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Opportunities and challenges in Magnetized Liner Inertial Fusion

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Sandia National Laboratories, Albuquerque, NM, USA

8th Euro-Asian Pulsed Power Conference

23rd International Conference on High-Power Particle Beams

7th International Conference on Megagauss Magnetic Field Generation

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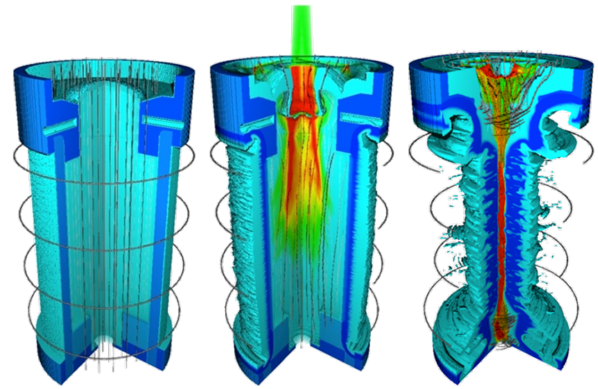
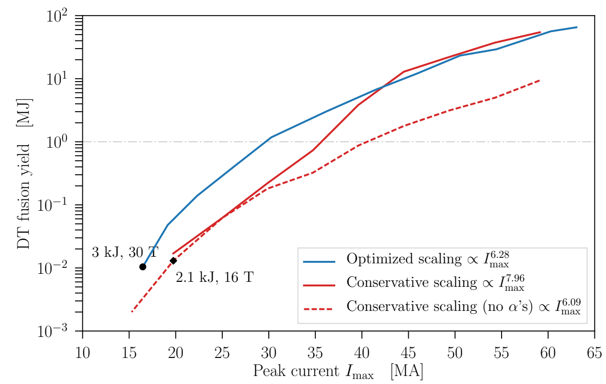
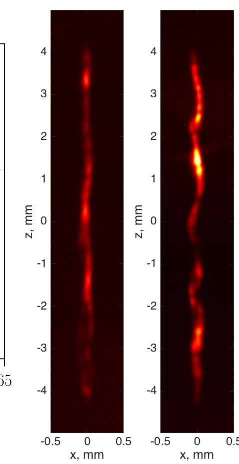
Summary: Magnetized Liner Inertial Fusion is a promising approach to reaching multi-MJ yields with pulsed power

- Magnetized Liner Inertial Fusion (MagLIF) is a Magneto-Inertial scheme that uses a combination of magnetic field coils, laser preheat and pulsed-power-driven compression to reach fusion conditions
- A self-similar scaling theory has been developed to set requirements for a MJ-class facility and guide target design
- Scaling risks have been identified in the areas of preheat, implosion stability and mix, and detailed physics studies are underway to address these
- Research efforts are currently concentrating on testing self-similar scaling, improving performance on Z and on focused physics studies







Outline

Overview of Magneto-Inertial Fusion (MIF) and Magnetized Liner Inertial Fusion (MagLIF)

Scaling MagLIF to a future driver

Experiments that have been performed to understand scaling uncertainties with MagLIF

Opportunities for collaboration

In collaboration with

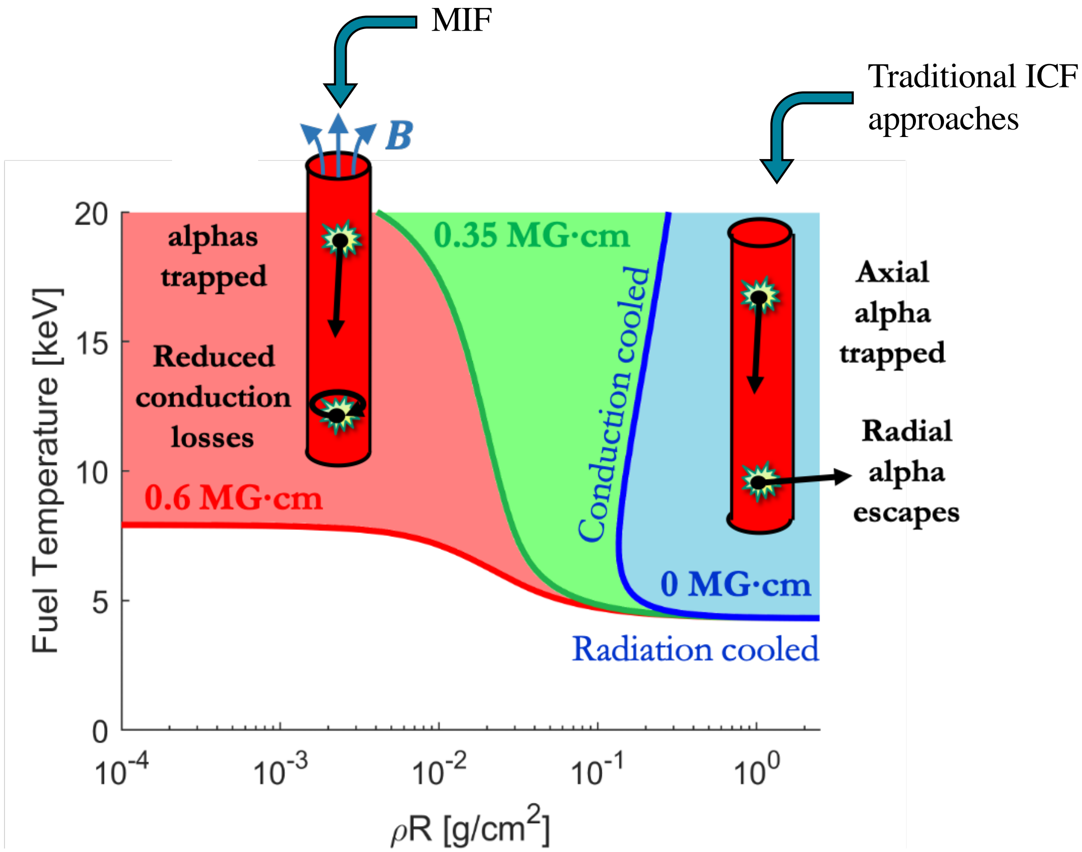
M.R. Gomez, S.A. Slutz, C.A. Jennings, M.R. Weis, A.J. Harvey-Thompson, D.E. Ruiz, P.F. Schmit, M. Geissel, T.J. Awe, E.P. Yu, D.C. Lamppa, G.A. Chandler, J.A. Crabtree, J.R. Fein, G. Shipley, S.B. Hansen, E.C. Harding, W.E. Lewis, M. Mangan, I.C. Smith, D.A. Yager-Elorriaga, G. Robertson, L. Perea, K. Beckwith, G.A. Rochau, D.B. Sinars (SNL)

B. Pollock, J. Moody (LLNL)

Overview of Magneto-Inertial Fusion (MIF) and Magnetized Liner Inertial Fusion (MagLIF)

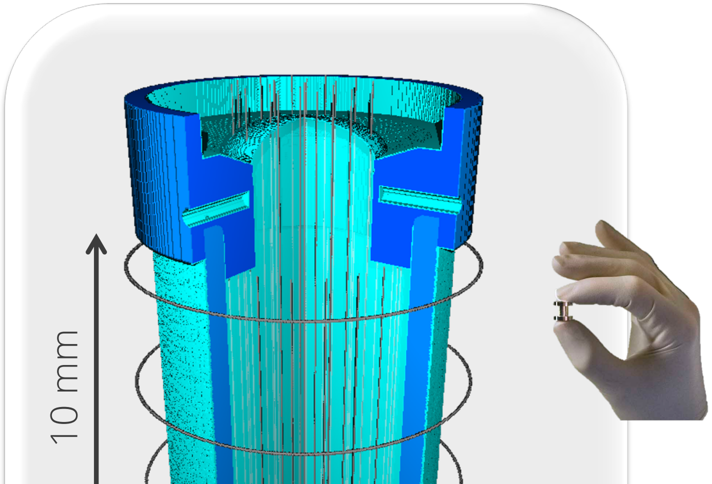
Magneto-Inertial Fusion uses magnetic fields to relax the requirements for alpha heating

