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IFE TARGET FABRICATION AND INJECTION — ACHIEVING “BELIEVABILITY”

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ABSTRACT

At the heart of an inertial fusion energy (IFE) power plant is a target that has been compressed and heated to fusion conditions by the incident driver energy beams. For direct drive, the target consists of a spherical capsule that contains the deuterium tritium (DT) fuel. For indirect drive, the capsule is contained within a cylindrical or spherical metal container or "hohlraum" which converts the incident driver energy into x-rays to implode the capsule. The "Target Factory" at an inertial fusion power plant must produce about 500,000 targets per day, fill them with deuterium-tritium fuel, cool them to cryogenic temperature, and layer the solid fuel into a symmetric and smooth shell inside the capsule. The target must then accurately be delivered to the target chamber center at a rate of about 5 Hz, with a precisely predicted target location. These fragile targets must survive injection into the target chamber without damage. While IFE power plant design studies have presented plausible scenarios for IFE target fabrication and injection, these issues have become "believability" issues for IFE. A credible pathway for development of accurate, economic and reliable IFE target fabrication and injection must be demonstrated before we can proceed with the next major step in the IFE Program, the construction of an IFE Integrated Research Experiment (IRE).

Work has begun as part of the Office of Fusion Energy Sciences' Virtual Laboratory for Technology to develop the scientific basis needed for IFE target fabrication and injection. Target designs, materials and fabrication techniques suitable for low-cost mass production are being evaluated. Studies of target filling techniques and materials properties are underway. General Atomics is designing, constructing, and testing an experimental Target Injection and Tracking System to develop the scientific understanding necessary for injection of IFE targets into a high temperature reaction chamber.

This paper summarizes the requirements for IFE target fabrication and injection, reviews the results from the studies that predict success, discusses the development program now underway, and presents the current status of and results from that program.

1. INTRODUCTION

There have been several detailed design studies of inertial fusion energy (IFE) power plants, and these have concluded that plausible design solutions can be developed for the technical challenges of IFE, and that, if successful, this development will lead to power plants offering attractive technical, safety, environmental and economic features [1,2] (Table 1).

TABLE 1
DESIGN STUDIES PREDICT
REASONABLE IFE COST OF ENERGY

Study	Cost of Energy (cents/kW-hr)
OSIRIS	5.6
SOMBRERO	6.7
HYLIFE-II	6.5

In addition to potentially leading to cost effective fusion power, IFE has the potential to offer a cost effective development pathway. The IFE community is pursuing a cost-effective, phased development strategy shown on Fig. 1 [3]. The development process has been divided into a sequence of logical steps or phases. At each phase, the options are weighed and down-selection is done. For each phase, only the minimum development needed to support the decisions to be made at that step would be done. The first decision point of this development strategy is scheduled for the end of Phase I, when the decision must be made as to whether to proceed with an IFE Integrated Research Experiment (IRE), and, if so, what technologies will be used for this experiment. The IFE development program is focused on providing the information needed for this IRE decision.

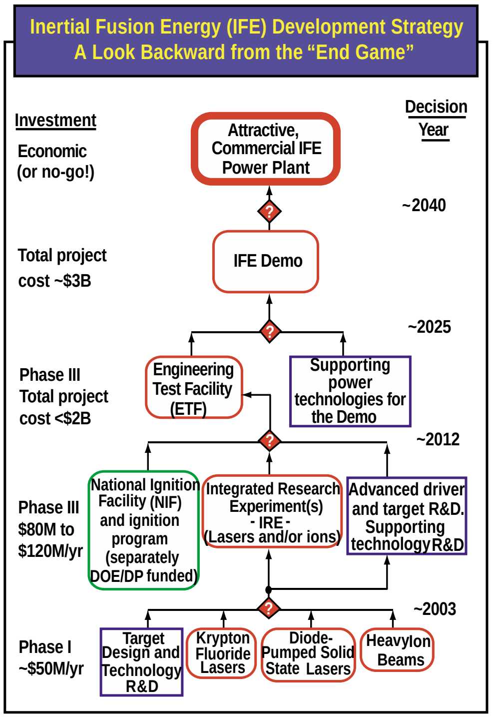

Fig. 1. IFE has a cost effective, phased development strategy [3].

