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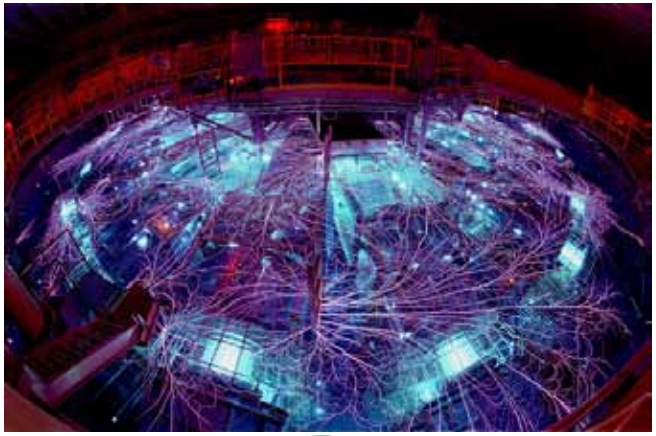

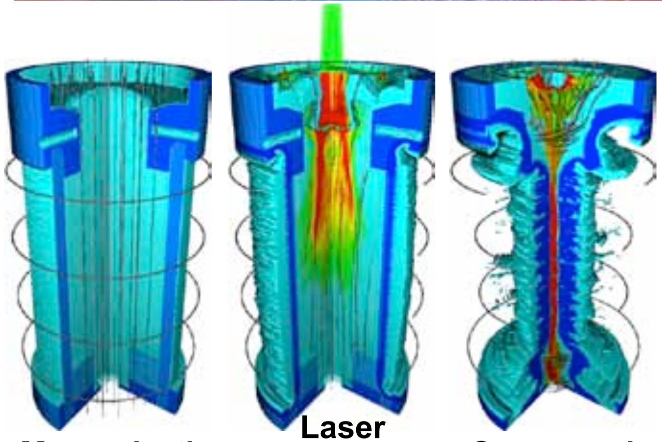

Magnetized Liner Inertial Fusion (MagLIF) Research: A Promising Beginning

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Sandia National Laboratories

High Energy Density Sciences Association Seminar
APS-DPP Meeting,
October 26-31, 2014

U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

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The Magnetized Liner Inertial Fusion (MagLIF) effort on Z has many direct and indirect contributors:

T.J. Awe, C.J. Bourdon, 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.H. Hess, C.A. Jennings, B. Jones, M. Jones, R.J. Kaye, P.F. Knapp, D.C. Lamppa, M.R. Lopez, M.R. Martin, R.D. McBride, L.A. McPherson, J.S. Lash, 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

B.E. Blue, D.G. Schroen, K. Tomlinson
General Atomics, San Diego, CA

M.C. Herrmann, D. Ryutov
Lawrence Livermore National Lab, Livermore, CA

+ Additional Collaborators at LLE, MIT, LANL, and Universities

+ Many additional support personnel at Sandia

The NNSA laboratories are collectively pursuing three main approaches to ignition

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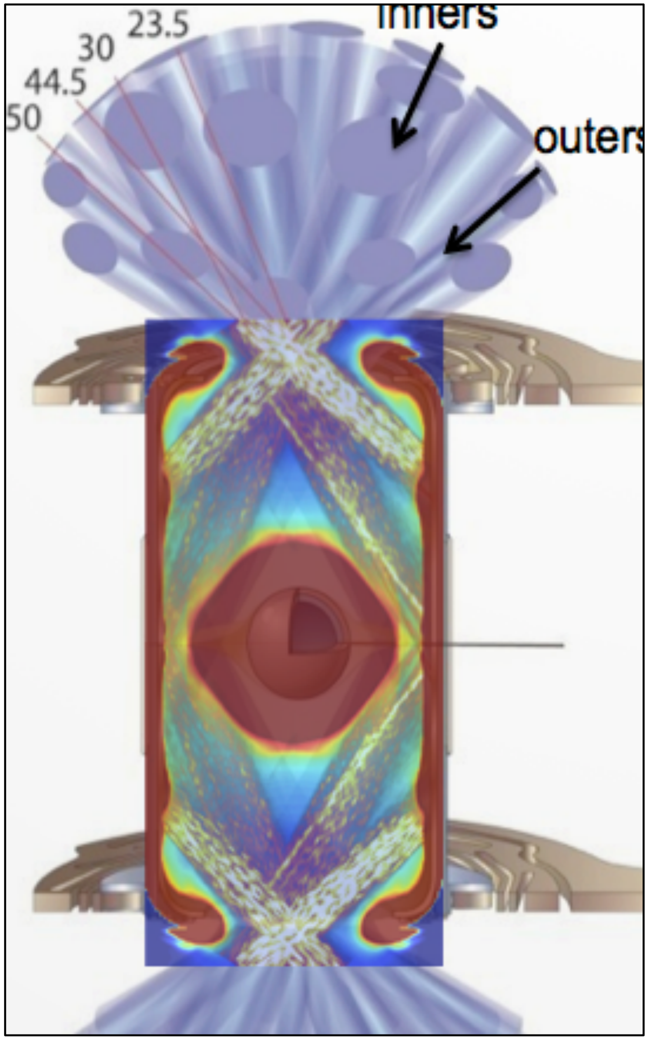
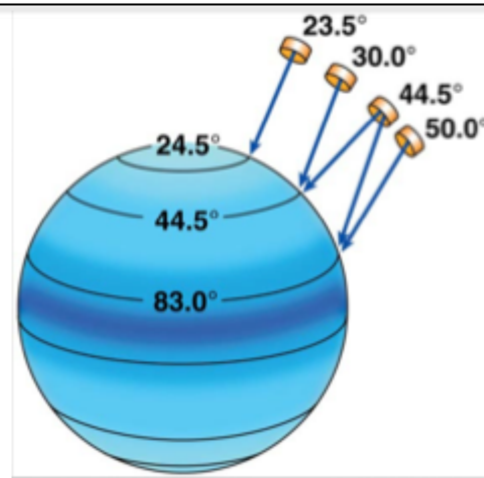
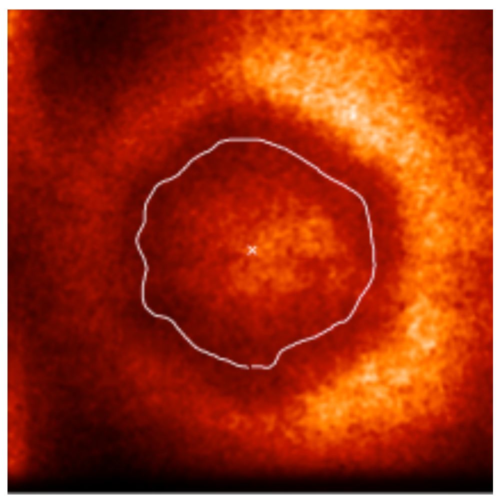
Radiation-driven implosions

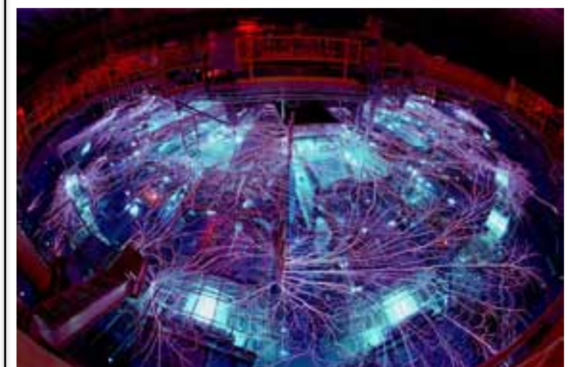


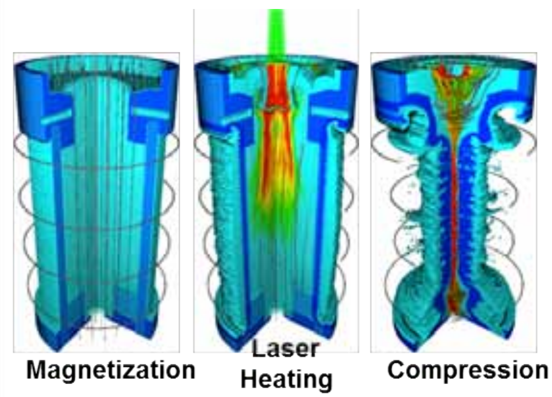
Laser-driven implosions





Magnetically-driven implosions





Focus of today's talk

The Sandia Z pulsed power facility uses magnetic pressure to efficiently couple energy to drive relatively large targets for a wide variety of stockpile stewardship applications

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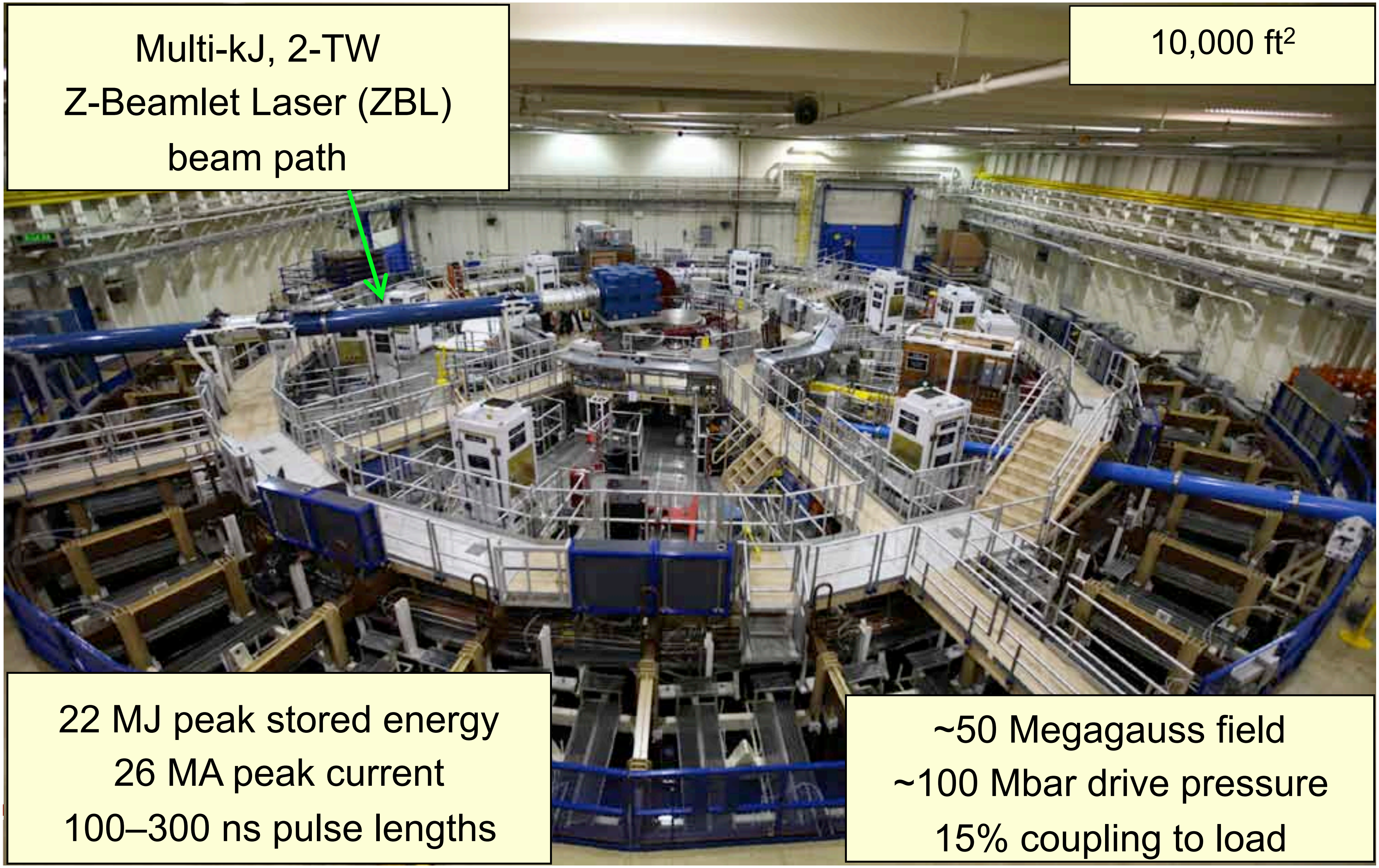

Magnetically driven implosions may be a compelling alternative path to significant fusion yields (>10s MJ) for stockpile stewardship applications