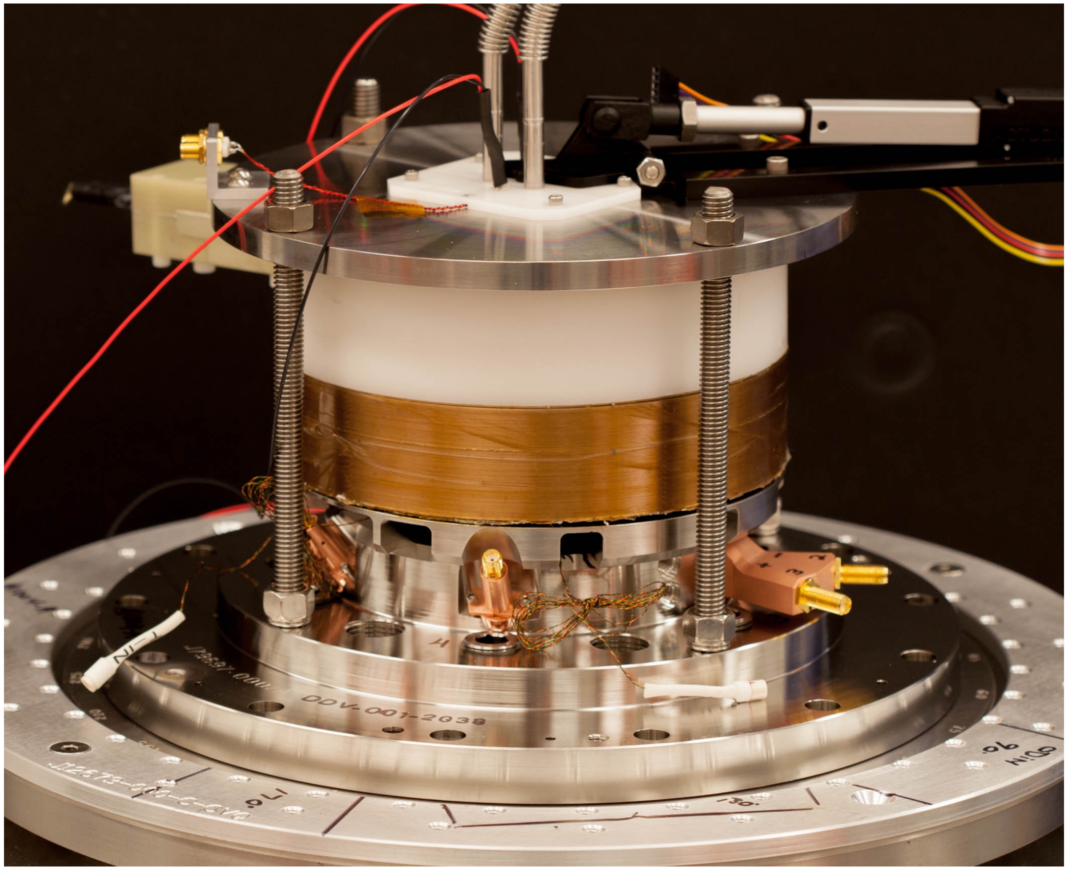
- Inertial Confinement Fusion requires
  - High temperatures ($\gtrsim 4.3$ keV)
  - High areal densities $\rho R \gtrsim 0.2\ \mathrm{g/cm^2}$
- Magneto-Inertial Fusion uses magnetic fields to:
  - Reduce conduction losses (allow slower implosion) and
  - Trap alpha particles to magnetic field lines within the plasma column, relaxing the ρR requirements
- Data with MagLIF indicates that we reach Magnetic Field-Radius products ~0.4 MG-cm at stagnation



Basko et al., Nucl. Fusion 40, 59 (2000)
Schmit et al., PRL 113, 155004 (2014)
Knapp et al., POP 22, 056312 (2015)

Magnetized Liner Inertial Fusion (MagLIF) is a magneto-inertial fusion approach that uses an axial applied B-field and laser preheat.





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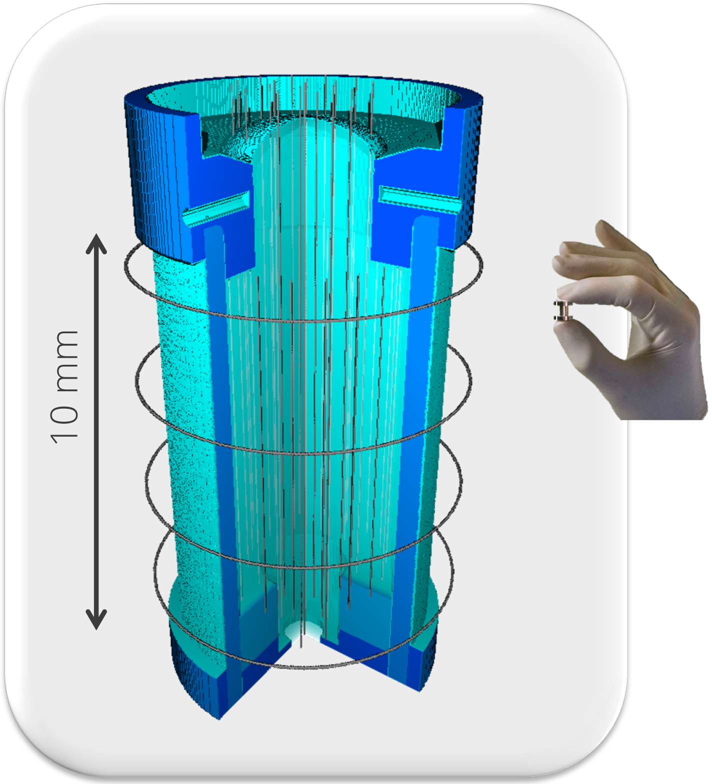
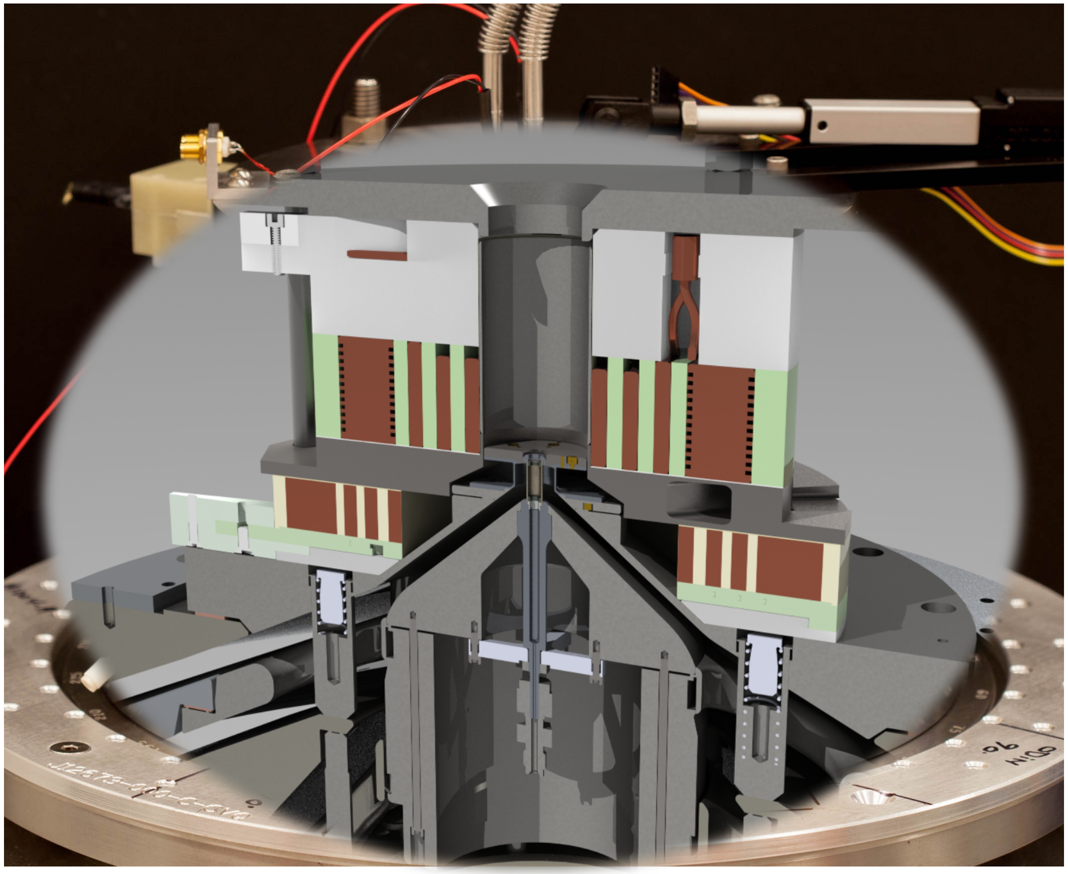
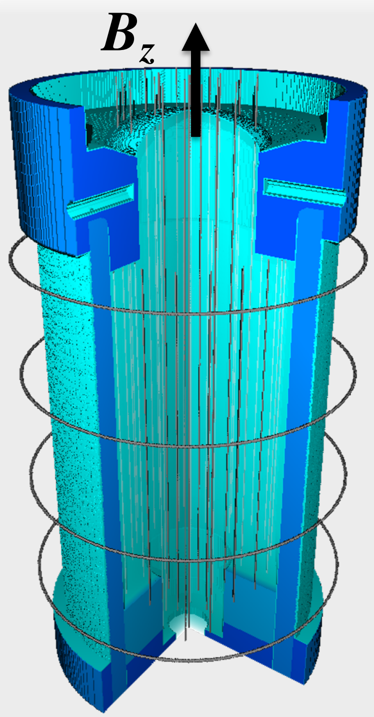
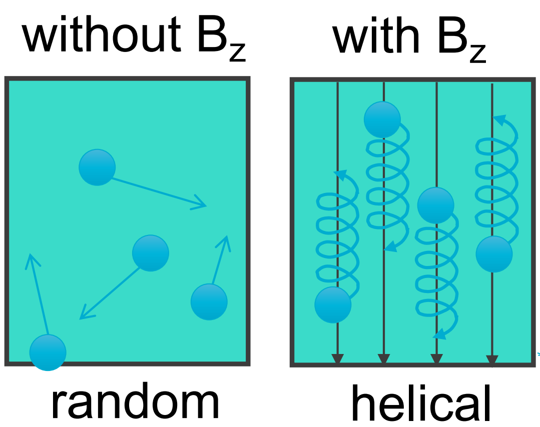




