

Completing the Viability Demonstration of Direct-Drive Inertial Fusion Energy Target Engagement

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Abstract— A significant challenge for the successful implosion of direct-drive inertial fusion energy (IFE) targets is the repeated alignment of multiple laser beams on moving targets with accuracy on the order of 20 μm . Adding to the difficulty, targets will be traveling up to 100 m/s through a chamber environment that may disturb their trajectories.

In the High Average Power Laser (HAPL) program, we have developed a target tracking and engagement system capable of meeting the goals for an inertial fusion power plant. The system consists of separate axial and transverse target detection techniques, and a final correction technique using a short-pulse laser to interrogate the target's position 1-2 ms before chamber center. Steering mirrors are then directed to engage the target at chamber center.

Over the past few years, we have constructed and improved upon an integrated tabletop demonstration operating at reduced speeds and path lengths. In August 2007, initial engagement of moving targets in with a simulated driver beam in air was 150 μm rms. Since then, we have taken an encompassing look at all error sources that contribute to the overall engagement error. By focusing on those individual component errors that have the most influence and improving their accuracy, we have substantially reduced the overall engagement error. In August 2008, we had achieved engagement of 42 μm rms in air by using this approach, and in March 2009, 34 μm rms in vacuum.

The final elements, which we believe are necessary to meet our goal, necessitate engaging lightweight targets in a prototypic vacuum environment with an understanding of the scalability of demonstration-scale errors to full-scale errors. In this paper, we present the latest improvements from the identification and reduction of errors and the resulting engagement data demonstrating near-completion of the viability demonstration of direct-drive target engagement to 20 μm .

Keywords—component; target tracking and engagement; glint system; Poisson spot.

I. INTRODUCTION

The HAPL direct-drive IFE power plant consists of an array of 60 driver beams to deliver an intense energy pulse directly onto the target. Targets must be injected into the chamber with a placement accuracy of ± 1 mm at a standoff distance of ~ 20 m. The required engagement accuracy of all driver beams on the target is ± 20 μm .

We have developed a target tracking and engagement concept to meet these requirements and have assembled a tabletop experiment that engages an injected target on-the-fly using a steerable simulated driver beam [1]. The system continuously tracks the target along its trajectory and makes a final steering correction that is made relative to the target itself. The tabletop experiment has demonstrated proof-of-principle at reduced speeds and distances and will establish the concepts' feasibility for a full-scale power plant.

Since an initial engagement accuracy of 150 μm , we have reduced individual component errors and improved the glint return imaging system, which has resulted in improved engagement to less than 50 μm . With all improvements already in place and those presented in this paper, we expect to meet our 20 μm accuracy goal and complete the viability demonstration of IFE target engagement.

II. SYSTEM DESIGN & OVERVIEW

The target tracking and engagement design is composed of three main subsystems [1]. First, a laser-based continuous tracking system sights along the target's flight path and uses position information from the target's Poisson spot to determine the target's transverse position. Second, a system using discrete crossing sensors provides the necessary timing to trigger a glint laser, driver beam laser, coincidence camera, and a verification camera. Finally, a short-pulse glint laser illuminates the target a few milliseconds before it reaches chamber center, thus using the glint return from the target itself as the final reference point for aligning the driver beams immediately before engagement. In the pre-steering scenario described in [2], information from the Poisson spot pre-steers the mirror to take up any gross position errors, while the glint system makes the final, small steering correction.

III. IDENTIFICATION & REDUCTION OF ERRORS

At the end of 2008, the best engagement achieved was 42 μm rms in air with heavy targets [2]. At that time, the experiment was on the cusp of moving into a vacuum chamber, which is a more prototypic environment for an actual power plant chamber than air.

We assembled a list of errors associated with every component of the tracking and engagement system that was believed to be contributing to the overall engagement error

(Table 1). By testing and improving individual errors on the component level, we aspired to improve the overall engagement error, as shown in Fig. 1. The direction that stemmed from this analysis focused on improving the Poisson spot wander, reducing electrical noise, specifically for the steering mirror, and moving the experiment to a vacuum environment. The sections that follow focus on these areas of improvement as well as other new and inconspicuous error sources.

One new error source, which was brought into consideration due to the new setup required with the installation of the vacuum chambers, is orthogonality. There are multiple axes of various components in different coordinate spaces that all must be orthogonal to one another. The optical table, verification camera, coincidence camera, Poisson spot camera, target calibration stage, steering mirror, and target dropping orientation must all be orthogonal to one another. One additional optic, a dove prism, was installed in the beam line to accommodate adjustments. Also, tests were conducted to ensure that the steering axis and the aforementioned cameras were all imaging orthogonal movement.

