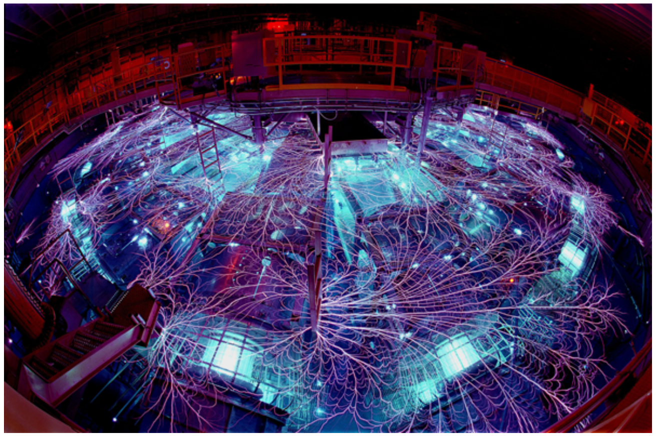
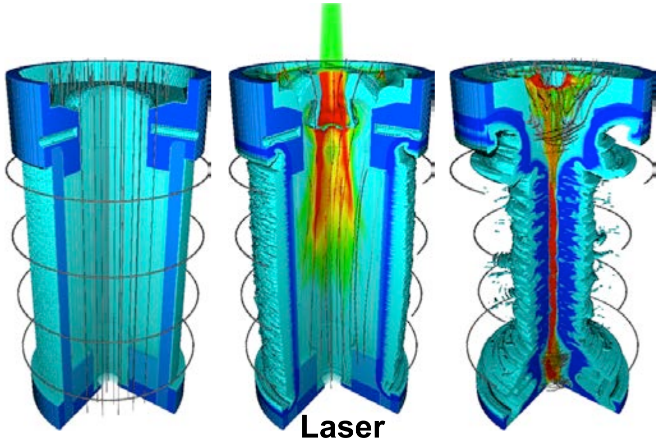
Exceptional service in the national interest

Sandia National Laboratories



Magnetized Liner Inertial Fusion (MagLIF) Research: A Promising Beginning



Daniel Sinars

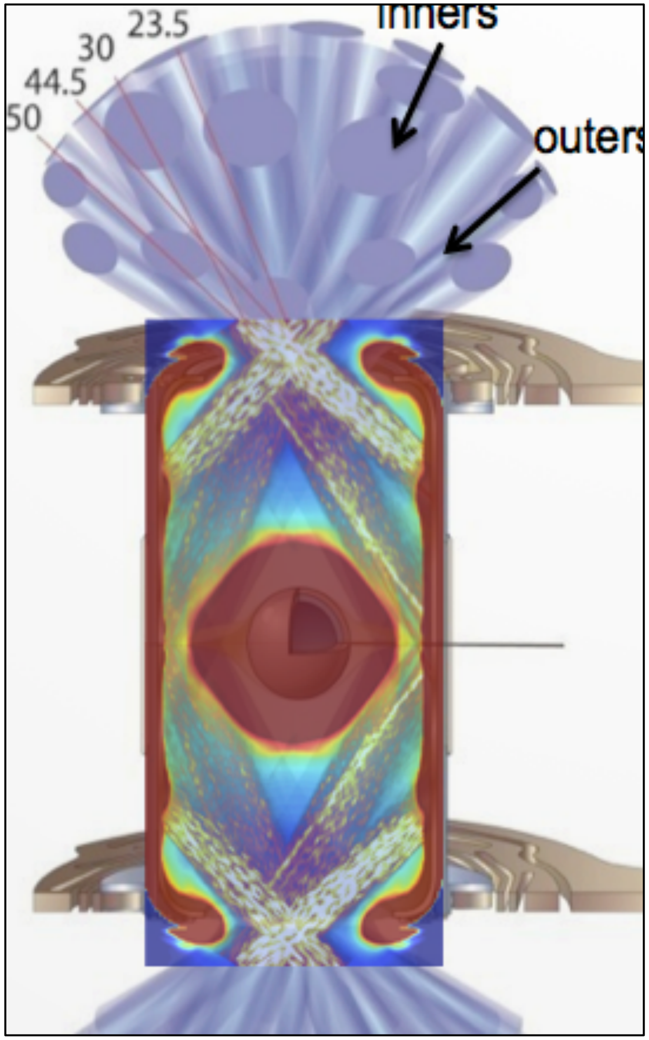
Senior Manager, Radiation and Fusion Physics Group
Sandia National Laboratories

Fusion Power Associates Meeting
Washington, D.C.
December 16-17, 2014

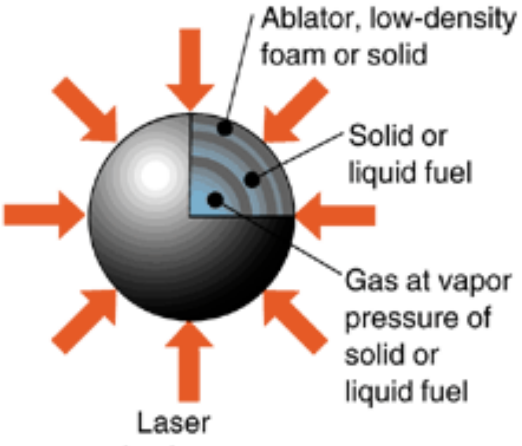
The NNSA laboratories are collectively pursuing three main approaches to ignition

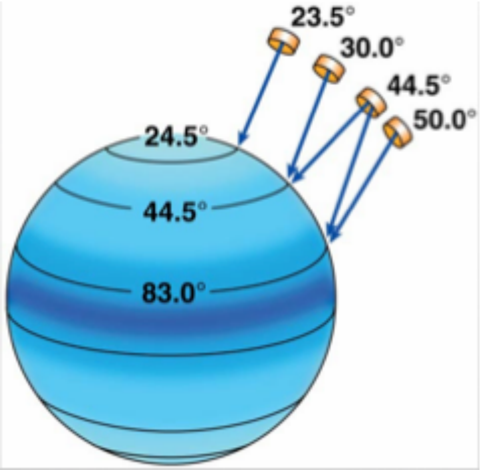
Sandia National Laboratories

Radiation-driven implosions

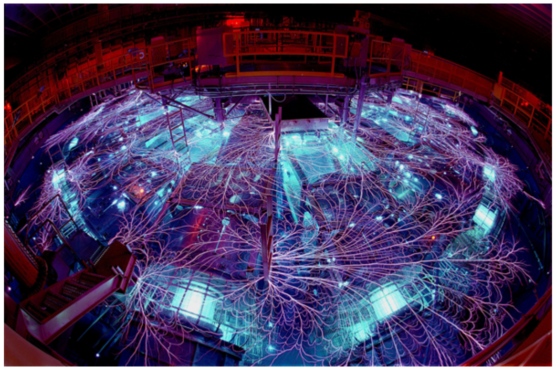


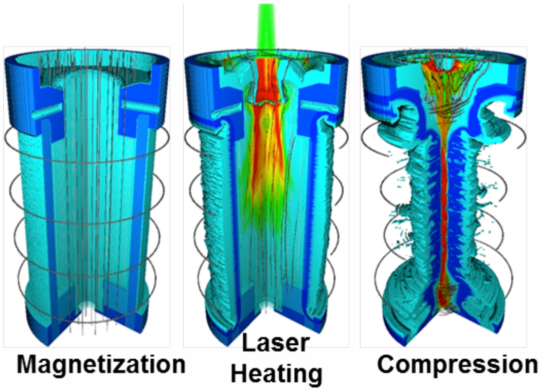
Laser-driven implosions





Magnetically-driven implosions





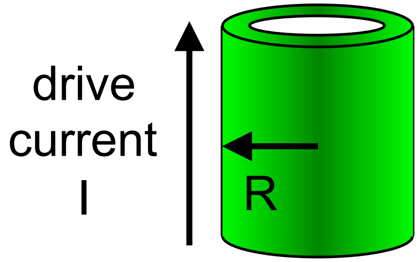
Focus of today's talk

Magnetically driven implosions may be a compelling path to significant fusion yields (>100 MJ) per shot

- Magnetic fields created by pulsed power can create the large drive pressures (high energy density) needed for fusion and stockpile stewardship
- Approach is fundamentally different than laser-driven target compression with unique physics, risks, and benefits
- Magnetic fields can also make laboratory fusion easier, e.g., strong fields can affect charged particles (electrons, alphas) and thus plasma heat transport and confinement properties
- Magnetically-driven targets driven by pulsed power drivers are energy efficient and could be a practical and cost-effective path to achieving significant fusion yields (>100 MJ). Z today couples ~0.5 MJ out of 20 MJ stored to MagLIF target (0.1 MJ in DD fuel).

Magnetically-Driven Implosion

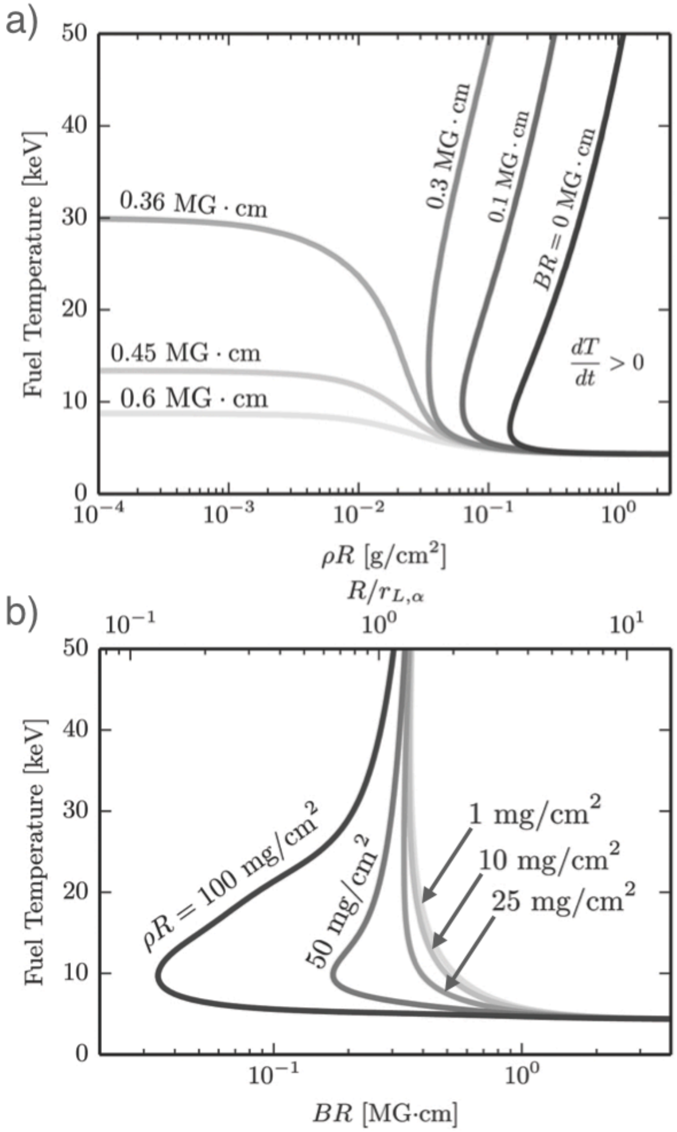
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



100 MBar at 26 MA and 1 mm

Much work is needed to make the target physics credible!

