University of California, San Diego

UCSD-CER-10-01

Target and Chamber Technologies for Direct-Drive Laser IFE

**M. S. Tillack, A. R. Raffray,
F. Najmabadi and L. C. Carlson**

30 April 2010

Center for Energy Research
University of California, San Diego
9500 Gilman Drive
La Jolla, CA 92093-0417

UC San Diego Final Report for the IAEA CRP:
"Pathways to Energy from Inertial Fusion (IFE) - an Integrated Approach"

Target and Chamber Technologies for Direct-Drive Laser-IFE

M. S. TILLACK, A. R. RAFFRAY, F. NAJMABADI and L. C. CARLSON
University of California San Diego, La Jolla, CA 92093-0417, USA

30 April 2010

Introduction

The University of California at San Diego maintained an active program of research on inertial fusion energy (IFE) technology for the duration of the IAEA Coordinated Research Program. Progress was made in two principal research areas:

A. Target engagement. We developed and demonstrated systems to track direct-drive targets in flight and to steer simulated driver beams onto the targets with the precision required for target ignition. Bench-top experiments were performed in order to demonstrate the feasibility of these systems and to characterize their performance.

B. Chamber design studies. We developed chamber design concepts that integrate armor and structural material choices with a blanket concept providing attractive features of design simplicity, fabrication, maintainability, safety and performance (when coupled to a power cycle). Advanced concepts (including magnetic intervention) that could result in smaller less costly chambers, better armor survival and lower cost of electricity also were investigated.

A. Target Engagement

A significant challenge for the successful implosion of direct-drive inertial fusion energy 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. As part of the High Average Power Laser (HAPL) program, we developed a target tracking and engagement system that is 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 a chamber center. Steering mirrors are then directed to engage the target at the chamber center.

The three main subsystems are shown in Figure 1 and described in more in detail in [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.

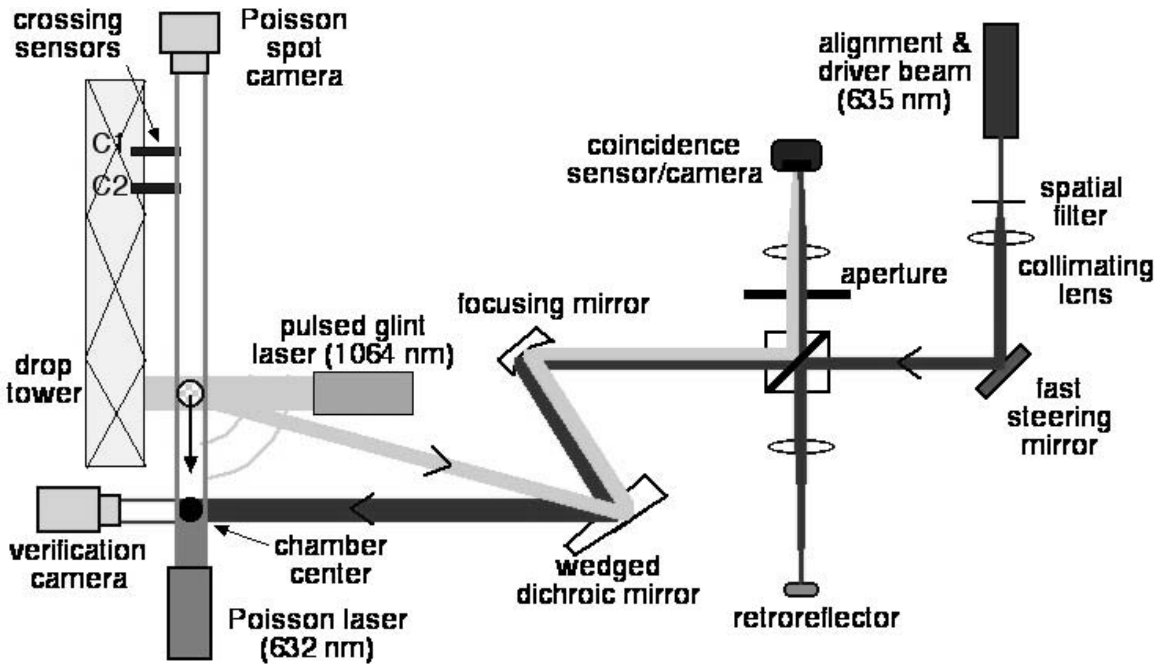


Figure 1. Schematic of integrated target tracking and engagement demonstration. Focusing mirror to chamber center is 2 m, drop tower is ~2 m tall. (Figure not to scale.)

