Demonstrating Fuel Magnetization and Laser Heating Tools for Low-Cost Fusion Energy

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This project is a collaboration between Sandia and the University of Rochester

- **Sandia National Laboratories, Albuquerque, NM**
  - Daniel Sinars, Senior Manager, Radiation & Fusion Physics Group
  - Kyle Peterson*, Manager, ICF Target Design Department
  - John Porter, Manager, Laser Operations & Engineering
  - Matthias Geissel, Principal Member of Technical Staff
  - Adam Harvey-Thompson, Research Scientist
  - Stephen Slutz*, Distinguished Member of Technical Staff
  - Matt Weis, Senior Member of Technical Staff

- **University of Rochester, Rochester, NY**
  - Jonathan Davies*, Research Scientist
  - Dan Barnak, Graduate Student
  - Riccardo Betti*, Professor of Mechanical Engineering
  - Mike Campbell*, LLE Deputy Director
  - Sean Regan, Experimental Group Leader
  - Vladimir Glebov, Research Scientist
  - Jim Knauer, Research Scientist

* In attendance today
This project is centered around the Magnetized Liner Inertial Fusion (MagLIF) target design for Z

- **Axial magnetization of fuel/liner** ($B_{z0} = 10-30$ T)
  - Inhibits thermal conduction losses and traps alphas ($\beta: 5 \sim 80; \omega\tau > 200$ at stagnation)

- **Laser heating of fuel** (2 kJ initially, 6-10 kJ planned)
  - Reduces radial fuel compression needed to reach fusion temperatures ($R_0/R_f$ about 25, $T_0 = 150-200$ eV)

- **Liner compression of fuel** (70-100 km/s, $\sim 100$ ns)
  - Low velocity allows use of thick liners ($R/\Delta R \sim 6$) that are robust to instabilities and have sufficient $\rho R$ at stagnation for inertial confinement

- $\tau \sim 1-2$ns, $\sim 100x$ lower fuel pressure than traditional ICF ($\sim 5$ Gbar vs. 500 Gbar)

**Goal is to demonstrate scaling:** $Y (B_{z0}, E_{laser}, I)$

DD equivalent of 100 kJ DT yield possible on Z

This project is using existing capabilities at both institutions to demonstrate magneto-inertial fusion scaling

<table>
<thead>
<tr>
<th>Sandia National Laboratories</th>
<th>Laboratory for Laser Energetics</th>
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</thead>
<tbody>
<tr>
<td>80-TW, 20 MJ Z pulsed power facility</td>
<td>60-beam, 30-TW, 30 kJ, OMEGA laser facility</td>
</tr>
<tr>
<td>1-TW, multi-kJ Z-Backlighter laser facility</td>
<td>4-beam, TW to PW, multi-kJ OMEGA-EP laser facility</td>
</tr>
<tr>
<td>10 T B-field system</td>
<td>10 T B-field systems</td>
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</table>

* All facilities are multi-user, multi-program facilities funded by the NNSA
We are working to demonstrate magneto-inertial fusion in relatively high-density, short-duration plasmas, and study the scaling of magneto-inertial fusion using modeling

- **Target pre-conditioning experiments**
  - Utilize Omega, Omega-EP, Z, Z-Backlighter (PECOS) to understand initial conditions and validate simulation codes
  - Determine a set of conditions needed to achieve functional fuel pre-conditioning (i.e., laser and magnetic field configurations)

- **Laser-driven MagLIF experiments on OMEGA**
  - Develop a platform to predict and scale the performance of magneto-inertial fusion targets over a wide range of size, time scale, and available energy (e.g., ~10 kJ to ~1 MJ absorbed)

- **Numerical Modeling & Theory**
  - Improve & refine simulation models using data collected
  - Examine not only MagLIF scaling, but also the general MIF parameter space over a broad range configurations using validated simulations

- **Tech transfer & Outreach activities**
OMEGA-EP experiments are providing key data at $3\omega$ that cannot be obtained with ZBL

- Effect of B field (underway)
- Effect of pre-pulse (complete)
- Effect of laser intensity (complete)
- Window mix (next year)
- $2\omega$ vs $3\omega$ surrogacy (next year)
- LPI (underway)

Harvey-Thompson et al., Recently submitted for publication
Recent preconditioning experiments have provided key data for the development of a new preheat platform.

**Optical Blastwave Measurements**

- **Original MagLiF Configuration**
  - 2 ns pulse
  - No DPP

- **4 ns pulse**
  - 750 micron DPP

**Key Accomplishments**

- Dramatically Improved Transmission
- Determined pre-pulse requirements
- Dramatically reduced LPI
- New Diagnostics & Capabilities

**LEH Window Transmission**

- 54psi He, 250J/1350J
MagLIF scaling study is complete for AR6 targets over a wide range of current and time scales*

A broad study of the MIF parameter space is now underway. Results will be reported soon.

* ~100ns results shown here
Laser-driven MagLIF on OMEGA is providing scaling data over a factor of 1000 in energy and more shots with more diagnostics than Z.