Magneto-inertial fusion seeks to compress heated fuel, using low fuel density and magnetization to minimize radiation and electron thermal conduction losses, respectively



The ρr needed for ignition can be significantly reduced by the presence of a strong magnetic field largely through inhibiting electron conduction

Lower ρr reduces the required final fuel density (e.g., ~1 g/cc << 100g/cc), reducing radiation loss

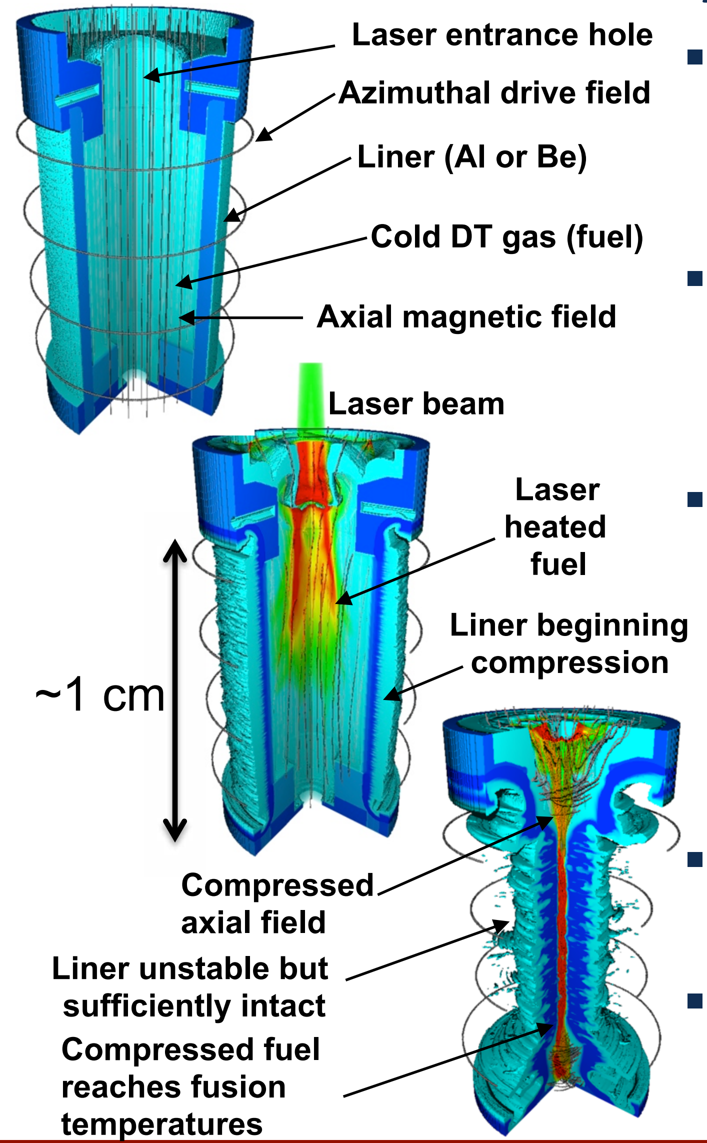
This means the stagnation plasma pressure at ignition temperatures is significantly reduced (e.g., ~5 Gbar << ~500 Gbar for hot spot ignition)

Large values of BR are needed and therefore large values of B are needed, B ~ 10,000 Tesla (Earth's B-field is ~0.00003 Tesla)

This field significantly exceeds pulsed coil technology (B_0 ~10-30 T), therefore flux compression is needed

* Basko *et al.,* Nucl. Fusion (2000); S.A. Slutz *et al.*, Phys Plasmas (2010); P.F. Knapp *et al.*, manuscript in prep.

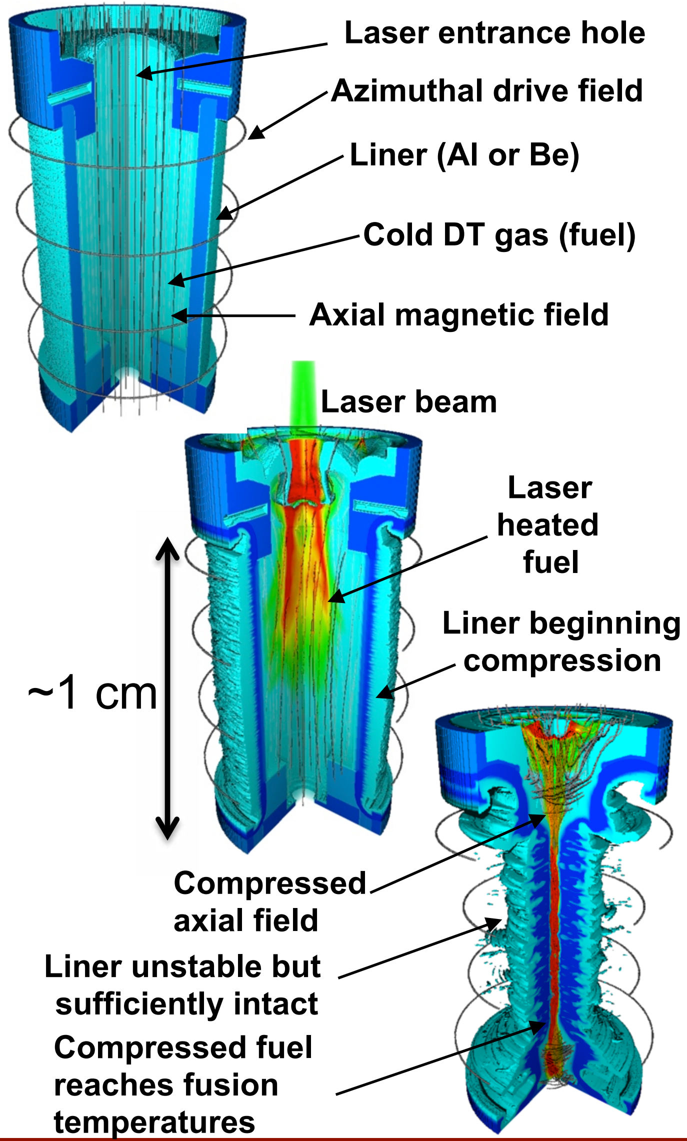
We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that is well suited to pulsed power drivers and that may reduce fusion requirements



- **<u>Axial magnetization</u> of fuel/liner (B_{z0} = 10-30 T)**
  - **Inhibits thermal conduction losses, may help stabilize liner compression (Nominal β: 5~80)**
- **<u>Laser heating</u> of fuel (2-10 kJ)**
  - **Reduces amount of radial fuel compression needed to reach fusion temperatures (R_0/R_f = 23-35)**
- **<u>Liner compression</u> of fuel (70-100 km/s, ~100 ns)**
  - **“Slow”, quasi-adiabatic compression of fuel**
  - **Low velocity requirements allow use of thick liners ($R/\Delta R$~6) that are robust to instabilities (need sufficient ρR at stagnation to inertially confine fuel)**
- **Combination allows fusion at ~100x lower fuel density than traditional ICF (~5 Gbar vs. 500 Gbar)**
- **DD equivalent of 100 kJ DT yield may be possible on Z in future—requires upgrades from our initial setup e.g., 10 T → 30 T; 2 kJ → >6 kJ; 19 MA → >24 MA**

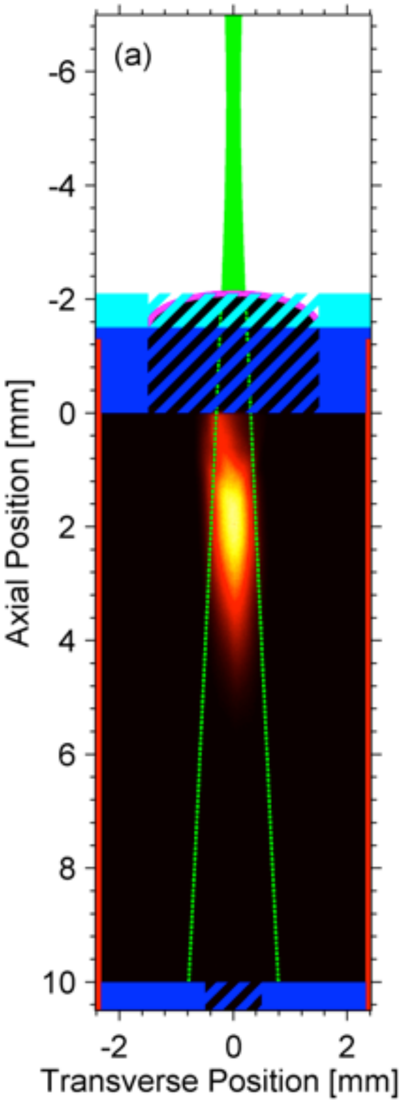
*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

We are about 1 year from our first integrated experiments on Z, and now have many observations that indicate that MagLIF targets are behaving consistently with expectations