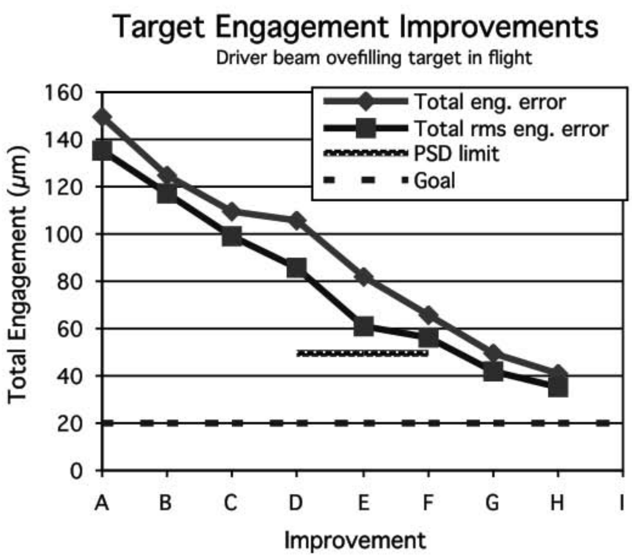
Over the past several years, we constructed and improved upon an integrated tabletop demonstration operating at reduced speeds and path lengths. In August 2007, initial engagement accuracy of moving targets in air using a simulated driver beam was 150-μm rms. Since then, we have taken an encompassing 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. Table 1 shows the major contributors to error and their individual improvements from 2008 to 2009, resulting in the current aggregate rms error of 34 μm. Figure 2 depicts the stepwise improvement in engagement accuracy as a result of various changes and improvements made to the apparatus and experimental techniques. Future 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.

A 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 arise from sources that are expected to scale well to the increased distances required for an IFE power plant. Engagement still must be demonstrated at prototypic, full-scale chamber distances (17 m rather than 1.5 m). Scaling the injection velocity from 5 m/s to 50-100 m/s will require an injector with a clear sight down the trajectory, faster target positioning measurements, and faster steering mirror positioning. Faster cameras and real-time processing are feasible with current technology, at a higher cost than the demo. However, 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 anticipated and better understood. The path forward looks promising and attainable but is not without challenges.

Table 1. Error Contribution List

	Oct. 2008 Errors (1σ)				***April 2009 (1σ)***		
Subsystem	***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 to the target's trajectory, X and Y axis are transverse.



A. initial setup, 4:1 magnification, defocused glint return
B. focused glint return
C. focused glint return, small aperture
D. 1:1 magnification
E. 1:1 mag., improved steering calibration, glint camera replaces PSD
F. stable beamsplitter, small steering Δ
G. vacuum chamber installed
H. thermal drift eliminated with on-the-fly calibration, vacuum chamber
I. electrical noise reduced
J. target surfaces scrutinized for imperfections

Figure 2. Step-wise improvement graph with effect on overall target engagement results.

B. Chamber Design Studies

The High Average Power Laser (HAPL) program is focused on the development of laser IFE power plants based on lasers, direct-drive targets and dry wall chambers [3]. As part of this program, we looked at the key issue of survival of the chamber wall under the ion threat spectra (representing ~25% of the yield energy and shown in Figure 3 for a 350 MJ direct drive target [4]). The ions would deposit their energy in the dry wall, which must accommodate the high cyclic temperature levels and gradients. Use of refractory metals such as tungsten as armor can provide the possibility to accommodate the thermal effects of the high-energy deposition with a large enough chamber size [5]. However, a major concern is the possible accumulation of helium from ion implantation. Helium migration in tungsten is slow and the concern is that a build-up of helium could result in local armor failure. For that reason, an engineered armor making use of nano-structured W with low porosity was investigated [5]. It provides a short pathway for the implanted He to diffuse to the inter-connected porosity and be released back to the chamber. Initial results on the He release are encouraging (when compared to the release from sintered W with larger microstructure). A parallel R&D effort was launched to assess the He behavior as well as the thermo-mechanical behavior of such an armor under representative laser IFE conditions.