Two more issues that are currently under consideration and investigation are thermal drift and daily laboratory-wide electrical noise fluctuations. Thermal drift is prevalent throughout the day and moves the driver beam at chamber center up to 50 μm in an open-loop steering configuration. This is correctable in closed-loop mode as the mirror locks on to a specific pixel on the coincidence camera. But any thermal fluctuations that change the calibration of the glint return location to steering voltage is detrimental to target engagement. Further investigation is being done in this area, which has been identified in the past, but not actively pursued. The ambient electrical noise in the laboratory can also be monitored and target engagement experiments timed to coincide with minimal lab noise. Over the period of about an hour during the lunch break, the laboratory activity is usually at a minimum and best engagement can be done then.

TABLE I. ERROR CONTRIBUTION LIST

Subsystem	Oct. 2008 Errors			April 2009		
	X (μm)	Y (μm)	Z (μm)	X (μm)	Y (μm)	Z (μm)
Poisson spot centroiding	(18)	(15)	6	(2)	(3)	1
Glint return	2	-	3	4	-	4
Verification algorithm	5	-	4	(4)	-	(4)
Mirror pointing	12	-	12	3	-	5
Timing prediction	-	-	35	-	-	(20)
Transverse target motion	24	(24)	10	5	(7)	5
Target diameter variation	3	(3)	3	4	(4)	4
Dynamic steering mirror	-	-	-	5	-	5
Calibration drift/error	-	-	-	12	-	12
Target eng. error (rms, compiled)	27	-	38	15	-	16
Target eng. error (rms, observed)	30	-	29	24	-	24
Total eng. error (total rms, observed)	42 μm			34 μm		

All errors converted to *target space*, errors in () do not contribute to the compiled error, Z-axis is axial, X,Y-axes are transverse.

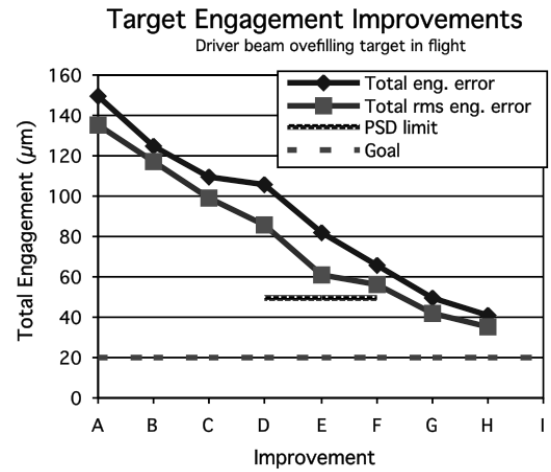


Figure 1. Step-wise improvement graph with effect on overall target engagement results. A. initial setup, 4:1 magnification, defocused glint return (GR), B. focused GR, C. focused GR, small aperture, D. 1:1 mag., E. 1:1 mag., improved steering calibr., glint camera replaces PSD, G. stable beam-splitter, small delta steering, H. vacuum chamber, I. thermal drift and electrical noise eliminated.

A. Transverse Tracking System

The Poisson spot tracking system's beam path in air was reduced from $\sim 7\text{m}$ to $\sim 2\text{m}$. This involved assembling the laser and spatial filter on the tower itself (Fig. 2), and moving the tracking camera as close to the bottom chamber as possible. The resulting standard deviation of the Poisson spot on the camera was substantially reduced from 15 μm to 3 μm . This provides the pre-steering system, movable area-of-interest, and wedge effect correction with a more dependable and stable target position report. For long path lengths, this error is dependent on the pointing stability of the laser light source and the propagation path in air. Providing that the Poisson spot beam is protected in a vacuum environment, this error is expected to scale consistent with the pointing stability of the illumination laser source.