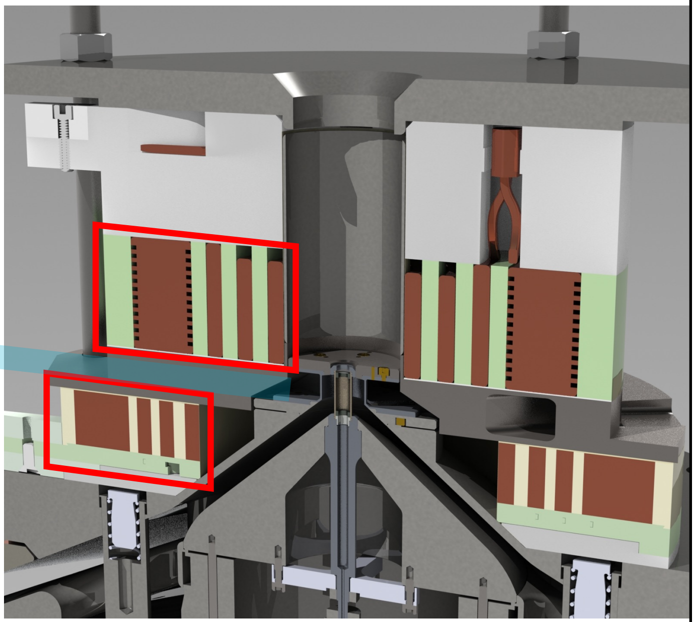
Helmholtz-like coils are used to premagnetize the MagLIF target to suppress radial thermal conduction losses, enabling slower implosions that are matched to pulsed power drivers and provide stable liner implosions





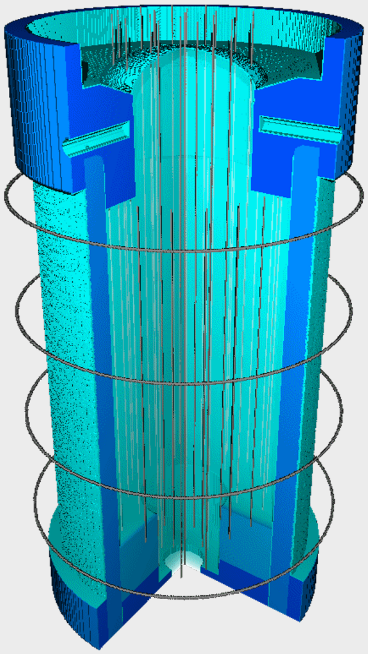
Premagnetize fuel

- Field coils embed 7-20 T field over millisecond timescale
- Field suppresses thermal conduction
- Compressed field at stagnation traps fusion products



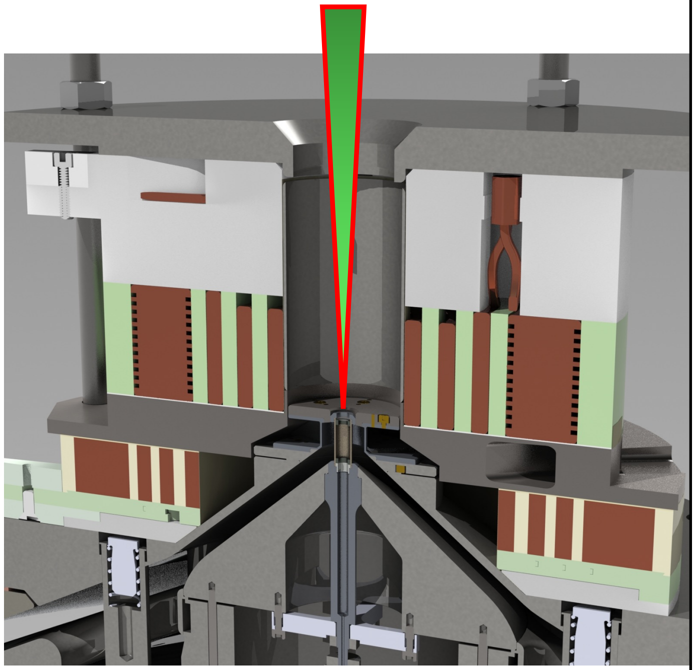
Rovang et al., RSI **85**, 124701 (2014).

The Z Beamlet laser is used to preheat the fuel, setting the adiabat for the implosion



Preheat the fuel

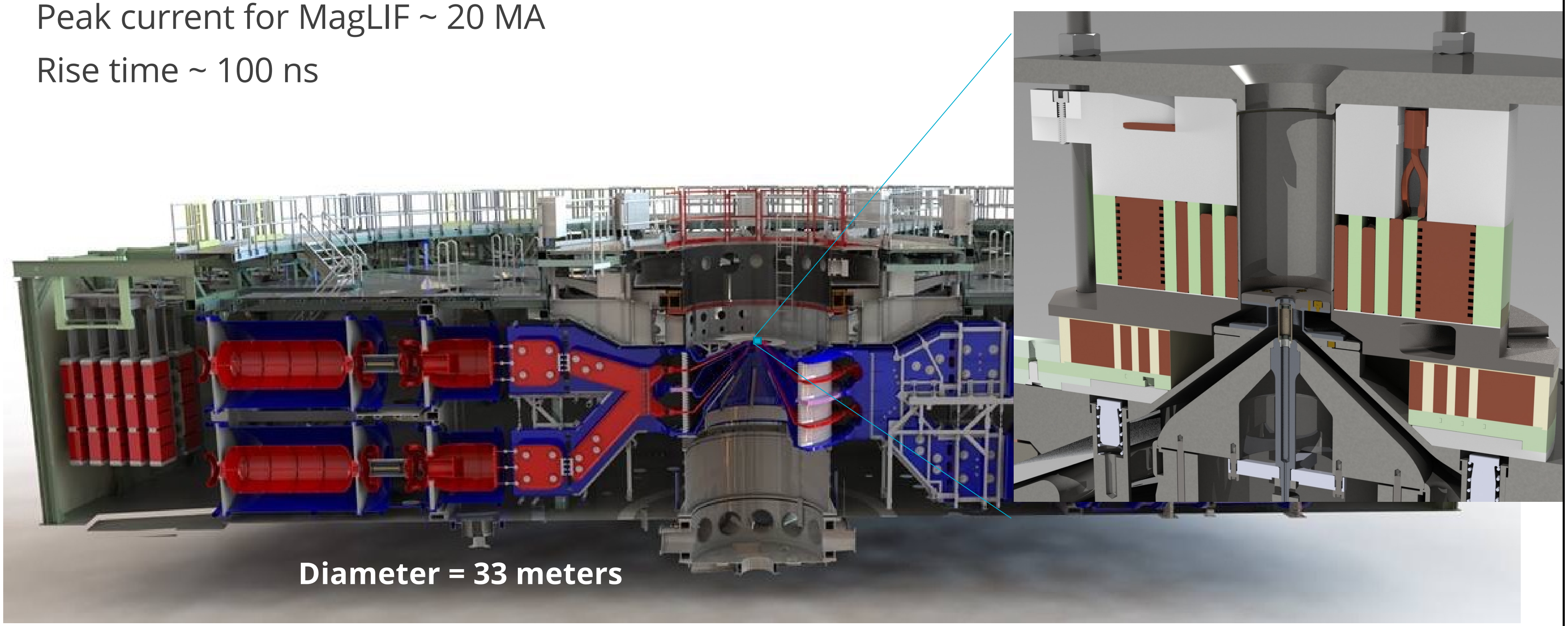
- Z-Beamlet laser delivers ~2-3 kJ to the Z chamber
- Laser heats fuel through Inverse Bremsstrahlung (~100-200 eV, 1-2 kJ)
- Temperature/pressure set adiabat for implosion



