Target injection, and engagement for inertial fusion energy

Neil B. Alexander *

Lane Carlson *

Kurt J. Boehm *

Wendi Sweet *

* General Atomics, 3550 General Atomics, San Diego, CA 92121

Contact Information: Neil.Alexander@ga.com, Lane.Carlson@ga.com, Wendi.Sweet@ga.com, Kurt.Boehm@ga.com

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

Executive Summary

For an IFE power plant chamber to survive the output from ignited targets under continuous operation, chambers are made multi-meter in size. This size combined with typical shot rates of ~5 Hz for laser or ion drive plants means targets must be injected (launched) into the chamber. The beams must hit, engage, the target on-the-fly. For laser or ion beam driven targets to ignite the beams must hit defined locations on the target accurately. The accuracy required is assumed to be better than ~25 μm, but this will vary by target type and will require verification by simulation and experiment. Target injectors have not shown this level of placement accuracy, to date. Thus successful target engagement will require tracking, in real-time, of each target as it flies to the chamber center, and steering the driver beams to meet each target. Thus target injectors and engagement systems (target trackers, and driver beam pointing) are critical issues to be developed for IFE power plants.

Full-scale target injectors (gas guns and linear induction accelerators [LIA]) have been built and operated at room temperature to access accuracy, but loading and shooting at high repetition rate has not been performed. Operation on cryogenic targets has either not yet been done (gas gun) or has been extremely limited (LIA). Loading of cryogenic targets into the injector at reactor shot rates has also yet to be explored.

Engagement of a slowly moving (5 m/s) spherical target by a low-power laser beam in a vacuum has been performed to an accuracy to an accuracy of 28 μm (1 standard deviation). This work should be extended to higher velocities, and other target types as needed.

Necessary development steps for the target injectors and target engagement for IFE reactors are include: staged scale up of target injectors to continuous operation and reactor shot rate (~5 Hz); loading and launching cryogenic targets; for engagement scale up tracking and beam steering to handle full target velocity, at IFE reactor shot rates, and integration of these target systems with a driver beamline test facility. These steps are best conducted within the arena of a full IFE reactor development program.

Introduction

Targets produce highly energetic outputs of photons, ions, and neutrons that can damage the chamber in which they are ignited. To avoid this damage, large multi-meter diameter chambers are typically used to contain and harness these output products from the target. For the higher shot rate of ion or laser drive, targets are injected into the chamber (shot/launched in free flight) from the outside of the chamber to the center of the chamber where they are hit (engaged) by the driver beams. For the slower shot rate of magnetic compression, the target, attached to a replaceable current transmission line, is mechanically placed into the chamber.

Launch forces on targets must controlled to levels that will not damage the targets. Targets are low mass to reduce the waste they produce and the damage they do to the chamber. However this also makes targets delicate. High accuracy is required of target injectors to reduce the slew range and rate requirements on the driver beams.

Injectors to date have shown mm’s of placement accuracy to chamber center at typical launch distances. Targets will be additionally buffeted and displaced by residual plasma and gas wind from previous shots. This placement accuracy is insufficient to hit the target for successful ignition, if the driver beams are not steered to the target in the last moments before the driver hits. To hit/engage the injected target with sufficient precision (~25 μm), the target position must be tracked deep into the chamber, and then the driver beams re-pointed at the target just before the target reaches chamber center. The necessary precision of beam-to-target engagement, in real time, on short time scales, makes target engagement a challenging issue.

This paper describes prior work we have done target injectors, and target engagement. Recommended directions for future development in these areas is also provided.

Target Injection

Target injectors for direct and indirect drive targets were built at full scale (velocity) and operated at room temperature to assess target placement accuracy. Gas guns were built for both direct (Ref 1 and Figure 1) and indirect drive targets, and an LIA for indirect drive targets (Ref 2 and Figure 2). These injectors did not include mechanisms to continuously load and shoot targets, so no assessment of wear or reliability was performed. The direct drive gas gun was sometimes operated with a revolver loading mechanism so that several shots could be taken successively at high shot rate. The gas guns were not operated cryogenically. The linear induction accelerator was also not operated cryogenically, with the exception that briefly one segment of the accelerator was installed into a cryostat to launch a liquid deuterium filled, wetted foam layered capsule. This was done to verify that the acceleration did not cause liquid deuterium to drain out of the foam and pool at the bottom of the capsule. Images taken immediately upon exit from the accelerator show that draining did not occur, at least to the extent of the quality of the high-speed camera image (unpublished).

