Status of the Magnetized Liner Inertial Fusion Research Program in the United States

Daniel Sinars

Senior Manager, Radiation and Fusion Physics Group
Sandia National Laboratories

Fusion Power Associates Meeting
Washington, D.C.
December 16-17, 2015
The U.S. ICF Program is pursuing three main approaches to fusion ignition to manage the scientific risk.

<table>
<thead>
<tr>
<th>Laser x-ray drive</th>
<th>Laser direct drive</th>
<th>Magnetic direct drive</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="Image1" alt="Image" /></td>
<td><img src="Image2" alt="Image" /></td>
<td><img src="Image3" alt="Image" /></td>
</tr>
<tr>
<td>192 beams, 1.8 MJ, 400 TW</td>
<td>60 beams, 30 kJ, 20 TW</td>
<td>26 MA, 80 TW</td>
</tr>
<tr>
<td><img src="Image4" alt="Image" /></td>
<td><img src="Image5" alt="Image" /></td>
<td><img src="Image6" alt="Image" /></td>
</tr>
</tbody>
</table>
Magnetic direct drive is based on efficient use of large currents to create high pressures

Z today couples ~0.5 MJ out of 20 MJ stored to magnetized liner inertial fusion (MagLIF) target (0.1 MJ in DD fuel).

Magnetically Driven Implosion

\[ P = \frac{B^2}{8\pi} = 105 \left( \frac{I_{MA}/26}{R_{mm}} \right)^2 \] MBar

100 MBar at 26 MA and 1 mm
Magnetized Liner Inertial Fusion (MagLIF) relies on fuel preheat and magnetization to achieve fusion.

- Axial Magnetic Field (10 T initially; 30 T available)
  - Inhibits thermal losses from fuel to liner
  - May help stabilize liner during compression
  - Fusion products magnetized

- Laser heated fuel (2 kJ initially; 6-10 kJ planned)
  - Initial average fuel temperature 150-200 eV
  - Reduces compression requirements ($R_0/R_f \approx 25$)
  - Coupling of laser to plasma in an important science issue

- Magnetic compression of fuel (~100 kJ into fuel)
  - ~70-100 km/s, quasi-adiabatic fuel compression
  - Low Aspect liners ($R/\Delta R \approx 6$) are robust to hydrodynamic (MRT) instabilities
  - Significantly lower pressure/density

Goal is to demonstrate scaling: $Y (B_{z0}, E_{laser}, I)$
DD equivalent of 100 kJ DT yield possible on Z

Experiments have demonstrated thermal fusion with $>10^{12}$ 2.45 MeV neutrons from a $\sim 70$ km/s, 1.5 mg/cm$^2$ implosion

- The initial MagLIF experiments demonstrated that there is merit to the idea of magneto-inertial fusion
- Laser heating of a magnetized initial plasma with minimal high-Z mix is critical
  - Initial experiments used “unconditioned” beams and thick (>3 µm) foils and deposition into the gas was lower than expected
  - Low energy deposition and mix is borne out by several different experiments on multiple facilities
- Research over the next five years at Z, Omega, Omega-EP, and the NIF will address:
  - The physics of laser preheat
  - Implosion and stagnated fuel performance
  - Exploring fusion performance and scaling as a function of laser preheat, initial B field, and drive
- Present modeling predicts fusion yields of $\sim 100$ kJ (DT) are possible on Z
We are taking a careful look at all stages of the target using multiple facilities and diagnostics.

**Laser Heating**
- $E_{\text{laser}} \sim 2-6 \text{ kJ @ .53\(\mu\)m}$
- $T_{\text{DT}} \sim 0.2 \text{ KeV}$
- $\omega \tau \sim 2-5$
- Research on Z, ZBL, Omega, Omega-EP

**Initial Conditions**
- $\rho_{\text{DT}} \sim 1-4 \text{ mg/cc}$
- $B_{z0} \sim 10-30 \text{ T (~0.1 MG)}$

**Implosion/stagnation**
- $V_{\text{imp}} \sim 70-100 \text{ km/sec}$
- $P_{\text{DT}} \sim 5 \text{ Gbar}$
- $T_{\text{ion}} > 5 \text{ keV}$
- $\omega \tau \sim 200 \text{ (B~100 MG)}$
- Research on Z, Omega
Magnetization ($BR$) can be used to reduce $\rho R$ requirements and reduce electron heat losses, lower density also reduces bremsstrahlung radiation losses

- Initial 10-30 T field greatly amplified during the implosion through flux compression
- Too much field is inefficient—want to stagnate on plasma pressure, not magnetic pressure