2. BACKGROUND AND ISSUES FOR IFE TARGET FABRICATION, INJECTION AND TRACKING

To some extent, target fabrication, injection and tracking have become "believability" issues for IFE. The IFE design studies [1,2] have shown plausible design solutions to the problems of IFE target fabrication, injection and tracking, with estimated target costs below the ~30¢ projected to be needed for economic IFE [4]. However, skeptics remain unconvinced. They point to the tight specifications that must be achieved for current inertial confinement fusion (ICF) experiments (Table 2) and question whether the design approaches proposed for IFE will prove to be technically feasible, whether they can meet the accuracy required, whether the targets will survive injection into the hostile target chamber environment, and whether all this can be done with high reliability and at a total cost per target of only about 30¢.

TABLE 2
TYPICAL IFE TARGET SPECIFICATIONS ARE STRINGENT

Typical IFE Target Specifications	
Capsule out-of-round, %	≤0.1
Ablator thickness uniformity,%	≤1
Outer surface smoothness, Å	≤200
Inner surface smoothness, µm	≤1
Capsule centered in hohlraum, µm	≤25
Allowed ΔT after layering, K	≤0.5
Location at shot time, µm	
Indirect drive	≤200
Direct drive	≤20
Reliability, %	≥99

Target fabrication, filling, layering, injection, and tracking at the rate required for IFE is, in fact, a significant technical challenge. About 500,000 targets must be prepared and injected each day at a rate of 5–10 Hz into a target chamber operating at elevated temperatures. These targets must have high precision and be prepared at reasonable cost. In order to justify proceeding with the IFE IRE, the technical feasibility of IFE target fabrication and injection concepts must be demonstrated, and it must be shown that a credible pathway exists to achieving the accuracy, reliability and economy requirements for IFE.

Before IFE can become a reality, target-manufacturing costs must be reduced by four orders of magnitude from today's "typical" ICF target cost of about $2500. The cost of the current ICF targets is at least partly due to the development needed for fabrication of each target design, the small number of targets produced of any single design and the extensive characterization required for each target. Large-scale target production will significantly reduce the manufacturing cost and, once targets are being mass-produced by a reproducible process, characterization must be reduced to that required by statistical quality control requirements. Some of the current ICF target manufacturing techniques may have the potential to meet the cost and production requirements of IFE. Indeed, some of the current processing steps, such as microencapsulation of target capsule inner mandrels by a triple-orifice droplet generator, already employ continuous processes that operate at rates consistent with IFE requirements. Nevertheless, significant issues are involved in scaling up these processes from the 1-mm capsules required currently for OMEGA to the 5–7 mm contemplated for IFE while still achieving the precise specifications required.

It isn't enough that a target, designed for high-gain energy production, can be produced economically. It must also lend itself towards economic and practical filling and layering, and it must survive injection into the target chamber without degradation. In the case of permeation filling, the strength of the capsule dictates the maximum over-pressure that can be used and thus the time required for filling. The strength of the target may limit the acceleration to which the target may be subjected during injection. The emissivity of the target, at the temperature of the target chamber, will dictate the velocity it must have to avoid excessive heating while traveling to chamber center. Indeed, all the ramifications of the target design on the various systems of the IFE power plant must be evaluated.

The overall goal of this work is to develop a self-consistent scenario demonstrating an economic path towards manufacturing, filling, layering, injecting, and tracking a plausible IFE target. This must not only consider the cost of mass-producing IFE targets, but also the impact of the target design on the total target supply system.