Current from the Z Pulsed Power generator is used to compress the liner and fuel

Peak current for MagLIF ~ 20 MA

Rise time ~ 100 ns



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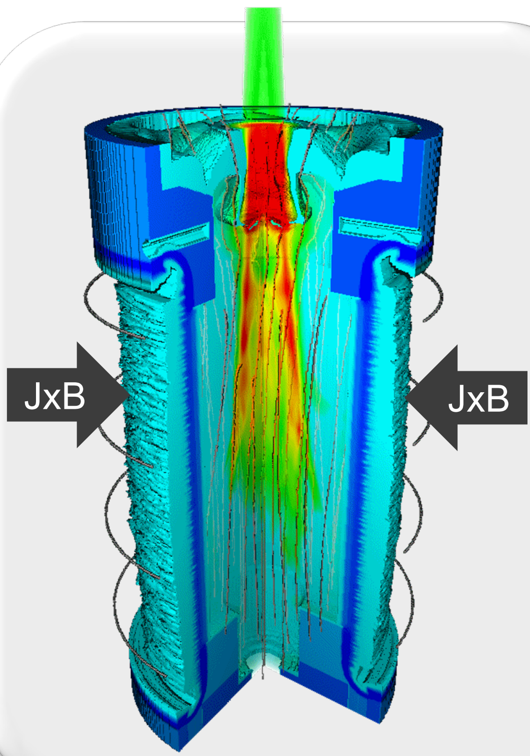
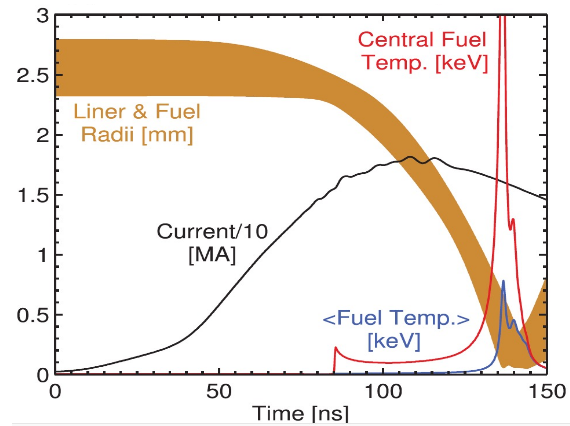
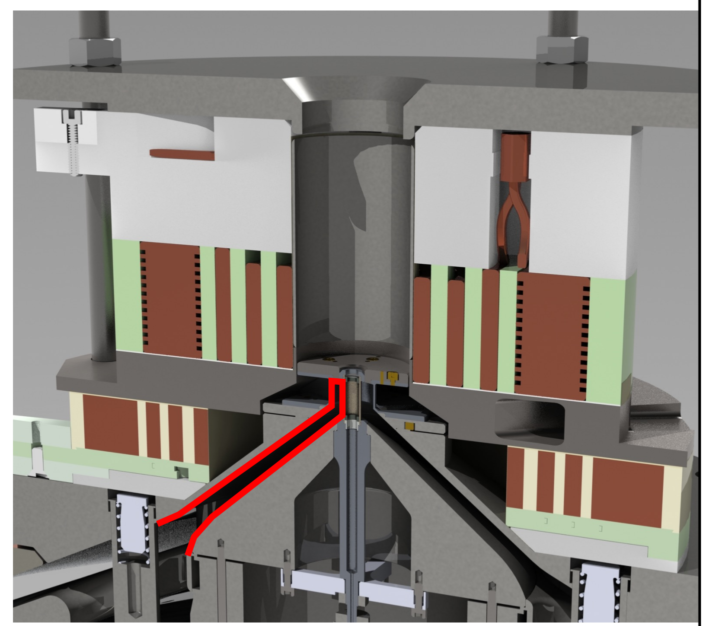




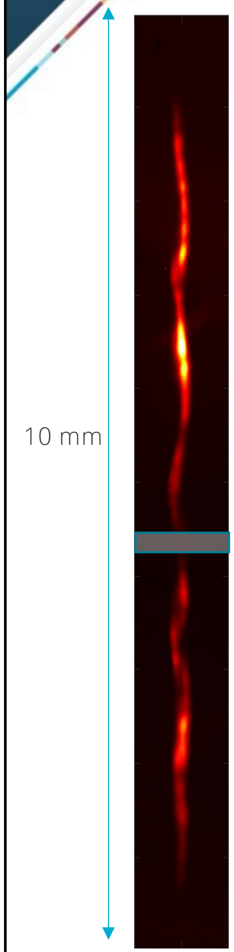


Compress liner and fuel

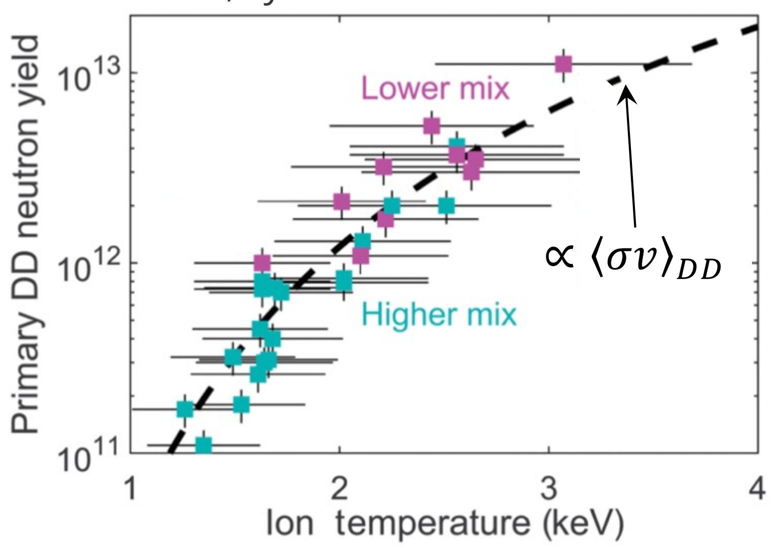
- Lorentz force due to current from Z used to compress liner
- Fuel is quasi-adiabatically compressed
- Liner and fuel implosion leads to flux compression, amplifying B-field

McBride et al., POP **23**, 012705 (2016)

MagLIF experiments have demonstrated the fundamental principles of MIF



MagLIF creates thermonuclear neutrons, multi-keV temperatures from high aspect-ratio, cylindrical fuel assemblies.



Hallmark of MIF: significant fusion only when both the **laser preheat** and **magnetization** stages are present.

DD neutron yields

	No B-field	B-field
No Preheat	3×10^{9}	1×10^{10}
Preheat	4×10^{10}	Up to 10^{13}

Experiments have demonstrated BR~0.4 MG.cm, sufficient to trap charged fusion products within the column

Gomez et al., PRL 113, 155003 (2014)
Gomez et al., PRL 125, 155002 (2020)

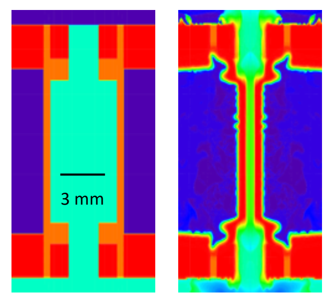
MagLIF is predicted to scale to multi-MJ fusion yields

To reach MJ fusion yields requires currents and preheat energies higher than those available on Z – we have developed scaling relations to guide target design and expected performance

Self-similar scaling theory developed by Schmit and Ruiz

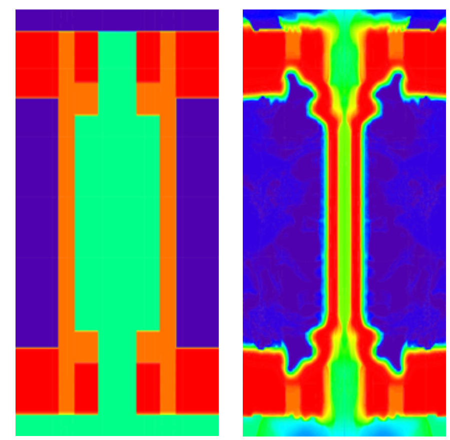
- Preserve key implosion characteristics as experiments are scaled up (or down)
- Conserves or reduces degradation mechanisms such as radiative losses

22 MA,
25 T, 4 kJ preheat



100 ns rise
0.13 MJ
$\chi_{\text{no }\alpha} = 0.7$

51 MA,
25 T, 33 kJ preheat



100 ns rise
13 MJ
$\chi_{\text{no }\alpha} = 4.3$

Implosion-time conserving

Schmit & Ruiz, POP **27**, 062707 (2020).