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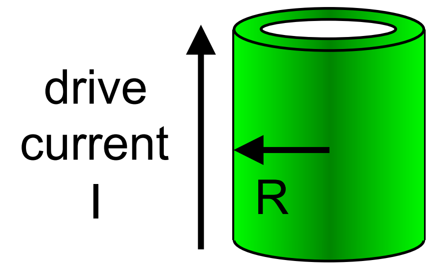
- Magnetic fields created by pulsed power can create the large drive pressures (high energy density) needed for fusion and stockpile stewardship
- Approach is fundamentally different than laser-driven target compression with unique physics, risks, and benefits
- Magnetic fields can also make laboratory fusion easier, e.g., strong fields can affect charged particles (electrons, alphas) and thus plasma heat transport and confinement properties

Magnetically-Driven Implosion

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

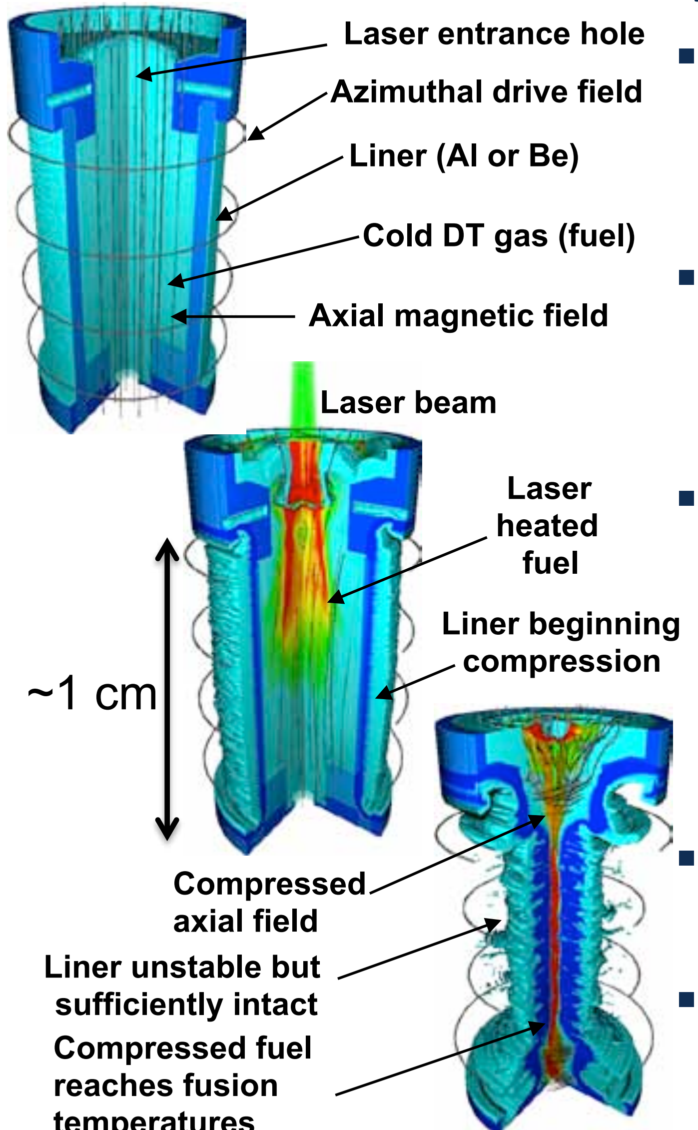


100 MBar at 26 MA and 1 mm

- 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 (>10s MJ). Z today couples ~0.5 MJ out of 20 MJ stored to MagLIF target (0.1 MJ in DD fuel).

Much work is needed to make this credible!

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 (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).

In principle, MagLIF designs achieve higher yields on future facilities using a cryogenic DT layer and substantial preheat

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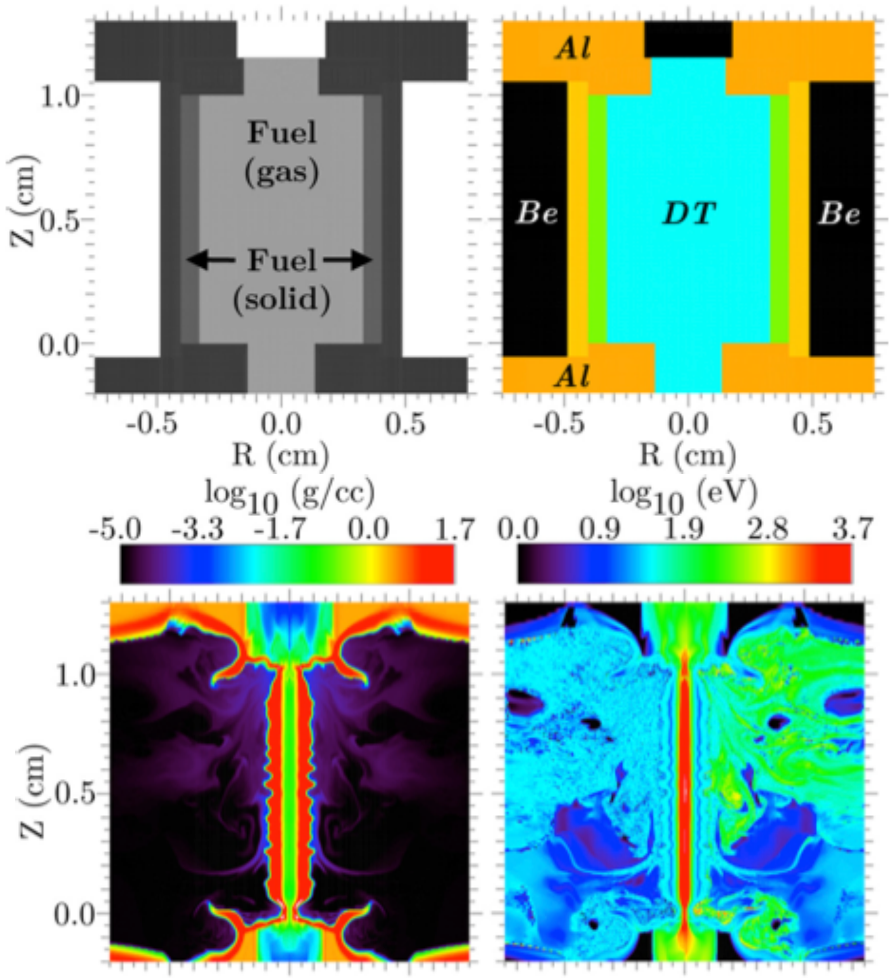
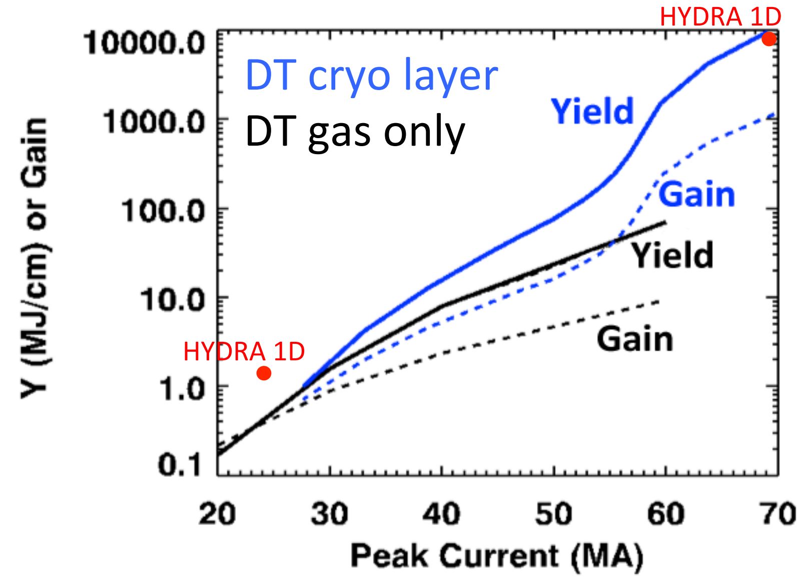
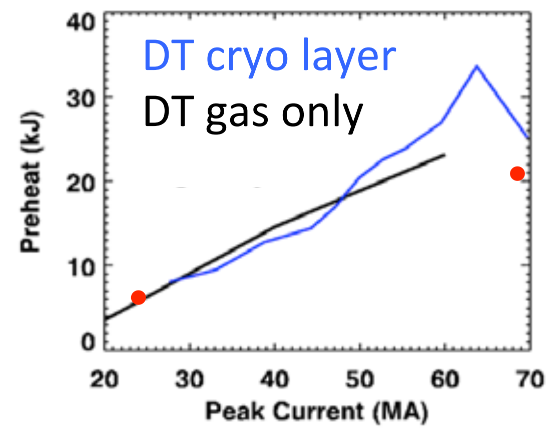






An intermediate regime exists wherein the B_z field is

- *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).

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

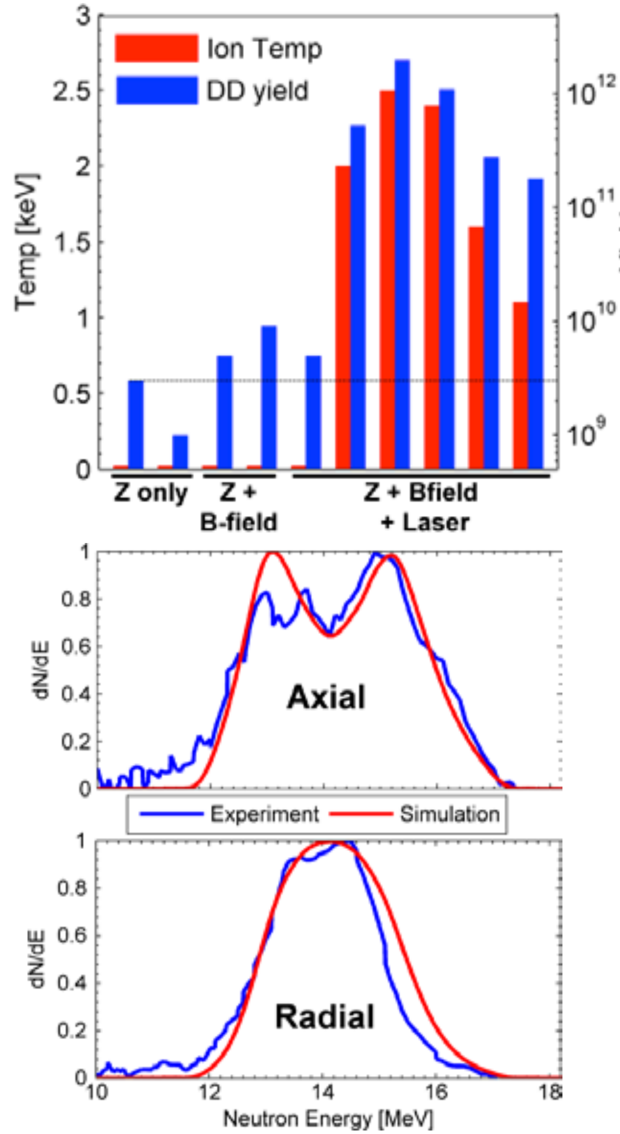
- **Study the underlying science** and major design elements using both "focused" and "integrated" experiments on multiple facilities (e.g., Z, Z-Beamlet, Omega, Omega-EP, universities, NIF a possibility)

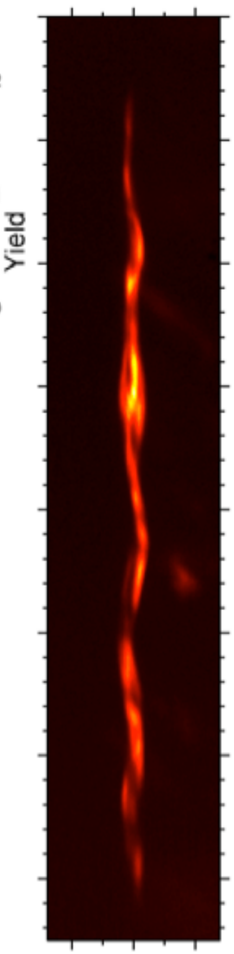
- **Demonstrate target scaling** on Z with enhanced drive conditions and/or better fuel assembly
  - DD equivalent of ~100 kJ DT yields may ultimately be possible on Z

- **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 (>10 MJ) & high-yield capable (~1 GJ) facilities
  - Develop the supporting technologies (pulsed power, cryo, etc.)