3. CURRENT STATUS

Targets currently fabricated for ICF experiments [5] have many of the characteristics that will be needed for IFE, although the size is smaller (capsule diameter ~0.5 mm for Nova, ~1 mm for OMEGA and ~2–3 mm for the NIF vs. ~5–7 mm for IFE). Several of the IFE target designs [6,7] (Fig. 2) also contain various foam materials that are not currently used for ICF targets. The current ICF target fabrication techniques may not be — and were not intended to be — particularly well-suited to economical mass production of IFE targets. Consideration of the various ICF target fabrication processes leads to the conclusion that some of these do extrapolate well to IFE, some do not, and all will require some level of development, as shown on Table 3.

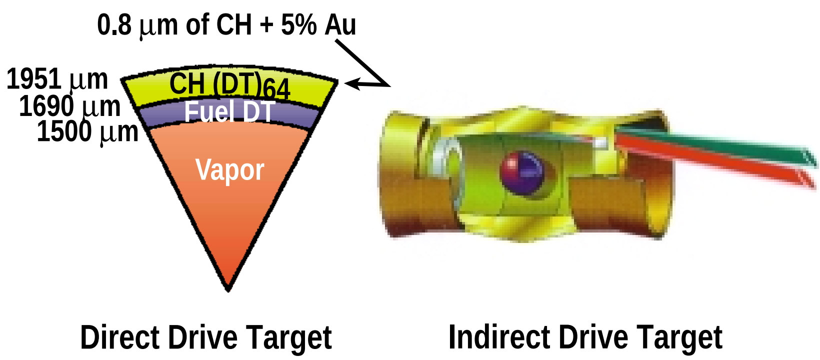

Fig. 2. Typical IFE target designs. Radiatively pre-heated direct drive capsule [6] and distributed radiator indirect drive hohlraum [7].

Fuel Capsules. ICF capsules are currently made using the "PAMS-GDP decomposable mandrel process" [8]. Microballoons of poly(α–methyl styrene) ("PAMS") are made by density-matched microencapsulation. Droplets of water, each surrounded by a droplet of PAMS dissolved in solvents, are dropped into a water bath where the solvents evaporate and the shells cure, giving a wall thickness of a few µm. Density-matched microencapsulation gives excellent sphericity, but less perfect wall uniformity. After drying, the PAMS shells ("mandrels") are coated with a few microns of amorphous polymer in a glow-discharge polymer (GDP) coater. The GDP process gives a coating with excellent wall uniformity and surface smoothness. The coated mandrel is heated in vacuum, decomposing the PAMS which permeates out of the GDP shell, leaving a

TABLE 3
SOME ICF TARGET FABRICATION PROCESSES EXTRAPOLATE TO IFE, SOME DO NOT; ALL REQUIRE SOME DEVELOPMENT

		Extrapolate to IFE?			
Fabrication Step	**ICF Process**	**Specs?**	**Cost?**	**Alternatives**	**Unknowns**
Capsules					
– Indirect drive	PAMS-GDP	Probably	Probably not	Direct microencap-sulation , alt. deposition processes and materials	
– Direct drive	PAMS-GDP	Probably	Probably		Equipment scale-up?
Foams	Microencapsulation	Probably	Yes		Strength at low density?
Hohlraums	Machine-plate-leach	Yes	No	Stamp, mold	Alternative materials
Assembly	Micro-manipulation	Yes	Yes (automate)		
Characterization	Extensive "pedigree"	Yes	Yes (statistical sampling)		Key parameters?
Filling	Permeation	Yes	Yes	Injection fill	Tritium inventory?
Layering	Beta layering, IR and µW enhanced	Yes	Probably	Fluidized bed	Tritium inventory?

finished GDP shell with excellent sphericity, wall uniformity and surface finish. This can be coated with additional GDP to add ablation layers and/or doped diagnostic layers. Current experiments use ablation layers of about 50 µm. IFE will need an ablation layer of about 100 µm for indirect drive, while for direct drive the DT ice itself will serve as the ablator and no additional polymer will be added to the GDP shell.