![Graphs showing $\rho R$ and $BR$ relationships](image)

\[
\frac{R}{r_{\alpha}} \approx 4BR \ [MG \cdot cm]
\]

- Fraction of trapped tritons (or $\alpha$’s) a function of $BR$
- Effects saturate at $BR > 0.6 $ MG-cm
- Measurements to date suggest $BR$ of 0.4 MG-cm
- Focused experiments have demonstrated flux compression w/ $B>1000$ T

Heating the fuel prior to compression can lower traditional ICF requirements on velocity and fuel convergence.

\[ \text{CR}_{10} = \text{Convergence Ratio } \left( \frac{R_0}{R_f} \right) \text{ needed to obtain } 10 \text{ keV (ignition)} \]

- Laser heating of fuel (6-10 kJ) offers one way to reach pre-compression temperature of \( \sim 200 \text{ eV} \)
- Detailed simulations suggest we can reach fusion temperatures at convergence \( R_0/R_f \sim 25 \)
MagLIF has a very different compression methodology and stagnation parameters than traditional ICF

<table>
<thead>
<tr>
<th>Metric</th>
<th>X-ray Drive on NIF</th>
<th>100 kJ MagLIF on Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive Pressure</td>
<td>~140-160 Mbar</td>
<td>26 MA at 1 mm is 100 Mbar</td>
</tr>
<tr>
<td>Force vs. Radius</td>
<td>Goes as $R^2$ (decreasing)</td>
<td>Goes as $1/R$ (increasing)</td>
</tr>
<tr>
<td>Peak velocity</td>
<td>350-380 km/s</td>
<td>70-100 km/s</td>
</tr>
<tr>
<td>Peak IFAR</td>
<td>13-15 (high foot) to 17-20</td>
<td>8.5</td>
</tr>
<tr>
<td>Hot spot $R_0/R_f$</td>
<td>35 (high foot) to 45</td>
<td>25</td>
</tr>
<tr>
<td>Volume Change</td>
<td>43000x (high) to 91000x</td>
<td>625x</td>
</tr>
<tr>
<td>Fuel $\rho R$</td>
<td>$&gt;0.3 \text{ g/cm}^2$</td>
<td>$\sim 0.003 \text{ g/cm}^2$</td>
</tr>
<tr>
<td>Liner $\rho R$</td>
<td>n/a</td>
<td>$&gt;0.3 \text{ g/cm}^2$</td>
</tr>
<tr>
<td>BR</td>
<td>n/a</td>
<td>$&gt;0.5 \text{ MG-cm}$</td>
</tr>
<tr>
<td>Burn time</td>
<td>0.15 to 0.2 ns</td>
<td>1 to 2 ns</td>
</tr>
<tr>
<td>$T_{ion}$</td>
<td>$&gt;4 \text{ keV}$</td>
<td>$&gt;4 \text{ keV}$</td>
</tr>
</tbody>
</table>
We have spent many years testing our liner implosion modeling, and have made some interesting advances.

- Single-mode magneto-Rayleigh-Taylor growth
- Magnetized MRT growth
- Dielectric-coated Al liner implosion
- Magnetized & dielectric-coated Be ($R_0/R_f \sim 17$)
- Uncoated

High-resolution 2D modeling can capture early growth down to the ~50-micron scale.

T.J. Awe et al., accepted for PRL.
The initial experiments used 10 T, 2.5 kJ laser energy, and a ~19 MA current to drive a D₂ filled (0.7 mg/cm³) Be liner.
An ensemble of measurements from our first MagLIF experiments are consistent with a magnetized, thermonuclear plasma!

- Nuclear Activation (yield)
- Neutron spectra (Tion)
- X-ray Imaging (plasma shape)
- X-ray Power (duration)
- X-ray Spectra (Te, mix)
Lower than predicted coupling of laser energy due to un-conditoned beam (poor foil burn through)? Z data can be modeled by assuming no mix and 200-300 J in fuel

**HYDRA Simulations**

main pulse
2 ns, 2 kJ

main pulse
0.2 ns, 0.2 kJ

Simulations with 200 J match not only the yield, but other parameters measured in the experiments (temperature, shape, BR, etc.)