What have we learned about MagLIF so far? Several talks at this meeting will describe recent experiments on Z, Omega-EP, and other facilities

- Magnetized (10 T) and laser-heated (2 kJ) cylindrical Be targets reached ~3 keV temperatures and produced fusion yield (up to 2×10^{12} DD) at 70 km/s implosion velocity
  M.R. Gomez *et al.*, Phys Rev Lett (2014);
  M.R. Gomez, Invited talk CI.5 Monday
- 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);
  P.F. Knapp, Invited talk CI.3 Monday
- Detailed analysis of stagnation conditions consistent with thermonuclear yield, though less energy in fusing plasma than predicted
  S.B. Hansen, Invited talk CI.6 Monday
- Additional experiments on multiple facilities focused on specific physics issues (laser-gas coupling, liner dynamics, flux compression)
  —see **GO4 on Tuesday; JP8 on Tuesday**





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

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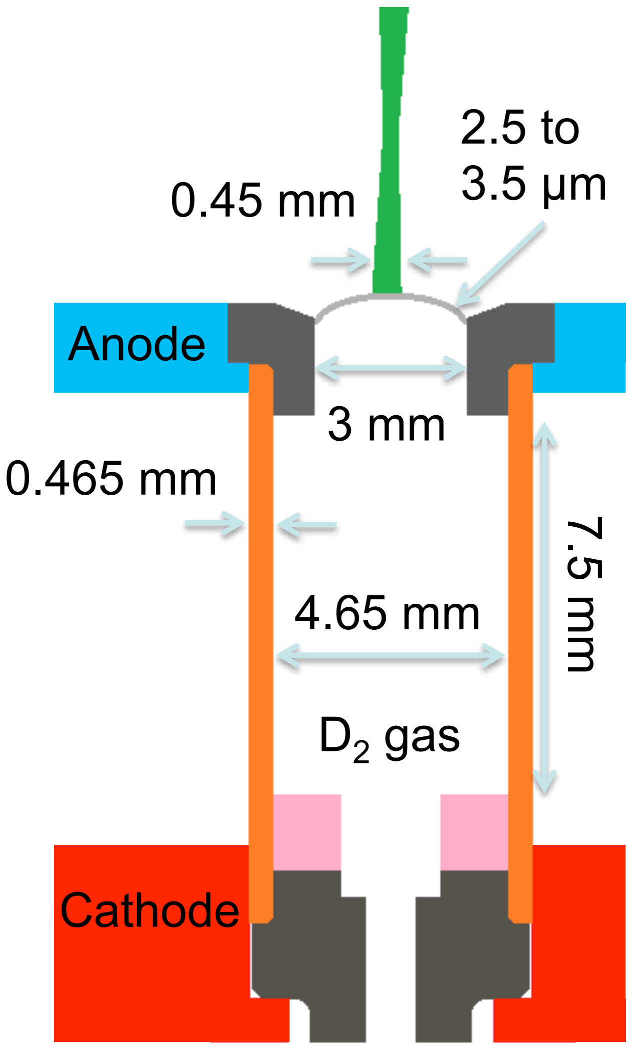
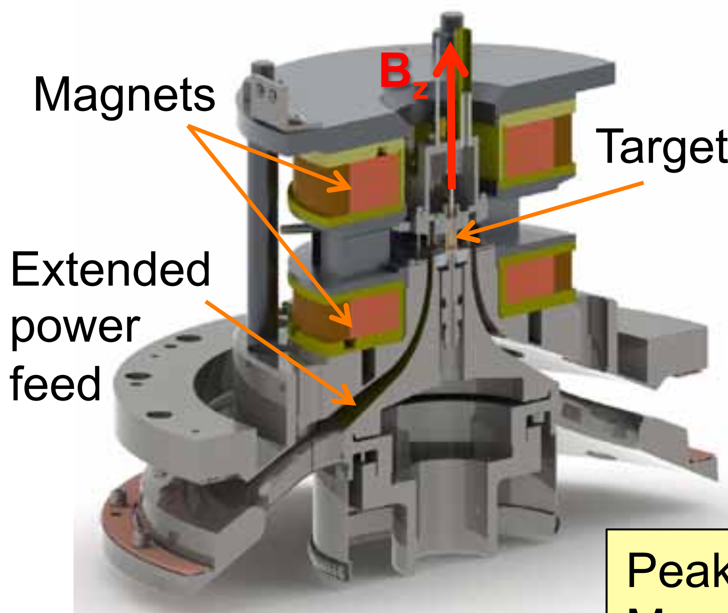
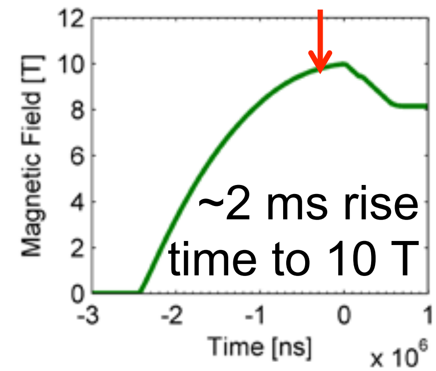
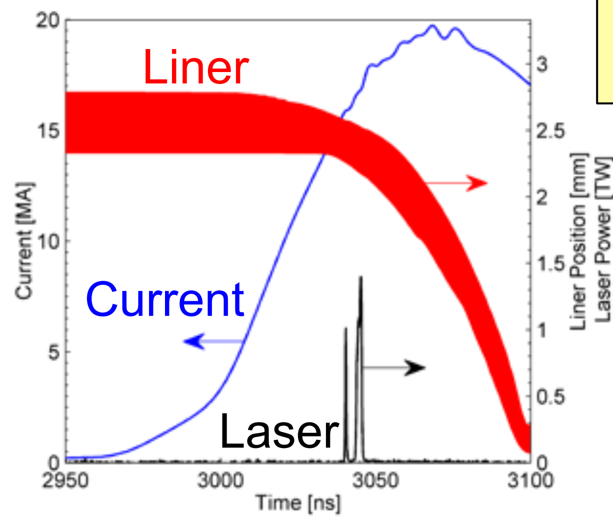
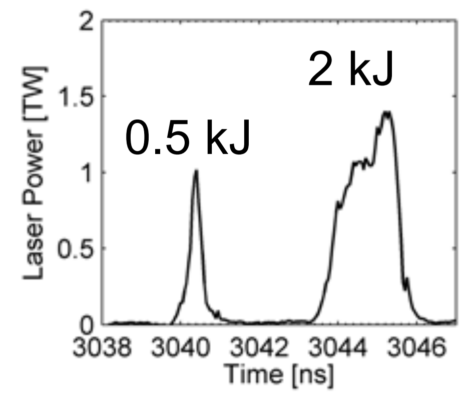






Peak current is 19 MA
Magnetic field is 10 T
Total laser energy is 2.5 kJ





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

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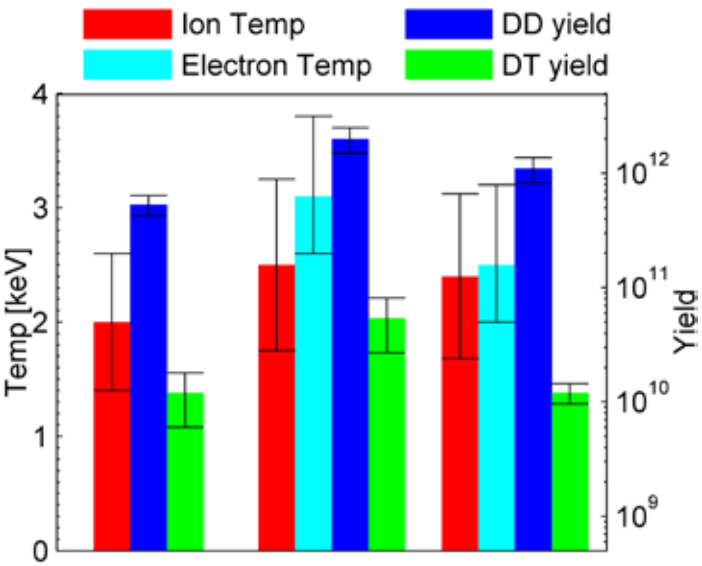
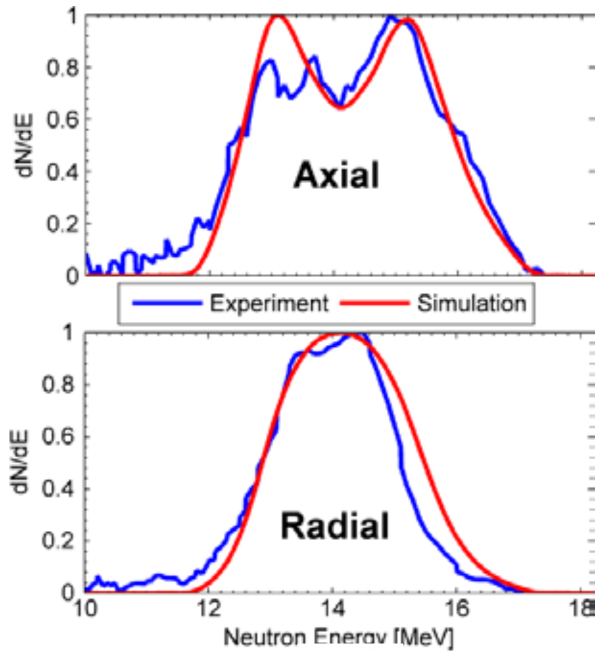
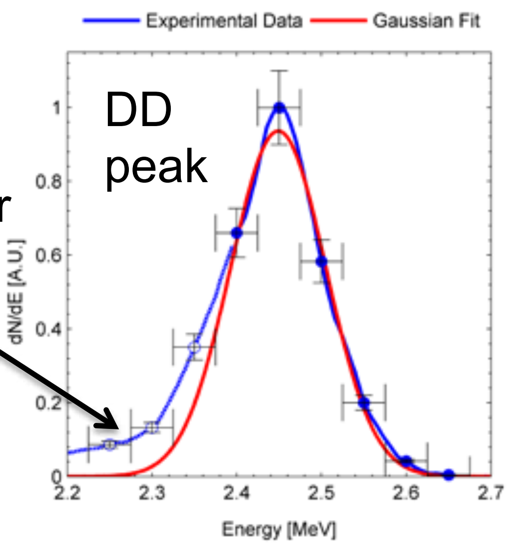
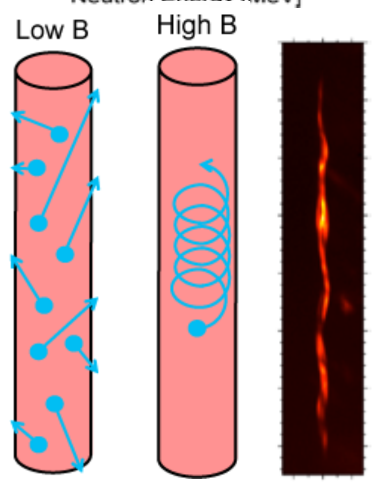




n scatter off Be liner around hot fuel





Inferred Stagnation Conditions

Volume = 2-5 x10^{-5} cm^3
Duration = 1-2 ns
ρ_{fuel} = 0.7-2 x10^{23} cm^{-3}
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).

While we are happy (and relieved) that MagLIF produced up to 2e12 DD yields, our pre-shot 2D calculations predicted yields in the mid-10^{13} range—can we improve the yield?