Polymer fuel capsules can be readily made by the density-matched microencapsulation process in the size needed for IFE, but they cannot meet the strict specifications for sphericity and wall uniformity that will be needed. As the capsule size is made larger, the gravity- and hydrodynamically-induced forces that cause non-uniformity get larger relative to the thermodynamic (primarily surface tension) forces that encourage uniformity. Because of the success of the PAMS/GDP process in producing excellent capsules for ICF experiments, and because of the flexibility this process offers for changing dimensions and compositions to respond quickly to the needs of the experimental program, it is the primary technique used in the US. The present GDP technique uses small batch sizes in expensive equipment and produces coatings at the rate of only a quarter micron an hour. It does not extrapolate directly to IFE well. Development will be needed to scale up batch size and coating rate while retaining product quality. Effort should also be devoted to understanding and improving the microencapsulation process. If adequate quality could be achieved at the sizes needed for IFE, this process would extrapolate well to economic production.

Hohlraums. For indirect drive ICF targets, the capsules are mounted inside a thin metal hohlraum. For current experiments, the hohlraums are a few millimeters in diameter and length. For the National Ignition Facility (NIF) these dimensions will be just under a centimeter; for IFE they will be just over a centimeter. The wall thickness is about 25 µm, although very thin metal walls (~2 µm) backed with epoxy for support are also used to minimize debris. ICF hohlraums are currently made by electroplating the hohlraum material, generally gold, onto a mandrel, generally copper, that has been turned in a very high precision lathe called a diamond turning machine. This lathe is computer controlled and uses a gem-quality diamond cutting tool to achieve dimensional tolerances of <1 µm and surface finish better than 200 Å. After plating, the mandrel is dissolved, leaving the empty hohlraum shell.

For IFE, current hohlraum designs employ a low density metal "distributed radiator" [7], and a new fabrication process such as die casting or injection molding must be used. Fortunately, this does appear to be practical. The tolerances required do appear to be within reach of these mass-production processes. What is needed is cooperation between the target designers and target fabricators to develop designs that promise to give good performance and to use practical fabrication techniques, and then to build and test these designs.

Target Assembly. ICF targets are assembled manually. The hohlraums are cut in half before the mandrel is dissolved. The capsules are mounted between two sheets of extremely thin (~0.3 µm) Formvar plastic, which are then placed between the two halves of the hohlraum, and the assembled target is fastened together with UV-cured epoxy. Assembly is done using micro-manipulators under a microscope. Placement of the capsule at the center of the hohlraum must be accurate to within 25 µm.

Target assembly for IFE will have to be fully automated, as opposed to today's completely manual operations. The accuracies required and the throughput rates needed appear to be attainable with currently envisioned equipment. The principal concern for automated assembly is the extreme fragility of most of the target components. Simply touching the surface of a capsule or a hohlraum mandrel with any foreign object will cause scratches that will render the part useless. With sufficient care and development, automated target assembly for IFE should be achievable.

Target Characterization. Precise target characterization is vital to ICF target fabrication. Batch characterization is used during the production process to verify that the target dimensions meet the acceptable parameter range for delivery. Individual characterization of every shell is needed to prepare the complete "pedigree" that accompanies each target that is delivered. The diameter and wall thickness of capsules are measured using a white light interference microscope with a precision z-stage. The location of the successive layers in the wall can be determined with an accuracy of <0.1 µm. Non-concentricity and out-of-round are measured with the same instrument. The elemental composition of doped capsules is determined with x-ray micro-fluorescence. The final measure of capsule surface characteristics is made with an atomic force microscope (AFM) spheremapper, which rotates the shell on a precision air bearing against an AFM head. Three mutually orthogonal sets of three parallel traces around the shell are taken and the Fourier transforms of these traces are averaged to obtain the power spectrum of the capsule. These procedures are very laborious but yield the precise characterization of every target demanded by the ICF experimentalists.

For IFE, the production processes will have to be refined to the point where only a small percentage of the components manufactured can be allowed to not fully meet spec. Each component or target will not be inspected. Characterization will only be used as part of the QA process, measuring a few components every now and then to keep the production line adjusted properly. The basic characterization techniques now used manually are for the most part amenable to full automation.