We are using OMEGA-EP to investigate preheat at parameters relevant to MagLIF

Target and drive parameters kept consistent with MagLIF targets:

- \( I \approx 2.5 \times 10^{14} \text{ W/cm}^2 \) (similar to 850 μm DPP smoothed ZBL pulse) – square pulse
- **Total preheat energy:** 3.1 kJ (c.f. 2.5-4 kJ for ZBL)
- **Visible target length:** 6.5 mm (c.f. 7.5-10 mm in MagLIF)
- **Thick LEH window**

Propagation in 3 gas densities tested (1st MagLIF experiments \( n_e = 0.052-0.1 \ n_c \))

- \( n_e = 0.055 \ n_c \) (10 atm pressure, 1.67 mg/cm³)
- \( n_e = 0.077 \ n_c \) (14 atm pressure, 2.34 mg/cm³)
- \( n_e = 0.10 \ n_c \) (18 atm pressure, 3.01 mg/cm³)
OMEGA-EP experiments are helping us understand when and how much we can trust our modeling

- Experiments in $D_2$ show the density ($n_e=0.1n_c$), increases LPI, affects energy deposition

- Increased LPI a result of thick LEH window disassembly – using a prepulse affects this

- For conditions where inverse Bremsstrahlung dominates, simulations can match experiments. Extrapolation to $Z$: multi-kJ heating possible

Experiments in pure Ar:

- $n_e=0.047n_c$, 1 µm thick LEH, $I\sim2.5\times10^{14}$ W/cm$^2$

- Developing thin-window cryo targets should improve target preheat, reduce LPI

Time gated emission images

Propagation in doped $D_2$

3.1 kJ delivered to targets

Distance (mm)
A design for laser-driven MagLIF on OMEGA has been developed and will be demonstrated in the next 2 years.

- Experiments in 2015 have established that we can couple the laser to the target and heat it all the way through to >100 eV.
- We have achieved cylindrical compression at the desired implosion velocity, and recent experiments have optimized the compression length over >0.7 mm.
- 1st integrated tests on OMEGA to start on June 1, 2016.

**Parylene-N Target**

- Outer diameter: 600 µm
- D₂ fill density: 1 – 2.1 mg/cc
- Shell thickness: 30 µm
- Preheat temperature: ≥ 100 eV
- Compressed length: 600 – 700 µm

**MIFEDS Coils**

- B ~ 10 T

**Fill Tube**

- Pressure transducer

**Ring 3 Only**

- 520±19 µm
- ~180 km/s (Ring 4)

**X-ray Image of Compression**
It may be possible to achieve ~100 kJ yields on Z. Achieving alpha heating and ignition may be possible on a future facility. A cryogenic DT layer could enable up to ~1 GJ yield.

An intermediate regime exists wherein the $B_z$ field is

- *strong enough* to reduce conduction losses, but
- *weak enough* not to inhibit the $\alpha$ deflagration wave

Experiments have demonstrated thermal fusion with $>10^{12}$ 2.45 MeV neutrons from a ~70 km/s, 1.5 mg/cm$^2$ implosion

- The initial MagLIF experiments demonstrated that there is merit to the idea of magneto-inertial fusion
- Laser heating of a magnetized initial plasma with minimal high-Z mix is critical
  - Initial experiments used “unconditioned” beams and thick (>3 µm) foils and deposition into the gas was lower than expected
  - Low energy deposition and mix is borne out by several different experiments on multiple facilities
- Research over the next five years at Z, Omega, Omega-EP, and the NIF will address:
  - The physics of laser preheat
  - Implosion and stagnated fuel performance
  - Exploring fusion performance and scaling as a function of laser preheat, initial B field, and drive
- Present modeling predicts fusion yields of ~100 kJ (DT) are possible on Z
We are currently exploring target designs and pulsed power architectures that may be on the path to 0.5-1 GJ yields and that also meet the needs of the science campaigns.

Yield = $E_{\text{fuel}}$?  
($\sim 100\text{kJ}_{\text{DT eq}}$)  
Physics Basis for Z300

Z
- 80 TW
- 33 Meter diameter
- 26 MA
- 22 MJ Stored Energy

Fusion Yield 0.5-1 GJ?  
Burning plasmas

Yield = $E_{\text{target}}$?  
(About 3-4 MJ)  
$\alpha$-dominated plasmas

“Z300”
- 300 TW
- 35 Meter diameter
- 47 MA
- 47 MJ Stored Energy

“Z800”
- 800 TW
- 52 Meter diameter
- 61 MA
- 130 MJ Stored Energy
We have successfully implemented 10-30 T axial fields over a several cm$^3$ volume and several ms for MagLIF

- Capacitor bank system on Z 900 kJ, 8 mF, 15 kV (Feb. 2013)
- Example MagLIF coil assembly with copper windings visible
- Cross section of coil showing Cu wire, Torlon housing, and Zylon/epoxy reinforcement

- Magnets
- Liner (~1 cm height)

Extended power feed

10 T configuration

- Time to peak field = 3.49 ms
- Allows field to diffuse through the liner without deformation

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 $2\omega$