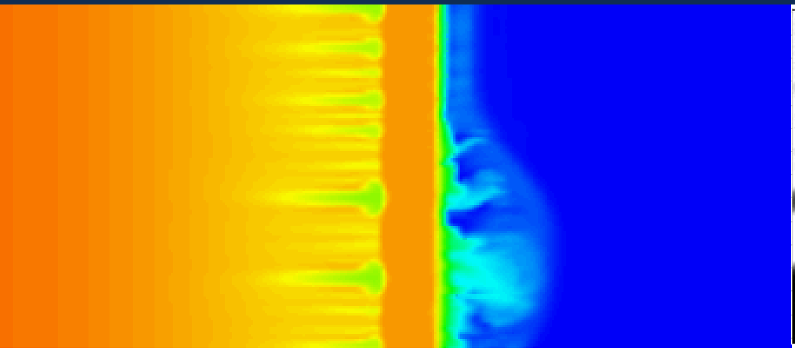
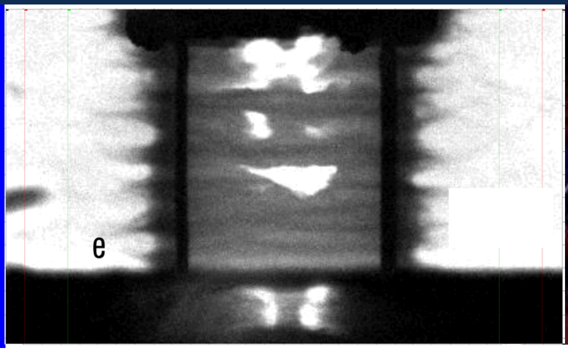
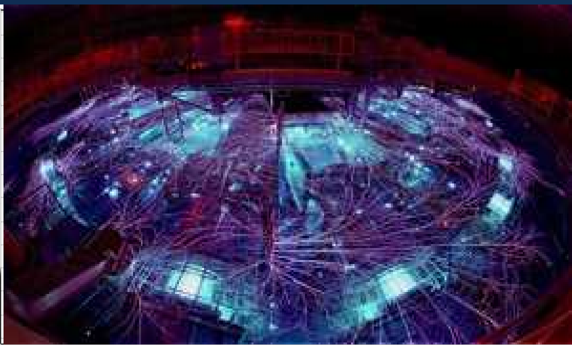
Exceptional service in the national interest

Sandia National Laboratories

SAND2015-4857C







Progress in Pulsed Magneto-Inertial Fusion

Kyle J. Peterson

Sandia National Laboratories, Albuquerque, NM 87185 USA

PPC 2015

May 31-June 4, 2015

Austin, Texas

Pulsed Power Sciences — Harnessing Extreme Environments

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

This presentation represents the work of many scientists and engineers working on the MagLIF project

T.J. Awe, C.J. Bourdon, E.M. Campbell, G.A. Chandler, P.J. Christenson, M.E. Cuneo, M. Geissel, M.R. Gomez, K.D. Hahn, S.B. Hansen, E.C. Harding, A.J. Harvey-Thompson, M.C. Herrmann, M.H. Hess, C.A. Jennings, B. Jones, M. Jones, R.J. Kaye, P.F. Knapp, D.C. Lamppa, J.S. Lash, M.R. Lopez, M.R. Martin, R.D. McBride, L.A. McPherson, T.N. Nagayama, K.J. Peterson, J.L. Porter, G.A. Rochau, D.C. Rovang, C.L. Ruiz, S.E. Rosenthal, M.E. Savage, P.F. Schmit, A.B. Sefkow, D.B. Sinars, S.A. Slutz, I.C. Smith, W.A. Stygar, R.A. Vesey, E.P. Yu

Sandia National Laboratories, Albuquerque, NM 87185 USA

B.E. Blue, D.G. Schroen, K. Tomlinson, M.S. Wei

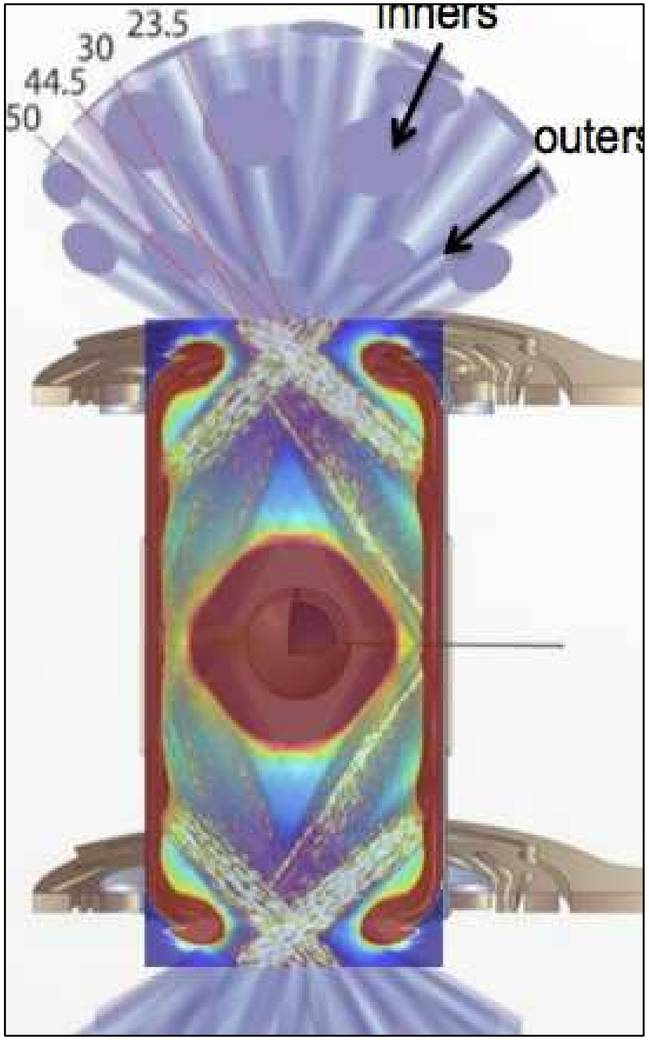
General Atomics, San Diego, CA 92186 USA

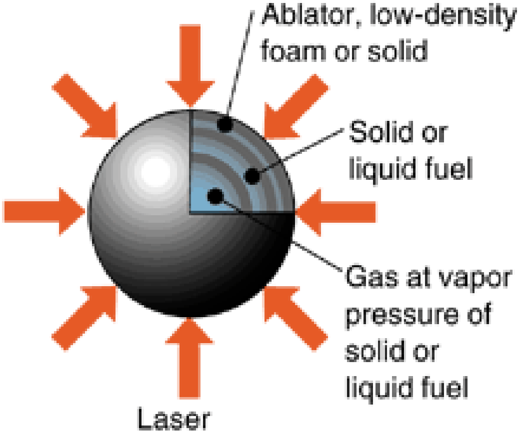
J. Davies, R. Betti, P.-Y. Chang, G. Fiksel, D. Barnak, V. Glebov

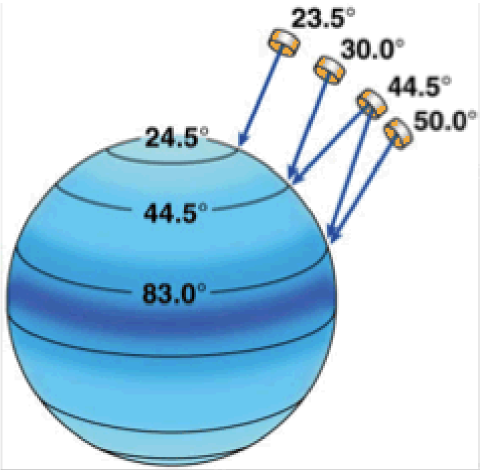
Laboratory for Laser Energetics, University of Rochester, Rochester, NY, USA

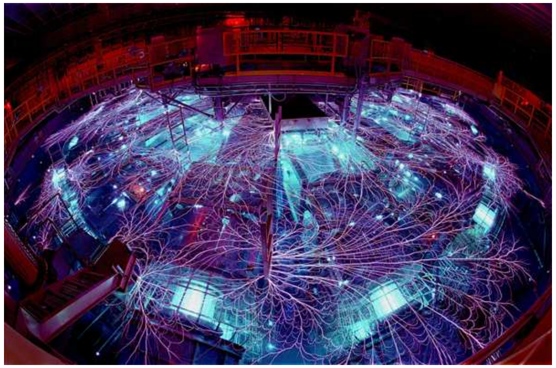
The United States ICF program is pursuing three main approaches to ignition

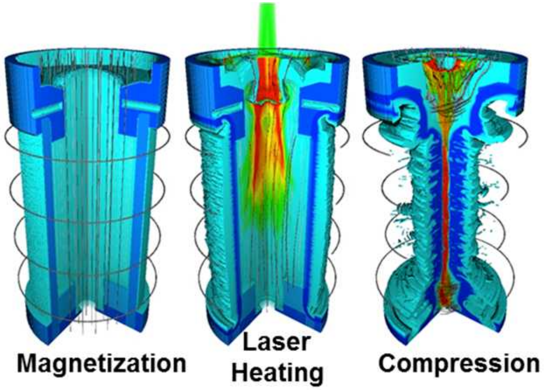
Radiation-driven implosions	Laser-driven implosions	Magnetically-driven implosions









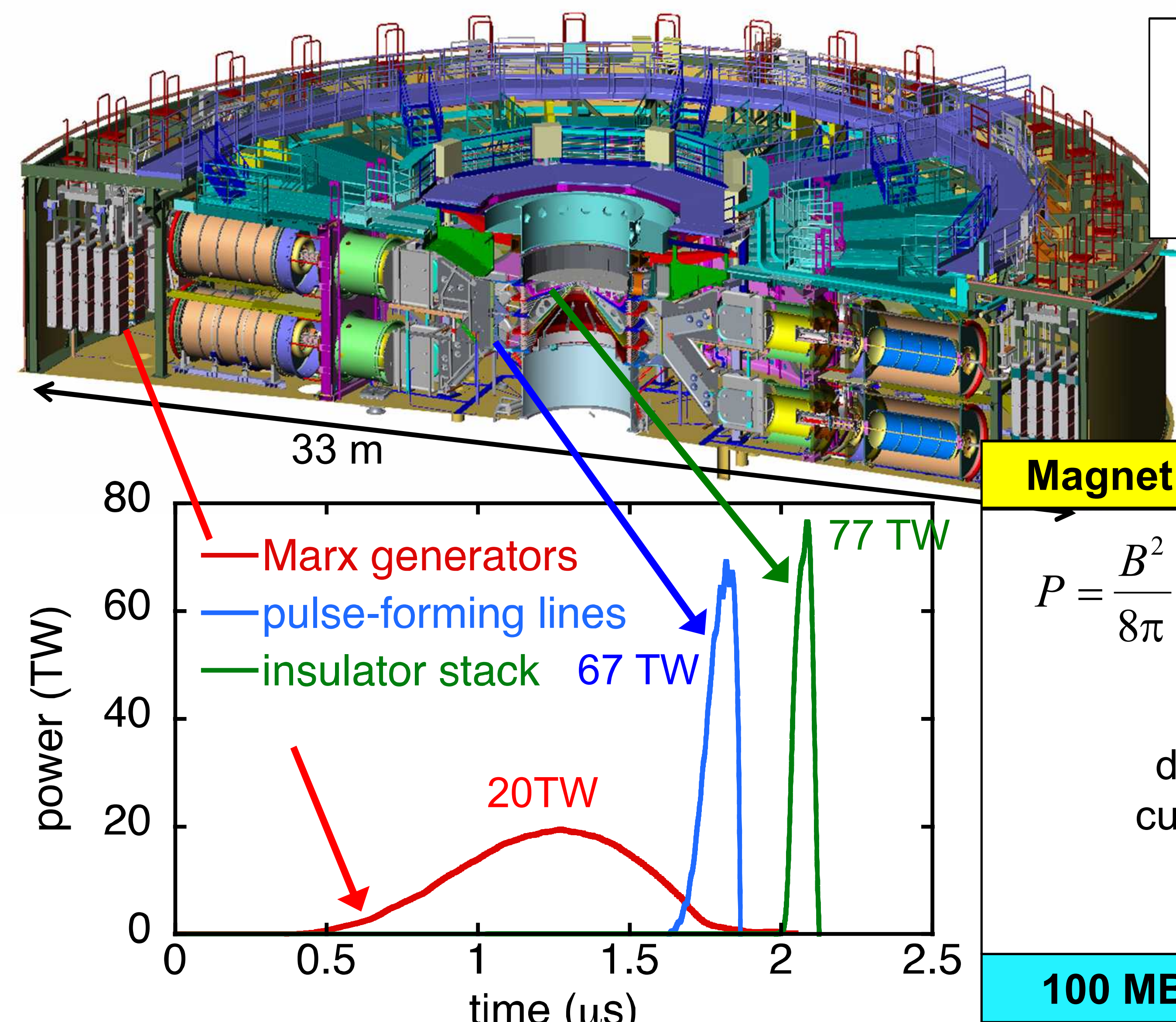


Focus of today's talk

"Magnetic direct drive" is based on the idea that we can efficiently use large currents to create high pressures