DT Filling. Targets for ICF experiments are filled by permeation. The capsules are placed in a pressure vessel which is first evacuated to pump out residual air, and then filled with DT gas at the required pressure for the shot — generally a few tens of atmospheres. The capsules may be heated to speed the permeation and the pressure may have to be raised in several controlled steps to avoid crushing the shells. For cryogenic targets, the capsules are filled to high pressure and then cooled to condense the fuel. The very thin shells (<3 µm) and the very high pressures (>1100 atm) that will be needed for cryogenic shots on OMEGA require a very careful sequence of gradually stepping up the pressure and then gradually stepping down the temperature to fill and cool the capsules without crushing or bursting them. The fill-cool sequence can take as long as 80 hours for thin-walled cryogenic capsules.

The principal concern for scale up of the DT fill process to IFE is the tritium inventory that will be needed and the vulnerability of that inventory. For diffusion fill requiring a day or two, the minimum inventory to provide five targets per second approaches 10 kg, all of which would be vulnerable, that is, at high pressure in gaseous form. While this is clearly a manageable inventory, total release would have an impact on the safety rating of the power plant. Techniques such as injection fill of the capsules using micro-hypodermic needles have been proposed [1] that could significantly reduce the inventory.

DT Layering. After the capsules are filled and cooled to condense the fuel, the DT must be formed into a uniform, smooth spherical shell layer on the inside of the capsule. If the exterior of the capsule is maintained at a uniform temperature of about 19.5 K, the natural beta decay energy of the tritium will accomplish this through a process known as "beta layering"[9]. The very low energy beta particles from tritium decay deposit their energy very close to the location of the original tritium atom. This means that a region that is thicker will generate more heat than a thinner region and the DT will tend to sublime from the thicker zones and deposit on the thinner ones until a uniform thickness is achieved. This requires very precise temperature uniformity (<25 µK) around the capsule, but will produce very uniform layers. The inner surface of the DT ice layer must be very smooth. For indirect drive targets a surface smoothness of <1 µm RMS is expected to be needed. Direct drive may require smoothness as good as 0.1 µm RMS. The surface roughness is due to crystallites in the DT ice and may be controlled by adjusting the temperature at which beta layering is done and the rate of cooling of the layer. Surface smoothness of about 1 µm RMS can be achieved, which should be adequate for heavy ion driven (indirect drive) targets.

The primary issue for DT layering for IFE is confirming the DT ice inner surface finish requirement. It appears that 1 µm is sufficient for heavy ion driven targets indirect drive and this can be achieved by unassisted beta layering.

Target Injection and Tracking. Design studies of target injection were done as part of the several IFE power plant studies completed in the early 1990s. A gas gun system was proposed for injection with crossed dipole steering magnets to direct the beams. More recently, analyses of target injection and tracking systems have been carried out at LLNL and predicted that IFE targets could survive the mechanical and thermal environment during injection. A gas gun indirect drive target injection experiment was then constructed and operated at Lawrence Berkeley National Laboratory (LBNL) [10]

(Fig. 3). The results showed that relatively simple gas gun technology could repeatedly inject a simulated indirect drive target to within about 5 mm of the driver focus point, easily within the range of laser or beam steering mechanisms to hit, but not sufficient to avoid the need for beam steering. Photodiode detector technology was adequate to detect the target position with sufficient accuracy that the driver beams should be able to achieve the approximately ±200 µm accuracy needed for indirect drive targets. This work has recently been extended to show similar results for low speed (~100 m/s) injection of simulated direct drive targets at room temperature, using a sabot.