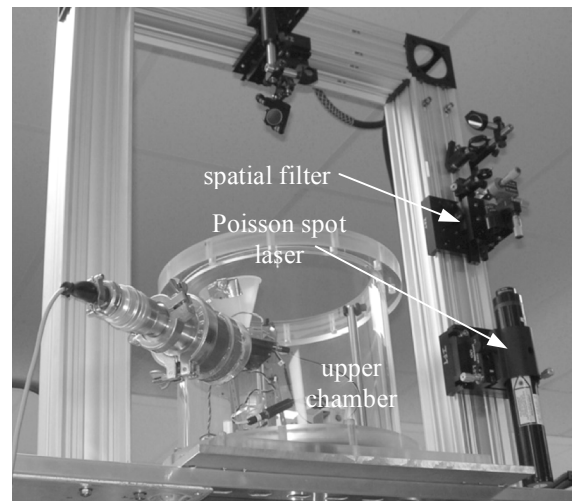


Figure 2. Upper vacuum chamber with Poisson spot illumination laser

B. Target Injection

The new tri-dropper mechanism as introduced in [2] allows for the dropping of multiple targets in vacuum. The recoil-free design transfers minimal transverse motion to the falling target by simultaneously activating three solenoids that pull away ruby-tipped pins riding on ball-bearing linear slides. The placement accuracy of stainless steel and brass BBs ~ 1.5 m away in vacuum is < 0.4 mm stdev and for lightweight ($\sim$ few mg) targets it is < 0.5 mm stdev. This is helpful in reducing the final steering mirror requirement. For any full-scale power plant injector, whether pneumatic, mechanical, electrostatic, or gravity-driven, a placement accuracy of < 1 mm will permit an adequate field of view for target engagement.

The vacuum chamber is now operational, as shown in Fig. 3. It is constructed of clear $\frac{1}{2}$ -inch thick acrylic and consists of two 12-inch diameter chambers with a tube, which contains the crossing sensors, connecting the two. The top chamber houses the supply of targets and the dropping mechanism, while the lower chamber catches the dropped targets and allows the glint, Poisson, and driver laser beams to sight through its windows. Initial vacuum reached ~ 100 mTorr with the lab's house vacuum system. Since then, a small turbo-molecular pump has been installed to achieve < 0.5 mTorr, which might be expected for the final large chamber.

Transitioning to vacuum from air was needed because it is more prototypic of an actual power plant chamber. It permits the dropping of lightweight targets, which is nearly impossible in air due to drastic wake effects that buffet them as they fall. This curving effect, which influences the target between the glint location and the driver location (~ 6 cm) has been reduced from $24\text{ }\mu\text{m}$ to $6\text{ }\mu\text{m}$, due to the better placement accuracy achieved in vacuum.

In anticipation of dropping lightweight targets in vacuum, we have begun measuring the diameter of various gold-coated PAMS targets using an optical technique with $1\text{-}\mu\text{m}$ resolution. Most target engagement tests thus far have utilized heavy stainless steel or brass BBs of similar diameter and reflectivity as the PAMS targets. A more prototypic test will be the engagement of lightweight targets (2-10 mg vs. 300 mg). A necessary requirement, though, is that the diameter must not vary more than $10\text{ }\mu\text{m}$. There will be a glint return offset on the coincidence camera depending on the angle between the glint illumination laser and the glint return signal. A method of measuring the target diameter on-the-fly and adjusting accordingly for the known offset has been proposed, but not yet implemented.

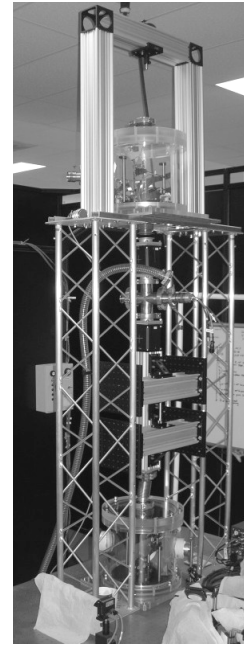


Figure 3. Drop tower (~ 2 m tall) with upper and lower vacuum chambers

C. Glint System

The target moves several centimeters between the time the glint illuminates the target and the driver beam fires. The wedged dichroic mirror reflects the outgoing driver beam from one surface and incoming glint return signal from the other so that both can hit the target [1]. The prior configuration held the aluminum mirror and long-pass filter separately on their individual mounts. The optics have since been epoxied together to create a more monolithic structure and to set the wedge angle permanently (Fig. 4). In this new configuration, the simulated optics more accurately represent a true monolithic wedged dichroic mirror, which is expected to be used in the final design. In terms of scalability, the glint position precision in sensor space is simply a function of the intervening optical magnification, in our case 1:4. This assumes insignificant gas density variations and no high frequency vibrations of the optics, which can be preserved in a full-scale system.