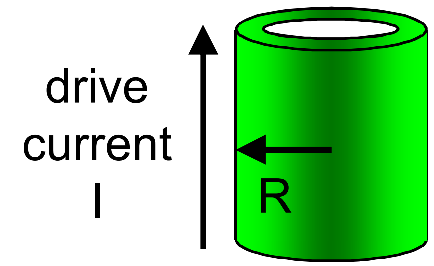
Sandia National Laboratories

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



Magnetically-Driven Implosion

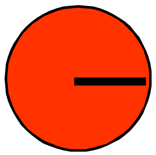
$$P = \frac{B^2}{8\pi} = 105\left(\frac{I_{MA}/26}{R_{mm}}\right)^2 \text{ MBar}$$



100 MBar at 26 MA and 1 mm

Implosion time ~50 ns; stagnation ~0.1-1 ns (1 atm = 1 bar = 10^5 Pascals)

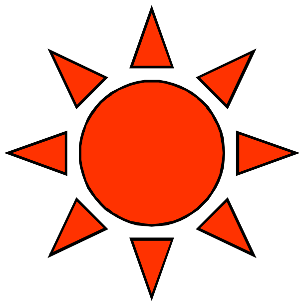
Under extreme conditions a mass of DT can undergo significant thermonuclear fusion before falling apart



ρ, R, T

- Consider a mass of DT with radius R, density ρ, and temperature T
- How does the disassembly time compare with the time for thermonuclear burn?

$$\tau_{disassembly} \sim \frac{R}{c_s} \sim \frac{R}{\sqrt{T}} \qquad \tau_{burn} \sim \frac{1}{n_i\langle\sigma v\rangle} \sim \frac{1}{\rho\langle\sigma v\rangle}$$



- **The fractional burn up of the DT (for small burn up) is:**

$$f_{burn} \approx \frac{\tau_{disassembly}}{\tau_{burn}} \sim \rho R \frac{\langle\sigma v\rangle}{\sqrt{T}}$$

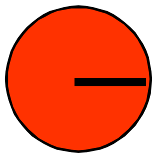
- **At sufficiently high ρR and T the fractional burn up becomes significant and the energy deposited by alpha particles greatly exceeds the initial energy in the fusion fuel ("ignition")**

- **Typical conditions are:** $\rho R \approx 0.4\,\mathrm{g/cm^2}$

  $T \approx 5\,\mathrm{keV}$ (50,000,000 K)

For hot spot ignition fusion fuel must be brought to a pressure of a few hundred billion atmospheres

Sandia National Laboratories



ρ, R, T

For ignition conditions: $\left\{ \begin{array}{l} \rho R \approx 0.4\,\mathrm{g/cm^2} \\ T \approx 5\,\mathrm{keV} \end{array} \right\}$

$$E_{HS} \propto m_{HS} T_{HS} \propto \rho_{HS} R_{HS}^3 T_{HS} \propto \frac{(\rho_{HS} R_{HS})^3 T_{HS}^3}{P_{HS}^2}$$

P_{HS}^2 ~$(CR)^6$
~$(\text{velocity})^6$

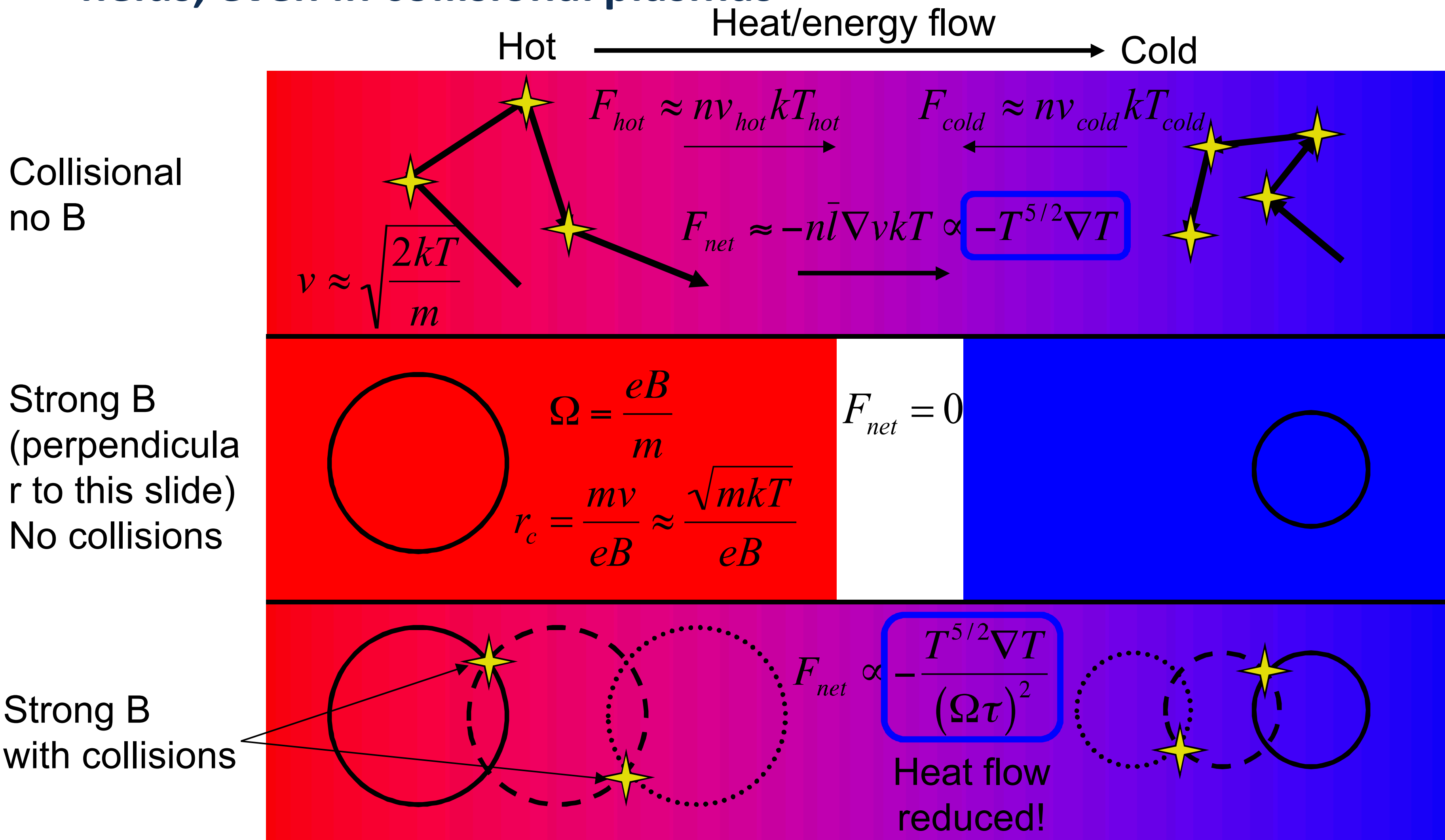
$E_{NIF} \sim 15\,\mathrm{kJ} \Rightarrow P \sim 400\,\mathrm{GBar}$ $\quad R \sim 30\,\mu\mathrm{m} \Rightarrow$ and $\rho \sim 130\,g/cm^3$

This is consistent with detailed calculations

Note: The key challenge for ICF is to make the fuel both ***dense*** and ***hot***. This leads to challenging compression requirements—a NIF capsule has a radial convergence of 35-45x, for a volume compression of ~50,000!

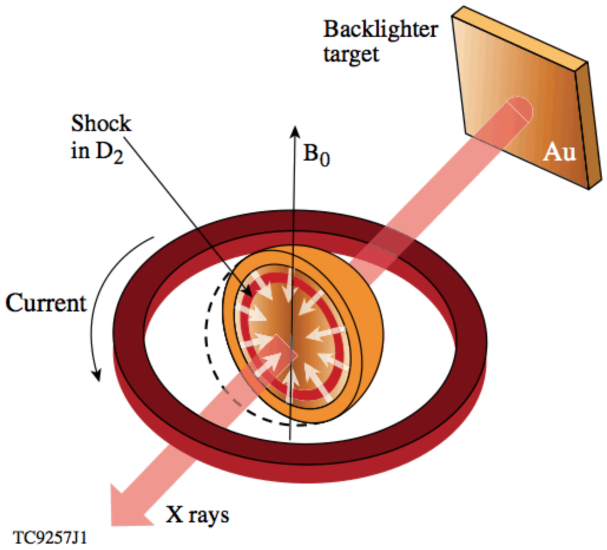
Magneto-inertial fusion is based on the idea that energy and particle transport can be reduced by strong magnetic fields, even in collisional plasmas

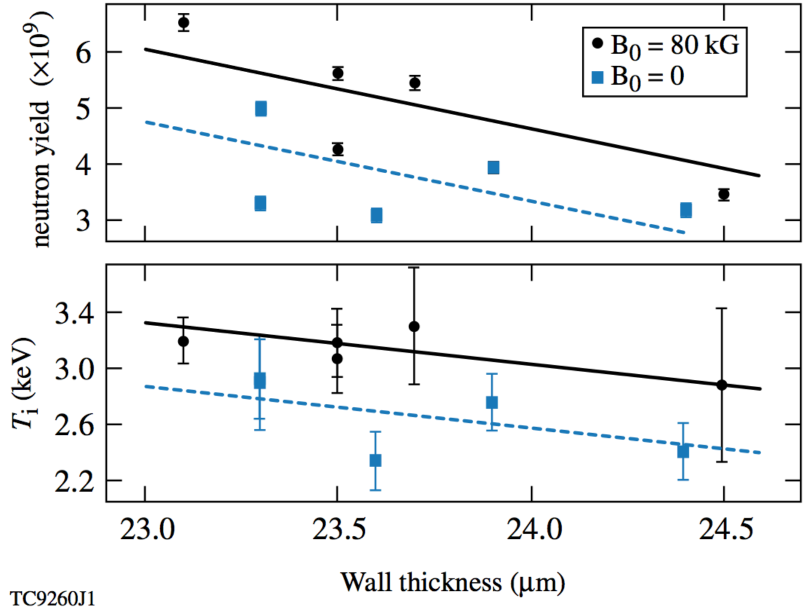
Sandia National Laboratories



"Anomalous" heat transport can reduce the benefit of magnetic fields (e.g., in tokamaks) but there remains a significant benefit

Laser-driven spherical capsule implosions at the University of Rochester* showed clear indicators of higher temperatures (and yields) due to fuel magnetization

