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Final Technical Report for the SNL/Rochester ALPHA Follow-on Project

Award:	DE-FOA-0001184
Lead Recipient:	Sandia National Laboratories and University of Rochester
Project Title:	Assess and Benchmark Magneto-Inertial Fusion (MIF) Scaling
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Public Executive Summary

This project was a follow-on to the Sandia National Laboratories (SNL) and the Laboratory for Laser Energetics (LLE) ARPA-E ALPHA project entitled “Demonstrating Fuel Magnetization and Laser Heating Tools for Low-Cost Fusion Energy”. The primary purpose of this follow-on project was to obtain additional data at the OMEGA facility to help better understand how MagLIF, a platform that has already demonstrated the scientific viability of magneto-inertial fusion, scales across a factor of 1000 in driver energy. A secondary aspect of this project was to extend simulations and analysis at SNL to cover a wider magneto-inertial fusion (MIF) parameter space and test scaling of those models across this wide range of input energies and conditions of the target. This work was successful in improving understanding of how key physics elements of MIF scales and improves confidence in setting requirements for fusion gain with larger drivers.

The OMEGA experiments at the smaller scale verified the hypothesis that preheating the fuel plays a significant role in introducing wall contaminants that mix into the fuel and significantly degrade fusion performance. This contamination not only impacts target performance but the optimal input conditions for the target. However, analysis at the Z-scale showed that target performance at high preheat levels is limited by the Nernst effect, which advects magnetic flux from the hot spot, reducing magnetic insulation and consequently reduces the temperature of the fuel. The combination of MagLIF experiments at the disparate scales of OMEGA and Z along with a multi-scale 3D simulation analysis has led to new insight into the physical mechanisms responsible for limiting target performance and provides important benchmarks to assess target scaling more generally for MIF schemes. Finally, in addition to the MagLIF related work, a semi-analytic model of liner driven Field Reversed Configuration (FRC) was developed that predicts the fusion gain for such systems. This model was also validated with 2D radiation magneto-hydrodynamic simulations and predicts that fusion gains of near unity could be driven by the Z machine.

Acknowledgements

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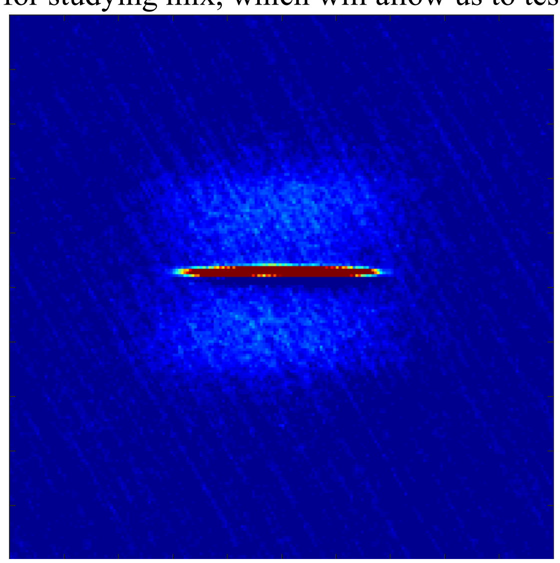
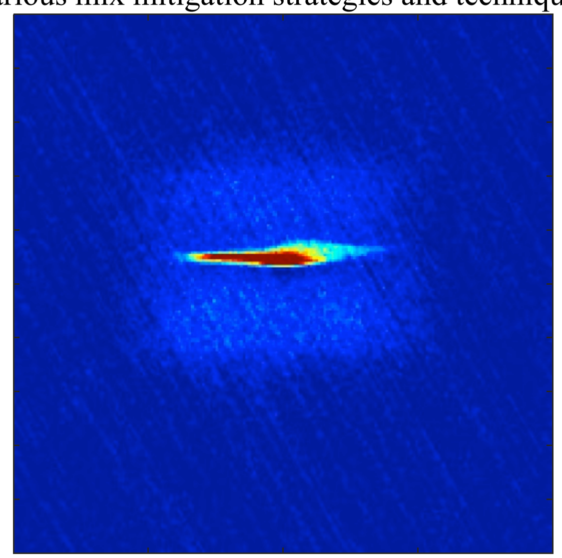
Accomplishments and Objectives

This award allowed LLE and SNL to demonstrate a number of key objectives. The main focus of the project was to obtain additional data on the mini-MagLIF platform in order address a hypothesis to describe descrepancies in predicted performance and optimal preheat energy in previous OMEGA experiments funded by ARPA-E and improve understanding of MIF scaling in general. To this end, an experimental campaign was conducted on the OMEGA laser facility in early November 2020. These experiments utilized the mini-MagLIF experimental platform, which can preheat and magnetize an imploding cylinder scaled to a tenth the linear size of MagLIF targets at Sandia. This campaign focused on diagnosing and determining the cause of mix in the miniaturized MagLIF implosion. The interior wall of the cylindrical targets were coated with 100-200 nm of titanium to act as a dopant layer. Images captured by x-ray pinhole cameras and a Fresnel Zone plate tuned to titanium He-α provide strong indication that scaled MagLIF implosion performance is significantly affected by mix from the inner wall layer caused by the preheat beam.