- Evidence that fuel is heated before implosion
- Evidence that fuel is magnetized during implosion
- Produces significant yield when magnetization, laser heating, and liner compression is applied
- DD yield is isotropic
- No significant yield when either radiation losses or thermal conduction losses are increased
- Fusion products are magnetized with gyro-radii comparable to plasma radius (BR ~ 0.34 MG-cm)
- Similar neutron and multi-keV x-ray bang times
- Narrow cylindrical plasma with high T_e (2.5-3 keV)
- Comparable T_i is observed along with T_e(2.5 keV)
- Significant opacity from Be liner surrounding the heated fusion fuel is observed (about 0.9 g/cm^2)
- Significant down-scattered neutrons from Be liner surrounding fusion fuel is observed 0.1-1 g/cm^2

We are about 1 year from our first integrated experiments on Z, and now have many observations that indicate that MagLIF targets are behaving consistently with expectations

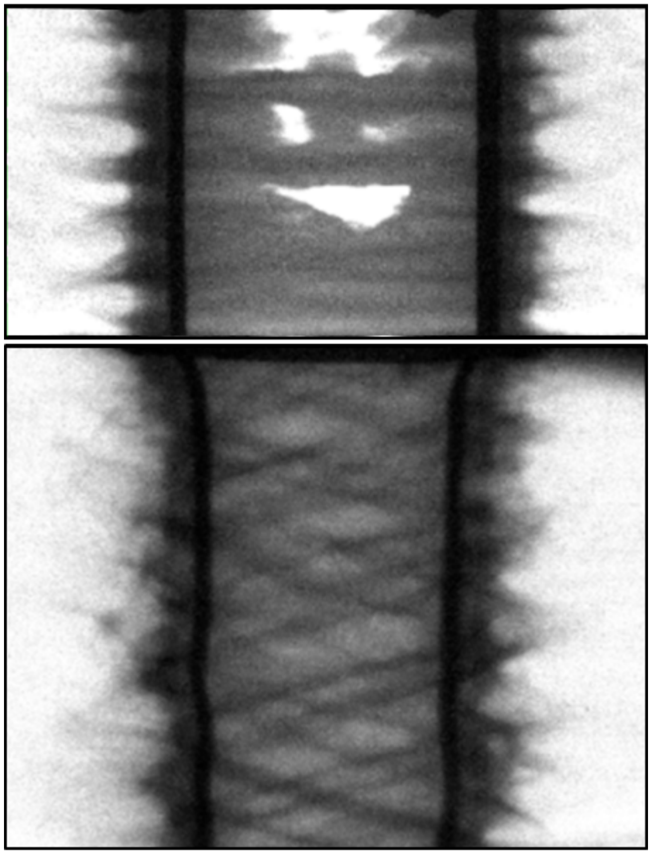


- Evidence that fuel is heated before implosion
- Evidence that fuel is magnetized during implosion
- Produces significant yield when magnetization, laser heating, and liner compression is applied
- DD yield is isotropic
- No significant yield when either radiation losses or thermal conduction losses are increased
- Fusion products are magnetized with gyro-radii comparable to plasma radius (BR ~ 0.34 MG-cm)
- Similar neutron and multi-keV x-ray bang times
- Narrow cylindrical plasma with high T_e (2.5-3 keV)
- Comparable T_i is observed along with T_e(2.5 keV)
- Significant opacity from Be liner surrounding the heated fusion fuel is observed (about 0.9 g/cm^2)
- Significant down-scattered neutrons from Be liner surrounding fusion fuel is observed 0.1-1 g/cm^2

* M.R. Gomez *et al.*, manuscript in preparation for Physics of Plasmas; M. Geissel *et al.*, private comm.

We are about 1 year from our first integrated experiments on Z, and now have many observations that indicate that MagLIF targets are behaving consistently with expectations

Without Magnetic Field

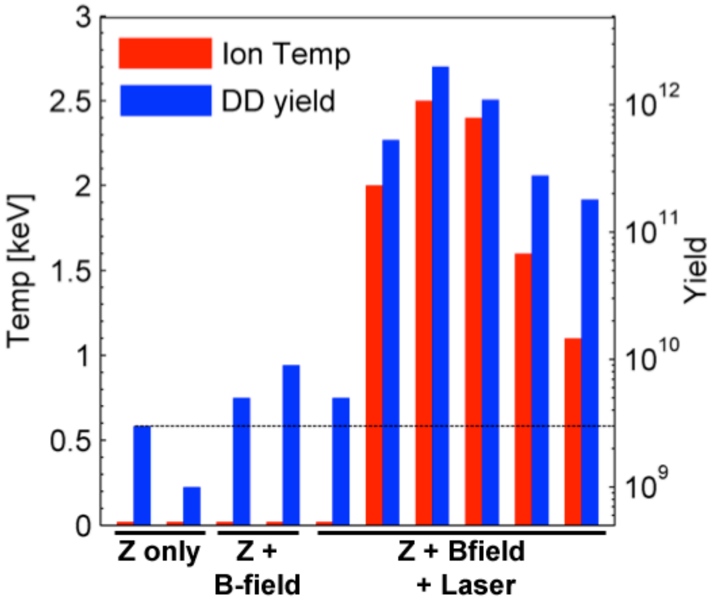


With Magnetic Field

- Evidence that fuel is heated before implosion
- Evidence that fuel is magnetized during implosion
- Produces significant yield when magnetization, laser heating, and liner compression is applied
- DD yield is isotropic
- No significant yield when either radiation losses or thermal conduction losses are increased
- Fusion products are magnetized with gyro-radii comparable to plasma radius (BR ~ 0.34 MG-cm)
- Similar neutron and multi-keV x-ray bang times
- Narrow cylindrical plasma with high T_e (2.5-3 keV)
- Comparable T_i is observed along with T_e(2.5 keV)
- Significant opacity from Be liner surrounding the heated fusion fuel is observed (about 0.9 g/cm^2)
- Significant down-scattered neutrons from Be liner surrounding fusion fuel is observed 0.1-1 g/cm^2

* T.J. Awe *et al.*, Phys. Rev. Lett. (2013); T.J. Awe *et al.*, Phys. Plasmas (2014).

We are about 1 year from our first integrated experiments on Z, and now have many observations that indicate that MagLIF targets are behaving consistently with expectations



- Evidence that fuel is heated before implosion
- Evidence that fuel is magnetized during implosion
- Produces significant yield when magnetization, laser heating, and liner compression is applied
- DD yield is isotropic
- No significant yield when either radiation losses or thermal conduction losses are increased
- Fusion products are magnetized with gyro-radii comparable to plasma radius (BR ~ 0.34 MG-cm)
- Similar neutron and multi-keV x-ray bang times
- Narrow cylindrical plasma with high T_e (2.5-3 keV)
- Comparable T_i is observed along with T_e(2.5 keV)
- Significant opacity from Be liner surrounding the heated fusion fuel is observed (about 0.9 g/cm^2)
- Significant down-scattered neutrons from Be liner surrounding fusion fuel is observed 0.1-1 g/cm^2

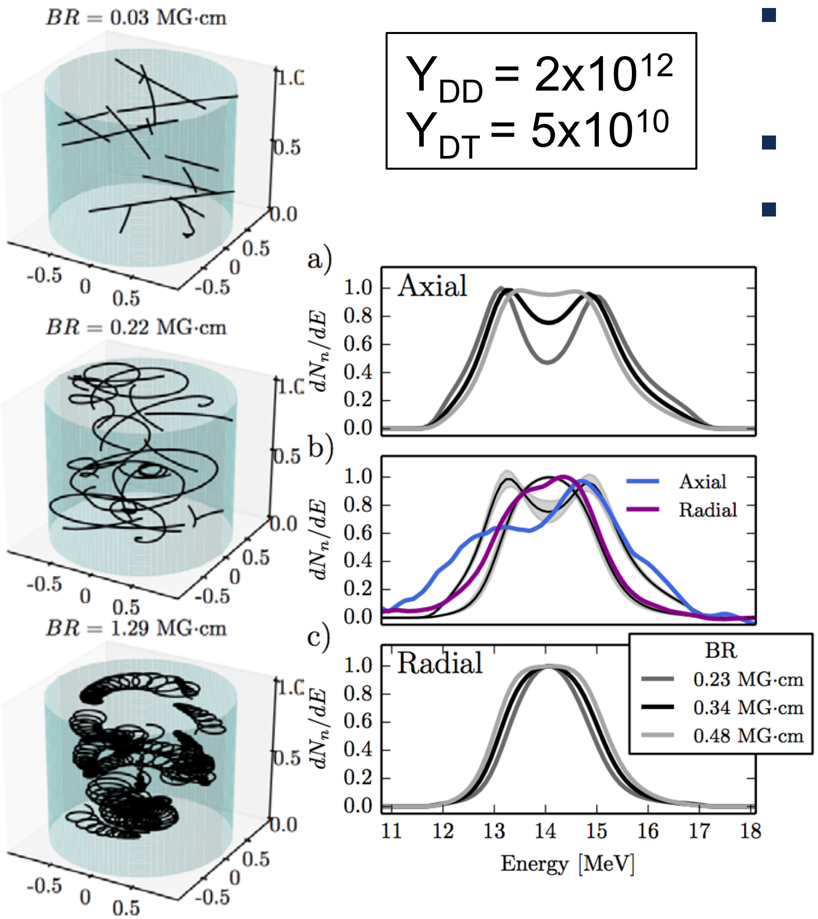
* M.R. Gomez *et al.*, Phys. Rev. Lett. (2014); M.R. Gomez *et al.*, manuscript in prep. for Physics of Plasmas.