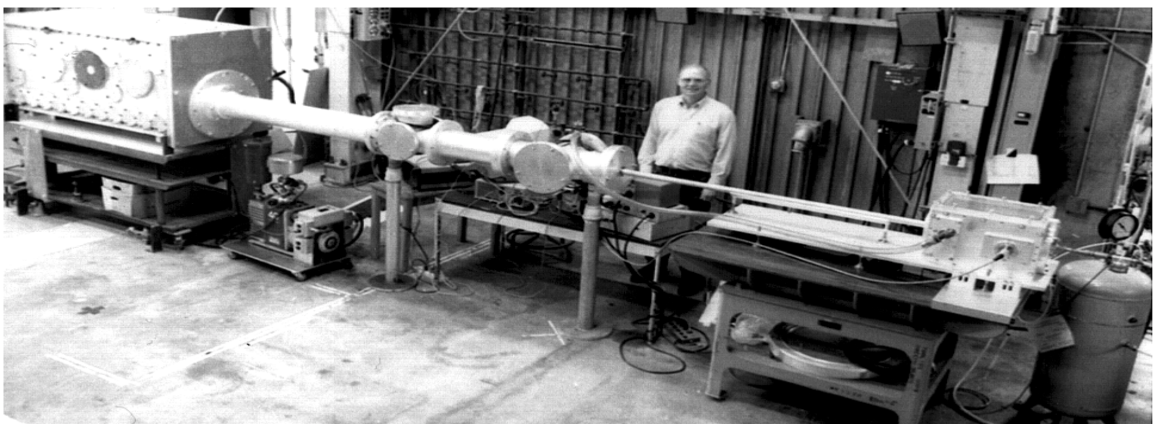

Fig. 3. IFE Target Injection Experiment at LBNL [10].

4. IFE TARGET FABRICATION, INJECTION AND TRACKING RESEARCH PROGRAM

IFE target fabrication, injection and tracking is being developed as a part of the IFE Chamber and Target Technology element of the US Department of Energy Office of Fusion Energy Sciences "Virtual Laboratory for Technology". The work is being done cooperatively by a team of individuals from Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, University of California Berkeley, Naval Research Laboratory and General Atomics. Our plans for Phase I are to demonstrate that a credible pathway exists for development of low cost IFE target fabrication, filling, layering, injection and tracking, in order to support the decision at the end of Phase I on whether to proceed with an IFE Integrated Research Experiment, and if so, how to proceed.

During Phase II we will direct the target fabrication studies towards the goal of developing prototype IFE targets for testing in NIF. We will pursue proof-of-principle demonstrations of IFE target filling and layering techniques, and recommend to inertial fusion target designers an integrated IFE target production system, including the design directions and design constraints that economic fabrication will impose. We will complete the construction of experimental equipment for cryogenic target filling, layering, handling, and loading systems for injection and tracking demonstrations. We will integrate these systems with the high-temperature furnace and inject cryogenic targets into the simulated chamber. Parametric injection and tracking experiments with a variety of target designs, both direct and indirect drive will be performed with the objective of verifying the effect of thermal radiation and chamber gas environments on the capability to inject and track targets, and on the condition of the target upon reaching the shot position in an IFE plant. The development plans for IFE Target Fabrication and Injection are shown on Table 4.

TABLE 4
IFE TARGET FABRICATION, INJECTION AND TRACKING DEVELOPMENT PLANS

Development Plans for IFE Target Fabrication

Phase I:

Work with target designers and power plant studies to select promising designs, optimizing gain, robustness and cost

Develop materials for IFE requirements, such as
- Robust foams, doped ablators, distributed converter hohlraums for HIF

Develop mass production fabrication processes
- Identify suitable industrial technologies, eg., microencapsulation, fluid bed coaters, die casting/injection molding for hohlraums
- Demonstrate they can achieve the accuracy needed
- Project they can meet cost goals

Develop statistical on-line quality control characterization

Phase II: IRE

Bench-scale experiments for production processes

Evaluate processes for accuracy, reliability and cost

Provide prototype targets to the IRE

Development Plans for IFE Target Injection and Tracking

Phase I:

Work with target designers and power plant studies to select promising target and chamber designs and to define their injection requirements