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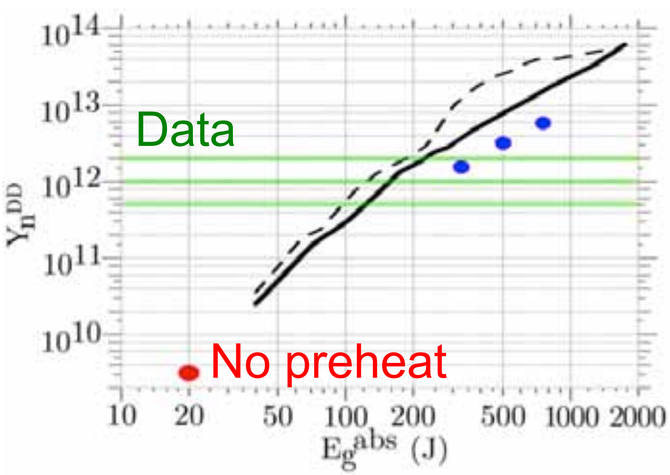
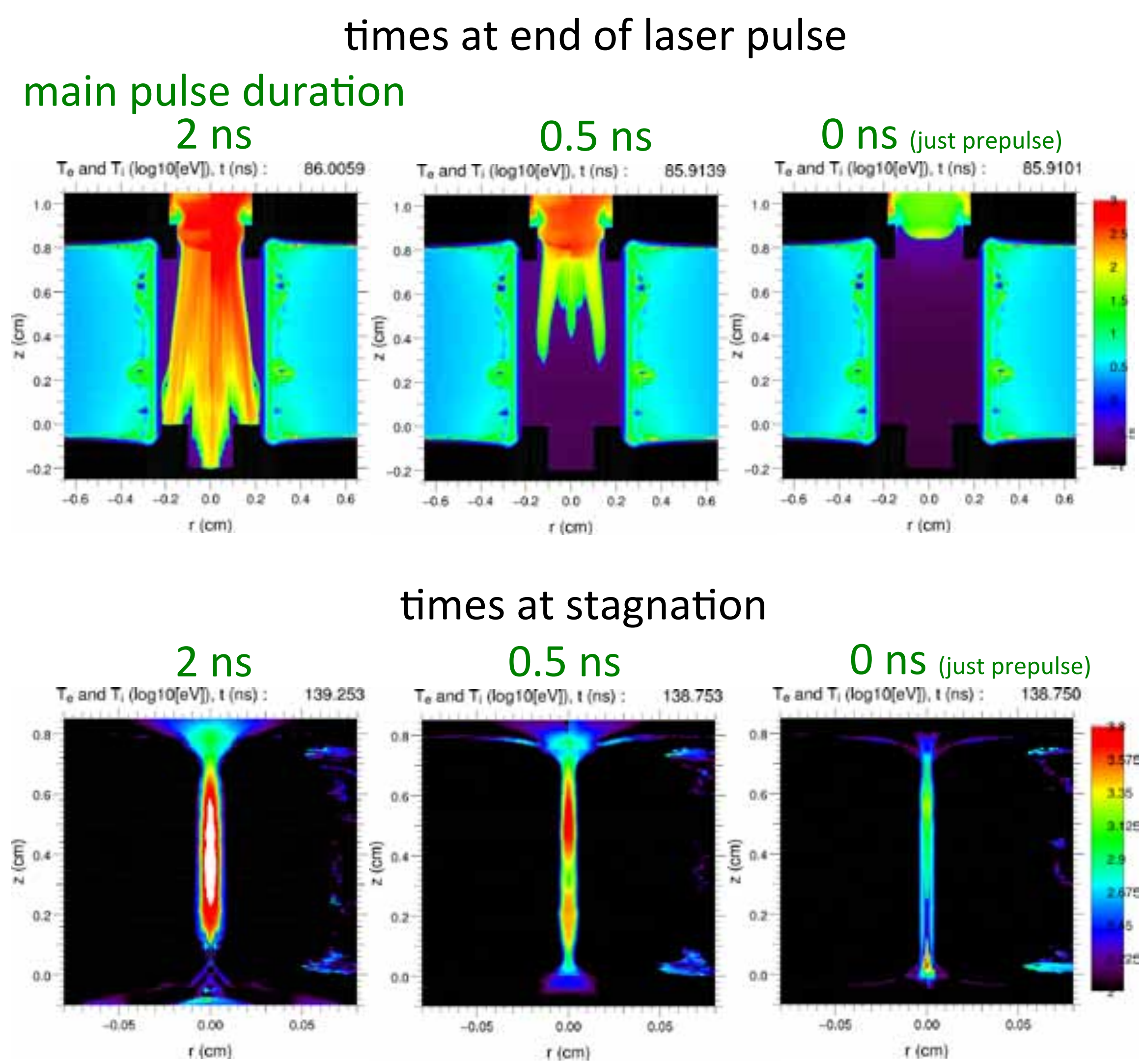
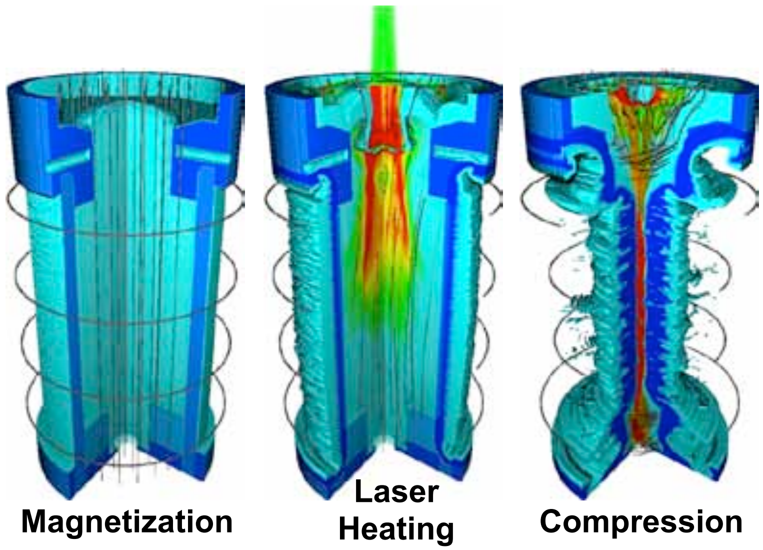
- Essentially means fuel at stagnation has less energy than expected (~5-10x)
- Did we put less energy in at the beginning (e.g., poor laser-gas coupling)?
- Did we lose more energy during implosion (e.g., Braginskii models wrong, mix leads to high radiation loss)?





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

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

- 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!

Liner Compression: Why is the instability growth in un-magnetized liner implosions so cylindrically symmetric?

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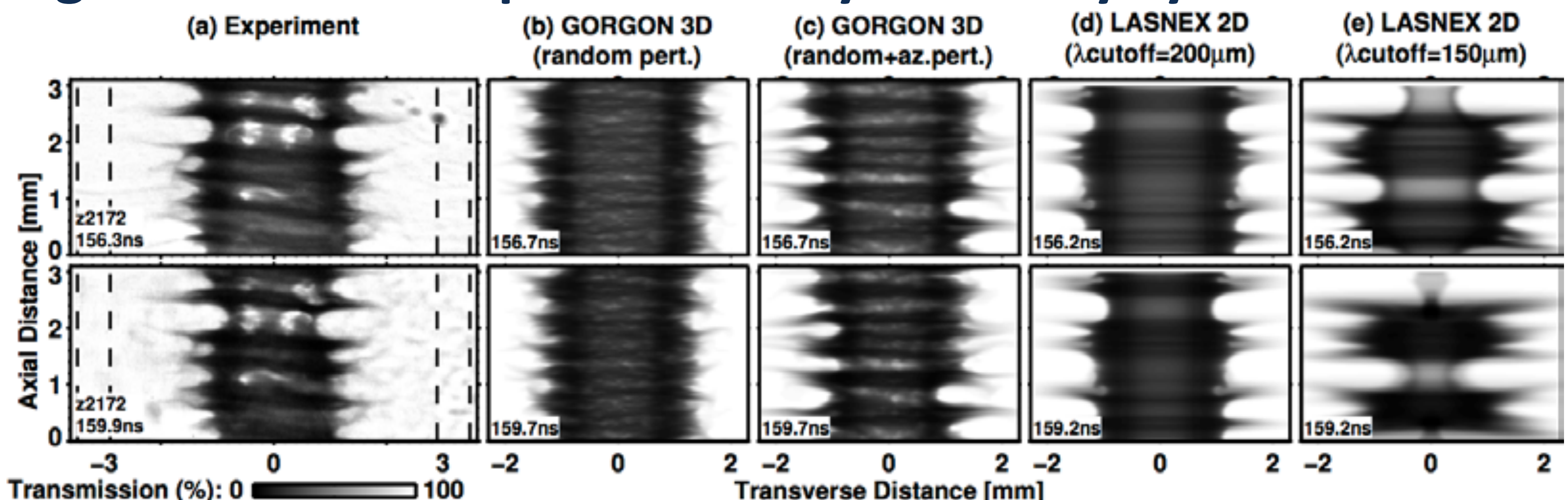
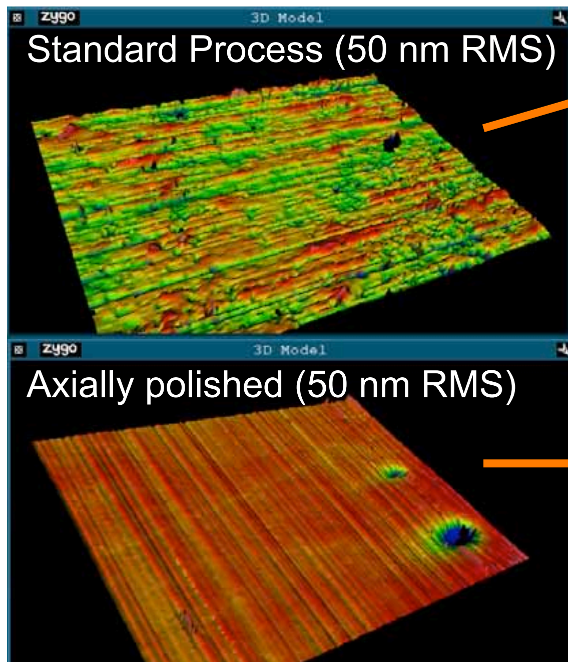
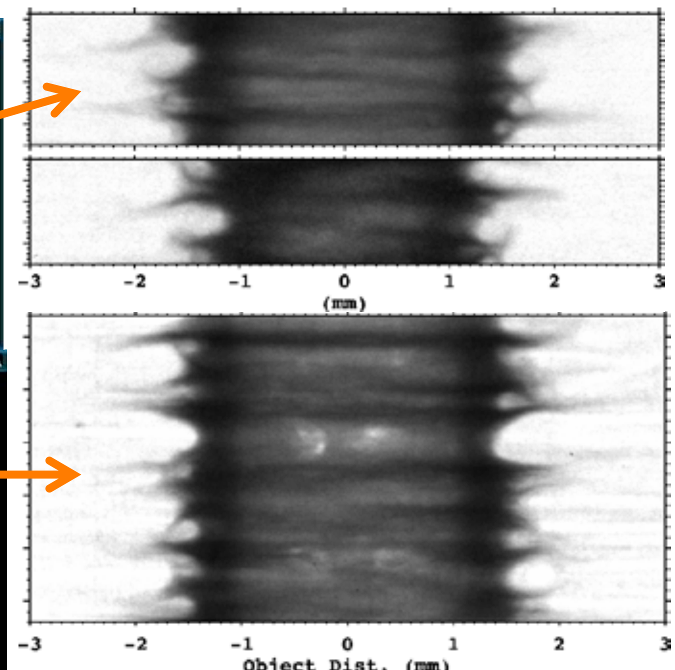


To have a 3D simulation look like the data, it needs to be seeded with a two dimensional perturbation.