We are about 1 year from our first integrated experiments on Z, and now have many observations that indicate that MagLIF targets are behaving consistently with expectations

$$\text{Primary}: D + D \rightarrow \begin{cases} n + {}^3\text{He} \\ p + T \end{cases}$$

$$\text{Secondary}: D + T \rightarrow n + \alpha$$

$Y_{DD} = 2\text{x}10^{12}$
$Y_{DT} = 5\text{x}10^{10}$



- Evidence that fuel is heated before implosion
- Evidence that fuel is magnetized during implosion
- Produces significant yield when magnetization, laser heating, and liner compression is applied
- DD yield is isotropic
- No significant yield when either radiation losses or thermal conduction losses are increased

Fusion products are magnetized with gyro-radii comparable to plasma radius (BR ~ 0.34 MG-cm)

Similar neutron and multi-keV x-ray bang times

Narrow cylindrical plasma with high T_e (2.5-3 keV)

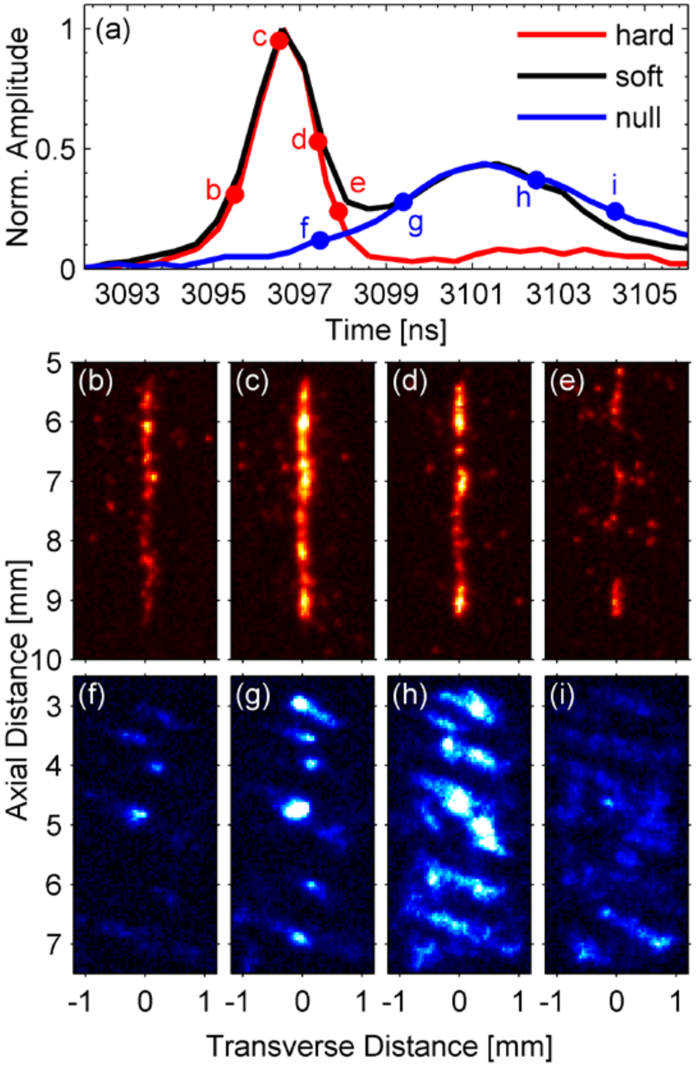
Comparable T_i is observed along with T_e(2.5 keV)

Significant opacity from Be liner surrounding the heated fusion fuel is observed (about 0.9 g/cm^2)

Significant down-scattered neutrons from Be liner surrounding fusion fuel is observed 0.1-1 g/cm^2

* P.F. Schmit *et al.*, Phys. Rev. Lett. (2014); P.F Knapp *et al.*, manuscript in prep. for Physics of Plasmas.

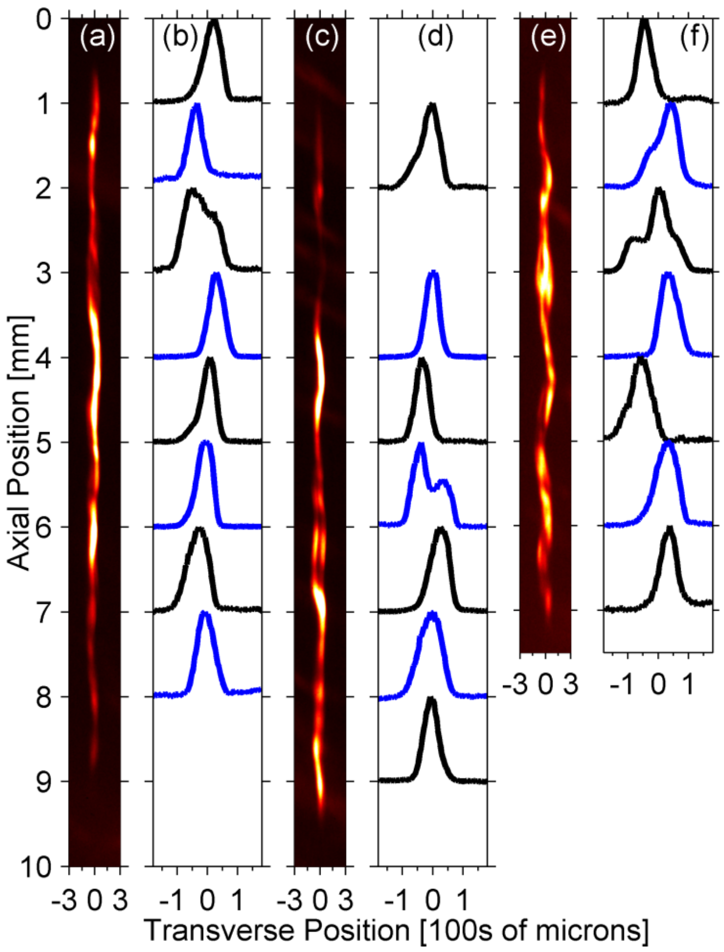
We are about 1 year from our first integrated experiments on Z, and now have many observations that indicate that MagLIF targets are behaving consistently with expectations



- Evidence that fuel is heated before implosion
- Evidence that fuel is magnetized during implosion
- Produces significant yield when magnetization, laser heating, and liner compression is applied
- DD yield is isotropic
- No significant yield when either radiation losses or thermal conduction losses are increased
- Fusion products are magnetized with gyro-radii comparable to plasma radius (BR ~ 0.34 MG-cm)
- Similar neutron and multi-keV x-ray bang times
- Narrow cylindrical plasma with high T_e (2.5-3 keV)
- Comparable T_i is observed along with T_e(2.5 keV)
- Significant opacity from Be liner surrounding the heated fusion fuel is observed (about 0.9 g/cm^2)
- Significant down-scattered neutrons from Be liner surrounding fusion fuel is observed 0.1-1 g/cm^2

* M.R. Gomez *et al.*, Phys. Rev. Lett. (2014); M.R. Gomez *et al.*, manuscript in prep. for Physics of Plasmas.

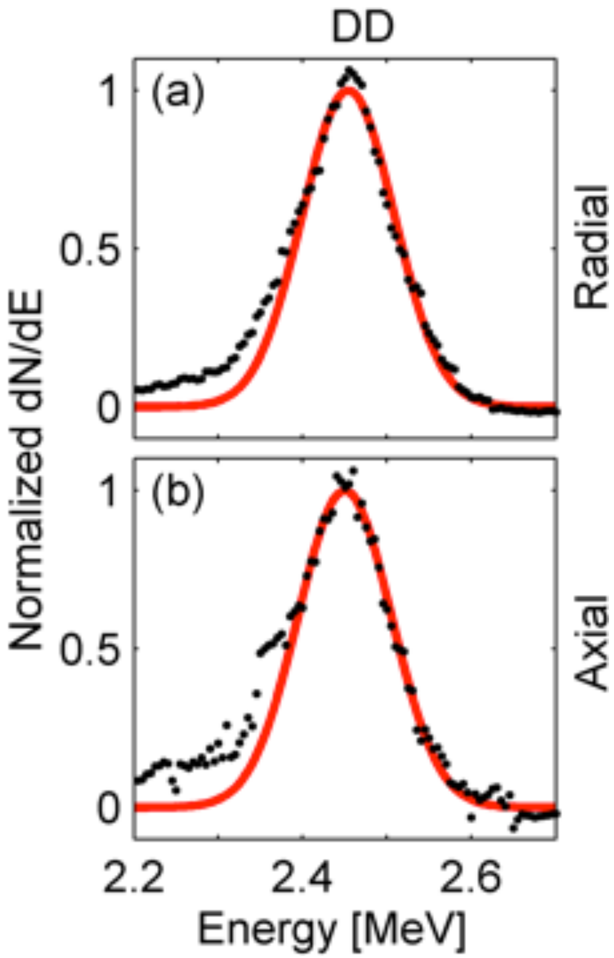
We are about 1 year from our first integrated experiments on Z, and now have many observations that indicate that MagLIF targets are behaving consistently with expectations



- Evidence that fuel is heated before implosion
- Evidence that fuel is magnetized during implosion
- Produces significant yield when magnetization, laser heating, and liner compression is applied
- DD yield is isotropic
- No significant yield when either radiation losses or thermal conduction losses are increased
- Fusion products are magnetized with gyro-radii comparable to plasma radius (BR ~ 0.34 MG-cm)
- Similar neutron and multi-keV x-ray bang times
- Narrow cylindrical plasma with high T_e (2.5-3 keV)
- Comparable T_i is observed along with T_e(2.5 keV)
- Significant opacity from Be liner surrounding the heated fusion fuel is observed (about 0.9 g/cm^2)
- Significant down-scattered neutrons from Be liner surrounding fusion fuel is observed 0.1-1 g/cm^2

* M.R. Gomez *et al.*, Phys. Rev. Lett. (2014); M.R. Gomez *et al.*, in preparation; S.B. Hansen *et al.*, in preparation.