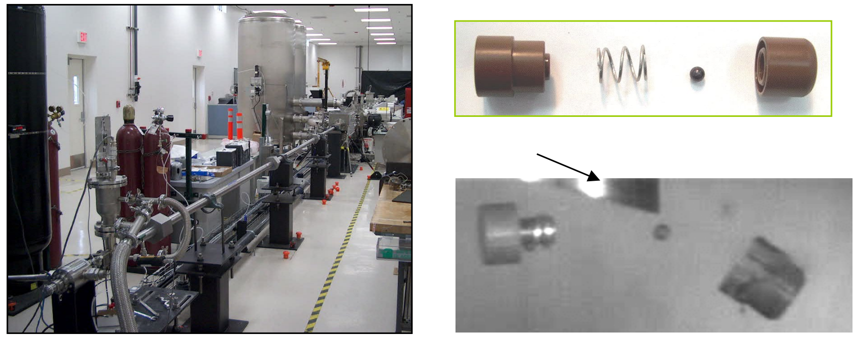

Figure 1: Left: Gas gun for direct drive targets. Right top: Two piece spring loaded sabot that holds target in gun barrel. Right bottom: Sabot in flight being deflected by wedge, allowing the target to continue on the flight path.

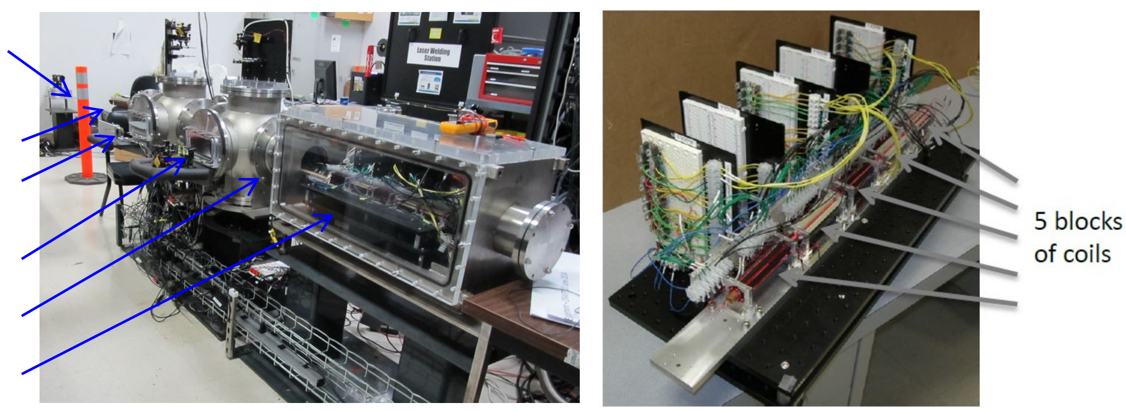

Figure 2: Linear induction accelerator target injector for indirect drive. Left: full system with trajectory correction steering coils (magnetic lenses). Right: Coil set of the LIA, includes solenoid coils for axial acceleration and saddle coils to spin the target to gyroscopically stabilize that target against tumble in flight.

The accuracy results for the direct drive gas gun and the indirect drive LIA are shown in Table 1. Note that the LIA had both passive and actively controlled magnetic lens added to its exit to improve accuracy; their effect is shown in Table 1. For direct drive targets, a similar trajectory correction system based on adjusting voltage of four rods arranged in a quadrapole around the flight path was demonstrated. For electrically charged spherical targets dropped in a vacuum, with feedback from a tracking system, the placement accuracy improved to 10 µm (1 σ) from 500 µm (1 σ) at a distance 0.5 meters from the end of the steering rods.

The accuracy achieved is such that a flight many meters to reach the reactor center chamber will result in only mm's of placement accuracy. Light-weight targets will additionally be buffeted by residual gas and plasma in the chamber. Thus, target tracking and beam steering will be required. The achieved accuracy informs required slew range of the driver beams, which if unattainable will require additional development to improve injector accuracy.

For targets that use a solid DT layer (layered via beta-layering) and maintained at a temperature near the DT triple point, 19.7K, additional concerns come into play. The target injector must keep the acceleration of the target below ~1000 g because of the low strength of solid DT at this temperature. Lowering the temperature further causes increased roughness of the DT ice surface.