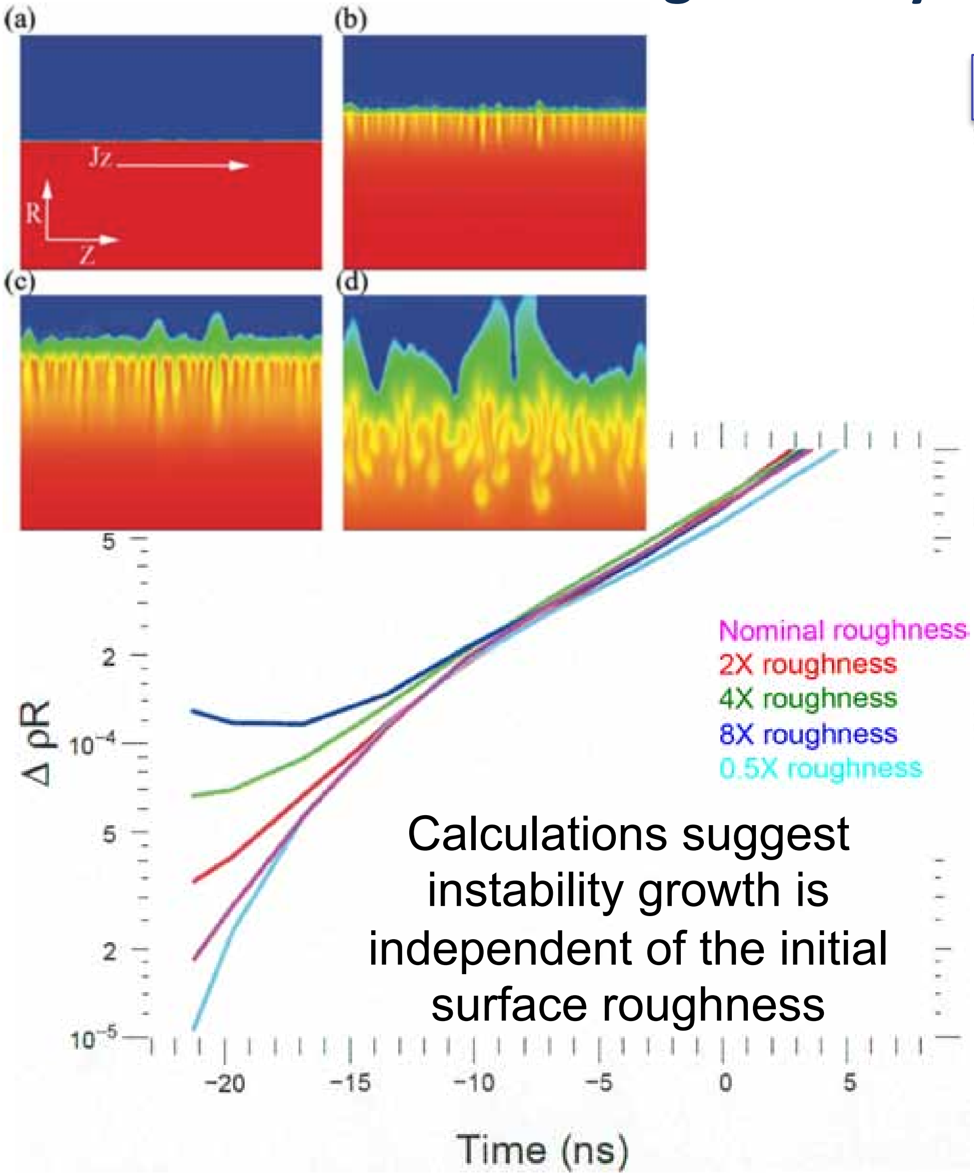
Surface roughness would be one obvious candidate, but experiments with axial grooves instead of radial grooves don't seem to change things much?





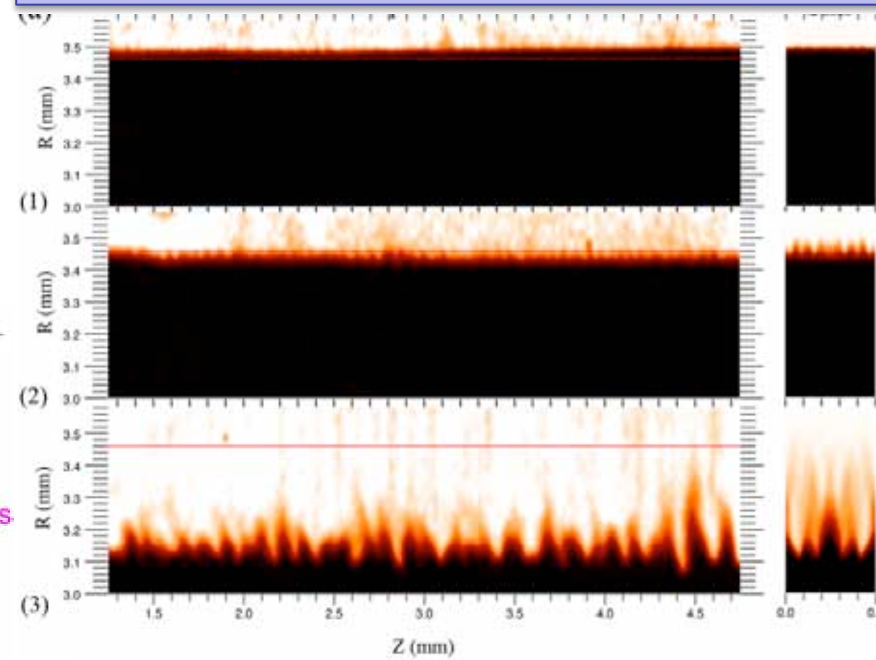
R. D. McBride et al., PRL 109, 135004 (2012).

Liner Compression: Is the electro-thermal instability the main seed for the magneto-Rayleigh-Taylor instability?



Calculations suggest instability growth is independent of the initial surface roughness

Experimental (left) & simulated (right) radiographs



Perturbation Growth Comparison

Time	Est. MRT (λ=100 μm)	h=0.06Agt^2	Observed
A	0.36 μm	6.2 μm	13 ± 7 μm
B	24 μm	41 μm	80 ± 7 μm

K.J. Peterson *et al.*, Phys. Plasmas (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).

Liner Compression: Is it possible to suppress the growth of the magneto-Rayleigh-Taylor instability?

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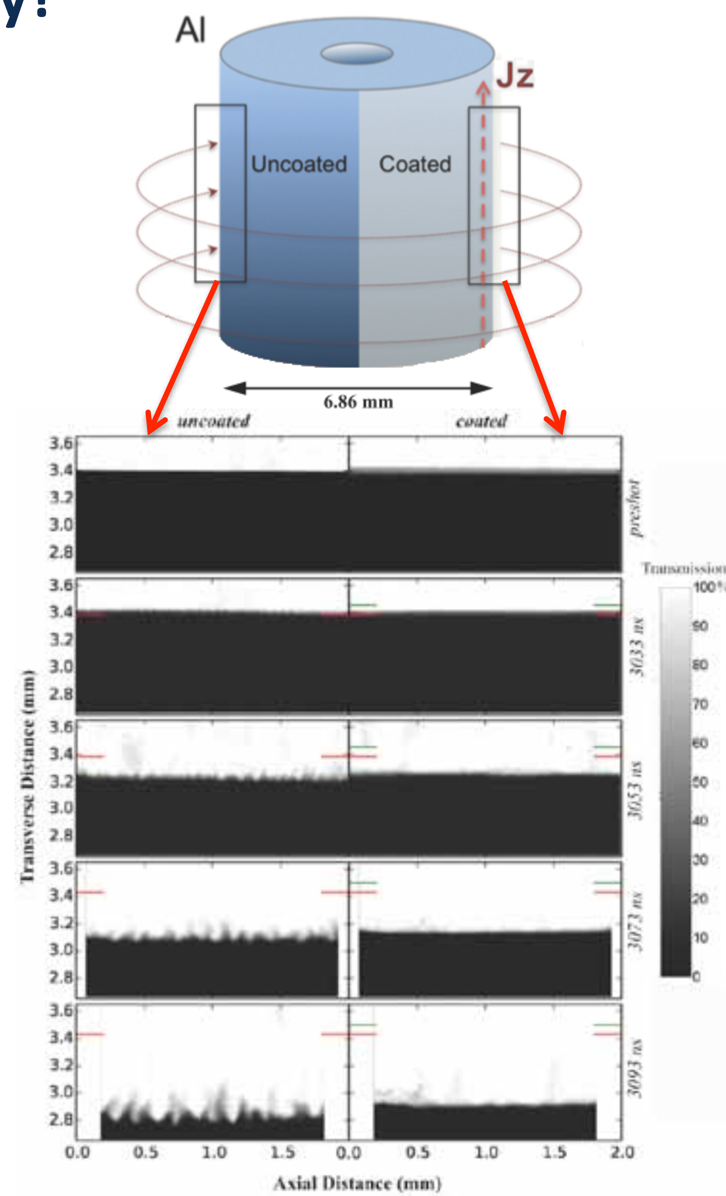
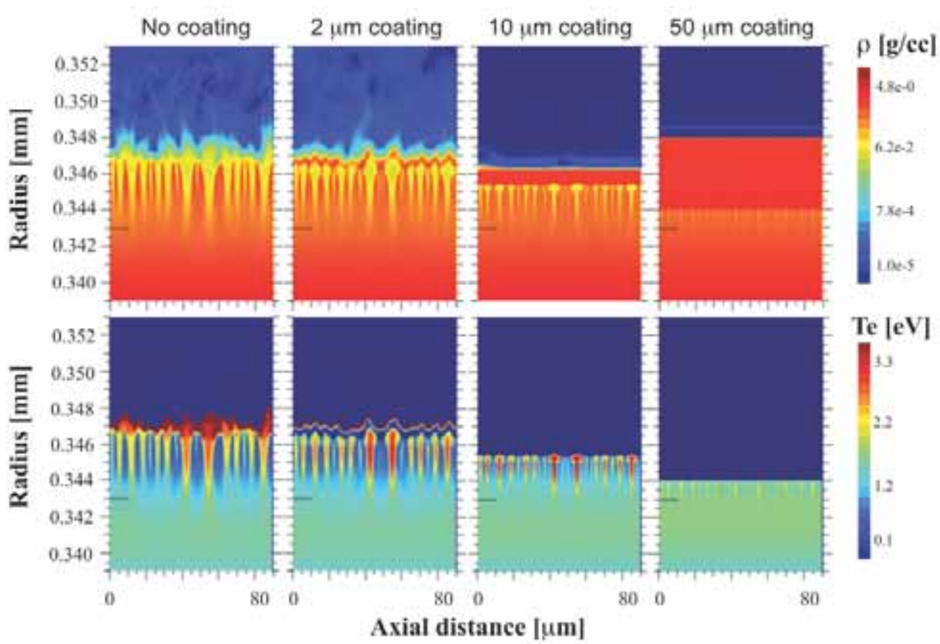
- No ETI growth in plastic coating
  - Carries very little current
  - Theoretically ETI stable
- Demonstrated to help suppress early-time growth, but will it help with full implosion?

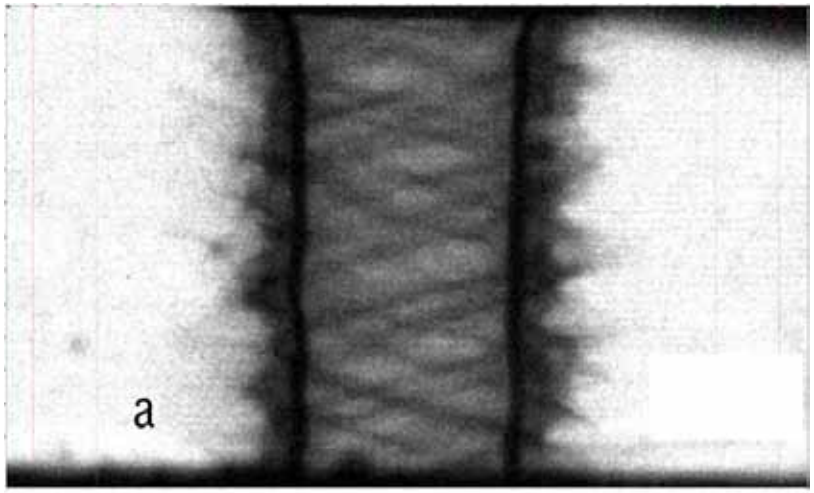


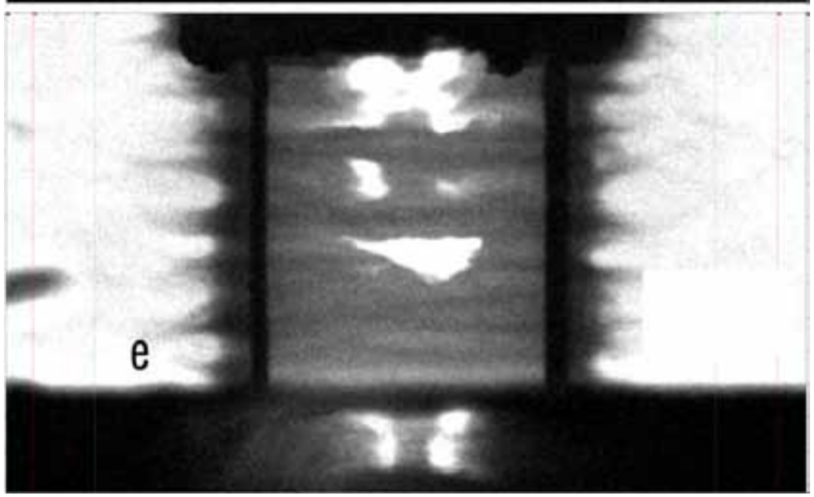


K.J. Peterson *et al.*, Phys. Rev. Lett. 112, 135002 (2014). See also GO5.00012 on Tues.