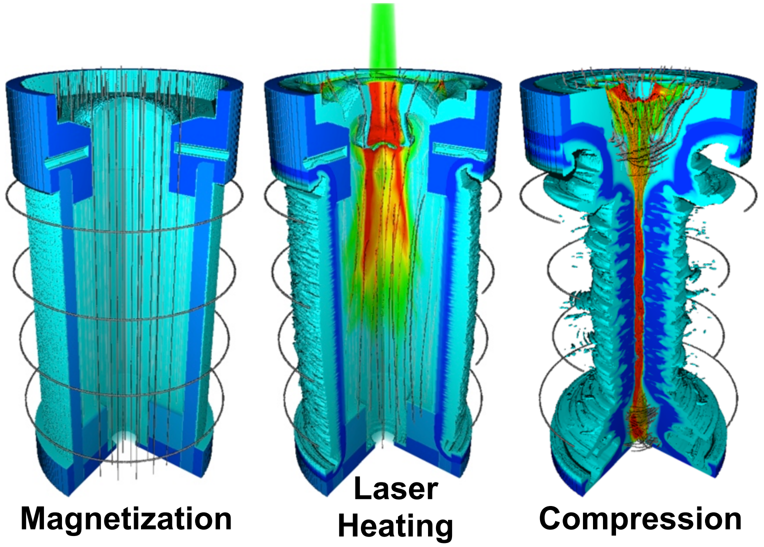
We are about 1 year from our first integrated experiments on Z, and now have many observations that indicate that MagLIF targets are behaving consistently with expectations



- Evidence that fuel is heated before implosion
- Evidence that fuel is magnetized during implosion
- Produces significant yield when magnetization, laser heating, and liner compression is applied
- DD yield is isotropic
- No significant yield when either radiation losses or thermal conduction losses are increased
- Fusion products are magnetized with gyro-radii comparable to plasma radius (BR ~ 0.34 MG-cm)
- Similar neutron and multi-keV x-ray bang times
- Narrow cylindrical plasma with high T_e (2.5-3 keV)
- Comparable T_i is observed along with T_e(2.5 keV)
- Significant opacity from Be liner surrounding the heated fusion fuel is observed (about 0.9 g/cm^2)
- Significant down-scattered neutrons from Be liner surrounding fusion fuel is observed 0.1-1 g/cm^2

* M.R. Gomez *et al.*, Phys. Rev. Lett. (2014); M.R. Gomez *et al.*, in preparation; S.B. Hansen *et al.*, in preparation.

We plan to test the underlying models & assumptions using a mixture of focused & integrated experiments—there are also a number of physics questions raised by data so far!

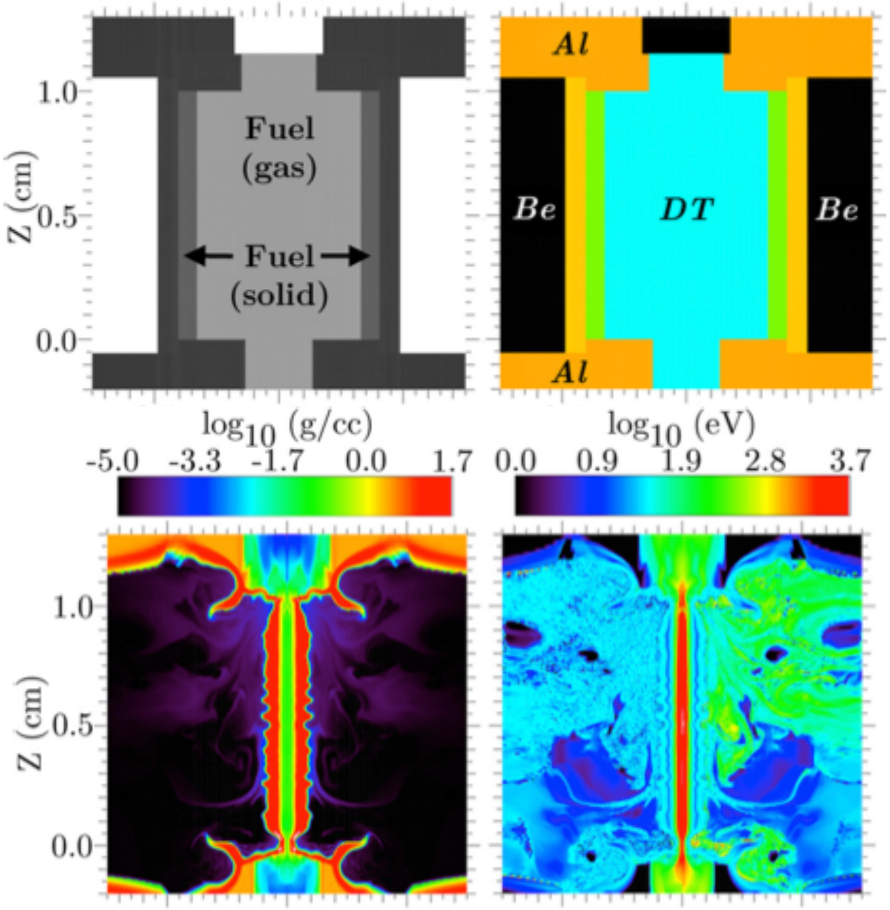


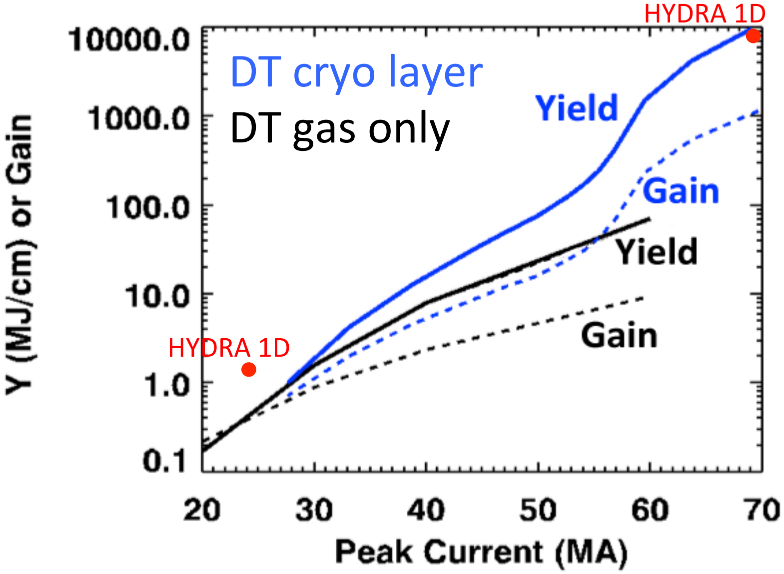
- Key target design elements
  - Liner compression
  - Laser heating
  - Magnetization
  - Magnetized burn (high current)

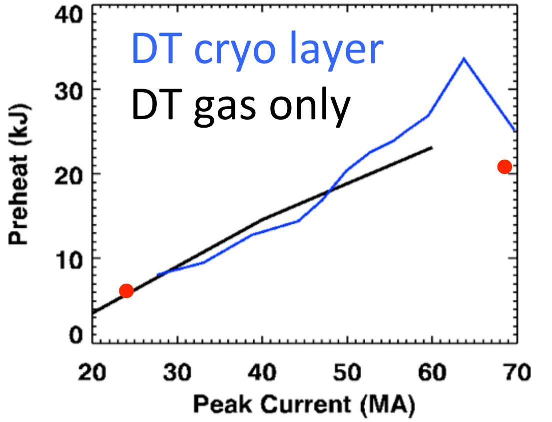
- Key physics model uncertainties
  - Can we model liner instabilities?
    - Electro-thermal
    - Magneto-Rayleigh-Taylor
    - Deceleration RT
    - Impact of 3D fuel assembly
  - Liner/fuel interactions (affected by shocks, blast wave, radiation)
  - Laser-window and laser-fuel scattering, absorption, uniformity
  - Suppression of electron heat transport in dense plasma by magnetic fields (Braginskii models)
  - Magnetic flux compression (Nernst)

Experiments to address some of these are being done on the Z pulsed power facility and the Z-Beamlet and Omega-EP lasers—many other opportunities exist!

In principle, MagLIF designs achieve higher yields on future facilities using a cryogenic DT layer and substantial preheat—we can test most of the physics of these targets on Z today!







An intermediate regime exists wherein the B_z field is

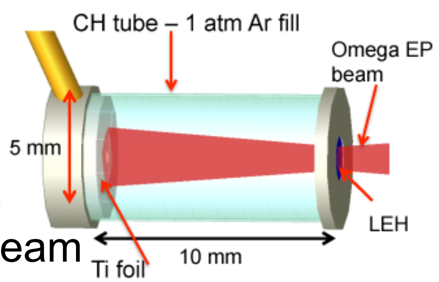
- *strong enough* to reduce conduction losses, but
- *weak enough* not to inhibit the α deflagration wave

S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

Based on the observations we have to date, the key physics challenge for MagLIF will be coupling initial energy to the fuel—this is a common issue for all magneto-inertial fusion

- Poor coupling? Integrated modeling of the initial experiments can match the observations if the energy coupled by the laser to the fuel is only 100-300 J instead of 2 kJ
- Standalone laser heating experiments with Z-Beamlet laser are consistent with low coupling through foils—an issue made worse by lack of any beam smoothing technology
- All integrated experiments in which we have increased the laser coupling to the fuel by (1) increasing laser energy, (2) using thinner foils, and/or (3) using phase plates, have produced lower temperatures and lower yields
- Some hints in existing data that increased laser coupling to fuel is also increasing early-time mix, which reduces the yield through radiation losses. This will be examined going forward.