To reach MJ fusion yields requires currents and preheat energies higher than those available on Z – we have developed scaling relations to guide target design and expected performance

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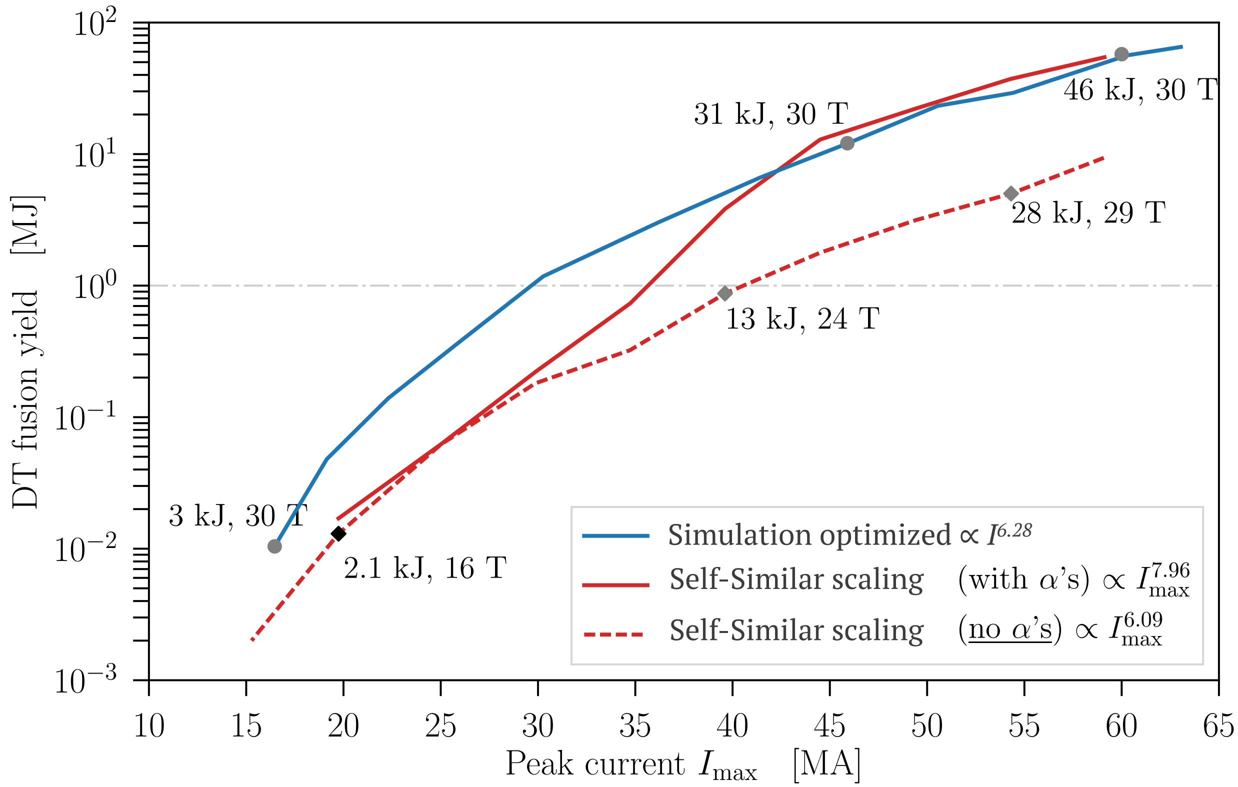
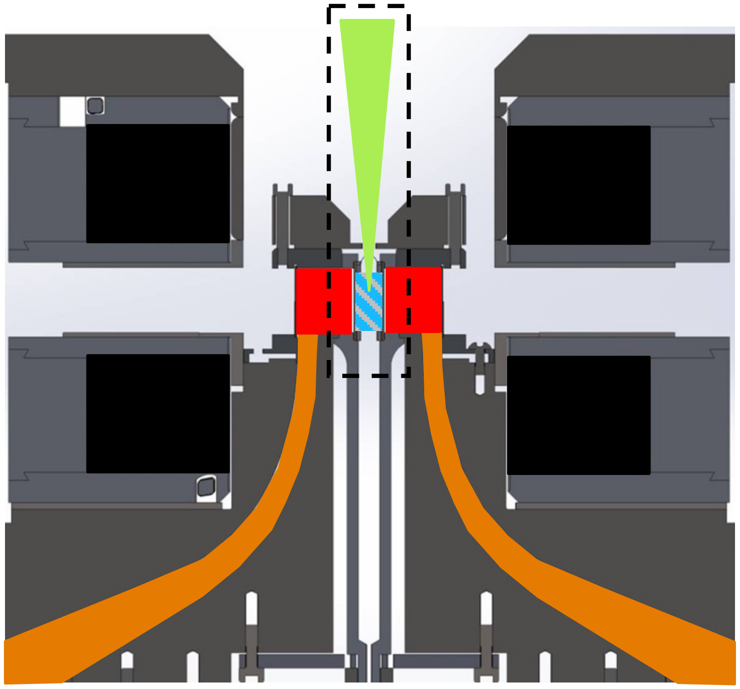


Slutz, et al., POP **23**, 022702 (2016).
Schmit & Ruiz, POP **27**, 062707 (2020).

Experiments that have been performed to address scaling uncertainties and challenges

Five key focus areas highlight the innovations, opportunities, and risks for MagLIF

MagLIF Experimental Assembly



Performance and Physics Scaling

Implosion Stability and Mix

Preheat Efficacy

Platform specific, so concentrate on here

Current distribution within the target volume

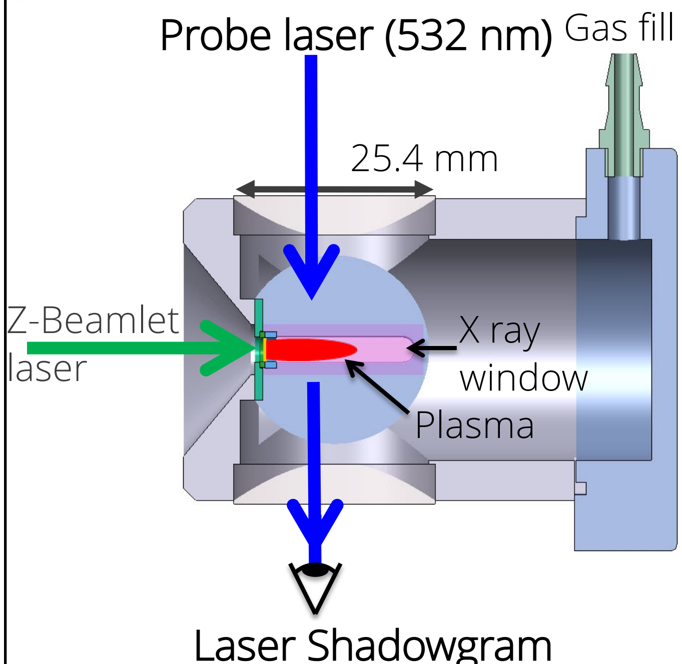
Transmission line to the target

Preheat

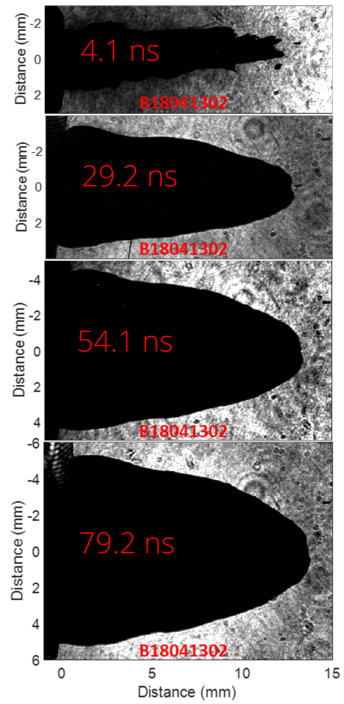
Can we characterize preheat on Z?

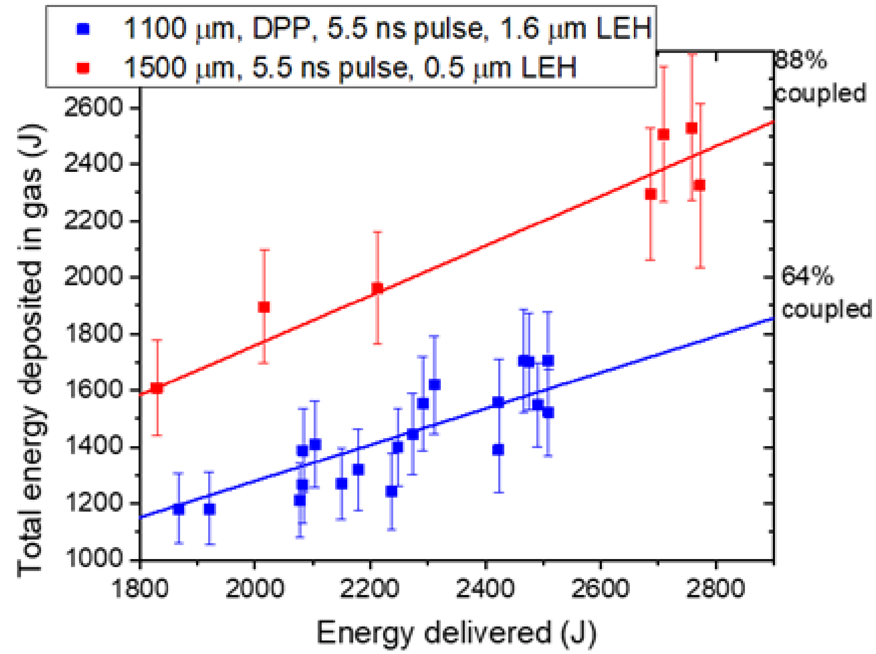
Can we couple sufficient energy into the fuel on a future generator?