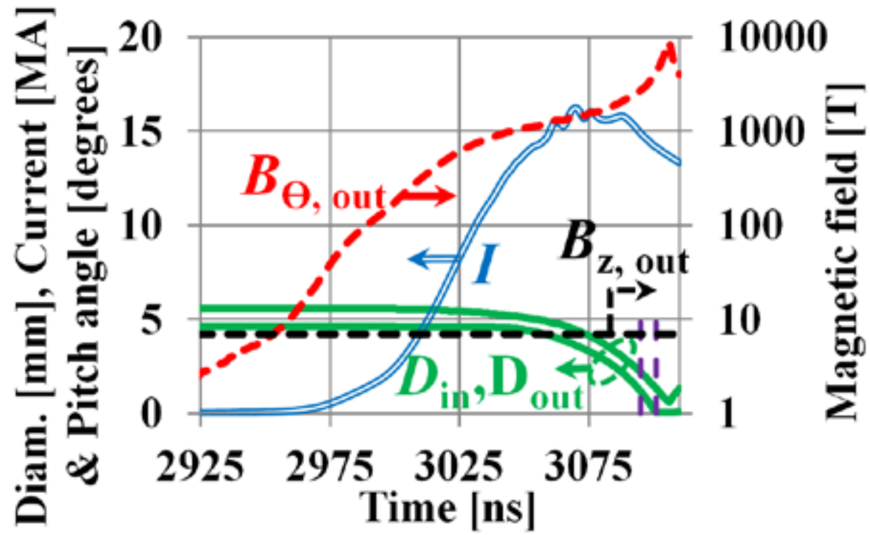
Liner Compression: What is the physical mechanism behind the helical instability seen in magnetized liner implosions? Does it help mitigate liner instability growth?

Axially magnetized implosion





Same target, un-magnetized



- Observed pitch angle inconsistent with expected Bt vs. Bz at radiograph time
- Idea 1: Angle is "frozen in" at early time when two are comparable—simulations suggest a helical perturbation early on persists (Awe)
- Idea 2: Since Bz permeates entire load region, maybe much of it is being swept up and compressed (Ryutov)

T. J. Awe et al., Phys. Rev. Lett. 111, 235005 (2013). T. J. Awe et al., Phys. Plasmas 21, 056303 (2014).

Liner Compression: How do different modes of the MRT instability interact with each other?

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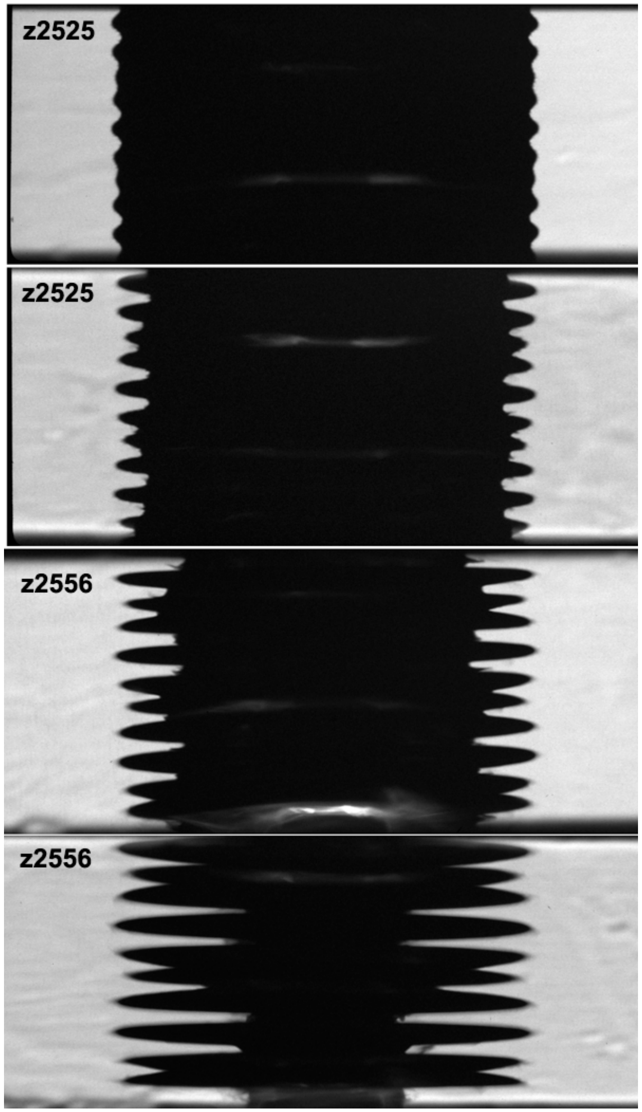
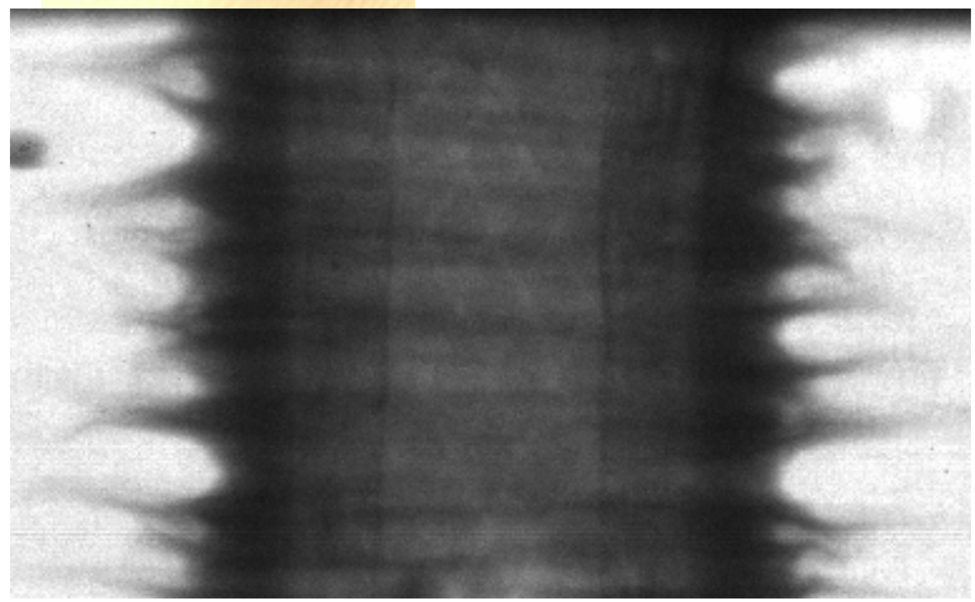
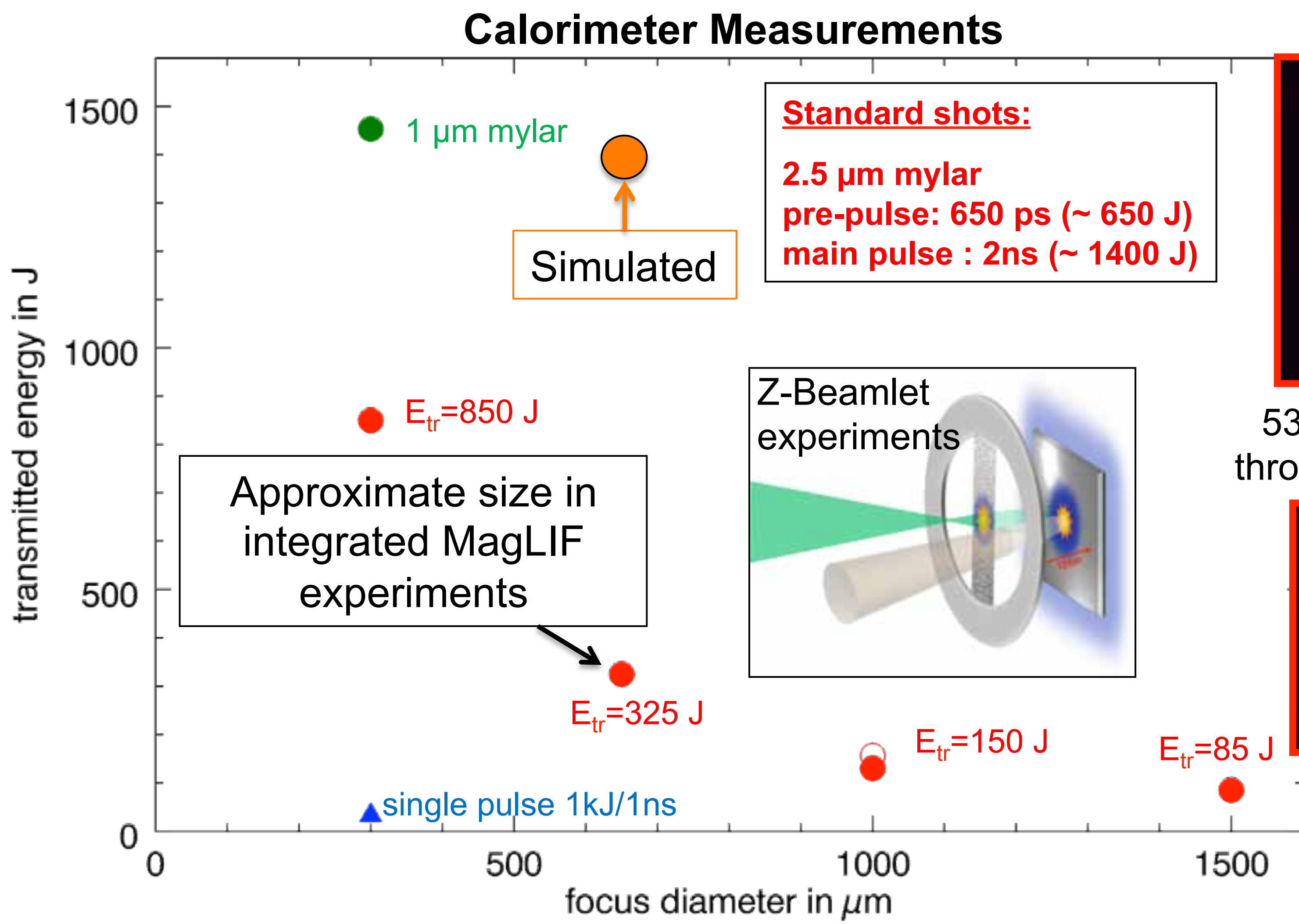


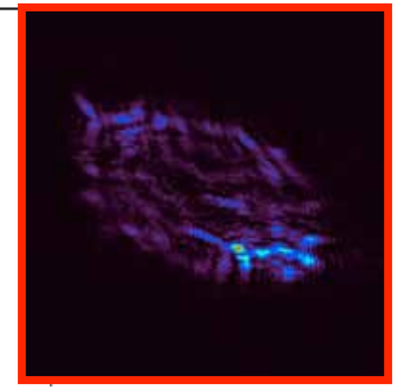
Helically-perturbed target shows both helical structure and the usual cylindrically symmetric structure superimposed at late times!



Laser heating: Why can't we model the transmission of intense laser light through thick plastic foils?



Beam profile for 800 μm diam. (no main amps)

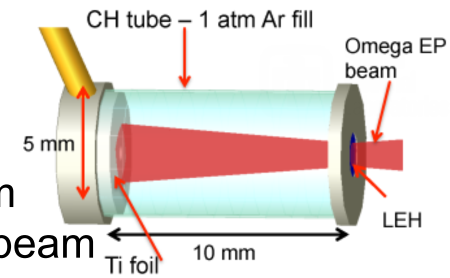


532 nm transmission through foil during pulse

Experiments by M. Geissel (see also talk GO4.00011)

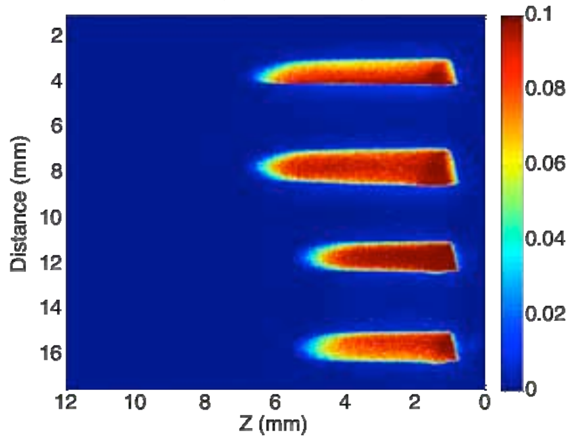
Laser Heating: Can we accurately model the laser absorption in a deuterium gas fill?