Table 1: Injector accuracy results

Injector	Repeat-ability 1 σ (mm)	Repeat-ability 1 σ (mRad)
Gas gun with two piece sabot, 400 m/s, and 1 mg direct drive target	10	0.59
Gas gun barrel with one piece shuttle, mechanically driven, 50 m/s, and 1 mg direct drive target	4	0.24
LIA with indirect drive target surrogate – no steering - horizontal	5.97	2.5
LIA with indirect drive target surrogate – passive steering - horizontal	0.6	0.3
LIA with indirect drive target surrogate – active steering - horizontal	0.24	0.1
LIA with indirect drive target surrogate – no steering - vertical	5.42	2.3
LIA with indirect drive target surrogate – passive steering - vertical	0.68	0.3
LIA with indirect drive target surrogate – active steering - vertical	0.24	0.1

The success of the LIA for indirect drive targets, and the lack of warm propellant in close proximity to the target, suggests the development of an electromagnetic (EM) injector for direct drive targets. EM forces would act on a one-piece pusher sabot. This could be LIA based or based on a magnetic reconnection launcher (Ref.s: 3 & 4). EM forces could gently decelerate the sabot and return it for reuse at the loading point of the injector.

Continued development of target injectors would include the following. Develop an electromagnetic injector for direct drive targets. For all injectors being carried forward, develop the loading mechanism to allow continuous target injection. Assess reliability and wear of injectors under continuous operation. Upgrade the injectors and target loading mechanisms to handle cryogenic targets. Construct a full engineering prototype of the cryogenic injector and loader. Integrate these at a beamline test facility with the addition of a target layering station, target tracking, and a heated surrogate target chamber. Assess beam engagement of target and check for target degradation in hot thermal environment of surrogate target chamber.

Target Engagement

The principal components of target engagement are the ability to track and predict the position of the injected target in real time, and the ability to steer the driver beam to the target's predicted location. High-precision target engagement was demonstrated (Ref. 5, and Figure 3) at low velocity (~5 m/s) with a low-power laser beam steered by a fast, voice-coil actuated, steering mirror. The targets were spherical gold-coated, polymer capsules with a mass of a few mg. Targets were dropped in a vacuum. Initial tracking consisted of a) a set of three shadow crossing detectors at the beginning of the flight line for axial position prediction; b) for position transverse to the flight line, a laser backlit the target along the flight line, and the resultant Poisson diffraction spot was continuously monitored with a high-speed camera. Initial tracking allowed for pre-positioning of the steering mirror and initiation of final tracking. Final tracking consisted of pulsing a large-diameter laser beam onto the target sphere just before it reached chamber center. The glint off the target from this laser beam traveled up the optics chain of the driver laser to a position detector which effectively "sighted-in" the target through the optics of the drive beam for a final small adjustment the steering mirror. The engagement precision achieved was 28 μm (1 μ). Accomplishing this level of engagement (or better if required from target ignition simulations and experiments) is required for full target injector velocity and at the reactor relevant stand-off distances (i.e., on the scale of the reactor chamber size).

Instead of a glint, for a non-spherical target such as a hohlraum or the cone of a cone-in-shell target, micro corner cube reflectors can be indented into the outer surface, or patterns of diffuse reflectors etched onto the outer surface of the part. GA has implemented such indented micro-corner cubes with a size of ~15 μm).

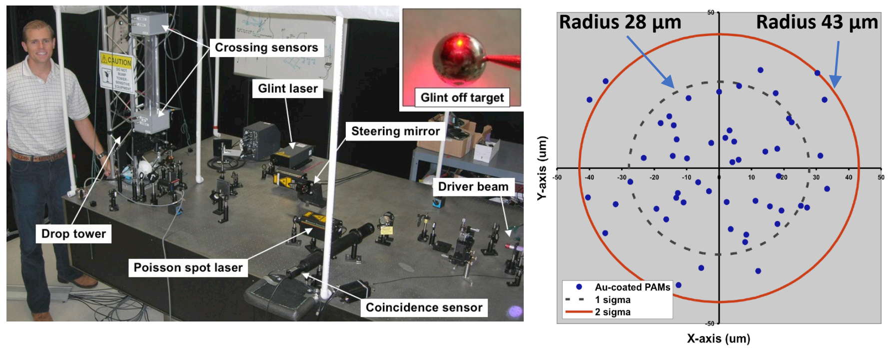

Figure 3: Left: Demonstration of accurate engagement of a low speed (~5 m/s) target with a low power laser beam. Right: Accuracy of hitting spherical target center was 28 μm (1 σ) and 43 μm (2 σ).

Continued development in target engagement is called for. For target tracking, this entails the following: Upgrade the demonstration tracker to operate on targets moving at full velocity, shot rate, and at stand-off distances appropriate for IFE reactors. This includes the initial tracking sensors of the Poisson spot detector, the shadow crossing sensors, and the final glint detection sensors, as well as appropriate timing and triggering. For non-spherical targets, implement these methods using light returned from the target by non-glint methods (e.g., indented micro corner cubes or pattering of diffuse reflectors on the target surface).