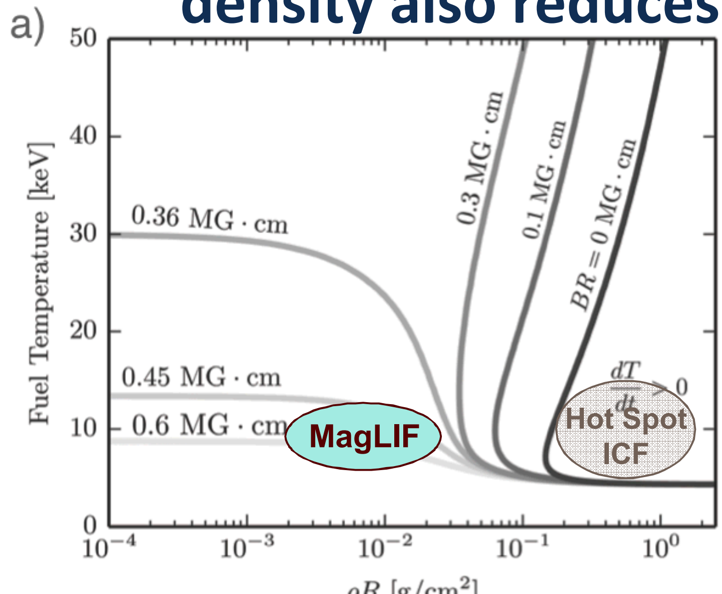




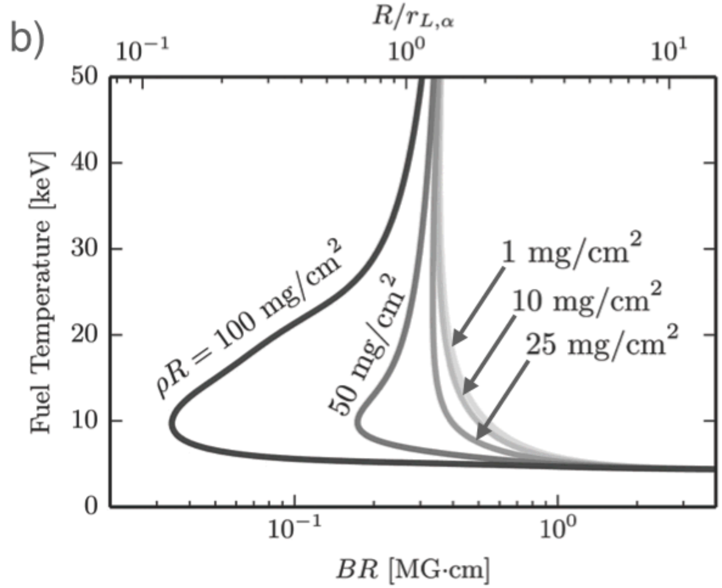
- Simple axial field used in a spherical implosion geometry
- Field suppressed electron heat conduction losses along one direction
- The resulting 30% increase in temperature and 15% increase in yield is consistent with rough estimates for heat loss suppression
- This is an example of success with a target that produced fusion yield without magnetization—can we produce yield in targets that wouldn't produce significant yield otherwise? (and gain benefit from doing so?)

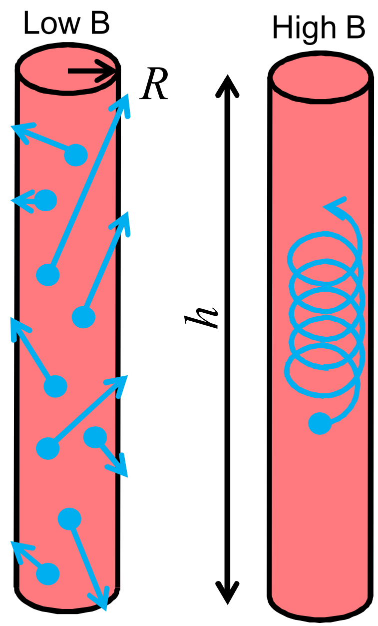
* P.Y. Chang *et al.*, Phys. Rev. Lett. 107, 035006 (2011).

Magnetization ("BR") can be used to reduce rho-R requirements and reduce electron heat losses, lower density also reduces bremsstrahlung radiation losses



$$\frac{R}{r_\alpha} = \frac{BR\,[T\cdot\mathrm{cm}]}{26.5} = \frac{BR\,[G\cdot\mathrm{cm}]}{2.65e5} \approx 4BR\,[MG\cdot\mathrm{cm}]$$





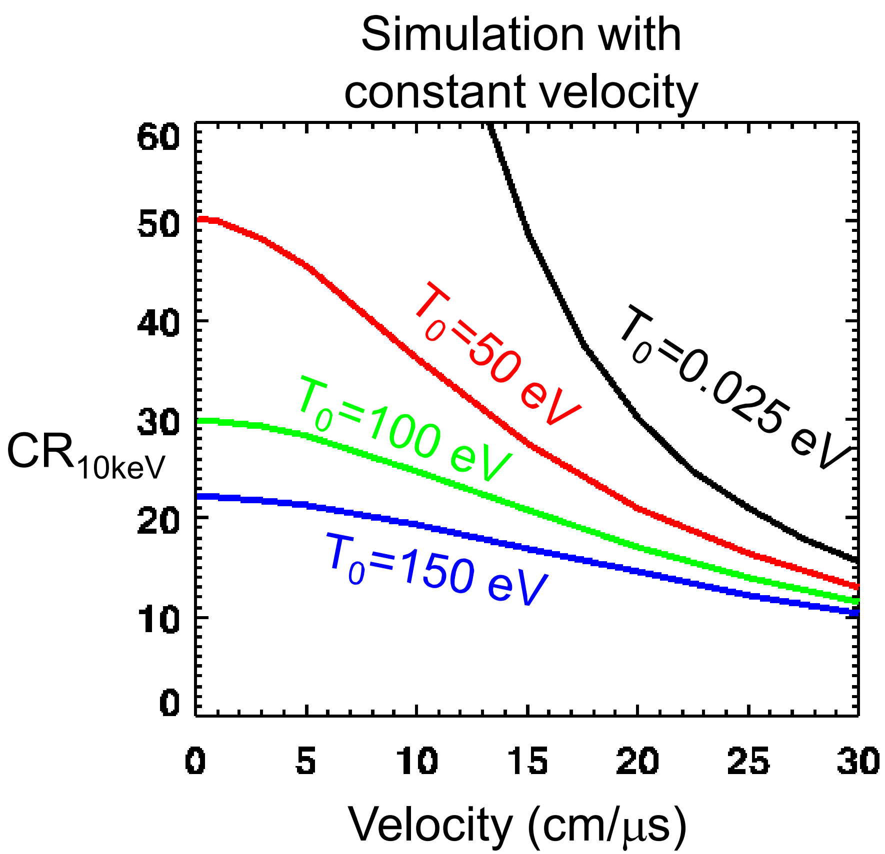
Fraction of trapped α's (tritons) is a function of ***BR*** only

At BR>0.5 MG-cm the effects saturate (particles are well confined). Measurements to date suggest 0.4 MG-cm!

Basko *et al*. Nuclear Fusion 40, 59 (2000); P.F. Knapp *et al*., Phys. Plasmas (2015).

Typical ICF implosions need high velocities to reach fusion temperatures—starting the implosion with heated fuel potentially reduces requirements

Sandia National Laboratories



CR_{10keV} = Convergence Ratio (R_0/R_f) needed to obtain 10 keV (ignition) with no radiation losses or conductivity

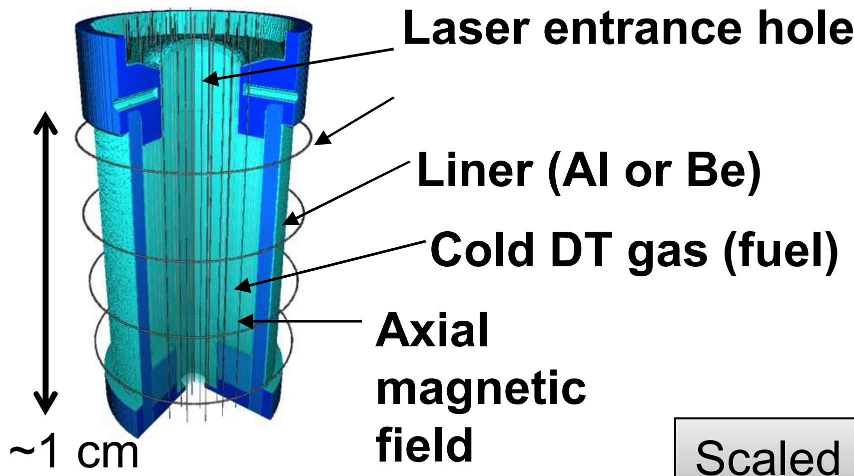
Heating fuel to ignition temperatures is typically done with a high-velocity shock (or series of shocks)

High velocities make it easier to reach fusion temperatures and also reduce the time available for losses (e.g., electron heat conduction or radiation)

Heating the fuel prior to the implosion ***in the absence of losses*** can allow low-velocity, low-convergence implosions to reach ignition temperatures – **magnetization is the key!**

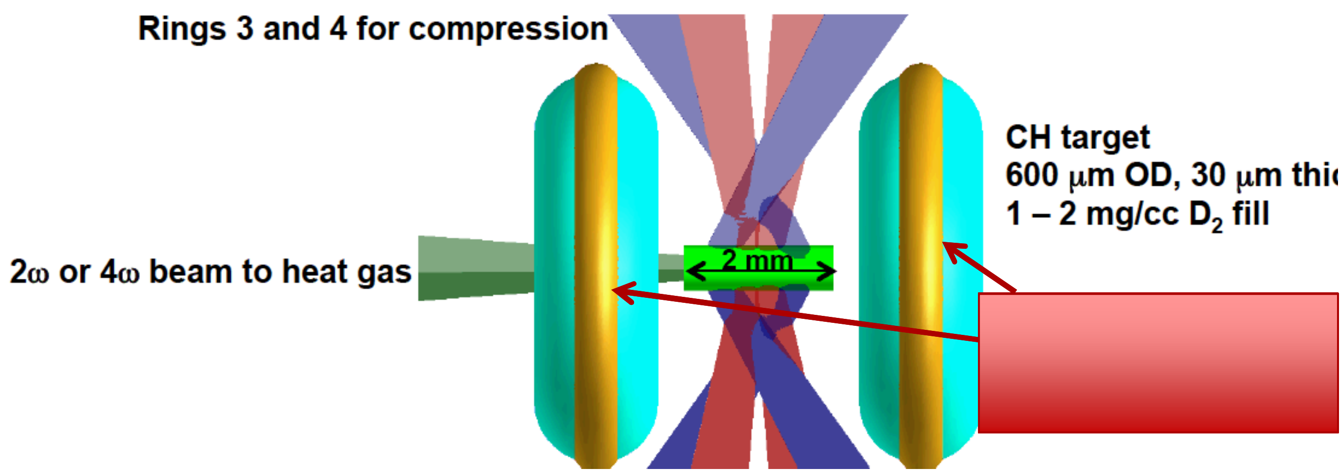
We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that is well suited to pulsed power drivers and that may reduce fusion requirements

MagLIF on Z



- Axial magnetization of fuel/liner (B_{z0} = 10-30 T)
  - Inhibits thermal conduction losses, may help stabilize liner compression, ions magnetized too (β: 5~80; $\omega\tau$>200)