<table>
<thead>
<tr>
<th></th>
<th>$r$ (mm)</th>
<th>$\Delta r$ (mm)</th>
<th>$r/\Delta r$</th>
<th>$\rho_{\text{fuel}}$ (mg/cm$^3$)</th>
<th>$B_0$ (T)</th>
<th>$T_0$ (eV)</th>
<th>$V_{\text{imp}}$ (km/s)</th>
<th>Convergence ratio</th>
<th>$T_{\text{max}}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>3.48</td>
<td>0.58</td>
<td>6</td>
<td>3 (DT)</td>
<td>30</td>
<td>250</td>
<td>70</td>
<td>25</td>
<td>8.0</td>
</tr>
<tr>
<td>OMEGA</td>
<td>0.30</td>
<td>0.03</td>
<td>10</td>
<td>2.4 (D$_2$)</td>
<td>10</td>
<td>200</td>
<td>154</td>
<td>26</td>
<td>2.9</td>
</tr>
</tbody>
</table>

** MIFEDS: magneto-inertial fusion electrical discharge system
The objective of laser preheating of D$_2$ gas to > 100 eV was demonstrated in preliminary OMEGA experiments.

Total laser backscatter < 1% with no backscatter from the gas.

Time-resolved soft x-ray spectrometer shows window, gas and wall emission.

Streaked optical emission shows uniform heating along length of interest.

3-channel soft x-ray framing camera shows gas temperature > 100eV.
A nine shot day program (> 100 shots) was drawn up for the ALPHA program

1. Optimize ring 3 – ring 4 energy balance without preheat (1 Sept 15)
2. Optimize ring 3 – ring 4 energy balance and reduce shell thickness without preheat (24 Nov 15)
3. Optimize preheat timing and vary preheat energy (19 July 16)
4. Complete B/no-B and preheat level data set (22 Sept 16)
5. B-field 1: measure axial B-field evolution using D³He protons with H₂ fill to avoid proton production from target and with preheat (8 Nov 16)
6. B-field 2: use EP if D³He unsuccessful or extend data set (7 Feb 17)
7. B-field scan: include a higher value if possible with 2 MIFEDS and/or transformer coil (under development) with preheat (16 May 17)
8. Fill density and shell thickness scans with B and preheat (1 Aug 17)
9. Contingency: fill in missing data, address unforeseen issues or extend data set
The first two shots days have been successfully executed

1. Optimize ring 3 – ring 4 energy balance without preheat (1 Sept 15)
2. Optimize ring 3 – ring 4 energy balance and reduce shell thickness without preheat (24 Nov 15)
3. Optimize preheat timing and vary preheat energy (19 July 16)
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The objectives of uniform compression over 0.6 mm at a velocity of 150 km/s have been demonstrated.

**X-ray framing camera data**

- 0.05 ns temporal resolution
- Shell thickness: 20 μm
- D$_2$ density: 1.80 mg/cc
- Laser energy: 13.0 kJ
- Pulse length: 2.0 ns
- Neutron yield: 2.53 x 10$^7$
- No B, no preheat
The 3rd shot day was not executed as planned because the lens for the preheating beam was not delivered

1. Optimize ring 3 – ring 4 energy balance without preheat (1 Sept 15) ✓
2. Optimize ring 3 – ring 4 energy balance and reduce shell thickness without preheat (24 Nov 15) ✓
3. Optimize preheat timing and vary preheat energy (19 July 16)
4. Complete B/no-B and preheat level data set (22 Sept 16)
5. B-field 1: measure axial B-field evolution using D³He protons with H₂ fill to avoid proton production from target and with preheat (8 Nov 16)
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9. Contingency: fill in missing data, address unforeseen issues or extend data set
The shot day was used to obtain additional neutron data without preheat and without magnetic field

1. Optimize ring 3 – ring 4 energy balance without preheat (1 Sept 15) ✓
2. Optimize ring 3 – ring 4 energy balance and reduce shell thickness without preheat (24 Nov 15) ✓
3. Obtain neutron data without preheat and without B (19 July 16)
4. Complete B/no-B and preheat level data set (22 Sept 16)
5. B-field 1: measure axial B-field evolution using D³He protons with H₂ fill to avoid proton production from target and with preheat (8 Nov 16)
6. B-field 2: use EP if D³He unsuccessful or extend data set (7 Feb 17)
7. B-field scan: include a higher value if possible with 2 MIFEDS and/or transformer coil (under development) with preheat (16 May 17)
8. Fill density and shell thickness scans with B and preheat (1 Aug 17)
9. Contingency: fill in missing data, address unforeseen issues or extend data set
A new neutron time of flight diagnostic allowed neutron averaged ion temperatures to be determined at neutron yields $\geq 10^7$