At the Z scale we quantify energy coupling offline. We use cryogenic fuel to reduce window thickness, hence increasing coupling and reducing mix



Blast wave expansion – energy deposited





Primary sources of losses:

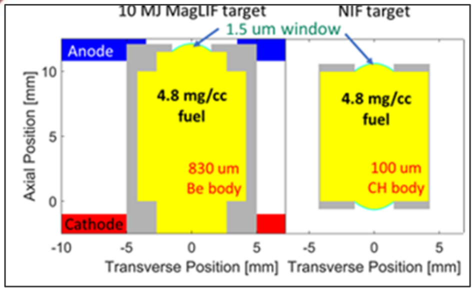
Energy invested in heating LEH foil

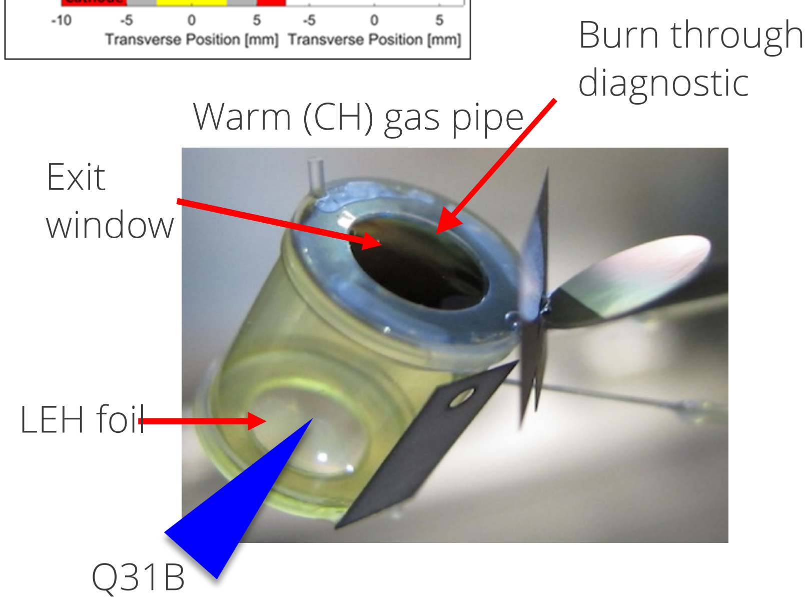
LPI backscatter losses from LEH foil and gas

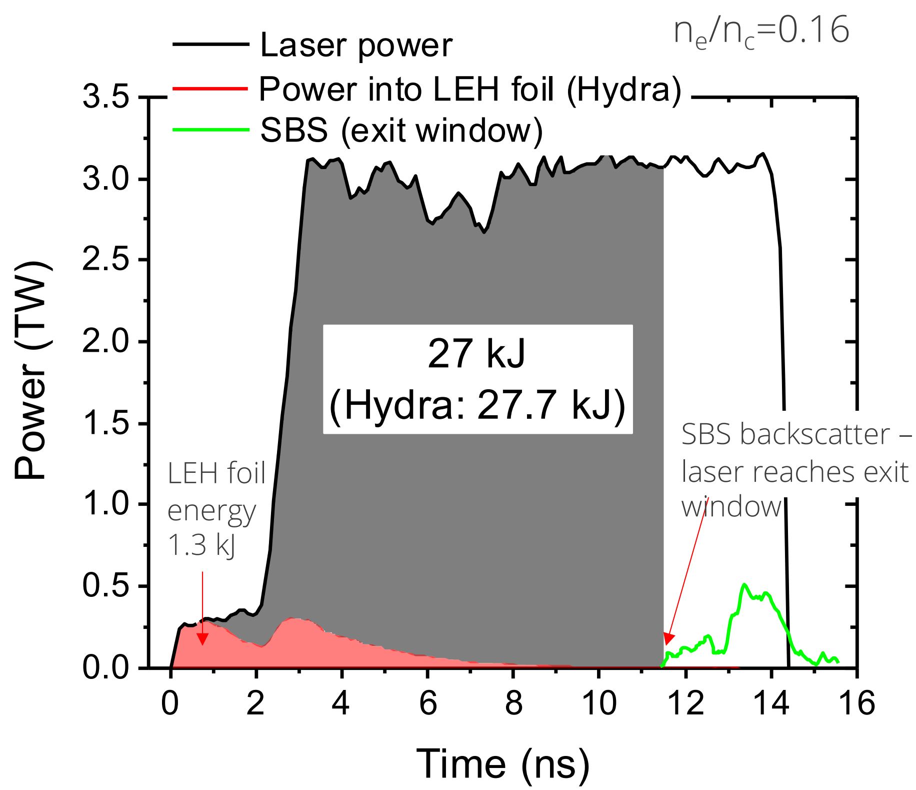
Laser overshooting the imploding region

Geissel et al., POP **25**, 022706 (2018)
Harvey-Thompson et al., POP **26**, 032707 (2019)

Experiments using one quad of the National Ignition Facility are assessing laser coupling efficiency and mix at the scale needed for a future generator







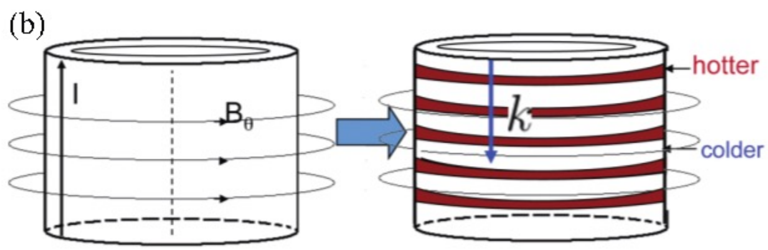
Experiments are underway to quantify coupling in pre-magnetized fuel and to quantify mix

Implosion stability

Do we understand the sources of instabilities?

How can we control?

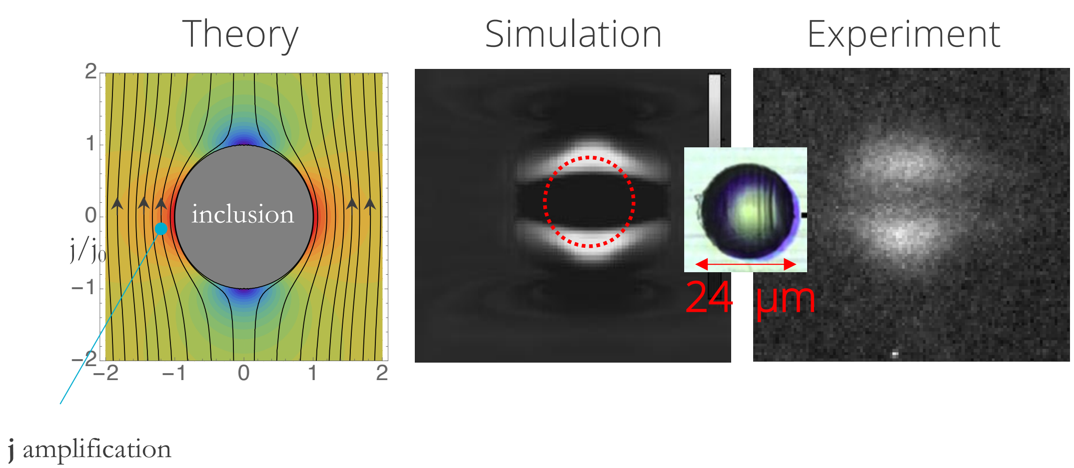
The leading hypothesis for the seed of implosion instabilities in MagLIF is the Electro-Thermal instability



- Electro-thermal instability forms when current flows in material with $\partial\eta/\partial T>0$

$$\uparrow \eta_0 \quad \uparrow \eta j^2 \quad \uparrow T$$

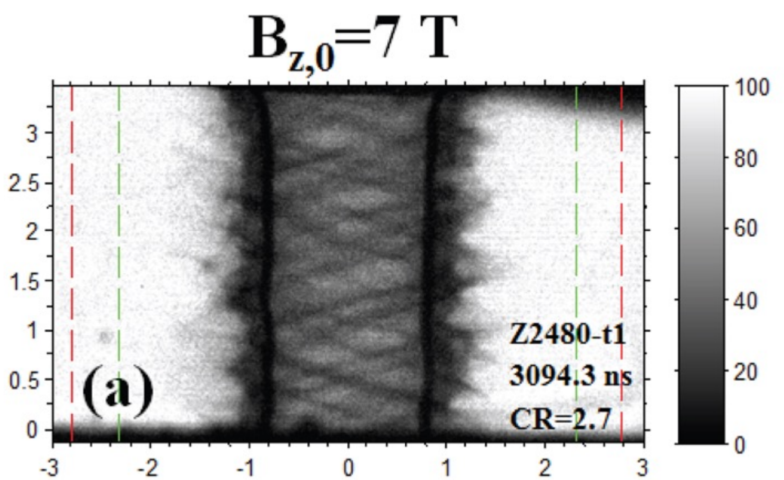
- Instability is active in the solid and liquid phases

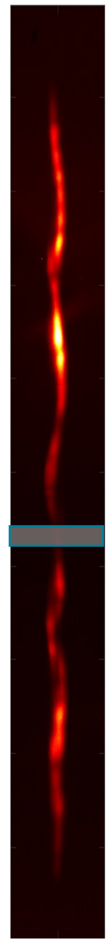


- 3-dimensional effects from inclusions exacerbate process, as shown in experiments on the 1 MA Mykonos driver