Scaled MagLIF on OMEGA

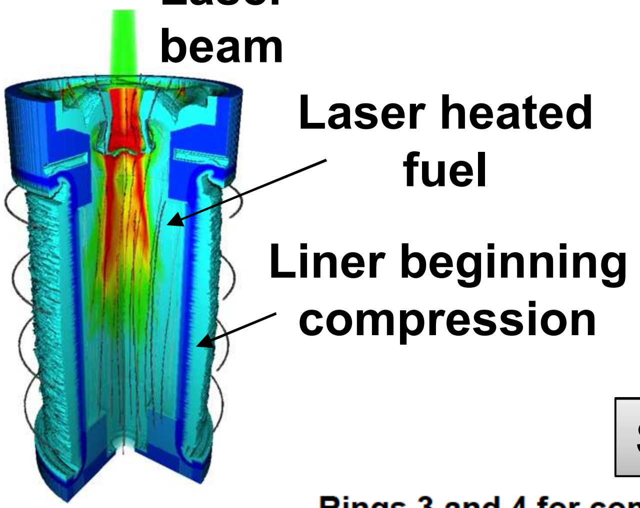


*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

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

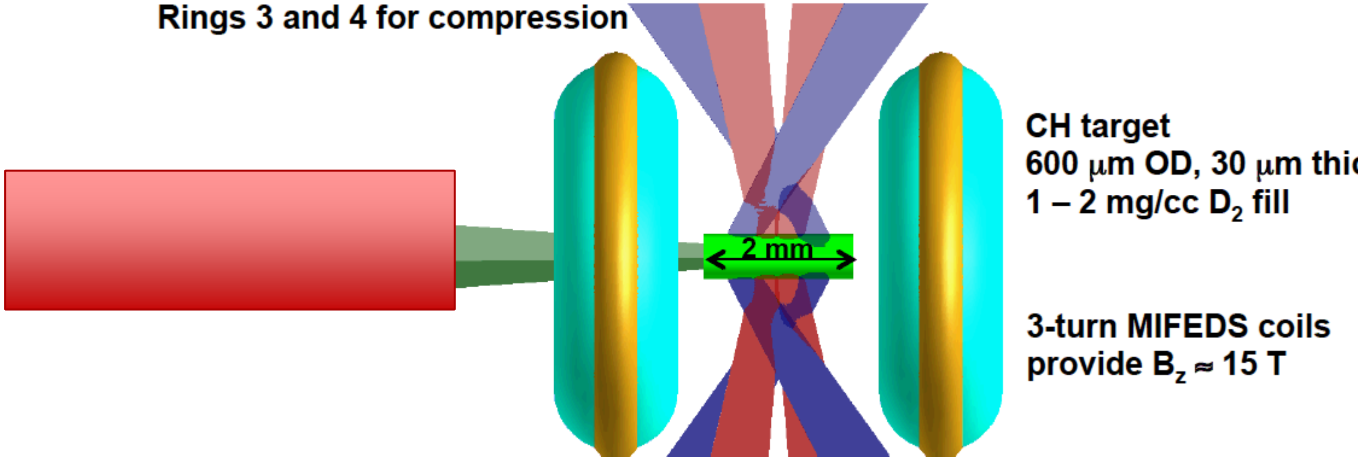
Sandia National Laboratories

MagLIF on Z



- <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)

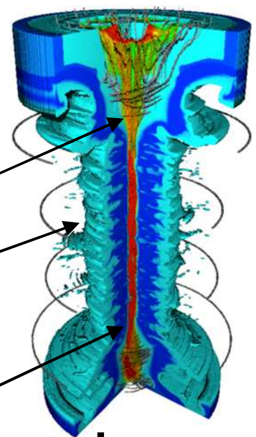
Scaled MagLIF on OMEGA



*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).

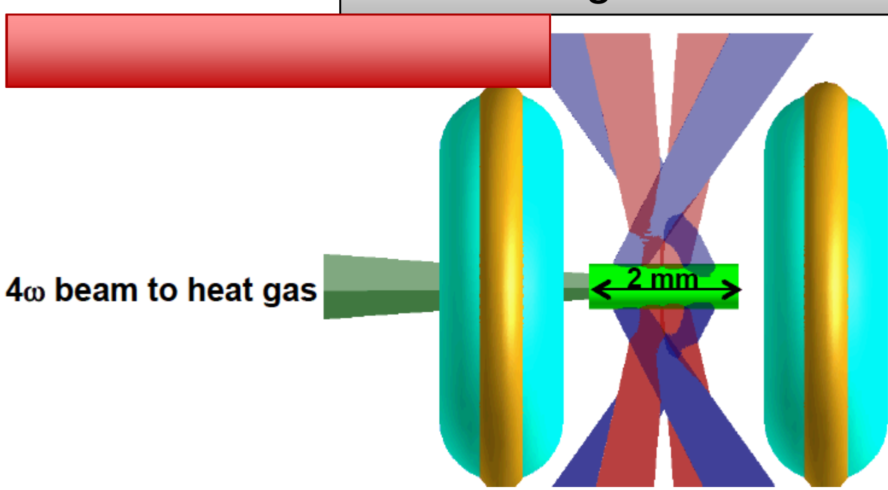
We are evaluating a Magnetized Liner Inertial Fusion (MagLIF)* concept that is well suited to pulsed power drivers and that may reduce fusion requirements

MagLIF on Z



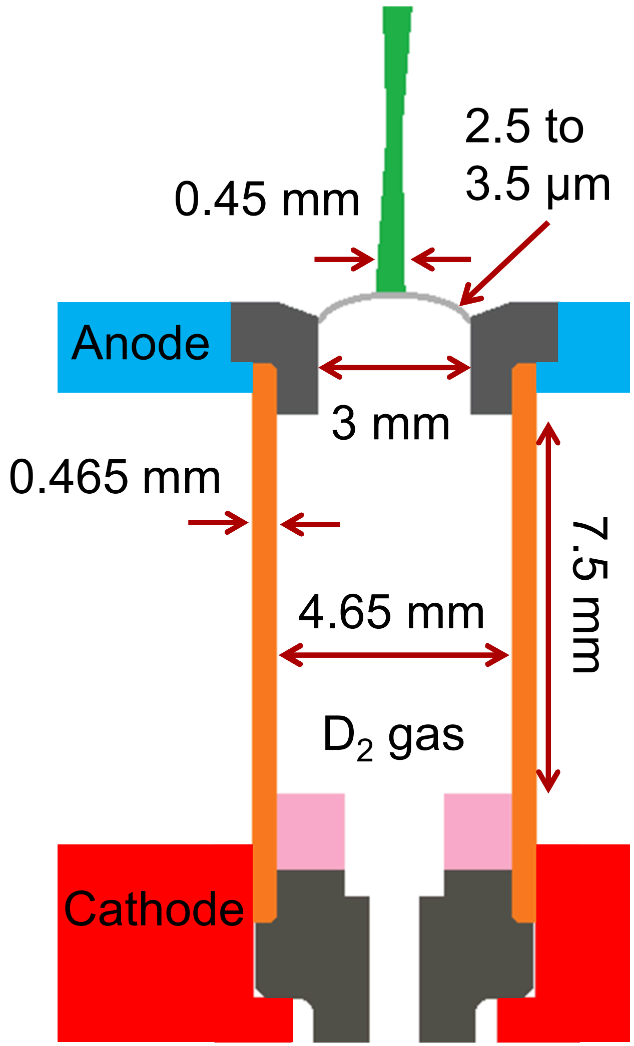
- <u>Liner compression</u> of fuel (70-100 km/s, ~100 ns)
  - "Slow", quasi-adiabatic compression of fuel
  - Low velocity requirements allow use of thick liners ($R/\Delta R$~6) that are robust to instabilities (need sufficient ρR at stagnation to inertially confine fuel)

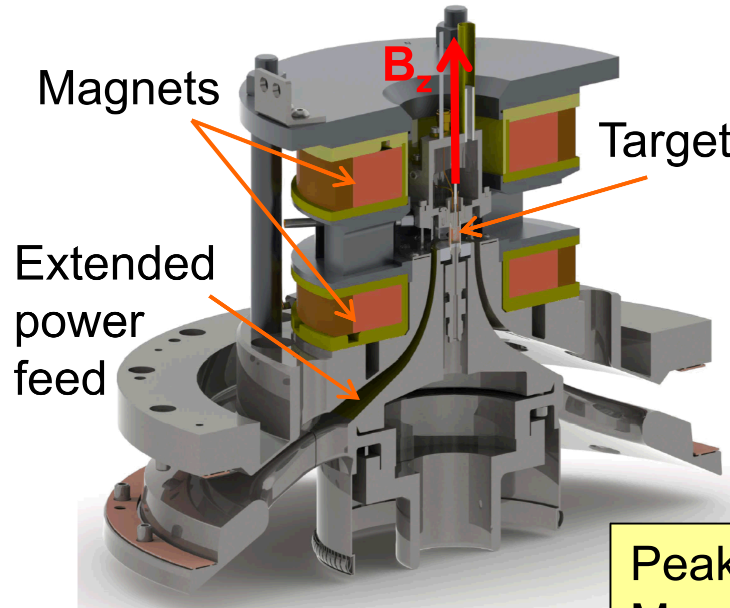
Scaled MagLIF on OMEGA

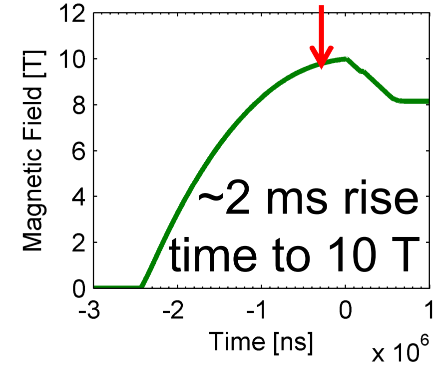


*S.A. Slutz *et al.*, Phys Plasmas (2010); S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

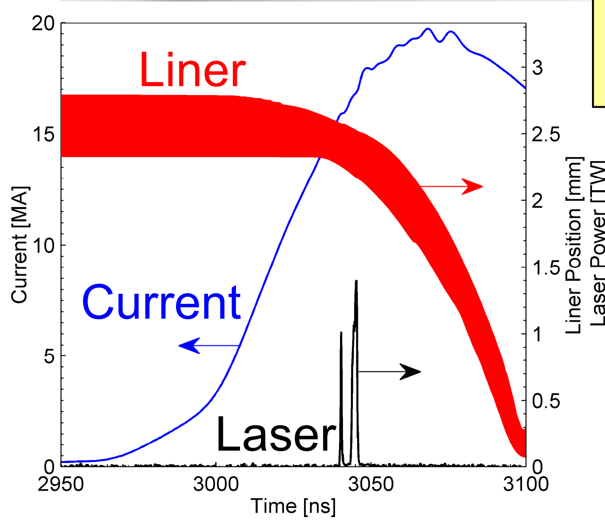
The initial experiments used 10 T, 2.5 kJ laser energy, and 19-20 MA current to drive a D_2 filled (0.7 mg/cc) Be liner