For beam steering, this entails the following: Develop full size, slew rate, and slew range beam steering methods. For lasers this could be voice coil or mechanically actuated grazing incident metal mirrors (GIMM), acousto-optic modulators, spatial light modulators, or large scales MEMS mirrors. The steering should be tested at all orientations and directions that would be utilized to illuminate the target in the reactor chamber. For ion beams steering may be accomplished by electrostatic or magnetic deflection. Static and dynamic beam pointing stability should be assessed.

For the development of both tracking and beam steering to be relevant they should be developed in conjunction and collaboration with the development of the driver beams systems. For target engagement this entails: Developing diagnostic methods for determining the accuracy to which the beam hits a target for a target travelling at full speed. Integrating the target tracking, and beam steering equipment with a full speed target injector and a low power driver beam. For a laser beam driver this could be illumination of the target or using enough power to ablate a mark on the target so it could be imaged (in flight or after non-destructively catching the target).

This would be followed by a full engineering prototypes of tracking and steering that would ideally be integrated on a full power beam line test facility. This facility would include ability to inject layered targets and a surrogate target chamber where reactor-relevant flight path conditions could be created (e.g., heated walls, heated residual gas with density fluctuations). The entire target injection, tracking, beam steering and engagement system would be tested for robustness, in the following areas: variations in target trajectory and velocity, chamber gas temperature and pressure, and targets dimensions; mechanical vibrations; chamber gas “wind” and debris at full reactor shot rate; and lifetime and aging effects. Finally, at a pilot IFE reactor facility robustness against variation and degradation of components due to the radiation environment would be assessed.

The challenge associated with demonstrating an integrated system is that it requires the integrated system to be built such that testing can be commensurate with IFE requirements. Advanced simulations must be developed to understand the full environment in which the systems are expected to operate at a high rep-rate (~5−10 Hz) and a high ignition reliability (99%). Additionally, experiments would be proposed or leveraged at NIF and Omega to determine tolerances of alignment and timing. A subscale IFE Demonstration plant could provide a steppingstone and pathway for an IFE facility with the full capabilities demonstrated at a smaller scale, possibly with a limited number of driver beams.

Key Metrics

The target injector should have a placement accuracy for the target at chamber center that is less than the pointing range of the driver at chamber center, be highly reliable and maintainable, match the shot rate of the reactor, should not damage target, have a long lifetime, and have a velocity such that the target survives transit to chamber center. Target design, and chamber protection schemes affect required velocity.

Target tracking and engagement accuracy (beam placement on target) must be sufficient to allow target to ignite. This is target specific and determined by target simulations and ultimately ignition experiments. It is currently assumed to be <~25 μm.

Principal steps to demonstrating target injection and target engagement 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 injection and engagement systems.
- Develop prototype target injectors that continuously operate at full velocity and shot rate. Pay particular attention to loading of targets into injector. Upgrade designs to handle cryogenic targets.
- Develop beam steering and tracking equipment that continuously operate with sufficient speed and accuracy to engage full velocity targets at reactor shot rate.
- Develop the apparatus to retrieve cryogenic targets from fuel layering system and load them into the cryogenic target injector.
- 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.
- Construct an injection and tracking engineering prototype that will be coupled to a full-scale IFE beamline test facility. 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 inject, track, engage, and ignite targets with high (>99%) reliability; demonstrate long-term subsystem reliability for the full-scale commercial power plant environment.

References

1. D.T. Frey, D.T. Goodin, R.W. Stemke, R.W. Petzoldt, T.J. Drake, W. Egli, B.A. Vermillion, R. Klasen & Cleary M.M. (2005) Rep-Rated Target Injection for Inertial Fusion Energy, Fusion Science and Technology, 47:4, 1143-1146, DOI: 10.13182/FST05-30
2. Ronald Petzolt, Neil Alexander, Lane Carlson, Eric Cotner, Dan Goodin & Robert Kratz (2015) Linear Induction Accelerator with Magnetic Steering for Inertial Fusion Target Injection, Fusion Science and Technology, 68:2, 308-313, DOI: 10.13182/FST14-915
3. Maynard Cowan (Apr. 4 1989), MAGNETIC RECONNECTION LAUNCHER, United States Patent number 4,817,494
4. M. Cowan, E. Cnare, B. Duggin, R. Kaye and T. Tucker, "The reconnection gun," in IEEE Transactions on Magnetics, vol. 22, no. 6, pp. 1429-1434, November 1986, doi: 10.1109/TMAG.1986.1064637.
5. Carlson, L.C., Tillack, M.S., Stromsoe, J., Alexander, N., Flint, G.W., Goodin, D., & Petzoldt, R.W. (2010). Completing the Viability Demonstration of Direct-Drive IFE Target Engagement and Assessing Scalability to a Full-Scale Power Plant. IEEE Transactions on Plasma Science, 38, 300-305