Oreshkin, POP **15**, 092103 (2008)
Peterson et al., POP **20**, 056305 (2013).
Yu et al., POP **27**, 052703 (2020)
Awe et al., POP **28**, 072104 (2021)

Premagnetized MagLIF liner implosions exhibit a helical implosion instability



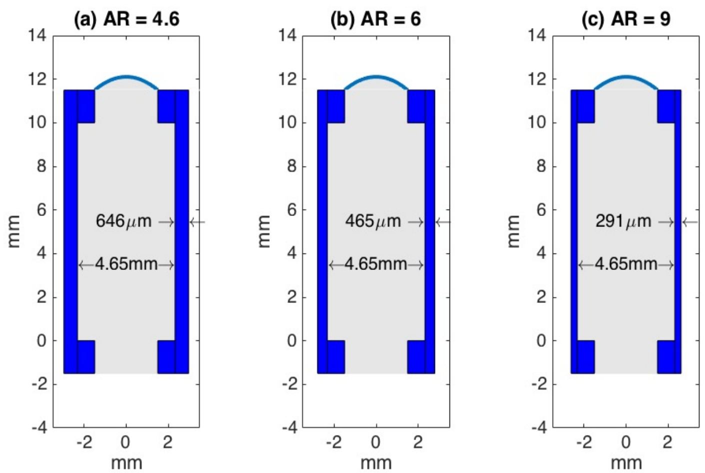


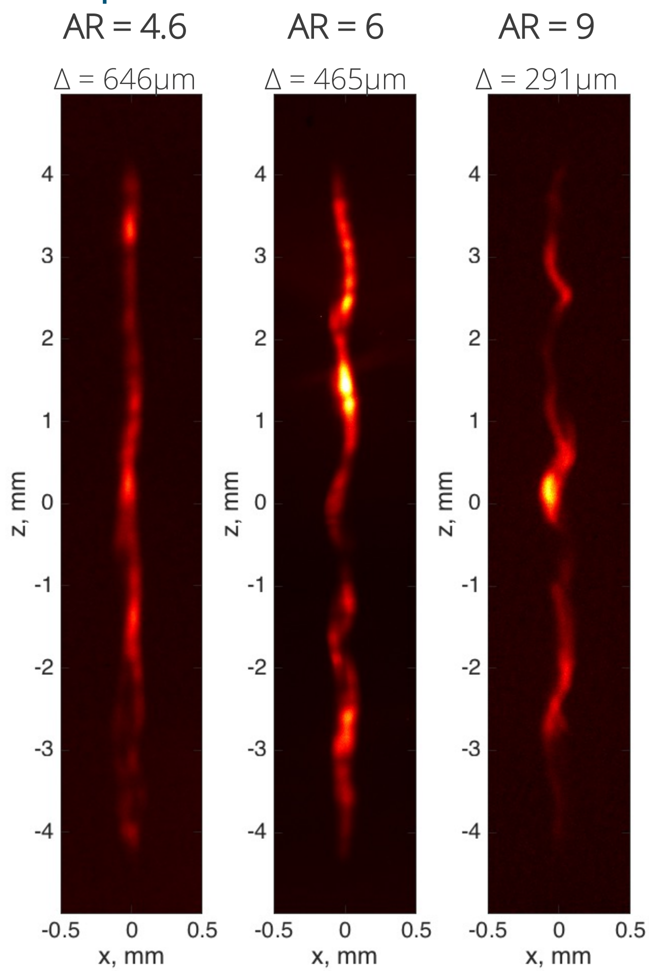
- When the MagLIF liner is pre-magnetized we see a helical instability form
  - One hypothesis is that this is also seeded by the electro-thermal instability
- Experiments are planned to attempt to discern different formation hypotheses
- During the MagLIF stagnation we also see a helical structure

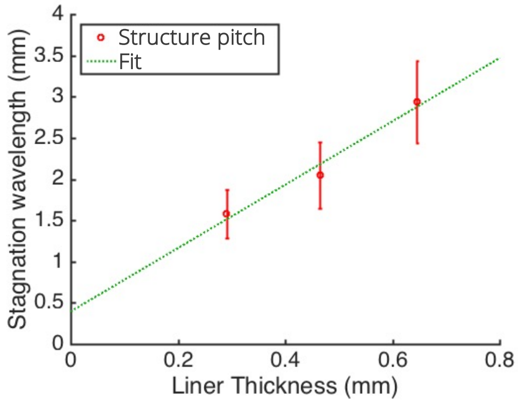
Awe et al., PRL **111**, 235005 (2013)

Helically-shaped x-ray images are observed at stagnation with increasing structure at increasing liner aspect ratio

- Helical structure is impacted by change in liner aspect ratio
- Higher aspect ratio leads to shorter helix period/wavelength
- Axial variation in brightness becomes more pronounced at higher aspect ratio







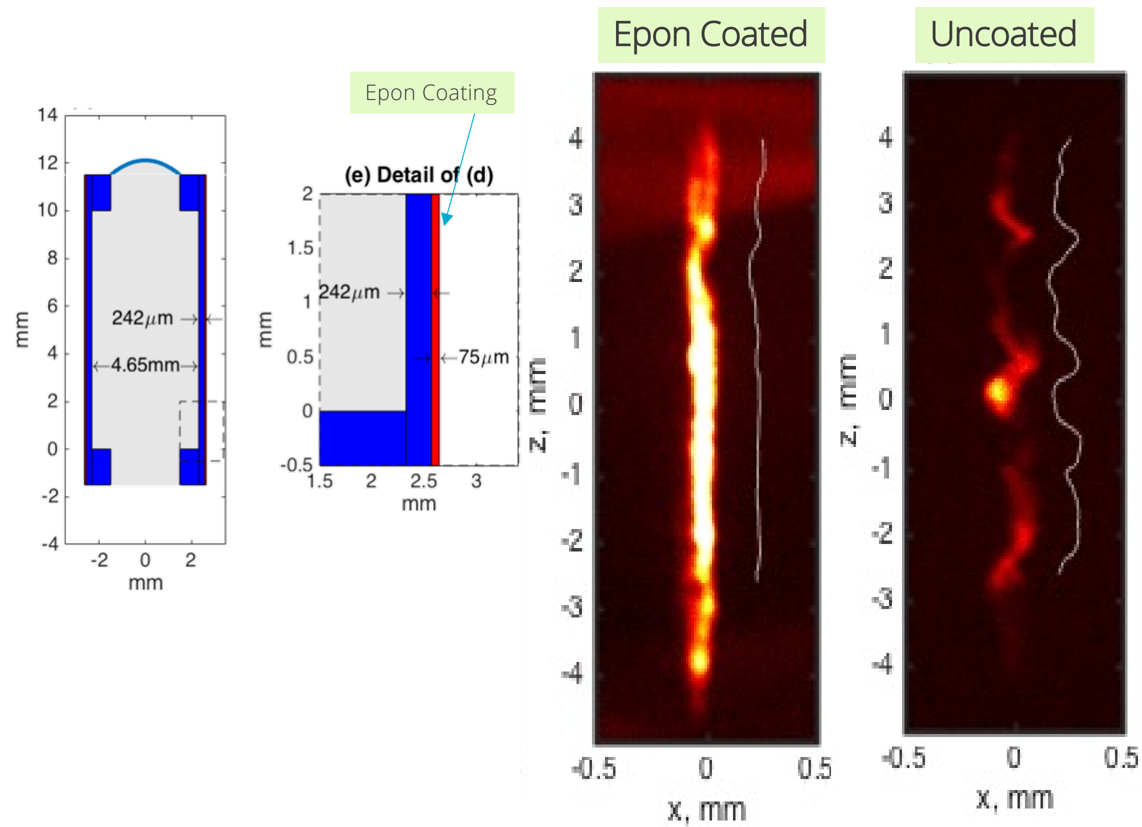
A uniform stagnation column is important for fuel confinement and for comparing with codes for predictable scaling

Introducing dielectric coatings on the outside of the liner reduces the ETI seed

Stagnation images demonstrate a more uniform stagnation column

As an alternative approach, we are also designing experiments with uncoated liners that reduce the convergence

- Increase fuel density, magnetization and preheat for a given current



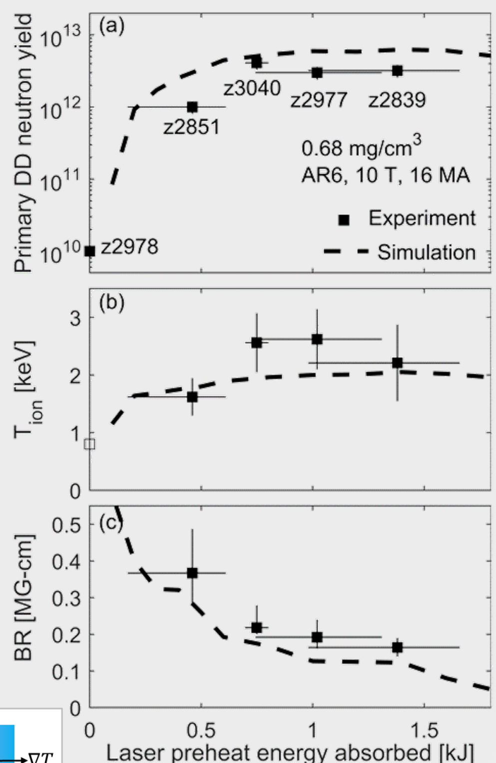
Integrated scaling

Can we predict how MagLIF scales with input parameters?