Select design and develop target protection and injection system best suited for direct drive targets

Demonstrate injection and tracking of simulated targets at room temperature

Measure the thermal response of cryogenic targets and demonstrate methods for thermal protection

Phase II: IRE

Add cryogenic target capability and high temperature surrogate chamber to Phase I injection-tracking system for experiments

Provide target injection-tracking system for the IRE

5. IFE TARGET INJECTION AND TRACKING EXPERIMENT

General Atomics is designing, constructing, and testing an experimental Target Injection and Tracking System [11]. The purpose of this system is to develop the scientific understanding necessary for injection of IFE targets into a reaction chamber. The system will be utilized to demonstrate successful injection into a high temperature environment. This system must allow development for target injection and tracking of both direct and indirect drive IFE power plants. For direct drive, the SOMBRERO [1] design, with a 7.5 m radius chamber filled with ~0.5 Torr of xenon gas and operating at ~1500°C, is used to set requirements. For indirect drive, the OSIRIS [1] or HYLIFE-II [2] designs, with a 3–4 m radius chamber with <0.001 Torr of pressure and operating at 600°C is used. The testing strategy is to build a single test system capable of testing both direct and indirect drive targets. The system is modular to allow both direct and indirect drive injection velocities, scaling to full scale prototype lengths, and accelerations well beyond the ~1000 G planned for IFE power plants to allow testing of targets to destruction. The injector system specifications are shown on Table 5, for direct and indirect drive IFE power plants and for the experimental injector.

A design concepts study was done for injectors to meet these requirements. Gas guns, electrostatic accelerators and electromagnetic accelerators were studied. Evaluation against the requirements is shown on Table 6. We chose a gas gun for the injection experiment because it meets all the stated requirements, and it offers the most cost-effective path to acquire target performance data. However, the electromagnetic accelerator, with additional development, could likely meet all requirements. Further, the gas gun does have the disadvantages of injection gas handling and a practical injection velocity limit of ~400 m/s at the acceleration an IFE target can tolerate. For these reasons, we will continue investigation of the electromagnetic launcher for ultimate IFE application. A schematic of the experimental IFE target injection and tracking system is shown in Fig. 4. It will allow several second long "bursts" of injection at 7 Hz with both indirect drive and sabot-encased direct drive targets. It will provide tracking, prediction and detection of target position and monitoring of target condition. Testing of target steering techniques will be possible if needed. During Phase II, use of cryogenic targets and a simulated high temperature reaction chamber will be possible.

TABLE 5
TARGET INJECTOR SYSTEM SPECIFICATIONS [11]

Requirement/ Parameter	Production Injector		Experimental Injector
	Direct Drive	Indirect Drive	
Target speed (m/s)	**400**	180	400 for direct drive 180 for indirect drive
Acceleration (g's)	1000	1000	5000
Repetition rate (Hz)	7	5	Multi-shot "burst" capability, upgradable to cryogenic
Target mass (g)	0.005 (without sabot)	1 (without supporting structure)	0.005 (direct drive) 1 (indirect drive)
Target diameter (mm)	5	15	5 (direct drive) 15 (indirect drive)
Target temperature range (K)	18–19	18–19	18–19 (Initial injections at room temperature)
Target spin (rotations per second)	NA	300	300
Target exit accuracy (mradians)	±0.3	±0.7	±0.3
Cryogenic fuel temperature rise (from start of injection to center of chamber) K	0.5	0.5	0.5
Availability (%)	>99	>99	Several shots per hour for experiments

TABLE 6
EVALUATION OF TARGET INJECTOR SYSTEM SPECIFICATIONS AGAINST DESIGN CONCEPTS [11]