Shots performed with the Ti layer but without preheat produced DD yields of $Y_{DD} = (4\pm2) \times 10^8$ neutrons, a quarter of the yield for comparable shots without the Ti layer ($Y_{DD} \sim 16 \times 10^8$). 3D HYDRA simulations, without mix, predicted only a 15% reduction in yield due to the Ti layer. These shots appeared to have nominal implosions from all x-ray imaging (left). However, when preheat was introduced the yield plunged to barely detectable levels ($Y_{DD} < 10^8$). This is the opposite effect on comparable implosions without the Ti layer with the preheat beam, which have yields 50 times higher. Implosion quality noticeably degraded, with greater deviations occurring on the preheat entry side of the target (right). These experiments confirm the hypothesis developed to explain the results of previous experiments: the preheated gas expands the inner wall of the cylinder inducing mix. This effect becomes more pronounced with increased preheat energy, which explains why previous experiments showed yield degradation at high preheat levels. This also demonstrates the capability of this experimental setup as a platform for studying mix, which will allow us to test various mix mitigation strategies and techniques.





On Z, the magneto-Rayleigh-Taylor instability (MRTI) substantially influences target performance. Experimental observables are generally matched quite well with simulations although the MRTI complicates interpretations of the influence of initial magnetic field or laser preheat variations. This fact coupled with the lower shot rate available at Z, makes the OMEGA experiments particularly useful in benchmarking models and assessing scaling. Three-dimensional HYDRA simulations of MagLIF on Z and OMEGA were completed using the same integrated workflow and model which allows for a more direct comparison of the physics scaling. It was found that target performance is limited by different physical effects at Omega and Z scales.

At Z, 3D HYDRA simulations showed that target performance at high preheat levels is limited by the Nernst effect, which advects flux from the hot spot, reducing magnetic insulation. While HYDRA cannot directly or self-consistently model the generation of atomic mix in the mini-MagLIF experiments, mechanisms that could be responsible for enhancing mix as well as the effects of that atomic mix on target performance can be modeled. Detailed analysis of 3D simulations of the OMEGA targets were found to support hypothesis that performance degradation is not dominated by Nernst, but rather enhanced mix as a result of laser preheat at the mini-MagLIF scale. Thermal conduction from the heated gas into the walls is greatly increased at small scale, which is a possible explanation for the observed effect. These simulations suggest an increase to the liner radius could help mitigate these effects, along with anti-mix layers. Such changes would ideally make the target more sensitive to the Nernst effect.

The other aspect of this project was to provide detailed science-based scaling to a broader class of magneto-inertial fusion (MIF) concepts. One key difference between MagLIF and other MIF concepts is that the field lines are not closed, and the plasma is not confined by the magnetic field. As an example, it has been proposed to use imploding liners to compress Field Reversed Configurations (FRCs), which are plasmas confined by closed magnetic field lines. Note that FRCs, which were originally developed as magnetic confinement fusion systems, can be self-sustaining for tens of microseconds, which would allow time for compression by either a metal liner or plasma jets. While significant efforts have gone into studying FRCs themselves, very little detailed work has been done to investigate scaling of this configuration and requirements for realistic fusion gains. For this project, we developed an semi-analytic model of liner compression of FRCs that determines what fusion gains could be expected. Results indicate that fusion gains of near unity could be achieved at Z.

A number of tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized here:

Table 1. Key Milestones and Deliverables.

Tasks	Milestones and Deliverables
Task 1: OMEGA Shot Day 1.1 Go/No-Go: Refine tasks and milestones (if applicable)	Milestone: refine tasks and milestones for the work plan (if applicable) Actual Performance: (Summer 2019) All tasks defined for meeting experimental goals with the mini-MagLIF platform on OMEGA

1.2 Go/No-Go: Doped shells for mix measurements 1.3 OMEGA shot day	Milestone: manufacture parylene-N shells for laser-driven MagLIF experiments on OMEGA with a doped layer, possibly Ti or Cl, to provide a tracer for shell-fuel mix Actual Performance: (10/27/2020) All target fabrication was completed successfully and within specification. In addition to COVID-19 delays, some delays were experienced in achieving this milestone due to the loss of key personnel with specialized expertise. We also have some unanticipated issues with the Ti coatings cracking on the inside of the target, but these were ultimately resolved. Milestone: Execute a shot day on OMEGA to obtain a preliminary shell-fuel mix measurement and to complete preheat and magnetic field scans Actual Performance: (11/3/2020) A series of mini-MagLIF experiments on OMEGA were performed on November 3, 2020. These experiments utilized a Fresnel Zone Plate monoenergetic imager in conjunction with a titanium dopant layer to assess mix in the mini-MagLIF implosions. Previous experiments found that low preheat levels were optimal for increased yield and temperature, while higher preheat levels caused significant yield degradation that was not anticipated in simulations. Analysis of these experiments showed that preheat is responsible for inducing enhanced mix, not captured in the pre-shot simulations, from the inner shell wall into the fuel.
Task 2: Simulations at SNL 2.1 FRC Scaling Study 2.2 Integrated MIF Implosion Model	Milestone: develop an analytic model for liner compression of Field Reversed Coil (FRC) configurations to study optimal implosion time and magnetic field strength parameter space. Determine what fusion gains can be realistically expected. Benchmark model against a high fidelity LASNEX simulation model. Actual Performance: (8/4/2020) An analytic model for FRC implosions was developed to assess the scaling of target gain across a wide range of parameters and input conditions.