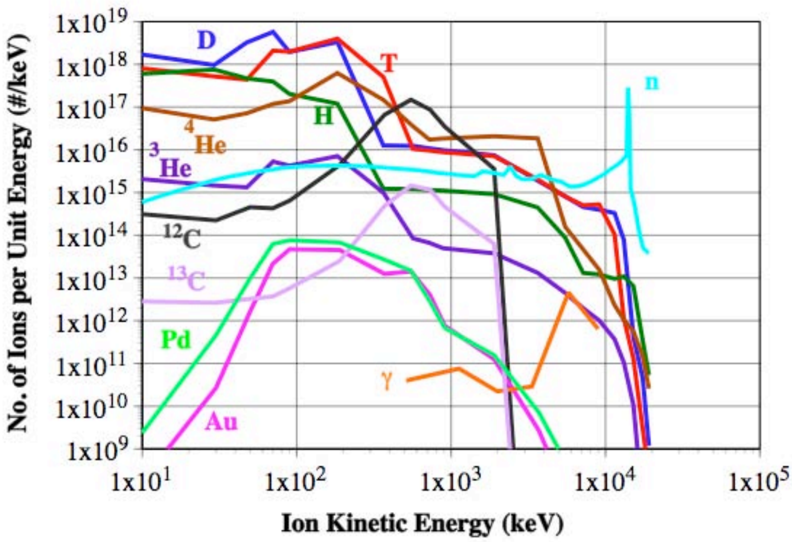


Figure 3. Ion spectra for HAPL 350 MJ direct drive reference target. [4]

In parallel, an effort was launched to investigate the possibility of steering the ions away from the chamber to specially designed dump chambers using magnetic intervention [6]. Options include a simple cusp configuration as well as a bell cusp configuration [7]. In the simple cusp configuration, the ions are contained within the magnetic bottle for, typically, 10-20 bounces after which they leak out of the chamber through a toroidal slot and holes at the poles, where they are directed to specially-designed large-area collectors, as shown in Figure 4. A biconical chamber configuration was developed to match the shape taken by the expanding plasma in the cusp field, as illustrated in Figure 5. Ion dump plates are shown schematically within the chamber at the equator, through which most of the ions escape, and at the poles.

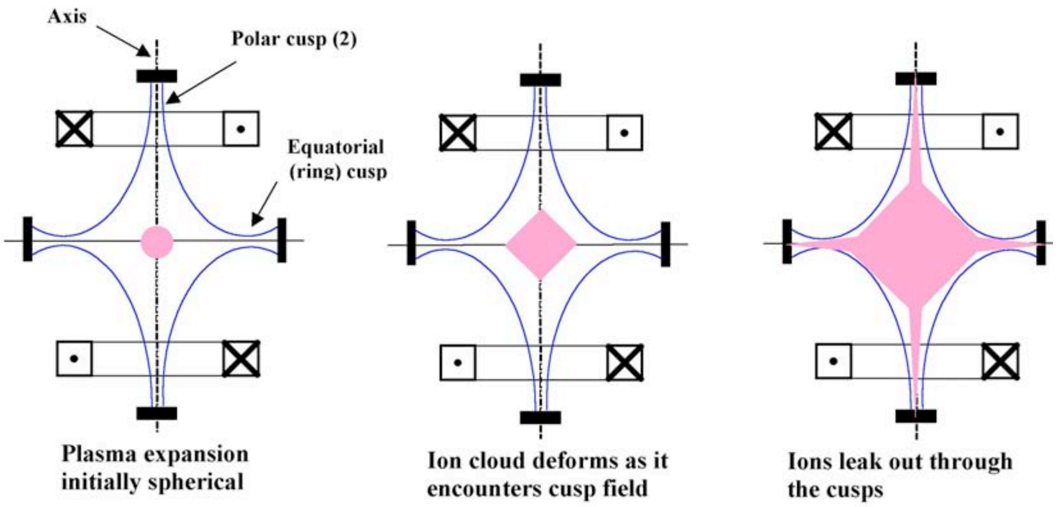


Figure 4. Simple cusp magnetic configuration.