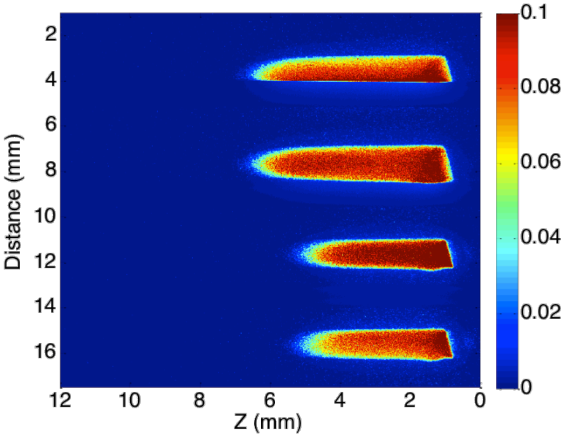
There are many opportunities to collaborate with colleagues at Omega, NIF, etc. to study the laser heating problem and this has been started



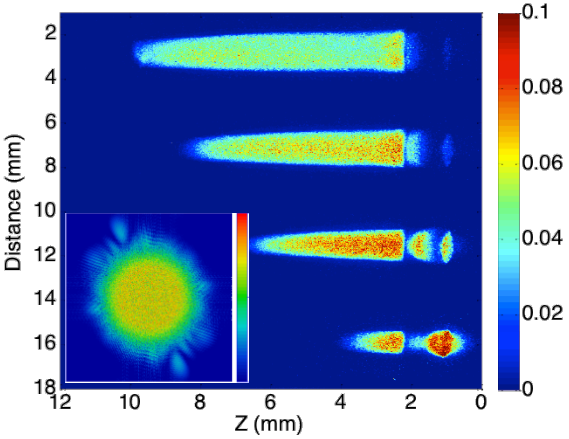
750 µm diam. beam

Omega-EP (Harvey-Thompson, Sefkow)

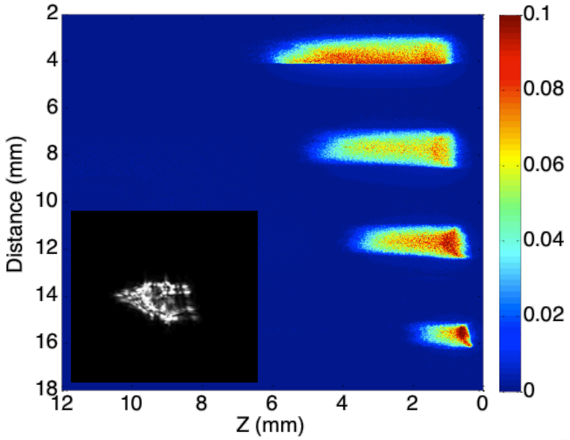
2 ns beam, 2.2 kJ, 1um LEH



4 ns beam, 3.1 kJ, 2um LEH

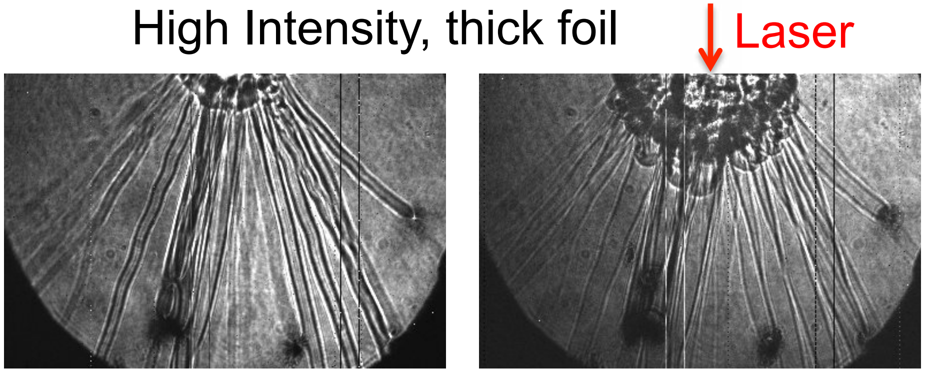


4 ns beam, 2.9 kJ, 2um LEH, No DPP



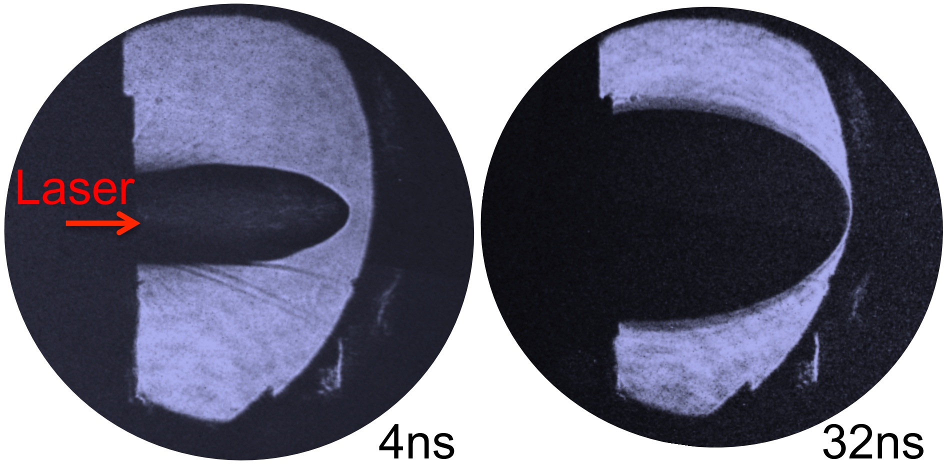
Z-Beamlet (Geissel, Porter, Lewis)

High Intensity, thick foil

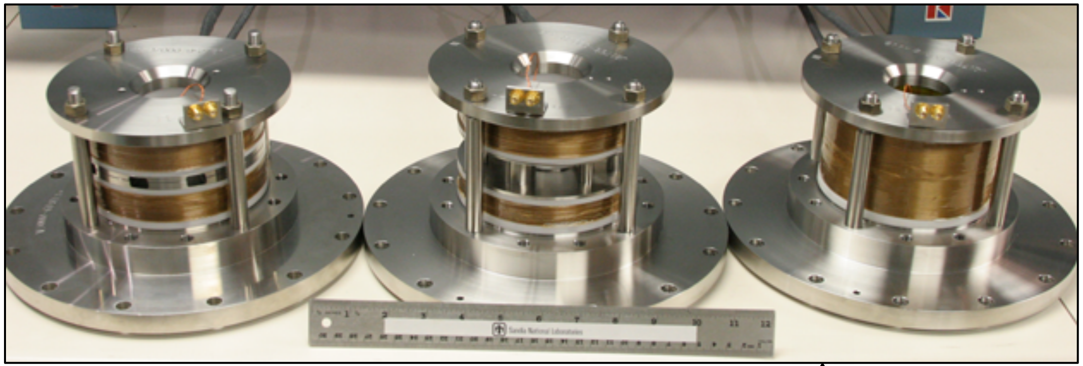


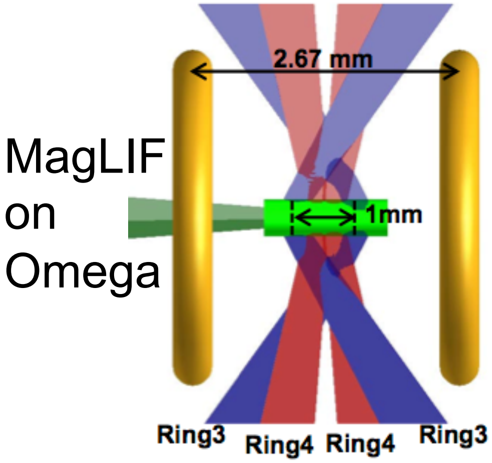
t = 10ns **t = 36ns**

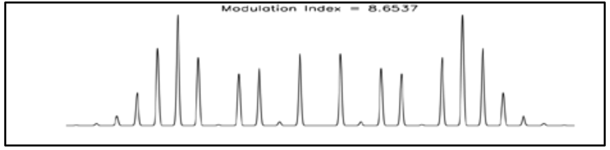
High Intensity, thin foil



Scaling: Over the next few years we are working to increase the drive conditions on Z to help understand how MagLIF scales. Scaling tests on Omega are also being planned.



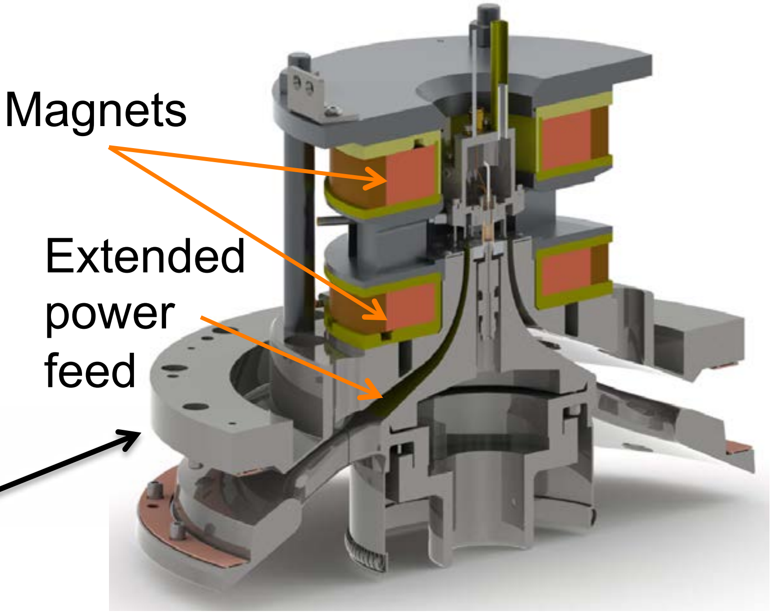




Increase B-field from 10 T to 30 T

Increase laser energy from 2 kJ to >6 kJ

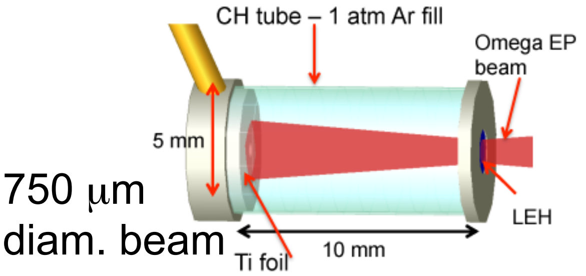
Increase current from 19 MA to >20 MA (Z facility upgrades; load hardware optimization)



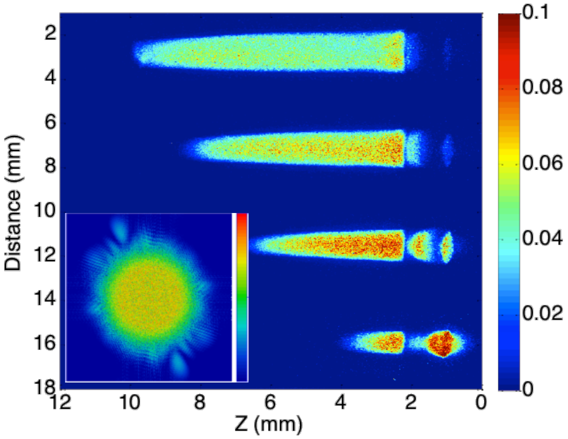
Magnets: Rovang, Lamppa ZBL: Porter *et al.* Omega: Davies, Betti, Chang *et al.*