<table>
<thead>
<tr>
<th>Shell thick. ($\alpha$m)</th>
<th>$D_2$ density (mg/cc)</th>
<th>Laser energy (kJ)</th>
<th>Pulse length (ns)</th>
<th>Neutron yield ($10^5$)</th>
<th>2D HYDRA</th>
<th>N. avg. $T_{ion}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>1.82</td>
<td>10.4</td>
<td>2.5</td>
<td>3.2</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>30</td>
<td>1.80</td>
<td>14.3</td>
<td>2.0</td>
<td>58.6</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>20</td>
<td>1.80</td>
<td>13.1</td>
<td>2.0</td>
<td>159.0</td>
<td>NA</td>
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<tr>
<td>30</td>
<td>1.58</td>
<td>14.7</td>
<td>1.5</td>
<td>527.0</td>
<td>1216</td>
<td>1.24</td>
</tr>
<tr>
<td>20</td>
<td>1.94</td>
<td>14.9</td>
<td>1.5</td>
<td>5610.0</td>
<td>8604</td>
<td>2.48</td>
</tr>
</tbody>
</table>
An extra shot day has been scheduled to carry out the first integrated shots with magnetization and preheat

1. Optimize ring 3 – ring 4 energy balance without preheat (1 Sept 15) ✓
2. Optimize ring 3 – ring 4 energy balance and reduce shell thickness without preheat (24 Nov 15) ✓
3. Obtain neutron data without preheat and without B (19 July 16)
3b. Optimize preheat timing and vary preheat energy (25 Aug 16)
4. Complete B/no-B and preheat level data set (22 Sept 16)
5. B-field 1: measure axial B-field evolution using D³He protons with H₂ fill to avoid proton production from target and with preheat (8 Nov 16)
6. B-field 2: use EP if D³He unsuccessful or extend data set (7 Feb 17)
7. B-field scan: include a higher value if possible with 2 MIFEDS and/or transformer coil (under development) with preheat (16 May 17)
8. Fill density and shell thickness scans with B and preheat (1 Aug 17)
9. Contingency: fill in missing data, address unforeseen issues or extend data set
A 3 beam not required for compression will be available from P9 by Aug 25 using either a new lens or a new lens mount for a standard OMEGA lens.

Mirror hardening shots up to full energy have been performed.
The OMEGA and Z experiments are being modeled with a number of MHD codes in 1, 2 and 3D.

- **2D HYDRA**
  - SNL
  - Integrated shot

- **2D DRACO**
  - LLE
  - Preheat shot
Laser-driven MagLIF on OMEGA is providing scaling data over a factor of 1000 in energy and more shots with more diagnostics than Z

- The same codes are being used to model OMEGA and Z experiments
- Laser preheating and implosion have been successfully tested independently
- ALPHA funds have been important in providing an optimal preheating capability on OMEGA for these experiments
- The first integrated laser-driven MagLIF experiment will be carried out on 25 Aug 2016
Questions?
ZBL/PECOS Upgrades

- Magnetic field system has been developed for PECOS chamber (up to 5 T)
- Near back & forward scatter imaging (SBS) capability complete on PECOS
- New distributed phase plates installed for PECOS
- New pressure test stand for PECOS targets is complete (60 psi, He)
- New targets that provide much better surrogacy to Z experiments
- Significant Improvements in ZBL shot rate
We are making good progress in developing an in-situ Te measurement for Z

- Important for understanding preheat conditions in a MagLIF implosion & validating simulation models
- First time resolved axial pinhole camera images of laser only experiments on Z have been obtained
- Development happening concurrently on PECOS & Z

Filtered soft x-ray diodes

ZBL

H33

Furi (frame 1)

Furi (frame 2)

Furi exp. (mV)

0

150

300

7.5 degree viewing angle

gas cell target
The Z-Beamlet laser at Sandia* is being used to radiograph liner targets and heat fusion fuel

Z-Beamlet (ZBL) is routinely used to deliver ~ 2.4 kJ of $2\omega$ light in 2 pulses for backlighting experiments on Z

In 2014 we added bandwidth to the laser; can now deliver ~4.5 kJ of $2\omega$ in a 4 ns pulse.

It should be possible to reach 6-10 kJ of laser energy (e.g., as on the NIF)

An advantage of laser heating is that it can be studied and optimized without using Z

Typical MagLIF initial fuel densities correspond to 0.10 to 0.30 x critical density for $2\omega$

Our major milestones focus on demonstrating magneto-inertial fusion scaling experimentally and using modeling

- **Target pre-conditioning experiments (Z, ZBL, OMEGA, OMEGA-EP)**
  - Demonstrate a set of functional laser pre-heating parameters (laser pulse shape, focal spot size, window thickness) to provide > 1 kJ of laser heating to the fusion fuel in an integrated MagLIF shot on Z
  - Determine the time-dependent Te history in a Z MagLIF experiment

- **Laser-driven MagLIF experiments (OMEGA)**
  - Confirm >100 eV and low-mix preheat
  - Symmetrically implode cylindrical target containing preheated fuel with > 1 kJ/cm of kinetic energy
  - Demonstrate > 30% increase in Te (as compared to unmagnetized target) in axially symmetric target compression over > 0.6 mm length

- **Numerical Modeling & Theory (Sandia, U. Rochester)**
  - Results from integrated OMEGA experiments agree with Flash and Hydra to within 20% of hydrodynamic variables and a factor of two in neutron yield
  - Report on key dependencies across the MIF parameter space for generalized scaling laws, and highlight most promising regimes; analysis to include both near-term and long-term fusion power cases