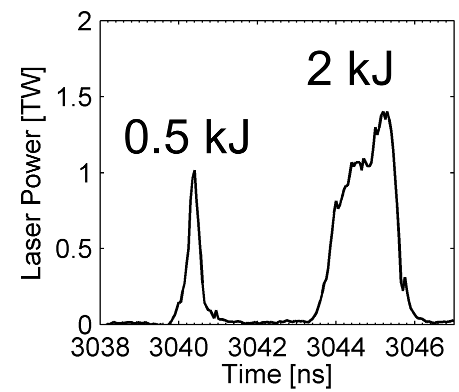






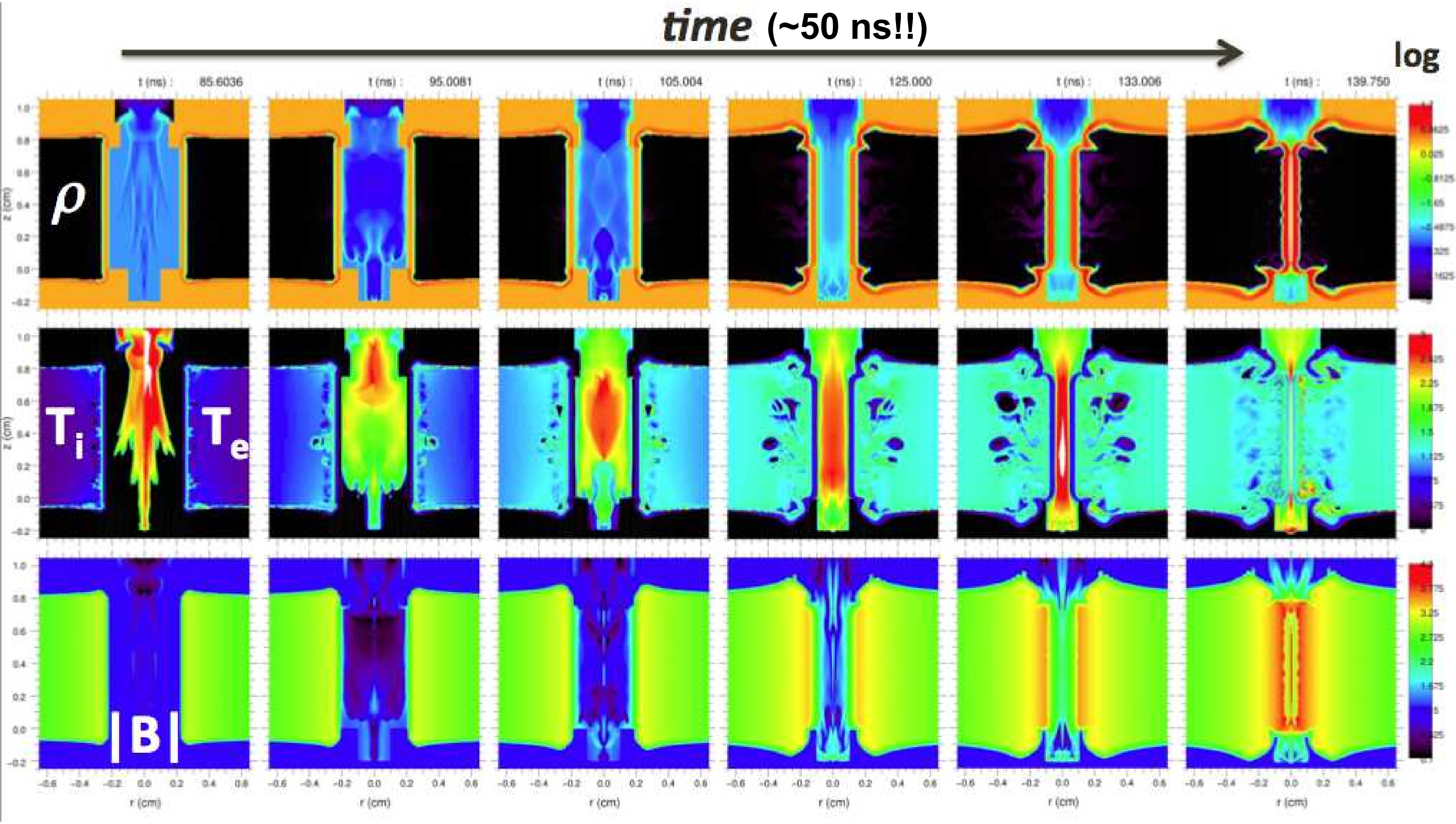
Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ





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

Example fully-integrated HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ) illustrate the stages of a MagLIF implosion

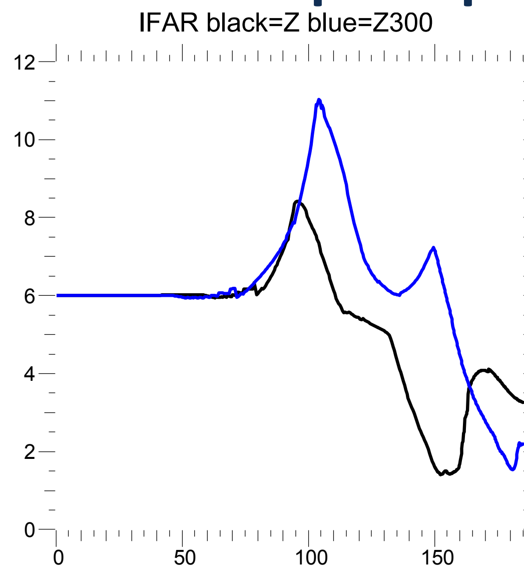


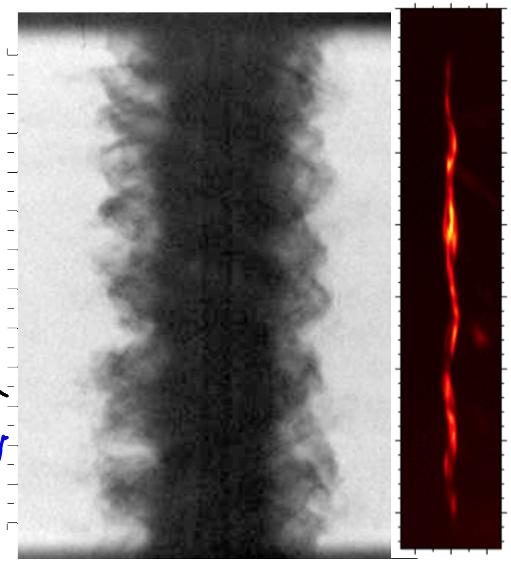
A.B. Sefkow, S.A. Slutz *et al.*, Phys. Plasmas 21, 072711 (2014).

Relative to the primary ICF approach, MagLIF uses a very different (conservative?) fuel compression method and largely untested magneto-inertial fusion principles

Sandia National Laboratories

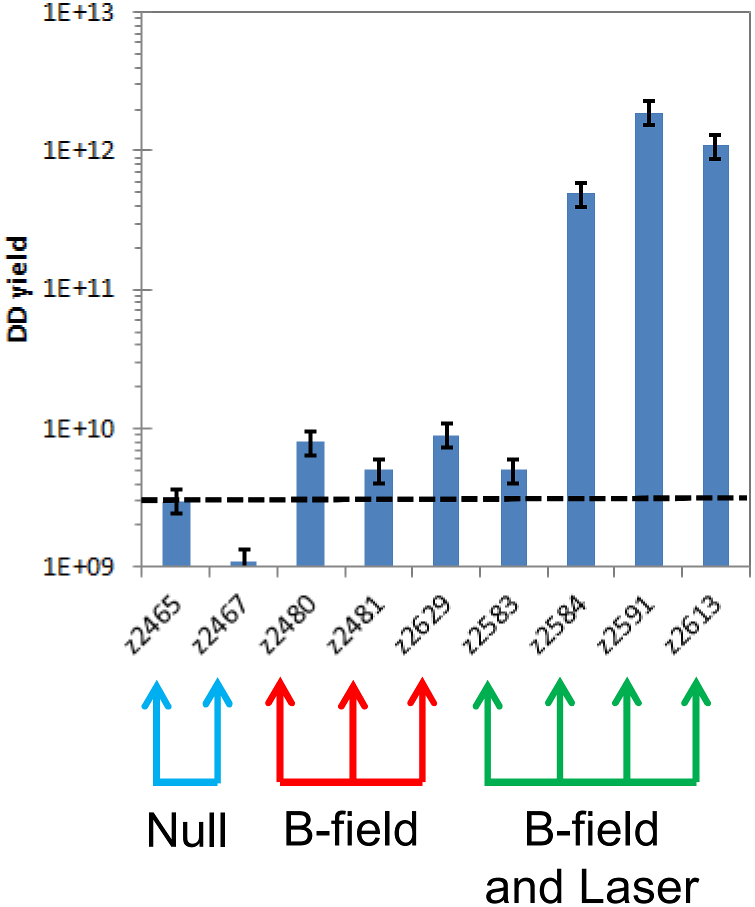
Metric	X-ray Drive on NIF	100 kJ MagLIF on Z
P	~140-160 Mbar	26 MA at 1 mm is 100 Mbar
P vs. R	Goes as R^2	Goes as 1/R^2
Drive nature	Surface-like	Can be significant redistribution from diffusion & low-density plasma
Peak velocity	350-380 km/s	70-100 km/s
IFAR	17 (high foot) to 20 (low foot)	8.5
Hot spot CR	35 (high foot) to 45 (low foot)	25
Volume Change	42875x to 91125x (high & low foot)	625x
Fuel rho-R	>0.3 g/cm^2	~0.003 g/cm^2
Liner rho-R	n/a	>0.3 g/cm^2
BR	n/a	>0.5 MG-cm
Burn time	~0.02 ns	~2 ns
T_ion	>4 keV	>4 keV





- By traditional ICF implosion metrics MagLIF is very conservative, though different P vs. R
- Reaching fusion conditions relies on largely untested MIF principles
  - Long stagnation time (2 ns) → more susceptible to high-Z contamination
  - Magnetic suppression of heat transport

Z shots producing DD yields in excess of 10^{12} were only observed in experiments with laser and B-field



- **High yields were only observed on experiments incorporating both applied magnetic field and laser heating**
- **Experiments without laser and/or B-field produced yields at the background level of the measurement**

1D Simulation

Bz	Preheat Energy	Peak Fuel <Ti>
0	0	0.5 keV
0	2 kJ	0.92 keV
10 T	0	0.33 keV
10 T	2 kJ	3.00 keV

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

Backups

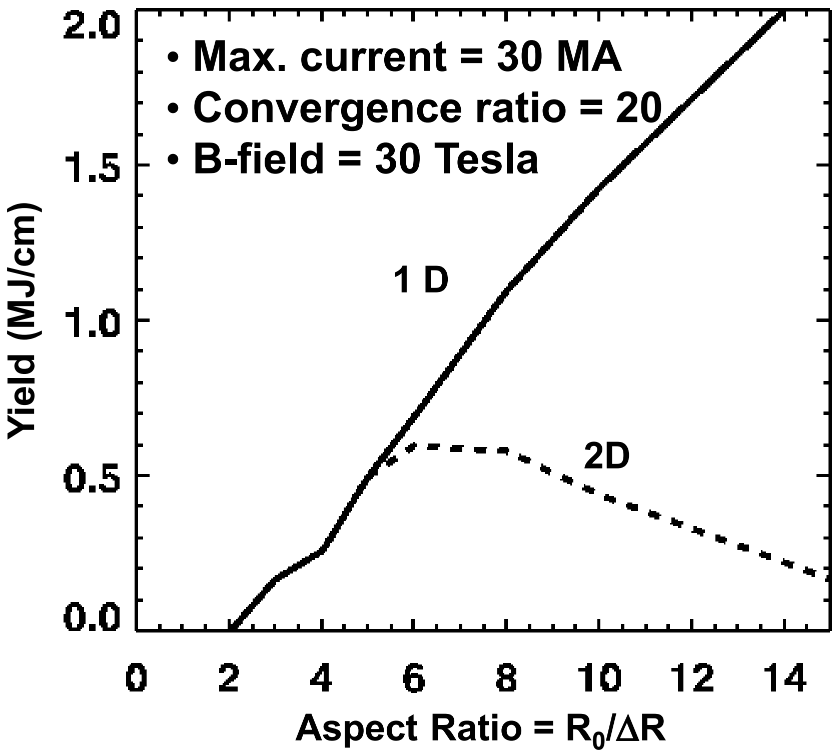
Comparison of 1D and 2D HYDRA calculations of near-term Z experiments (19 MA, 10 T, 2 kJ)

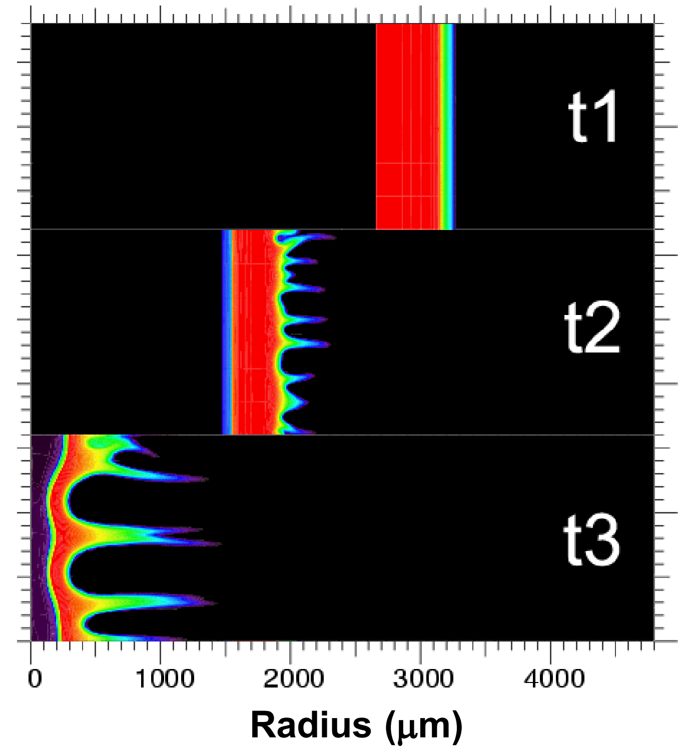
Parameter	1D ideal	2D integrated
• E_{gas}^{abs}	2.20 kJ	1.74 kJ
• m_{loss}	0%	43%
• Φ_{loss}	36%	38%
• CR_{2D}	28 (r_{stag} 84 μm)	37 (r_{stag} 63 μm)
• T_i^{peak}	5.0 keV	6.5 keV
• $<T_i>^{DD}$	2.9 keV	3.2 keV
• ρ_{gas}^{stag}	0.6 g cm^{-3}	0.5 g cm^{-3}
• ρR_{liner}^{stag}	1.0 g cm^{-2}	0.9 g cm^{-2}
• p^{stag}	2.5 Gbar	2.2 Gbar (peak in bottle)
• $B_z^f r_{stag}$	4.1e5 G cm (r_{stag}/r_α 1.5)	5.3e5 G cm (r_{stag}/r_α 2.0)
• Y_n^{DD}	2.6e14 (in 7.5mm)	6.1e13 (24% of 1D)
• Y_n^{DD}/Y_n^{DT}	23	44
• t_{burn}^{FWHM}	3.2 ns	2.1 ns

Note: A unique property of magnetic drive is increasing pressure with decreasing radius. If less energy is coupled to fuel, target converges farther in simulations until plasma pressure is sufficient to stop the implosion.