Figure 4. Simulated monolithic wedged dichroic mirror (2-in diameter)

D. Beam Steering

The steering mirror's steering accuracy and stability have been improved. The mirror has been "desensitized" by voltage-dividing the signal going to the mirror controller. This allows use of the entire dynamic range of the mirror controller (± 10 V), in which the signal-to-noise ratio is much lower than when just a small portion (± 1 V) is used. Electrical noise to the

mirror has also been reduced by ensuring a common ground between the steering signals and that no antennas or loops exist in the wiring harness. The combination of the desensitization and cleaning up the electrical noise has reduced the jitter of the driver beam at chamber center from 15 μm to 4 μm stdev. The effect of the electrical noise on the beam's position is proportional to the maximum distance through which the beam must be steered, which is about ± 1 mm in our experiment as well as in a power plant.

The steering algorithm now more precisely computes the final steering voltage from the glint return by taking the last steering voltage required to drive the alignment beam to chamber center, then computing a delta steering voltage from there to the glint return. This is a more precise way to compute the final steering requirement, rather than using the calibration voltage to align the beam on the coincidence camera, which may have been taken hours or days before. The thermal drift of the system necessitates that the reference alignment beam be taken immediately before the final steering voltage is calculated from the glint return.

E. Simulated Driver Beam

The simulated driver beam has been reconstructed from a Gaussian beam to provide a more stable, flat-topped beam to overfill the target at chamber center (Fig. 5). A target now occludes the driver beam very sharply, which improves the verification algorithm's precision from 7 μm to 2 μm stdev (for a stationary target occluding the beam.) This error is not dependent on the path length of the beam, but rather only on the driver beam's spatial profile. This measurement technique is helpful for measuring success on the engagement demonstration, but would potentially be used for initial testing on a full-scale startup plant.

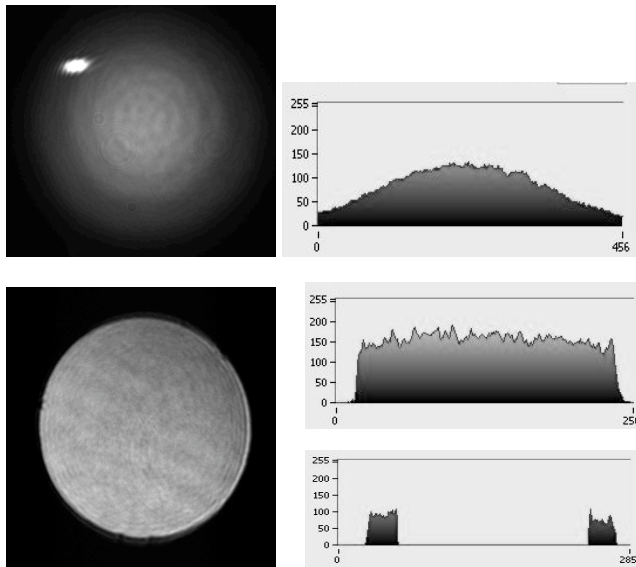


Figure 5. (Top) Prior Gaussian driver beam with lineout, (Bottom) new flat-top driver beam with lineout of the beam and the target occluding the beam.

IV. CURRENT ENGAGEMENT RESULTS

The current engagement result is 34 μm stdev in vacuum with brass BBs. This represents substantial progress from our early results of 150 μm [3] and has been the reward of much effort to identify and reduce error sources one by one (Fig. 1). Further effort will focus on understanding the effect of thermal fluctuations on the experiment and the drifting of the calibration. The engagement of lightweight targets is the next highest priority.

The question that arises concerning the promising engagement precision achieved on the tabletop demonstration is the applicability and scalability to that of a full-scale IFE system. As noted, most of our remaining errors identified in Table 1 are from sources that are expected to scale well to the increased distances required for an IFE power plant. Engagement must still be demonstrated at prototypic, full-scale chamber distances (20 m rather than 4 m). Scaling the injection velocity from 5 m/s to 50-100 m/s will require faster position measurements and more rapid steering mirror positioning, beyond the capabilities of our demonstration. Faster cameras and real-time processing are feasible with current camera technology, but positioning full-scale steering mirrors in the available time will be more difficult and must be demonstrated. The effect of possibly turbulent high-speed chamber gas on target trajectory must also be better understood. The path forward looks promising and attainable but is not without its difficulties.

REFERENCES

- [1] L.C. Carlson et al., "Target tracking and engagement for Inertial Fusion Energy – a tabletop demonstration," *Fusion Sci. Tech.* 52 No. 3 (Oct. 2007) 478-482.
- [2] L.C. Carlson et al., "Improving the accuracy of a target engagement demonstration," *TOFE proceedings*, (Oct. 2008).
- [3] L.C. Carlson et al., "Glint system integration into an IFE target tracking and engagement demonstration," *Journal of Physics* 112 (2008) 032039.