	This model was also benchmarked to 2D Lasnex simulations. Milestone: develop a unified, high fidelity 2D/3D multi-scale HYDRA simulation model that can be used to model both Z and OMEGA MagLIF experiments. Evaluate how well that model can match experimental observables across a 1000x difference in driver energy and report on consistencies and/or any potential deficiencies that arise.
Task 3: Tech Transfer 3.1 Presentations 3.2 Publications	Milestone: finalize a presentation of the results to be shown at the 2020 Annual Meeting of the American Physical Society Division of Plasma Physics. Actual Performance: (11/9-13/2020) Two presentations were given that were specific to this project: 1) JP18.00009 : Fusion from liner driven implosions of Field Reversed Configurations 2) CO09.00009 : Simulations of Laser Preheat Effects on Yield in mini-MagLIF Implosions at Omega Due to delays associated with COVID-19, some of the results of this work had not been fully analyzed or thoroughly peer reviewed in time for the 2020 American Physical Society Division of Plasma Physics meeting. Those results will be presented at the 2021 meeting. Milestone: manuscript submitted to Physical Review Letters, Physics of Plasmas or similar journal. Actual Performance: (1/21/2021) Publication entitled, "Fusion gain from cylindrical liner-driven implosions of field reversed configurations" was submitted in January of 2021 and published online in April on 2021 [S. A. Slutz and M. R. Gomez, Phys. Plasmas 28, 042707 (2021)]. Several additional publications on this work are also planned.

Project Activities

The primary goal of this work was to assess and benchmark magneto-inertial fusion (MIF) scaling and physical mechanisms limiting target performance in the context of MagLIF across a factor of 1000 in driver energy. The large difference in driver energy between the Z experiments at Sandia and the laser-driven experiments at OMEGA provides a unique opportunity to develop and test model predictions across a wide range of input energies and conditions in the target. This is critical in order to demonstrate understanding of key physics elements of how MIF concepts scale and to develop confidence in setting requirements for fusion gain with larger drivers. This project conducted a series of mini-MagLIF experiments at the OMEGA facility to examine the mixing of liner wall material into the fuel and assess descrepancies in predicted yield and optimal preheat conditions found in previous ARPA-E ALPHA supported experiments. These experiments verified the hypothesis that preheating the fuel plays a significant role in introducing wall contaminants that mix into the fuel and significantly degrade fusion performance. As part of this project, a single integrated 3D HYDRA model that was capable of simulation across this wide difference in driver energy was developed to explain these results. This model showed that at the Z scale target performance at high preheat levels is limited by the Nernst effect resulting in reduced magnetic insulation. It also showed that laser fillamention and the smaller physical scale size of the mini-MagLIF targets at OMEGA could explain the enhanced mix as a result of preheat at that scale.

Finally, a semi-analytical model of liner driven Field Reversed Configurations (FRCs) that predicts the fusion gain of such systems was developed. It was also found that an FRCs could be formed and imploded at Sandia's Z facility using the AutoMag liner concept [S. A. Slutz et al., Phys. Plasmas 24, 012704 (2017)]. With this model, it is predicted that a fusion gain of near unity could be achieved on the Z machine. 2D Radiation MHD simulations of the formation and implosion of an FRC were also completed and found to be in good agreement with the analytical model [S. A. Slutz and M. R. Gomez, Phys. Plasmas 28, 042707 (2021)].

While all project goals were met, COVID-19 did have a significant impact on the project timelines and schedule. Several extentions were granted after negotiations with ARPA-E project directors.

Project Outputs

A. Journal Articles

[1] S. A. Slutz and M. R. Gomez, Phys. Plasmas 28, 042707 (2021).

B. Papers

All papers were reported under journal articles.

C. Status Reports

Quarterly status reports were submitted to the program manager.

D. Media Reports

None

E. Invention Disclosures

None

F. Patent Applications

None

G. Licensed Technologies

None

H. Networks/Collaborations Fostered

N/A

I. Websites Featuring Project Work Results

None

J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

None

K. Awards, Prizes, and Recognition

None

Follow-On Funding

Additional funding committed or received from other sources (e.g. private investors, government agencies, nonprofits) after effective date of ARPA-E Award.

Table 2. Follow-On Funding Received.

- NNSA will continue to fund aspects of this research that are not specifically related to fusion energy applications.