A.B. Sefkow, S.A. Slutz *et al.*, Phys. Plasmas 21, 072711 (2014).

Reducing the implosion velocity requirements through fuel heating and magnetization allows us to use thicker, more massive liners to compress the fuel that are more stable





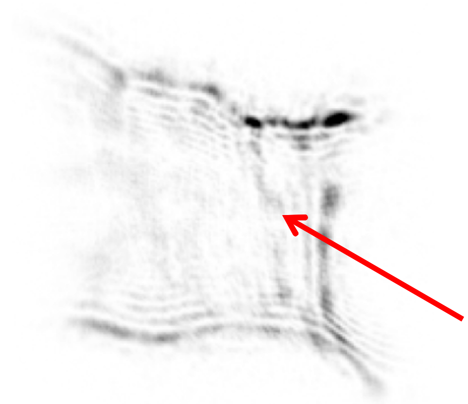
- The Magneto-Rayleigh-Taylor instability degrades the yield as the aspect ratio is increased (due to decreased liner ρR)

- Simulations of AR=6 Be liner show reasonably uniform fuel compression and sufficient liner ρR at stagnation to inertially confine the fuel—important because fuel density is low!

S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

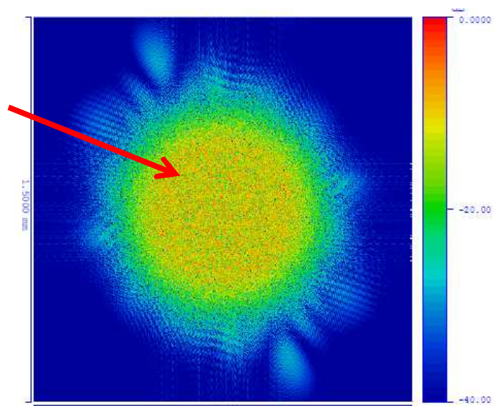
Poor beam spot quality may be one reason that we are struggling to couple well to the fusion fuel

Z-Beamlet currently does not use any beam smoothing techniques adopted by the laser community

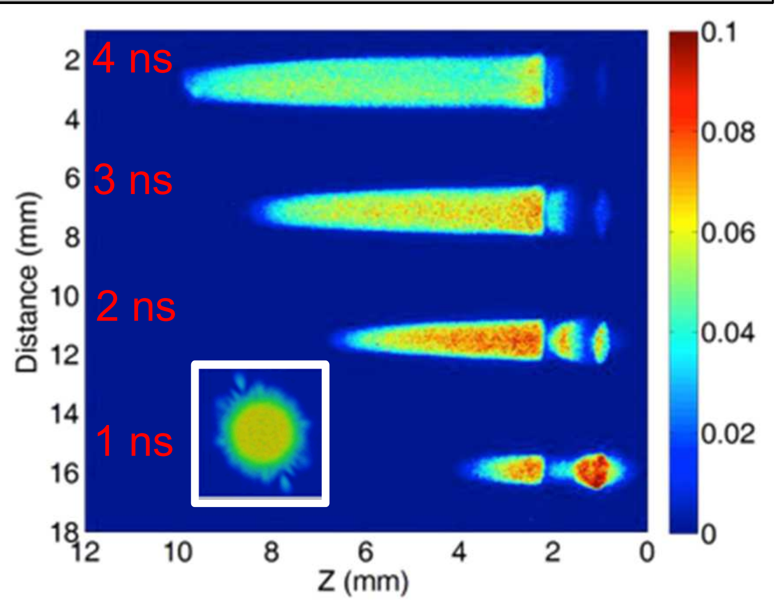


OMEGA-EP
750um DPP

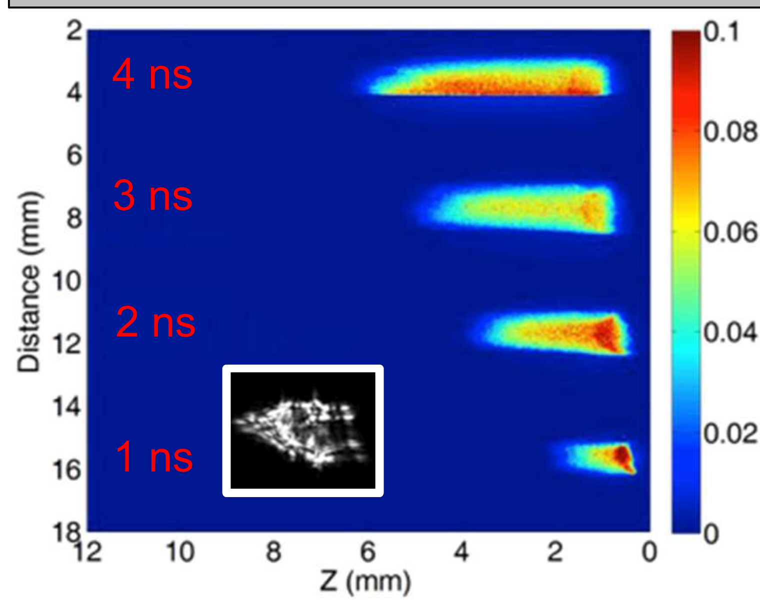
ZBL: No DPP
(representative)



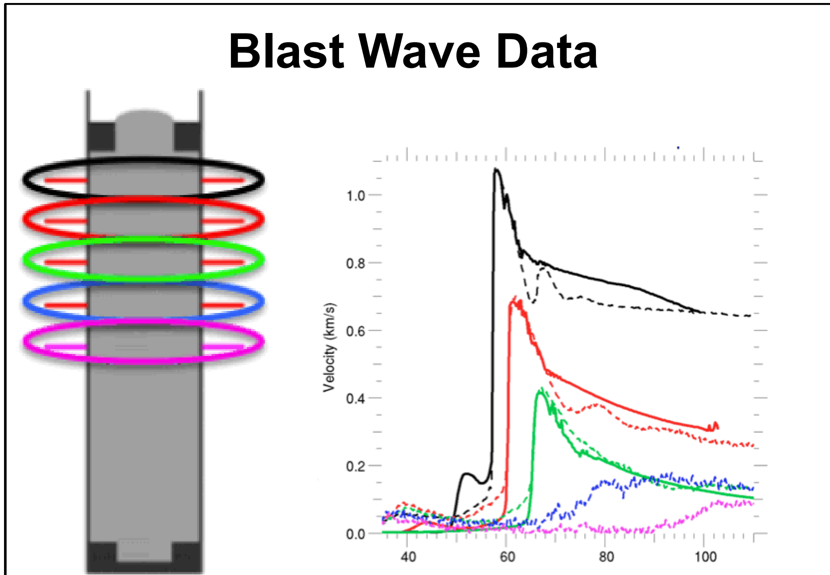
4 ns/3.1 kJ, 2 μm LEH, no prepulse
with DPP (SNL Omega-EP data)

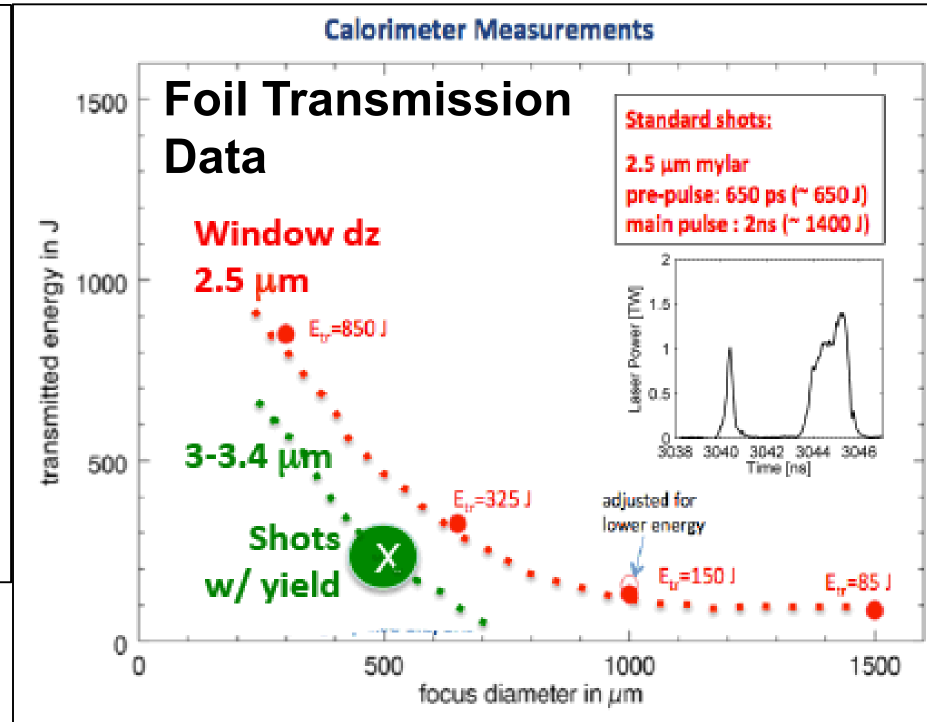


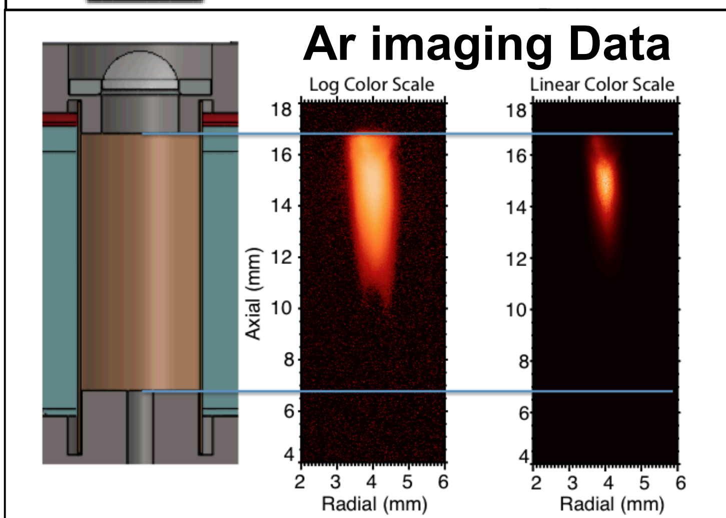
4 ns/2.93 kJ, 2 μm LEH, no prepulse
without DPP (SNL Omega-EP data)