			Electromagnetic Accelerator		
Requirement/ Parameter	**Experimental Injector Requirements**	**Gas Gun**	**Iron Insert**	**Super-conducting Insert**	**Electrostatic Accelerator**
Target speed (m/s)	400 for direct drive 180 for indirect drive	Yes Yes	Yes Yes	No Yes	No No
Acceleration (g's)	5000	Yes	No	No	No
Repetition rate (Hz)	Multi-shot "burst" capability Upgradeable to cryogenic	Yes Yes	Yes Yes	Yes Yes	Yes Yes
Target mass (g)	0.005 (direct drive) 1 (indirect drive)	Yes Yes	Yes Yes	Yes Yes	Yes No
Target diameter (mm)	5 (direct drive) 15 (indirect drive)	Yes Yes	Yes Yes	Yes Yes	Yes NA
Target temperature range (K)	18–19 Initial injections at room temperature	Yes Yes	Yes Yes	Yes No	Yes Yes
Target spin (rotations per second)	300	Yes	Yes	Yes	NA
Target exit accuracy (mradians)	±0.3	Yes	Yes	Yes	Yes
Cryogenic fuel temperature rise (from start of injection to center of chamber) K	0.5	Yes	Yes	Yes	Yes
Availability (%)	Several shots per hour for experiments	Yes	Yes	Yes	Yes

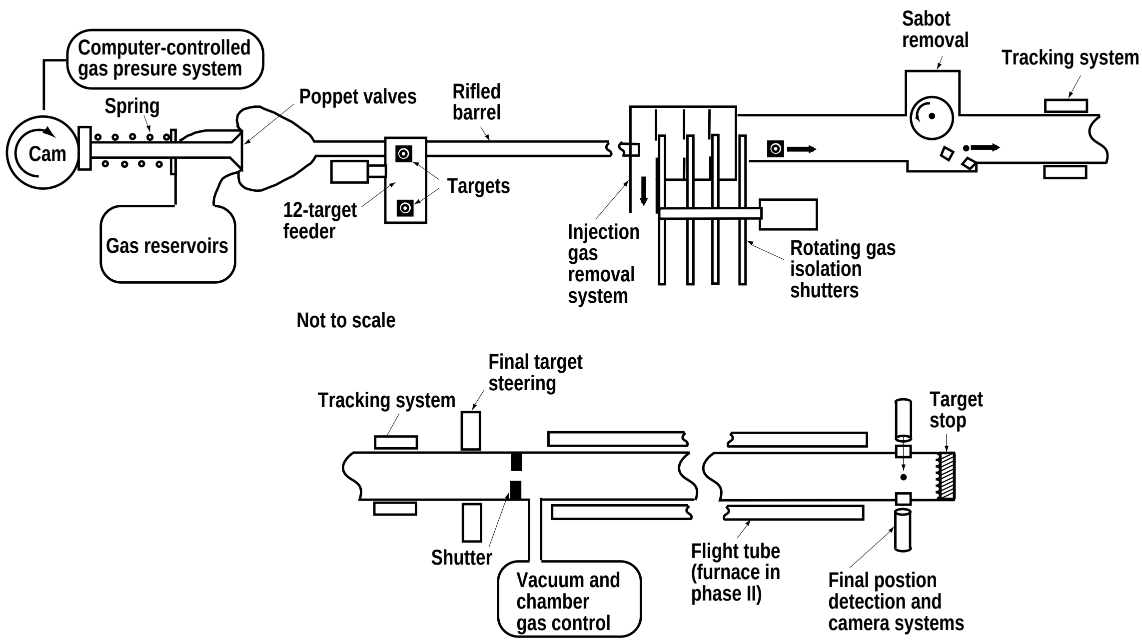

Fig. 4. Experimental Target Injection System [11].

6. CONCLUSIONS

We have begun work as part of the Office of Fusion Energy Sciences' Virtual Laboratory for Technology to develop the scientific basis needed for IFE target fabrication and injection. We can build upon the extensive experience of the ICF program and will take advantage of the development now under way for the NIF. Target fabrication techniques that extrapolate to low cost mass production have been proposed. An IFE target injection and tracking experiment is now under design. During Phase I of the IFE Roadmap, we plan to demonstrate that a credible pathway exists for development of "believable" IFE target fabrication and injection.

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