We look forward to a strong national effort in this area and collaboration with others in the next few years

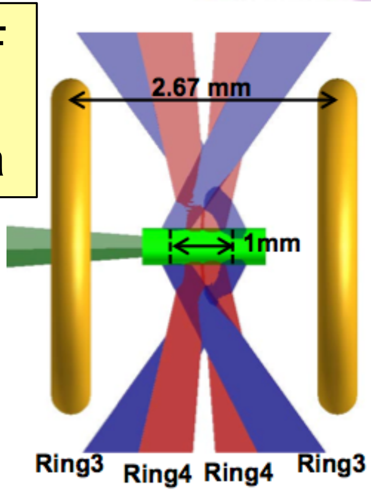
Laser heating on Omega-EP



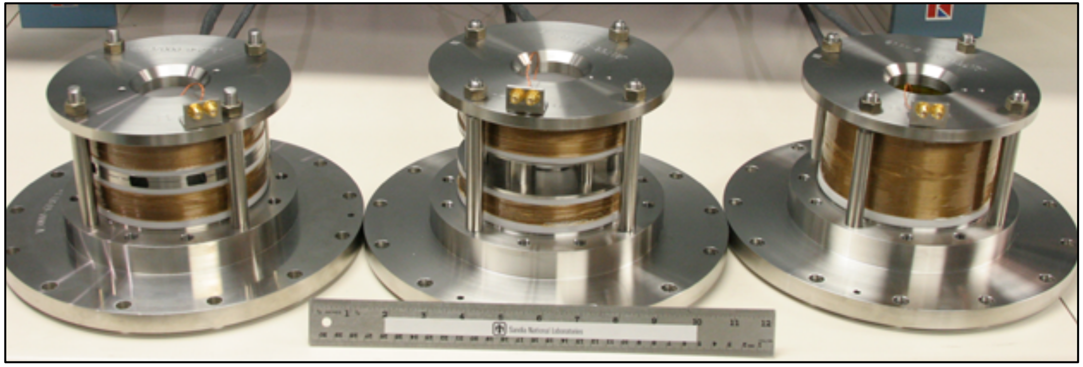
4 ns beam, 3.1 kJ, 2um LEH



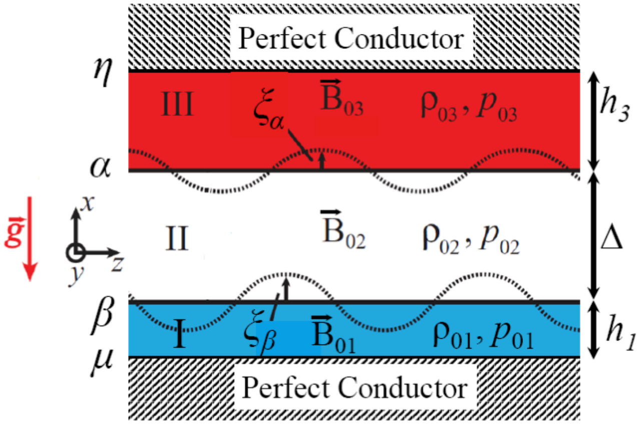
MagLIF on Omega



Development of Bfield coils with National High Magnetic Field Laboratory (LANL)



Liner dynamics theory & experiments (Universities)



There is a lot of work yet to do, but a promising beginning!

Our path forward during the next several years for Magnetically Driven Implosions has three broad goals

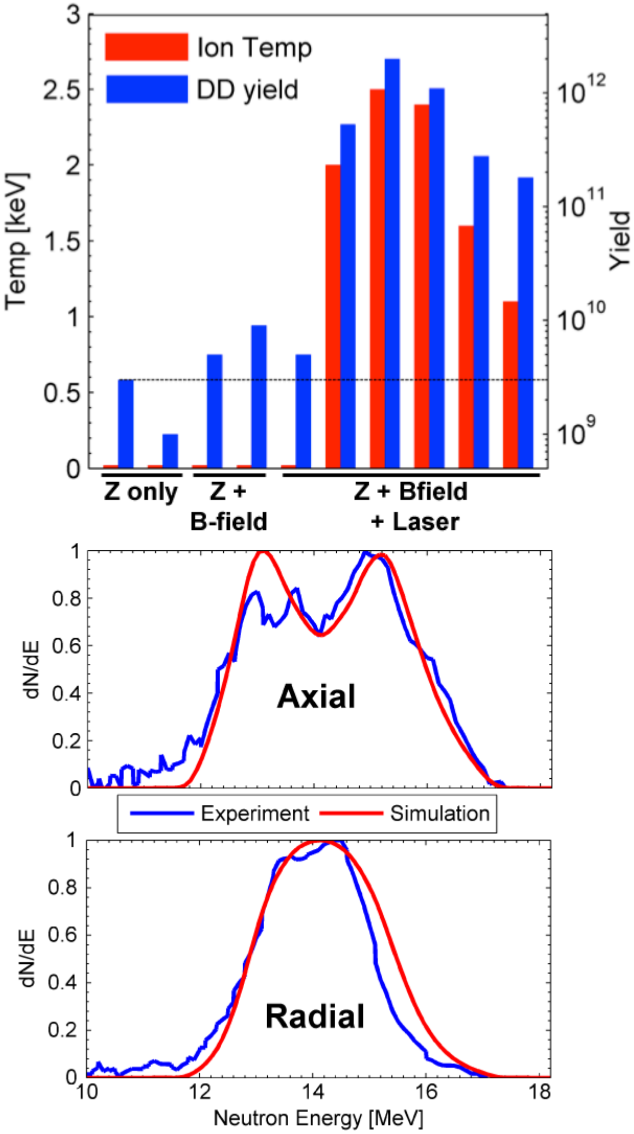
- **Study the underlying science** and major design elements using both "focused" and "integrated" experiments on multiple facilities (e.g., Z, Z-Beamlet, Omega, Omega-EP, universities, NIF a possibility)

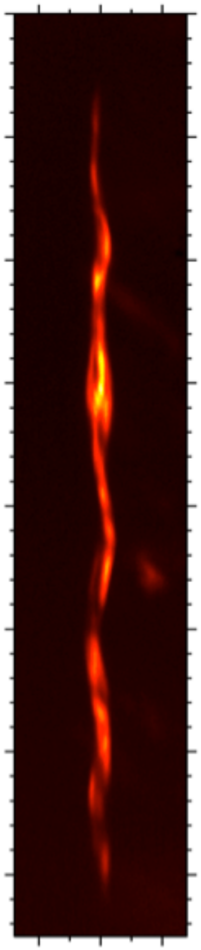
- **Demonstrate target scaling** on Z with enhanced drive conditions and/or better fuel assembly
  - DD equivalent of ~100 kJ DT yields may ultimately be possible on Z

- **Develop a path to ignition and beyond**
  - Define ignition for magnetically driven implosions! (5 MJ?)
  - Develop credible scaling of targets from Z to ignition-capable (>5 MJ) & high-yield capable (~1 GJ) facilities
  - Develop the supporting technologies (pulsed power, cryo, etc.)

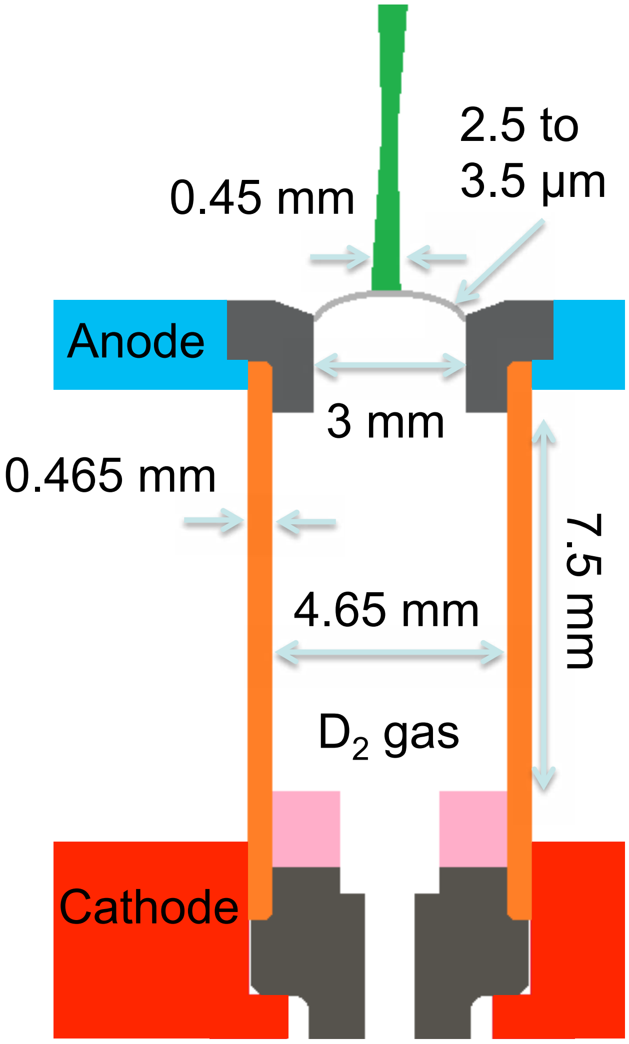
Our initial MagLIF results have been very promising!