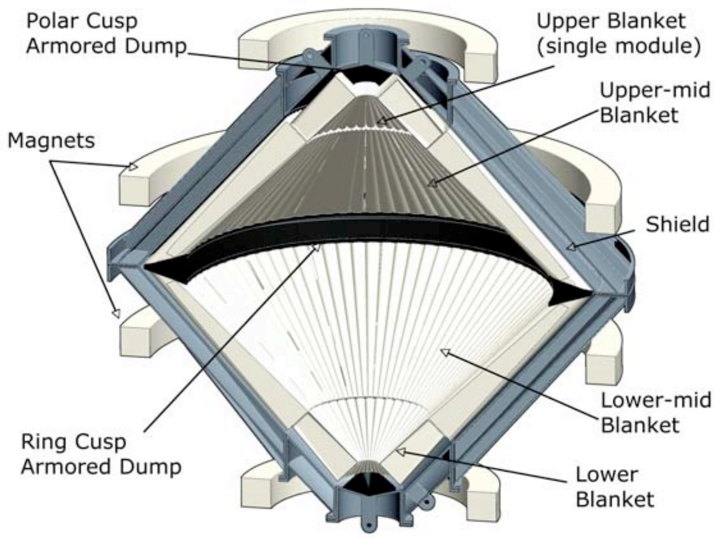


Figure 5. Biconical chamber for simple cusp configuration. [8]

In addition, to reduce the ion flux on the dumps the possibility of using magnetic dissipation in a resistive blanket was explored. A self-cooled liquid breeder blanket concept was developed for this configuration consisting of a number of SiC_f/SiC submodules arranged poloidally in the chamber. Both Pb-17Li and Flibe were considered as candidate liquid breeder. The concept allows for high outlet liquid breeder temperature (1000 C or higher) and, thus, high power cycle efficiency (50-60% depending on chamber size and SiC_f/SiC properties and temperature limits). The study also included a preliminary integration of the chamber within a reactor including all key systems such as the shield, magnet, vacuum pumping and supports [8]. Although resistive dissipation of >50% of the ion energy seemed possible, there were concerns about the high voltages generated between the blanket modules.

As long as the ions are deposited on solid materials, problems of ion damage and in particular helium retention remain, although now transferred from the chamber wall to an external location where they might be better accommodated. This led to the consideration of liquid dumps in subsequent concepts.

Steering the ions away to a separate dump chamber brings up the intriguing possibility of utilizing a liquid wall to accommodate the ion fluxes provided the right measures are taken to prevent the liquid from contaminating the main chamber. Such measures would include a curved duct geometry to prevent line-of-sight vapor transmission from the dump chamber to the main chamber as well as a condensation trap towards the port junction to the main chamber.

For example, use of a bell cusp was considered, whereby the field in the polar cusps is made as large as practicable so as to direct almost all the ions out of the equatorial cusp. By suitably shaping the field these ions can be directed through a curved duct into an external dump chamber. This configuration is particularly suited to a liquid wall, such as in the case of an oozing dump target. Under the ion energy deposition, the liquid surface would evaporate and then condense on the interior walls of the dump chamber. By avoiding line of sight between the dump surface and the main chamber, the amount of vapor entering the main chamber is negligible and transmission of droplets completely eliminated. Such a bell cusp arrangement, approximately to scale, is shown in Figure 6.