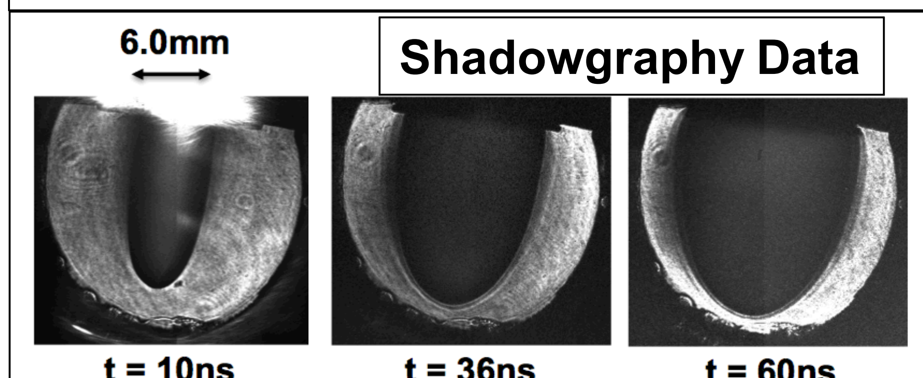


Laser-only experiments appear to confirm that laser-fuel coupling is a concern: Multiple measurements are consistent with 200-600 J in heated gas out of >2000 J



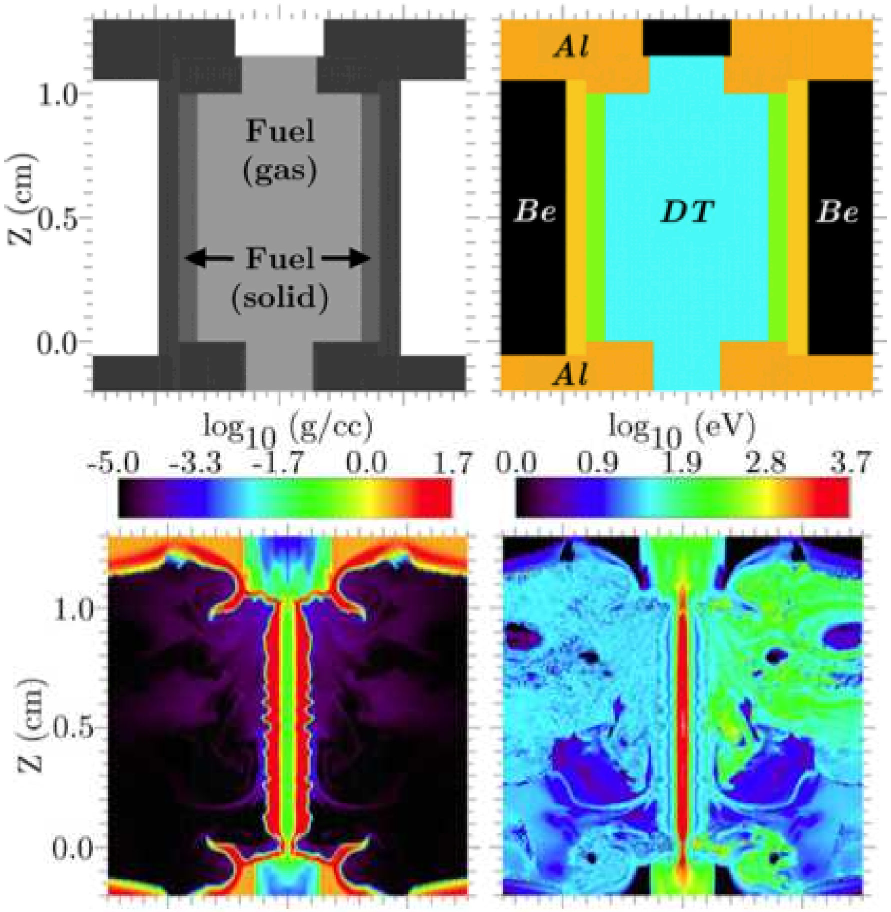


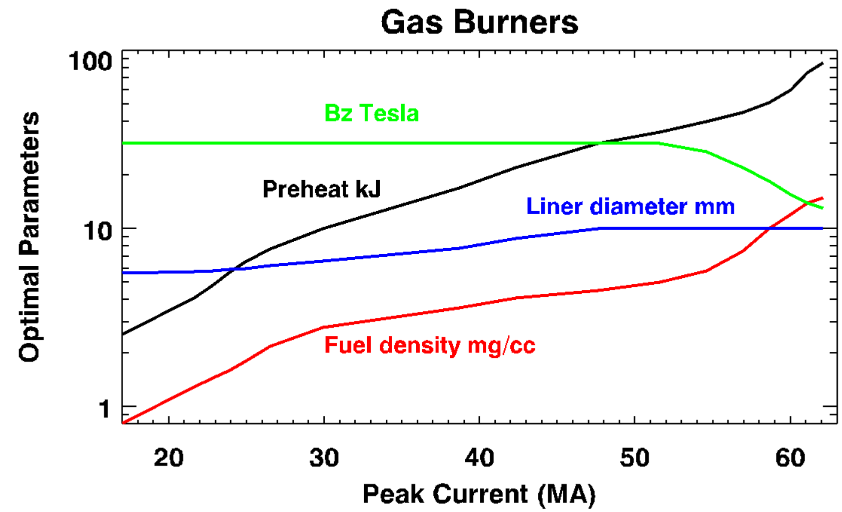


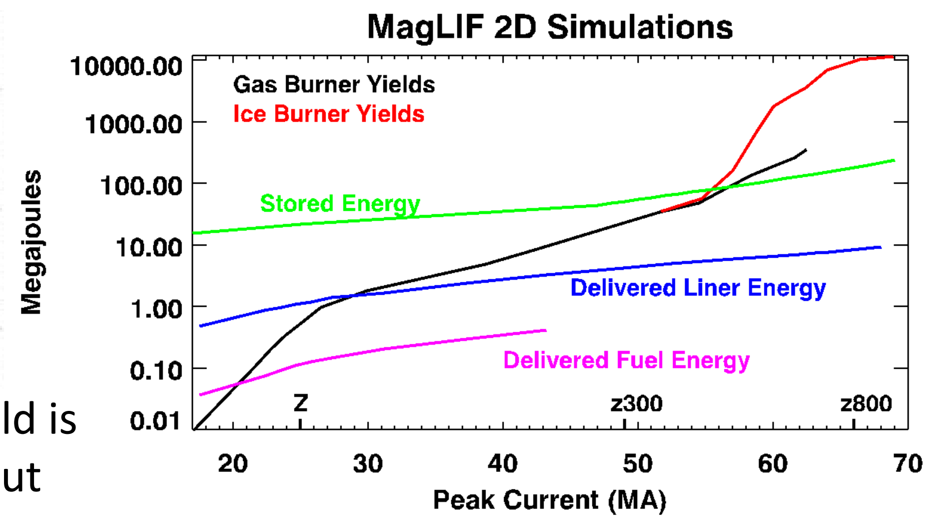


It may be possible to achieve ~100 kJ yields on Z. Achieving alpha heating and ignition may be possible on a future facility. A cryogenic DT layer could enable up to ~1 GJ yield.

Sandia National Laboratories







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

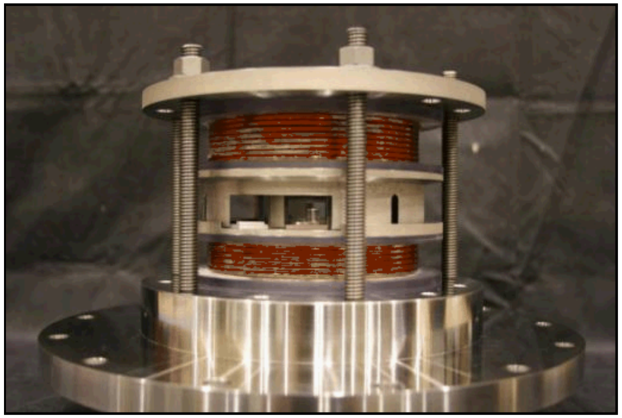
S.A. Slutz and R.A. Vesey, Phys Rev Lett (2012); A.B. Sefkow *et al.*, Phys Plasmas (2014).

We have successfully implemented 10 T axial fields over a several cm^3 volume for MagLIF and the capacitor bank is capable of driving 30 T field coils under development

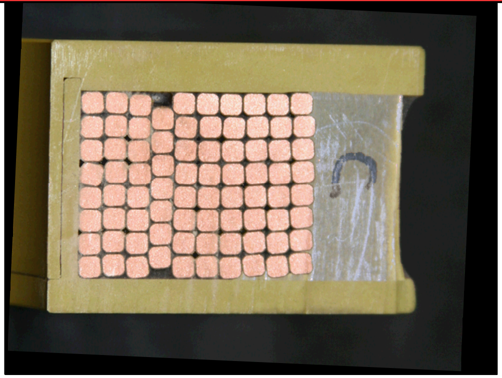
Sandia National Laboratories

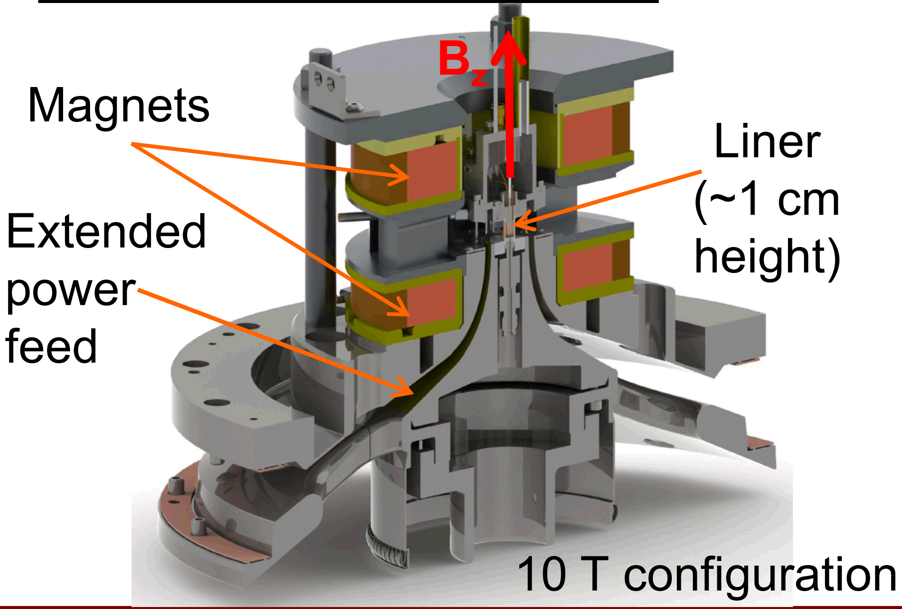
Capacitor bank system on Z
900 kJ, 8 mF, 15 kV (Feb. 2013)

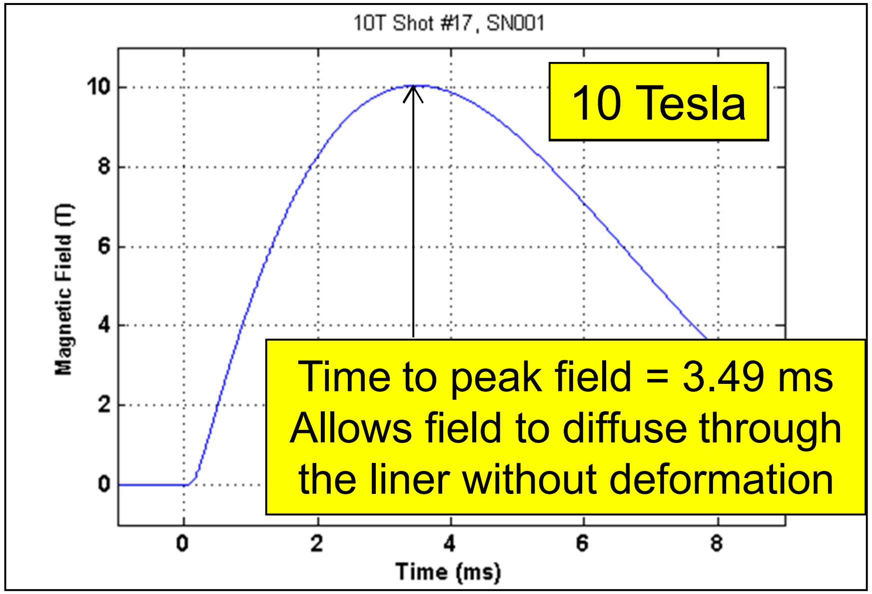
Example MagLIF coil assembly with copper windings visible