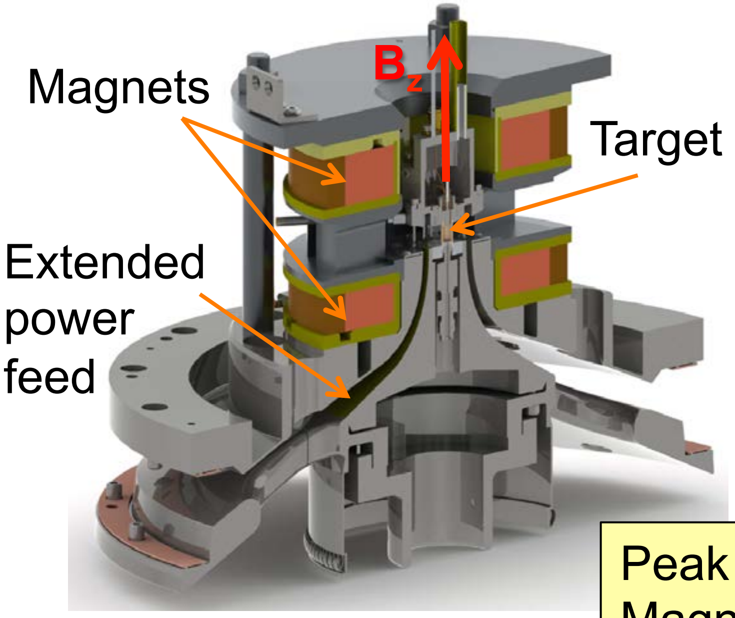
- Magnetized (10 T) and laser-heated (2 kJ) cylindrical Be targets reached ~3 keV temperatures and produced fusion yield (up to 2x10^{12} DD) at 70 km/s implosion velocity
  M.R. Gomez *et al.*, Phys Rev Lett (2014);
- Secondary neutron yield (>10^{10} 14 MeV) and spectra demonstrate that the fusing plasma was highly magnetized
  P.F. Schmit *et al.*, Phys Rev Lett (2014);
- Detailed analysis of stagnation conditions consistent with thermonuclear yield, though less energy in fusing plasma than predicted
- Additional experiments on multiple facilities focused on specific physics issues (laser-gas coupling, liner dynamics, flux compression)

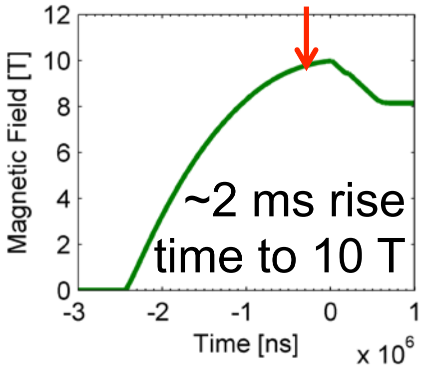


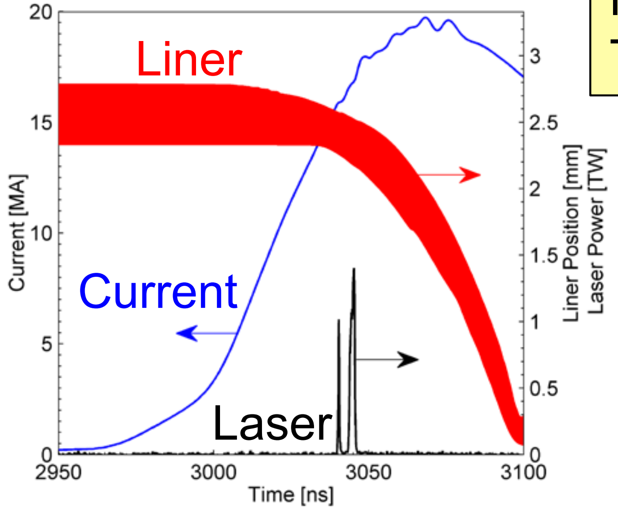


The initial experiments used 10 T, 2.5 kJ laser energy, and 19-20 MA current to drive a D_2 filled (0.7 mg/cc) Be liner

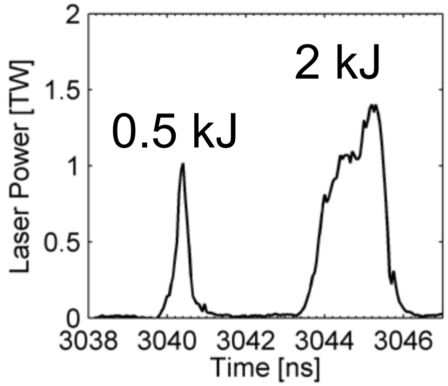






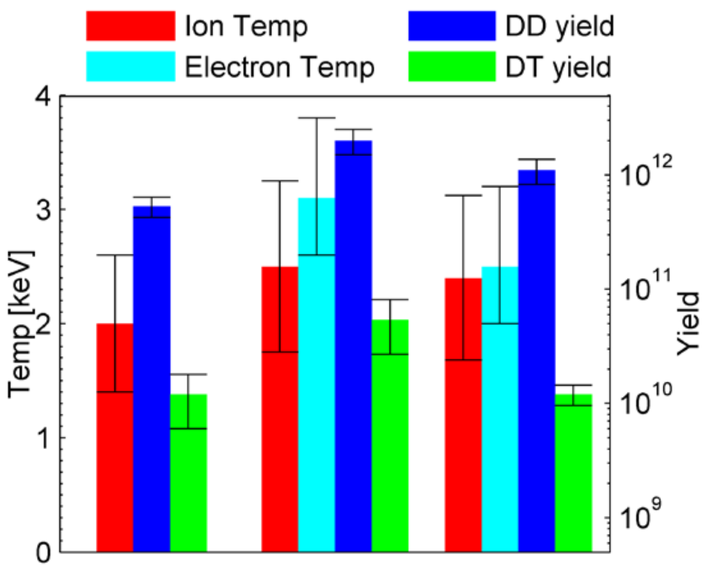


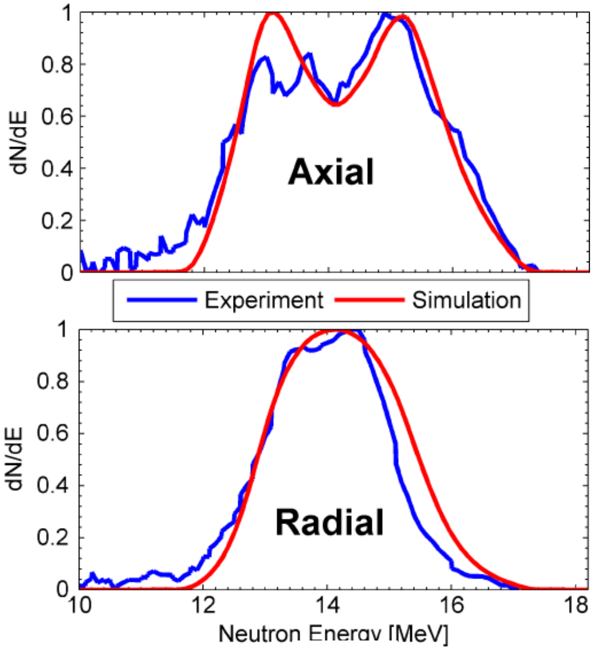
Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ

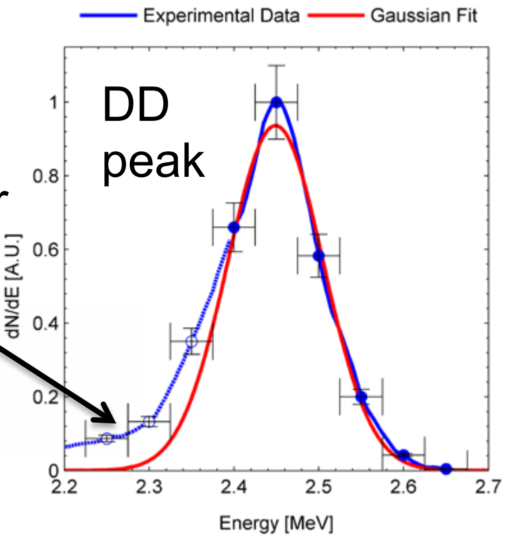


M.R. Gomez *et al.*, Phys. Rev. Lett. 113, 155003 (2014).

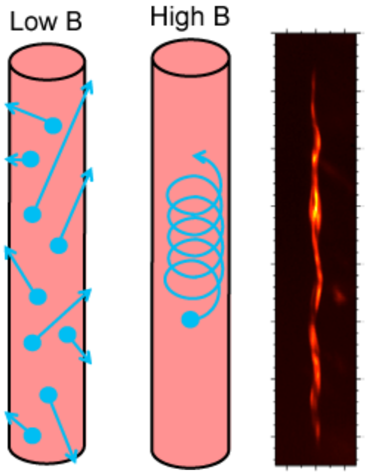
Our initial MagLIF experiments successfully demonstrated fusion yield consistent with a thermonuclear origin and with significant magnetization of the fusing plasma







n scatter off Be liner around hot fuel



Inferred Stagnation Conditions

Volume = 2-5 x10^{-5} cm^3
Duration = 1-2 ns
ρ_{fuel} = 0.7-2 x10^{23} cm^{-3}
= 0.2-0.6 g/cm^3
Temp. = 2.5-3.1 keV
<σv> = 1.3-2.8 x10^{-20}

Calculated Yield =
6 x10^{11} to 3 x10^{13} DD

Measured Yield =
2 x10^{12} DD

M.R. Gomez *et al.*, Phys Rev Lett 113, 155003 (2014); P.F. Schmit *et al.*, Phys Rev Lett 113, 155004 (2014).

We are about 1 year from our first integrated experiments on Z, and now have many observations that indicate that MagLIF targets are behaving consistently with expectations

- Evidence that fuel is heated before implosion
- Evidence that fuel is magnetized during implosion
- Produces significant yield when magnetization, laser heating, and liner compression is applied
- DD yield is isotropic
- No significant yield when either radiation losses or thermal conduction losses are increased
- Fusion products are magnetized with gyro-radii comparable to plasma radius (BR ~ 0.34 MG-cm)
- Similar neutron and multi-keV x-ray bang times
- Narrow cylindrical plasma with high T_e (2.5-3 keV)
- Comparable T_i is observed along with T_e(2.5 keV)
- Significant opacity from Be liner surrounding the heated fusion fuel is observed (about 0.9 g/cm^2)
- Significant down-scattered neutrons from Be liner surrounding fusion fuel is observed 0.1-1 g/cm^2