750 μm diam. beam

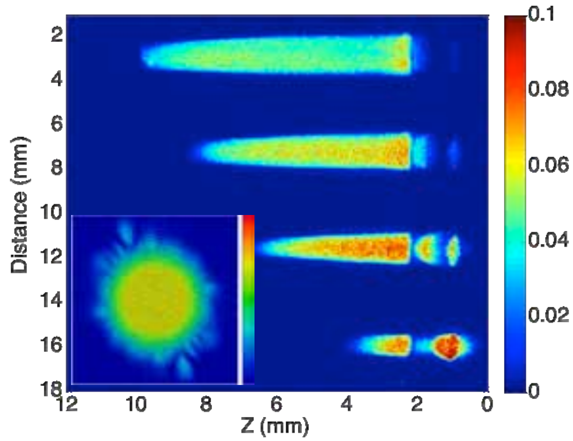


Omega-EP (Harvey-Thompson, Sefkow)

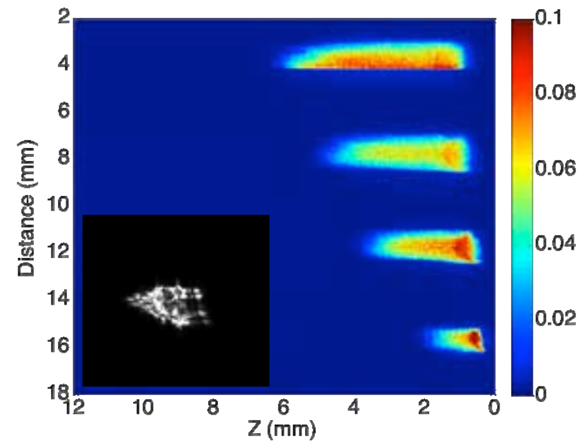
2 ns beam, 2.2 kJ, 1um LEH



4 ns beam, 3.1 kJ, 2um LEH

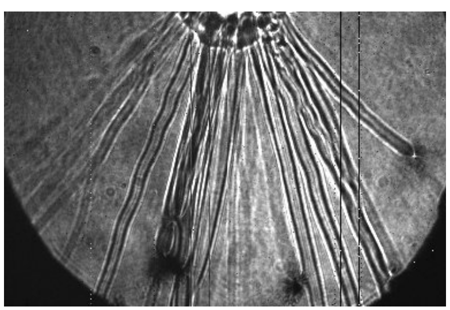


4 ns beam, 2.9 kJ, 2um LEH, No DPP

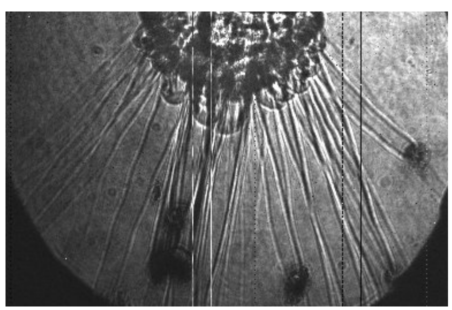


Z-Beamlet (Geissel, Porter, Lewis)

High Intensity, thick foil

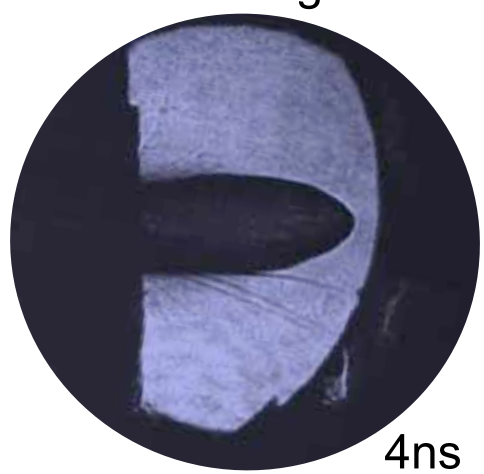


t = 10ns

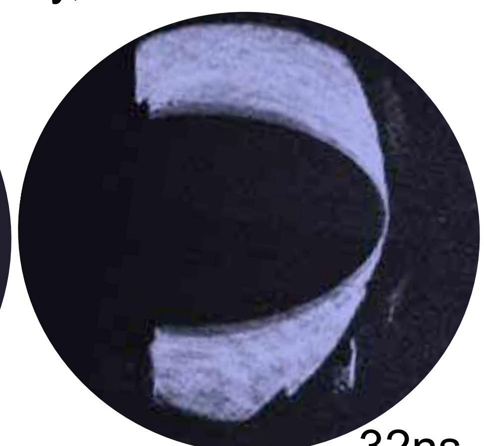


t = 36ns

High Intensity, thin foil



4ns

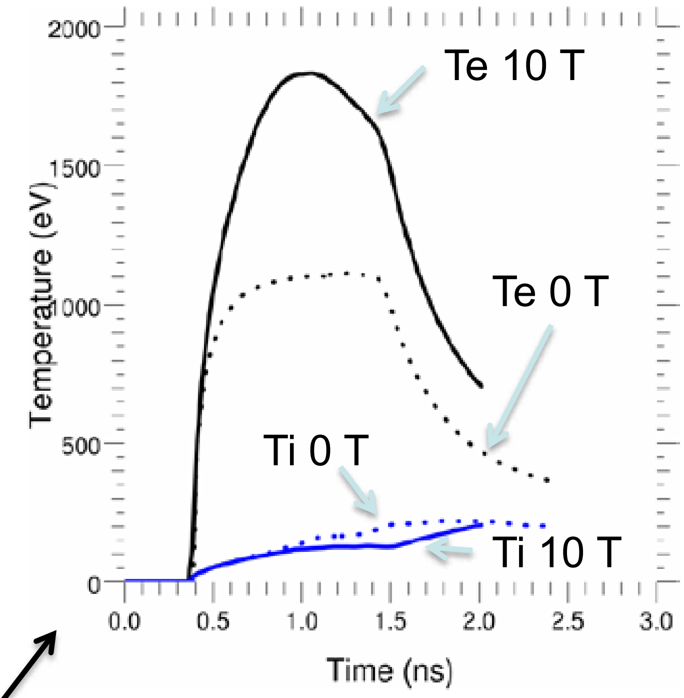


32ns

Magnetization: Can we design experiments to validate Braginskii heat transport models in MagLIF-relevant regimes?

- Previous work used a laser (1ω, 100 J, 1 ns) to heat a magnetized N jet (ne = 1.5e19/cc) with a 12 T peak B field (Froula, PRL 2007)
- Thomson scattering used to determine temperature profile perpendicular to B-field
- They found electron thermal conduction was suppressed according to classic Braginskii models for heat transport

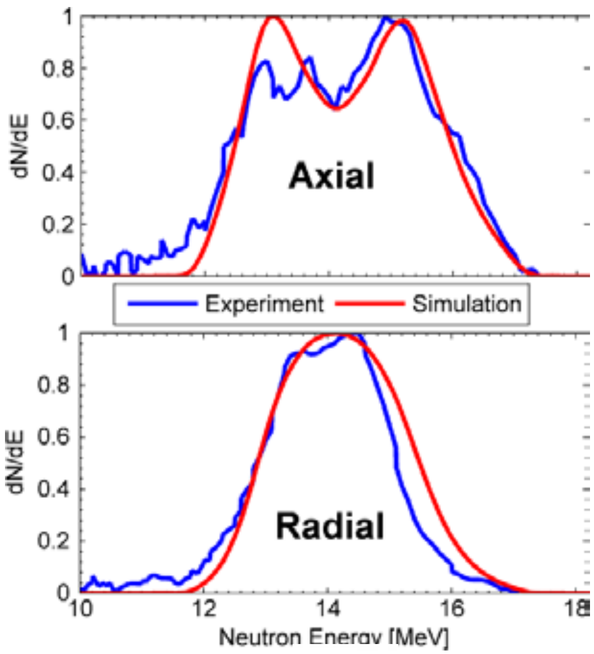
- We propose to extend this in Omega-EP experiments to plasma densities 20x higher, plasma temperatures 5x hotter, using 50x greater laser energy available there
- Effect of 10 T B field on laser-heated plasma dynamics/temperature of laser heated plasma expected to be large/observable
- Near-Braginskii transport under these conditions would be good news for MagLIF!

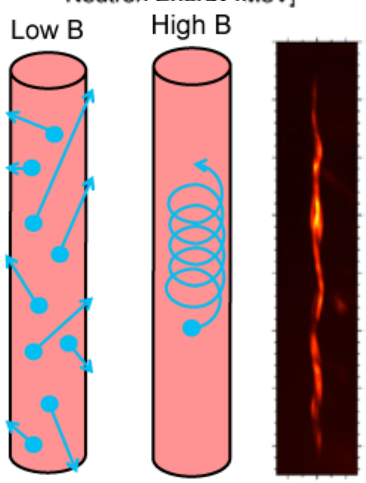


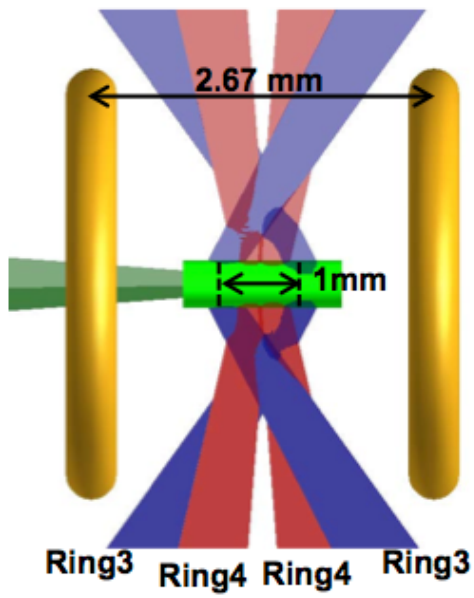
Ion and electron temperature profiles from HYDRA with and without a 10 T applied B field for a 2mg/cc D2 gas heated with a 3w laser delivering 2.5 kJ in 1 ns

REDUCE SLIDE DETAILS!

Magnetization: Can we accurately measure or benchmark magnetic flux compression at high convergence ratios?

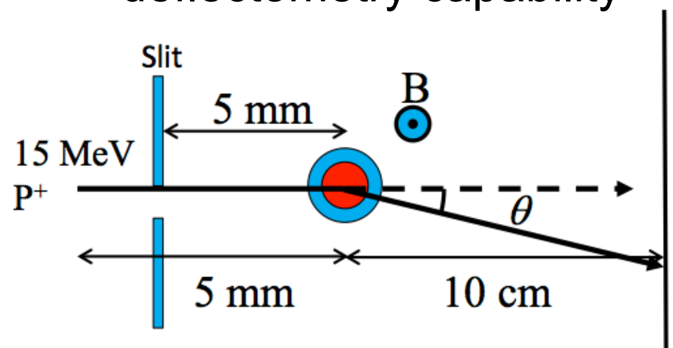


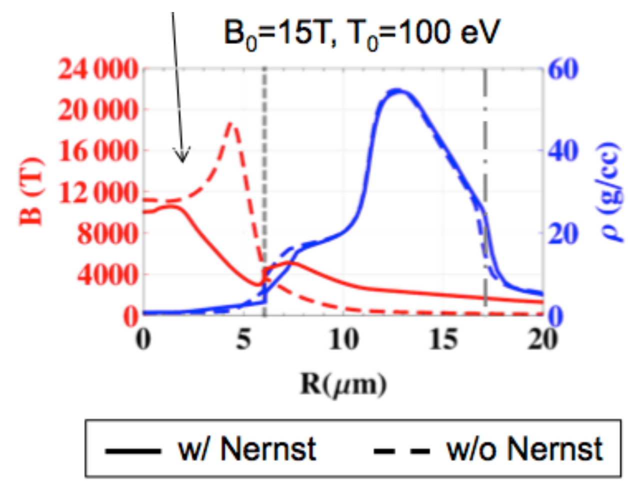




Measured BR at stagnation, but extracting B difficult?