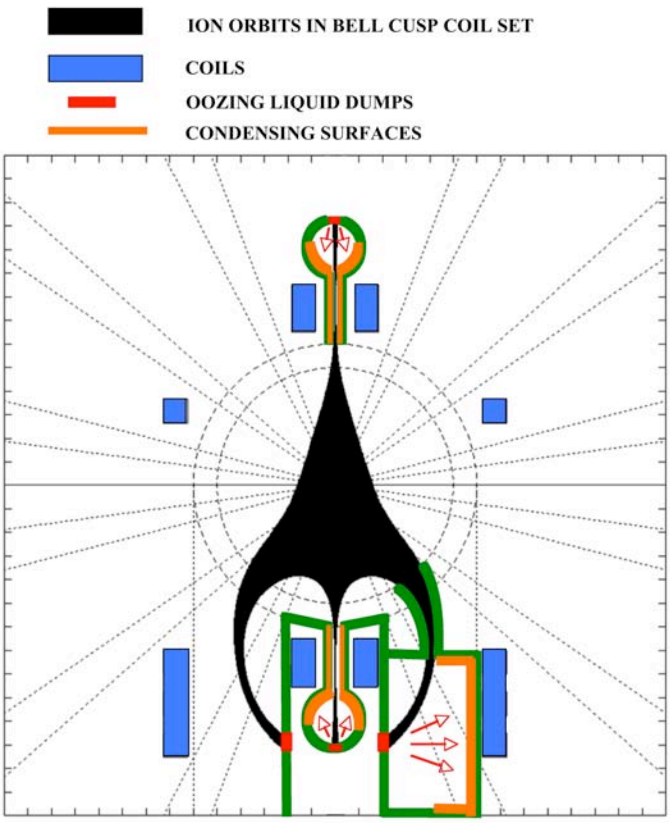


Figure 6. Schematic of bell or tulip cusp showing the ion trajectory through the port, the evaporation from the liquid dump and the condensation surfaces (the scale is in m with a main chamber radius of 5 m). [7]

Evaporation and condensation studies of the working fluid in the condensation chamber were performed [7]. Different fluids were assessed, including Pb, Sn and Ga. However, other factors including material compatibility would need to be considered before finalizing the design choice. Based on the analysis, condensation was found to be fast with the vapor pressure of Sn (for a 1100 C vapor temperature case) decreasing to 0.076 Pa (0.57 mTorr) after 0.2 s, close to the vapor pressure of Sn at 1010 C, ~0.04 Pa (0.3 mTorr). Similar results were obtained for Ga and Pb also. However, they are based on a simple, albeit conservative, model and would need to be confirmed through more detailed R&D.

Preliminary chamber layout consideration indicated the possibility of blanket coverage meeting the key nuclear requirements [8,9]. Although this initial assessment is encouraging, a more detailed study is required to obtain a better picture, including details of the liquid wall configuration in the dump chamber and of the mass transfer processes, of material compatibility under the operating conditions, of the design of the small polar condensation chambers, and a better assessment of possible contamination of the main chamber through both the dump and laser ports.

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," *Fusion Science and Technology* **56** (1) July 2009, 409-416.
3. J. Sethian, *et al.,* "An Overview of the Development of the First Wall and Other Principal Components of a Laser Fusion Power Plant," *Journal of Nuclear Materials* **347** (December 2005) 161.
4. Available at: http://aries.ucsd.edu/HAPL/DOCS/reftarget.html
5. A. R. Raffray, J. Blanchard, J. Latkowski, F. Najmabadi, T. Renk, J. Sethian, S. Sharafat, L. Snead and the HAPL Team, "Progress Towards Realization of a Laser IFE Solid Wall Chamber," *Fusion Engineering & Design* **81** (2006) 1627.
6. R. Raffray, J. Blanchard, A. E. Robson, D. V. Rose, M. Sawan, J. Sethian, L. Snead, I. Sviatoslavsky, and the HAPL Team, "Impact of Magnetic Diversion on Laser IFE Reactor Design and Performance," Proceedings, 4th International Conference on Inertial Fusion Science and Applications, Biarritz, France, September 2005, Journal de Physique IV, 133, 845-848, June 2006.
7. A. R. Raffray, A. E. Robson, J. Sethian, C. Gentile, E. Marriott, D. Rose, M. Sawan and the HAPL Team, "Laser IFE Direct Drive Chamber Concepts with Magnetic Inter-vention," *Fusion Science and Technology* **56** (1), 333-340, July 2009.
8. A. R. Raffray, F. Dahlgren, C. Gentile, C. Priniski, A. E. Robson, D. Rose, M. E. Sawan, J. Sethian, L. Snead, G. Sviatoslavsky, and X. R. Wang, "Conceptual Study of Integrated Chamber Core for Laser Fusion with Magnetic Intervention," Proceedings of the 22nd IEE Symposium on Fusion Engineering, 2007.
9. M. E. Sawan, C. S. Aplin, G. Sviatoslavsky, and A. R. Raffray, "Neutronics Analysis of a Molten Salt Blanket for the HAPL Laser Fusion Power Plant with Magnetic Intervention," Proceedings of the 22nd IEEE/NPSS Symposium on Fusion Engineering, Albuquerque, NM, June 18-21, 2007 (CD-ROM).

