusing the gas through the target wall, as is done at OMEGA, or through a fill tube, as is done at the NIF. The former method is a lengthy 18 hr. process due to the low buckling strength of the thin-wall target. Using this method to fill the larger IFE capsule will extend the filling time in proportion to the square of the wall thickness-to-shell radius ratio. The longer permeation time has two consequences: (i) reduced implosion performance due to helium-3 build-up in the target's void (from tritium decay), and (ii) requires a tritium inventory larger than is available in the world today (to process 1 million targets per day). For obvious manufacturing and processing reasons, using a fill tube is a non-starter; however, filling the target through a small hole in the capsule that is sealed after filling is an option - albeit a challenging one as the filling and sealing process will have to be done with a radioactive gas at cryogenic temperatures (20K), or at high pressures (>600 atm.).

The propose mechanism for filling a foam shell with DT uses high-frequency high-voltage electric fields to generate a dielectrophoretic force that can extract a droplet of DT from a liquid pool of DT and then transport it to the foam shell where it is wicked into the foam. This process was demonstrated with D_2 and shown in **Fig.2.** This process required <5 minute to complete. [14] Future work would be to demonstrate this behavior with DT.

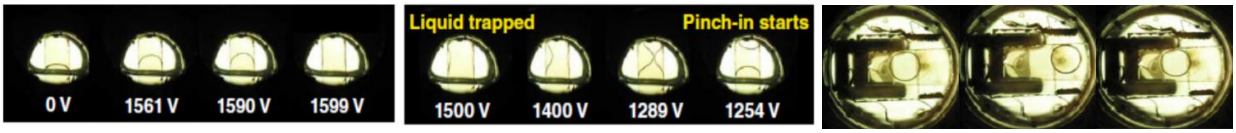


Figure 2. Images showing the formation of a 14μL droplet of liquid D_2 inside a cryostat. In the 1st sequence of images (side view) a droplet is elevated between two ITO-coated plates using a 1.6kV 20MHz electric field; in the 2nd sequence of images the voltage is lowered leaving the D_2 droplet trapped at the top of the plates; in the 3rd sequence of images (top view) the droplet is moved back-and-forth laterally between two alternately powered electrodes (1.8kV) where the foam shell will wick the liquid.

Sealing the fuel in the shell Despite the proposed target being a bare foam shell with liquid DT wicked into the foam, the only physical need for an overcoat would be to enhance laser-target absorption; there are alternative engineering methods for sealing and protecting the target. A permeation barrier (seal-coat) will not be needed to keep liquid DT in the target if the composition and pressure of the gas surrounding the target during all processing steps is same as it is inside the target, and is at the

saturated vapor pressure value (~210 Torr). Gas, usually helium, is always required to bathe the target to maintain its temperature, but DT gas could also provide that function without requiring any change in the radiological controls, and only a minor increase in the tritium inventory.

Should a seal-coat on the target be required (to enhance laser adsorption), it is proposed that a noble gas (Ne, Ar, or Xe) be condensed onto the target's surface after DT is wicked into the foam. The thickness of the coating would be controlled by controlling the amount of condensable gas admitted into the environment. This structure likely would not provide a complete permeation barrier but will slow evaporation/sublimation. If this feature is needed then development work will be required.

Target injection Methods for injecting the target into the Target Chamber is not proposed as part of this proposal. However, for any target production/delivery system to the credible, a target-injection concept that works with the proposed target design/delivery system is needed.

Earlier target-injection concepts involved enclosing the target is a sabot and injecting the assembly into the chamber, pneumatically or electromagnetically, at high velocity (up to 400m/s) to minimize the radiation load to the target. The sabot will support the target mechanically when it is subject to high jerk (rate of acceleration) forces, but will add the challenges of handling and disposing of spent sabots.

An alternative injection method is to use gravity, though this approach may not be fast enough for high rep-rate operation, nor provide adequate in-flight stability for accurate placement. An alternative method is to use the positive charge on DT-filled target (nano-coulombs and ~5keV) combined with stacked electrostatic plates, akin to an electromagnetic rail gun, to accelerate the target. Methods for injecting targets without damaging them is an area that will require extensive research.

Thermal considerations The thermal load to the target has both a radiative component (from the hot Chamber walls) and conductive/convective components. The wetted foam target design (without an outer solid plastic layer will experience only a small radiation load – this is because DT (liquid or ice) is a "quantum mechanical" solid held together by weak London forces (induced quadrupole moments), and as a result has very low emissivity due to narrow absorption bands, as is the case for other condensed noble gases. As a result, blackbody radiation will be absorbed by the foam structure only, which, given its low density, is minimal. (Adding a plastic ablator, which strongly absorbs over a wide frequency range in the IR, will substantially increase the radiation load.)

The primary thermal load will be from the target impacting gas molecules in the Chamber – gaseous remnants of previous implosions, or gas that is permanently present in the Chamber to protect the Chamber walls from high-energy fusion products (primarily high velocity alpha particles that embed in the Chamber walls causing it to spall). A parametric thermal study of different target designs, injection velocities, and Target Chamber conditions (temperature and pressure) for the HAPL program was done to define limits for subsequent experiments and calculations. [15] A surrogate IFE target-chamber environment was built to test the effect of supersonic and superheated argon gas (2000°C), with the appropriate mass flux to simulate heated gas striking a target moving at 400m/s, impacting a substrate at 20K: the substrates were both a silicon wafer imaged with a RHEED detector (reflection high energy electron diffraction) to measure the thickness and rate that argon condensed on the surface (to determine the heat load from gas condensing on the target), and a cell containing solid deuterium embedded with Pt wires to measure the rate of temperature change and degree of melting. [15, 16] No

condensation of argon was observed and the HAPL program ended before the deuterium-melting experiment was completed. A continuation of this experiment is proposed.

Conclusion

While target complexity and cost are not limitations for ICF experiments because achieving high yield is paramount, economic realities of an IFE program have those constraints. This proposal combines a target design that is likely to achieve high yield given the right laser driver (based on experiments/calculations) and modifies it by removing the outer plastic ablator to make it feasible to manufacture economically (based on target-related research and experiences fielding cryogenic targets).

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