Omega at LLE has proton deflectometry capability





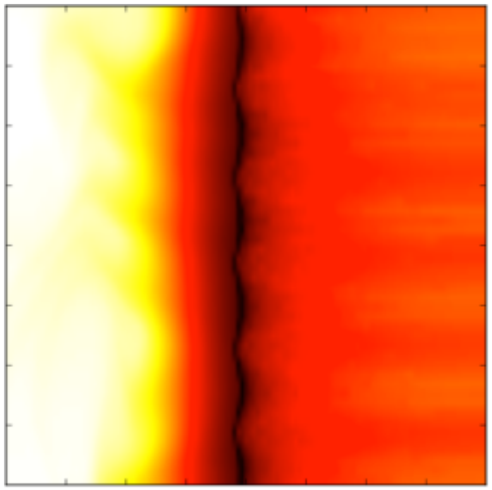
Preliminary simulations suggest results may be sensitive to Nernst

ADD CITATIONS

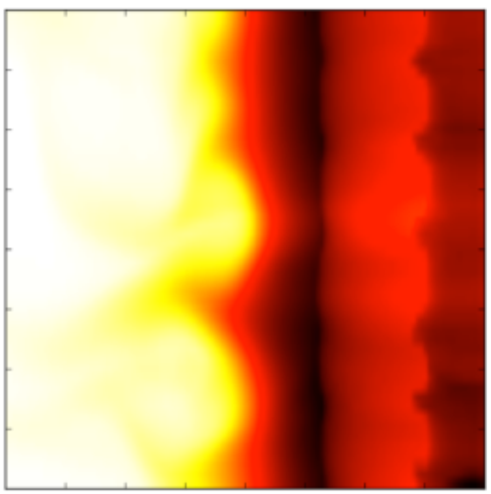
Integrated: How do we assess or measure physics at the fuel-liner interface? (e.g., Deceleration RT, shocks, radiation)

Sandia National Laboratories

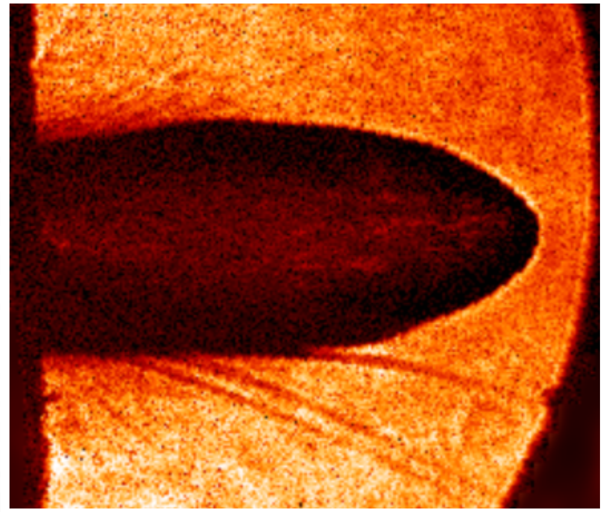
Simulated Radiographs



Decel. RT (perturbed liner)



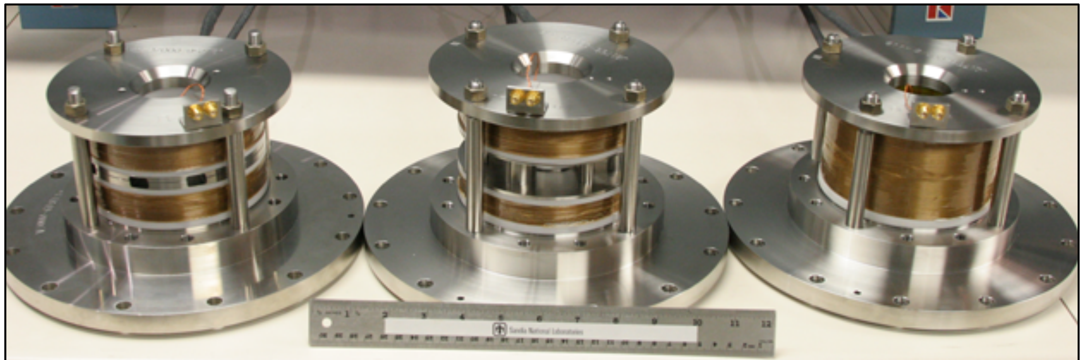
Decel. RT (perturbed on-axis rod)

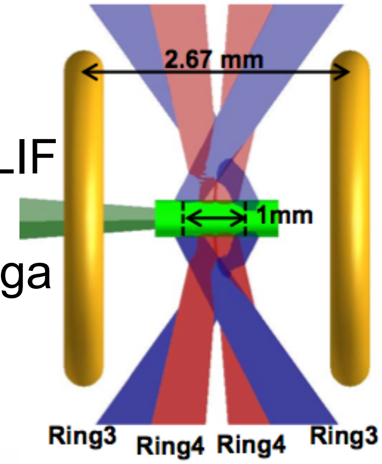


Laser heating creates a radiation wave that hits the liner, possibly filaments, and the blast wave—how well can we model this?

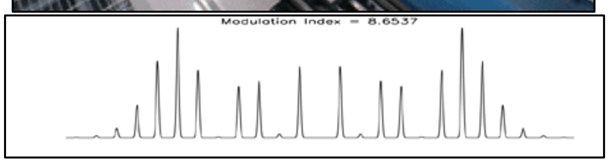
Can we use spectroscopic tracers on the inside liner surface, or embedded within it, to place bounds on the amount of “mix mass” created by these phenomena (as well as the implosion itself)?

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





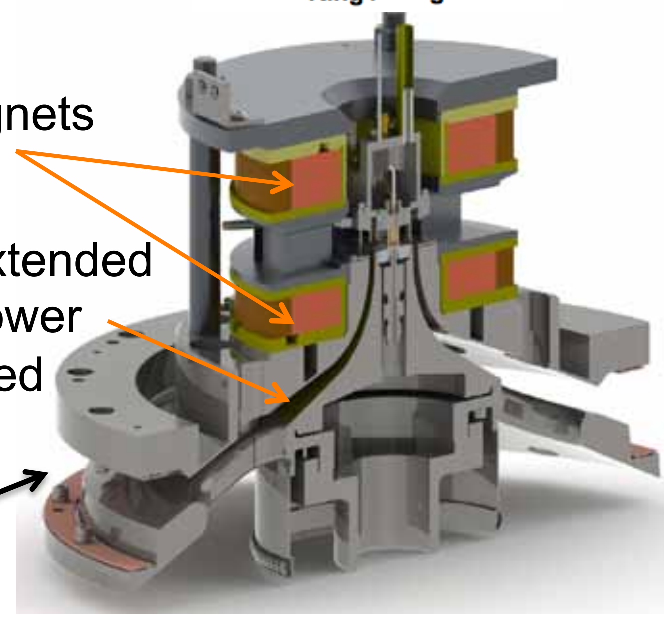
MagLIF on Omega



Increase B-field from 10 T to 30 T

Increase laser energy from 2 kJ to >6 kJ

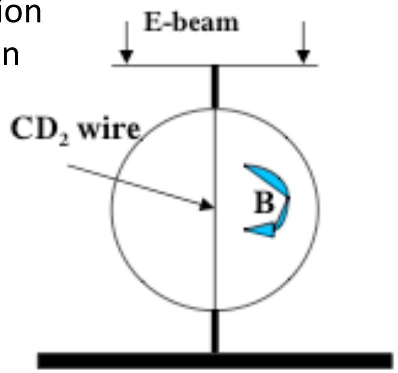
Increase current from 19 MA to >20 MA (Z facility upgrades; load hardware optimization)



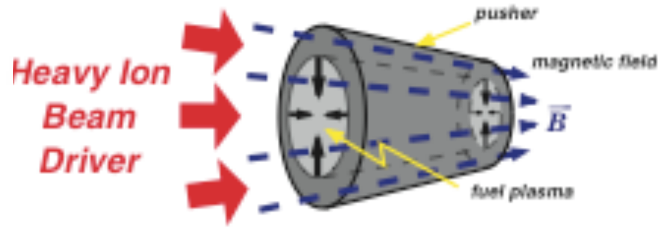
Many groups want to use magnetic fields to relax inertial fusion stagnation requirements—progress on MagLIF could be of broad interest

SNL Phi Target

1982 Demonstration of enhanced fusion yield with magnetization (~1e6 DD yield)



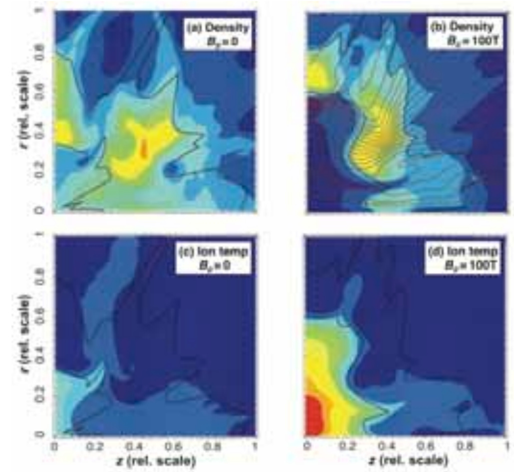
Max Planck/ITEP



Basko, Kemp, Meyer-ter-Vehn, *Nucl. Fusion* **40**, 59 (2000)
Kemp, Basko, Meyer-ter-Vehn, *Nucl. Fusion* **43**, 16 (2003)

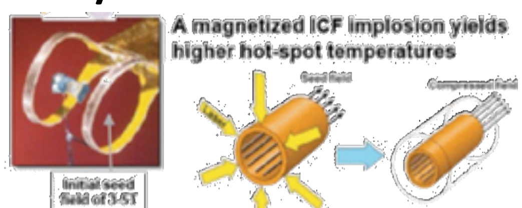
LLNL

(Perkins et al., Phys Plasmas 2013)

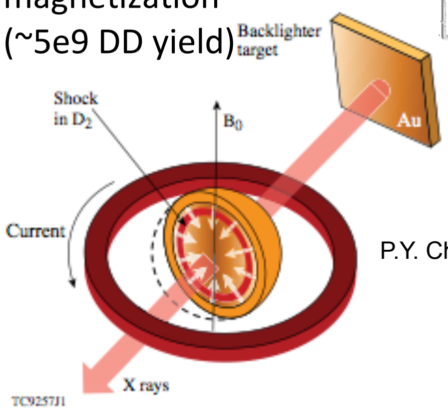


University of Rochester/LLE

2011 Demonstration of enhanced fusion yield with magnetization (~5e9 DD yield)



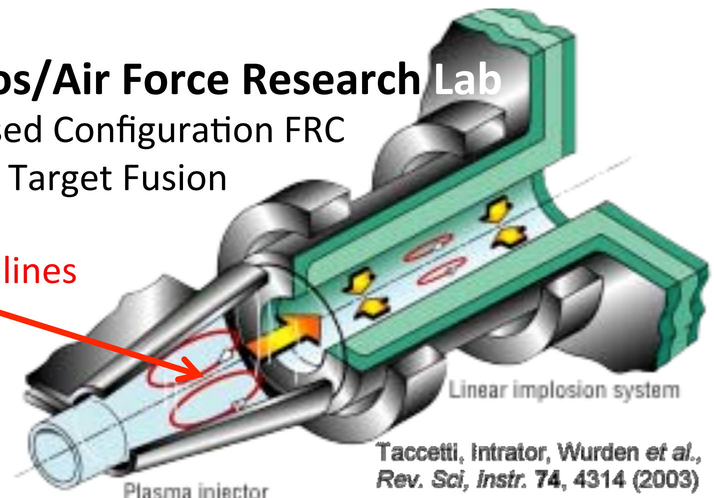
Gotchev *et al.*, *Rev. Sci. Instr.* **80**, 043504 (2009)



P.Y. Chang *et al.*, PRL (2011).

Los Alamos/Air Force Research Lab

Field Reversed Configuration FRC
Magnetized Target Fusion
Shiva Star
closed field lines
FRC



Taccetti, Intrator, Wurden *et al.*, *Rev. Sci, Instr.* **74**, 4314 (2003)
Degnan *et al.*, *IEEE Trans. Plas. Sci.* **36**, 80 (2008)

and many others…

We have a lot to do and we welcome help and ideas! Many additional presentations this week have more details!

Sandia National Laboratories

- Magnetized (10 T) and laser-heated (2 kJ) cylindrical Be targets reached ~3 keV temperatures and produced fusion yield (up to 2×10^{12} DD) at 70 km/s implosion velocity
  M.R. Gomez *et al.*, Phys Rev Lett (2014);
  M.R. Gomez, Invited talk CI.5 Monday
- 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);
  P.F. Knapp, Invited talk CI.3 Monday
- Detailed analysis of stagnation conditions consistent with thermonuclear yield, though less energy in fusing plasma than predicted
  S.B. Hansen, Invited talk CI.6 Monday
- Additional experiments on multiple facilities focused on specific physics issues (laser-gas coupling, liner dynamics, flux compression)
  —see **GO4 on Tuesday; JP8 on Tuesday**