List of Publications

A. Target Engagement

1. L. C. Carlson, M. S. Tillack, J. Stromsoe, N.B. Alexander, G.W. Flint, D.T. Goodin, R.W. Petzoldt, "Completing the Viability Demonstration of Direct-Drive IFE Target Engagement and Assessing Scalability to a Full-Scale Power Plant," Transactions on Plasma Science 38(3) March 2010, 300-305.

2 L. C. Carlson, M. S. Tillack, J. Stromsoe, N. A. Alexander, D. T. Goodin and R. W. Petzoldt, "Improving the Accuracy of a Target Engagement Demonstration," *Fusion Science and Technology* **56** (1) July 2009, 409-416.

3. Lane Carlson, Neil Alexander, Graham Flint, Dan Goodin, Thomas Lorentz, Ronald Petzoldt and Mark Tillack, "Target Tracking and Engagement for Inertial Fusion Energy: A Tabletop Demonstration," *Fusion Science & Technology* **52**(3), Oct. 2007, 478-482.

4. Ron Petzoldt, Neil Alexander, Lane Carlson, Graham Flint, Dan Goodin, Jon Spalding, Mark Tillack, "A Continuous, In-Chamber Target Tracking and Engagement Approach for Laser Fusion," *Fusion Science and Technology* **52**(3), October 2007, 454-458.

5. J. D. Spalding, L. C. Carlson, M. S. Tillack, N. B. Alexander, D. T. Goodin and R. W. Petzoldt, "Longitudinal Tracking of Direct Drive Inertial Fusion Targets," *Fusion Science and Technology* **52**(3), October 2007, 435-439.

6. L. C. Carlson, M. S. Tillack, T. Lorentz, N. B. Alexander, G. W. Flint, D. T. Goodin and R. W. Petzoldt, "Glint system integration into an IFE target tracking and engagement demonstration," Inertial Fusion Science and Applications 2007, Journal of Physics: Conference Series **112** (2008) 032039.

B. Chamber Design Studies

1. A. R. Raffray, A. E. Robson, J. Sethian, C. Gentile, E. Marriott, D. Rose, M. Sawan and the HAPL Team, "Laser IFE Direct Drive Chamber Concepts with Magnetic Intervention," *Fusion Science and Technology* **56** (1), 333-340, July 2009.

2. J. P. Blanchard and R. Raffray "Laser Fusion Chamber Design," *Fusion Science & Technology*, **52** (3), 440-444, October 2007.

3. M. E. Sawan, C. S. Aplin, G. Sviatoslavsky, I. N. Sviatoslavsky and A. R. Raffray, "Neutronics Analysis of a Self-Cooled Blanket for a Laser Fusion Plant with Magnetic Intervention," *Fusion Science & Technology*, **52** (4), 771-775, November 2007.

4. A. R. Raffray, A. E. Robson, M. E. Sawan, G. Sviatoslavsky, I. N. Sviatoslavsky and X. Wang, "A Self-Cooled Liquid Breeder Blanket for a Laser IFE Power Plant with Magnetic Intervention," *Fusion Science & Technology*, **52** (3), 603-608, October 2007.

5. R. Raffray, W. Meier, S. Abdel-Khalik, R. Bonazza, P. Calderoni, C. S. Debonnel, Z. Dragojlovic, L. El-Guebaly, D. Haynes, J. Latkowski, C. Olson, P. Peterson, S. Reyes, P. Sharpe, M. S. Tillack and M. Zaghloul, "IFE Thick Liquid Wall Chamber Dynamics: Governing Mechanisms and Modeling and Experimental Capabilities," *Fusion Science and Technology* **49** January 2006.

6. A. R. Raffray, J. Blanchard, J. Latkowski, F. Najmabadi, T. Renk, J. Sethian, S. Sharafat, L. Snead and the HAPL Team, "Progress Towards Realization of a Laser IFE Solid Wall Chamber," *Fusion Engineering & Design* 81, 1627-1638 (February 2006).

7. J. D. Sethian, A. R. Raffray, J. Latkowski, J. P. Blanchard, L. Snead, T. J. Renk and S. Sharafat, "An Overview of the Development of the First Wall and Other Principal Components of a Laser Fusion Power Plant," *Journal of Nuclear Materials*, **347** (3), 161-177, December 2005.