Cross section of coil showing Cu wire, Torlon housing, and Zylon/epoxy reinforcement

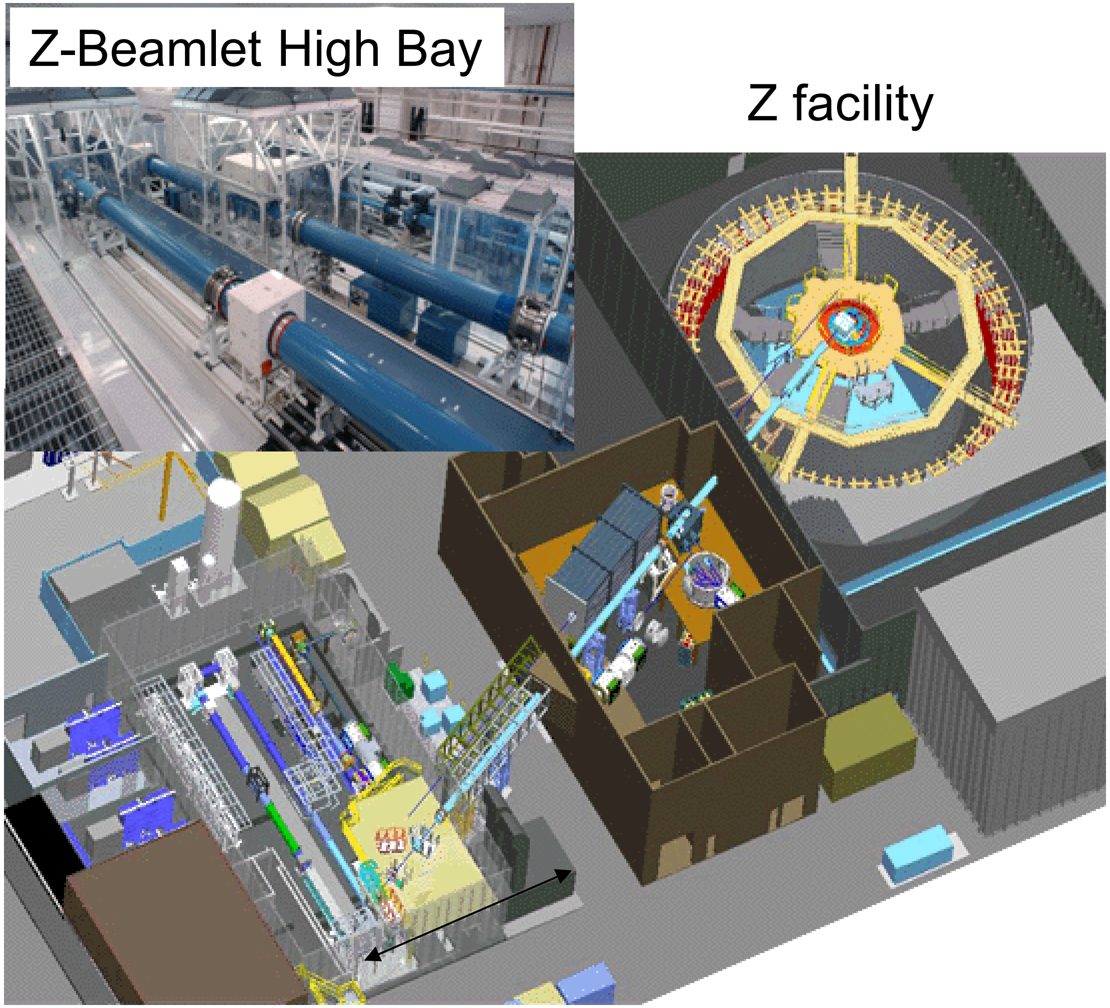






D.C. Rovang, D. Lamppa *et al.*, Rev. Sci. Instrum. (2014).

The Z-Beamlet laser at Sandia* can be used to radiograph liner targets and heat fusion fuel



Z-Beamlet and Z-Petawatt lasers

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

Modifications adding bandwidth to the laser enable us to reach 4-4.5 kJ in 4 ns today

Filling out the booster amps would enable longer pulses (5-7 ns) which would extract up to 6 kJ of 1ω, for 4.2 kJ of 2ω.

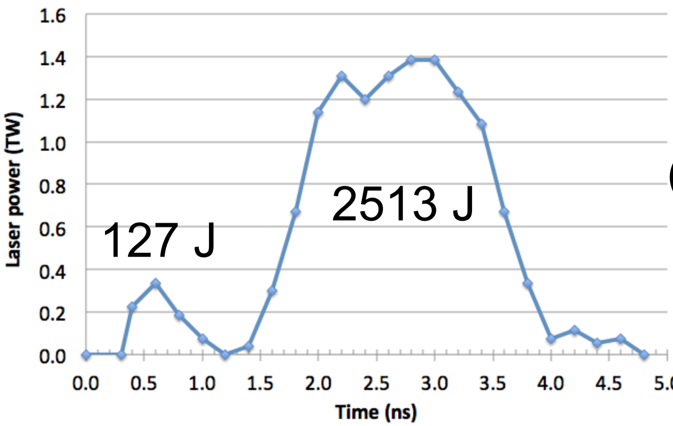
Typical MagLIF initial fuel densities correspond to 0.10 to 0.30 x critical density for 2ω

* P. K. Rambo *et al.*, Applied Optics 44, 2421 (2005).

In August 2013 we commissioned a new vacuum final optics assembly to safely enable 2 kJ of on-axis laser heating of fuel

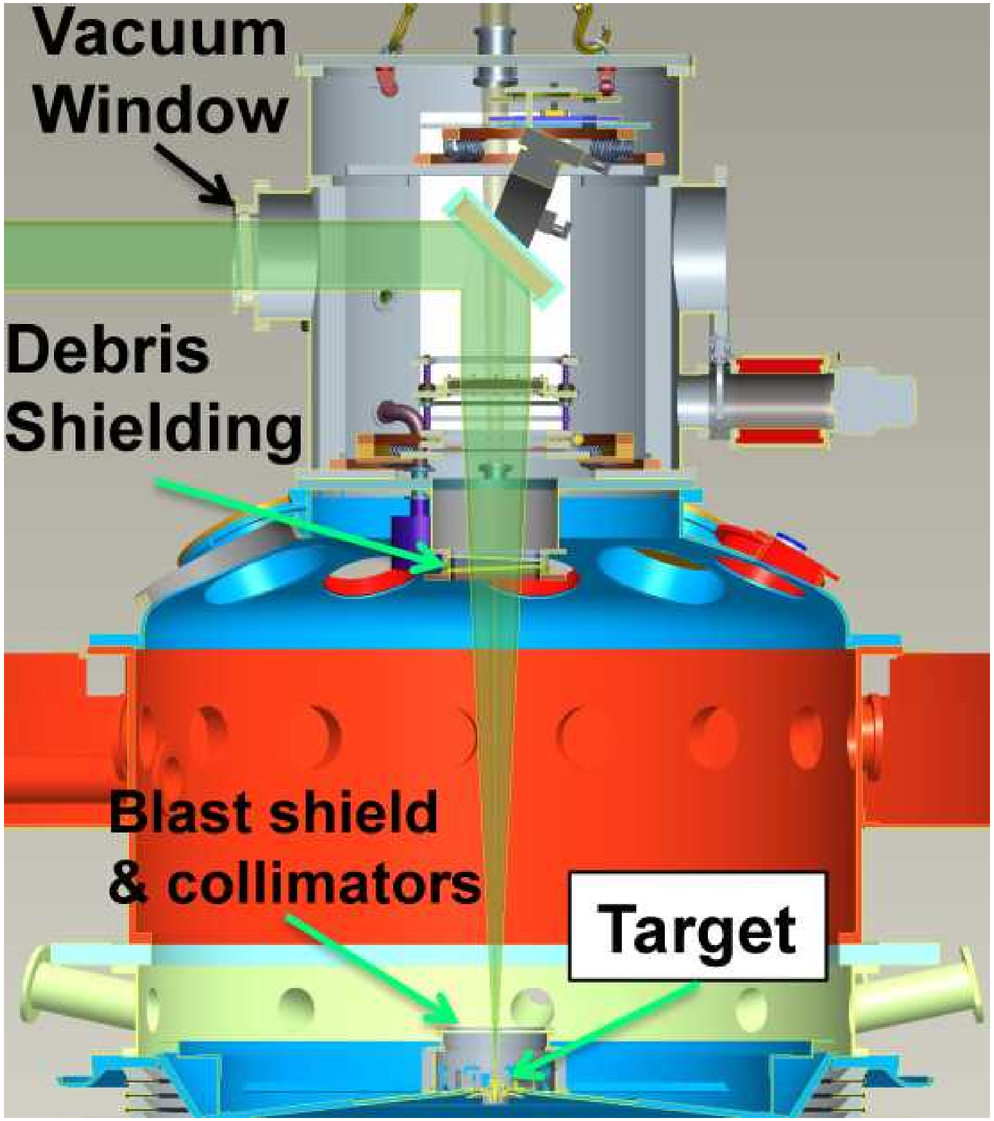
Sandia National Laboratories

Example pulse measurement



ZBL
2ω light
(2.64 kJ)

Prepulse vaporizes gas-containing foil; main pulse couples to DD fuel



Z couples several MJ of energy to the load hardware, ~equivalent to a stick of dynamite, making diagnostic measurements and laser coupling challenging

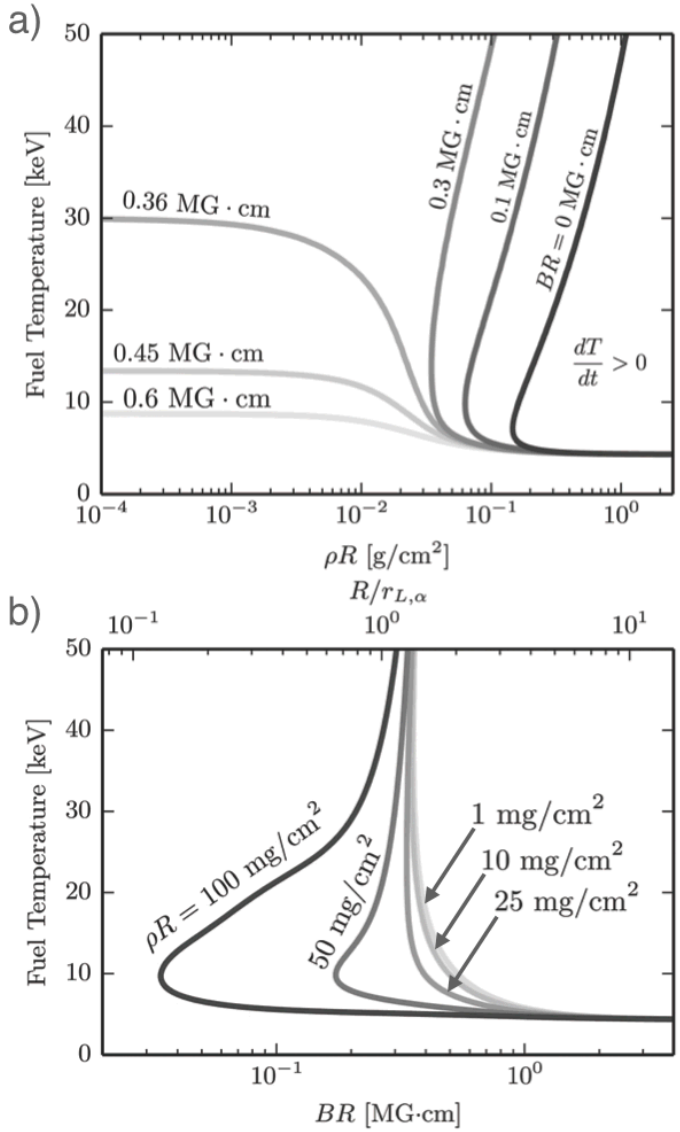
Pre-shot photo of MagLIF load hardware

Damage to FOA debris shielding

Post-shot photo

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

Sandia National Laboratories



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

Lower □r 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.*, Phys. Plasmas (2015).