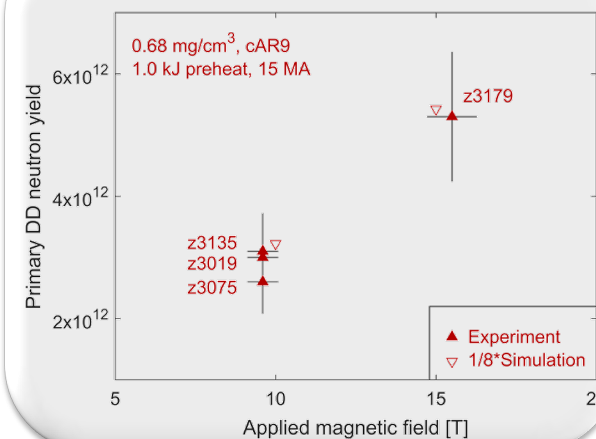
Can we test scaling theories?

Experiments are testing predictions from theory and simulations on scaling with individual and combinations of parameters

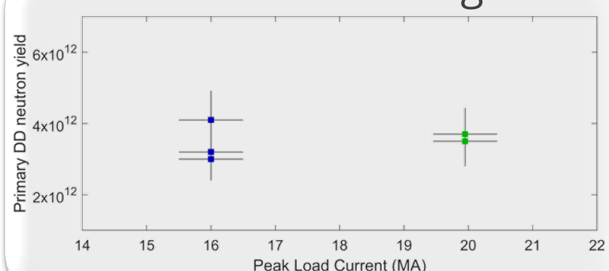
Preheat scaling



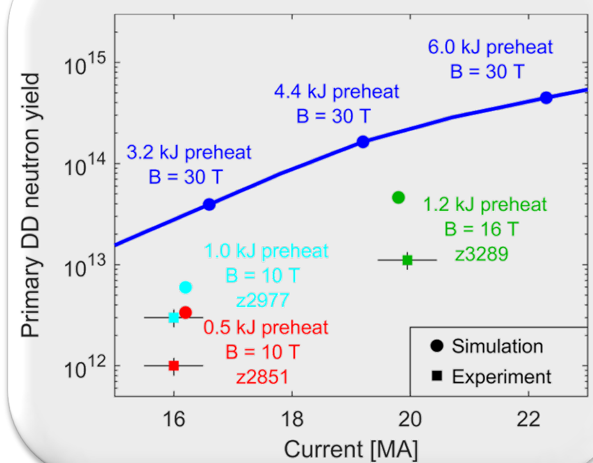
B-field scaling

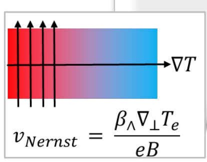


Current scaling



Combined scaling



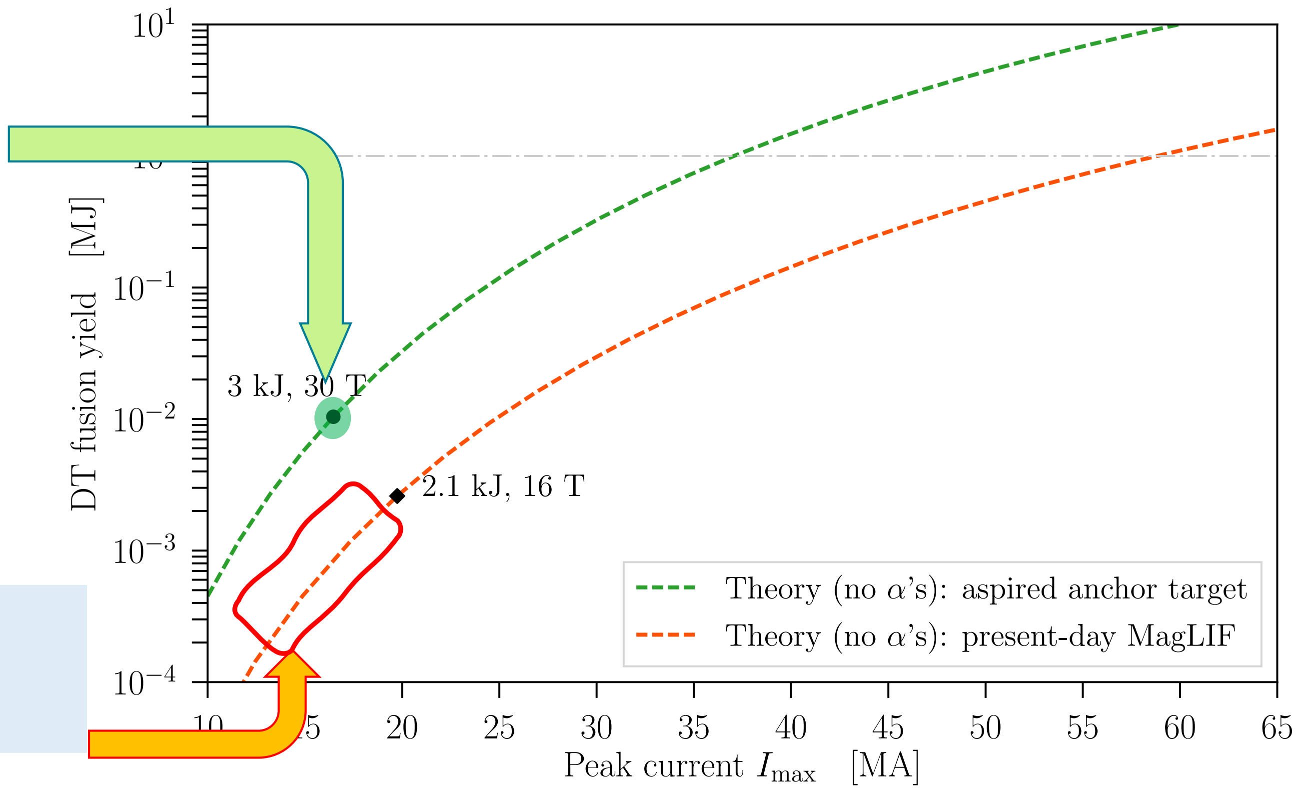


M.R. Gomez, et al., PRL. **125**, 155002 (2020).
W.E. Lewis, et al., POP, accepted (2021).

Experiments are planned over the next 18 months to establish a more efficient baseline and systematically test MIF scaling theory

Reach a higher-performing point (e.g., optimized) that can scale to multi-MJ yields.

Demonstrate the fundamentals of MagLIF scaling physics using self-similar theory at lower currents.

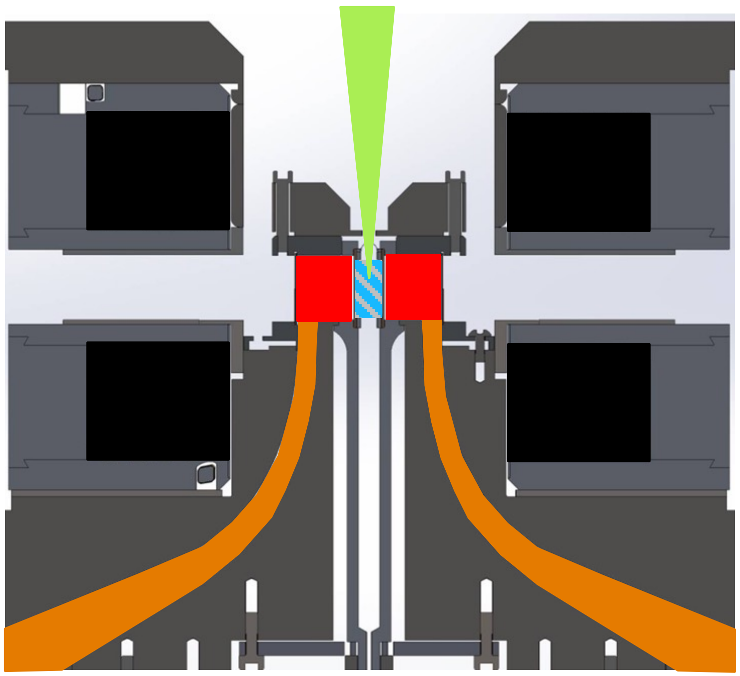


Schmit & Ruiz, POP **27**, 062707 (2020).

Opportunities for collaboration

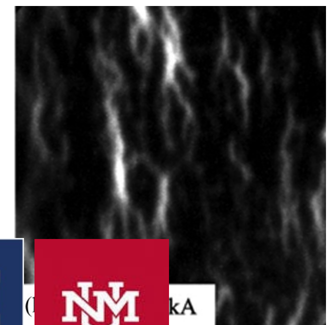
Five key focus areas highlight the innovations, opportunities, and risks for MagLIF

MagLIF Experimental Assembly

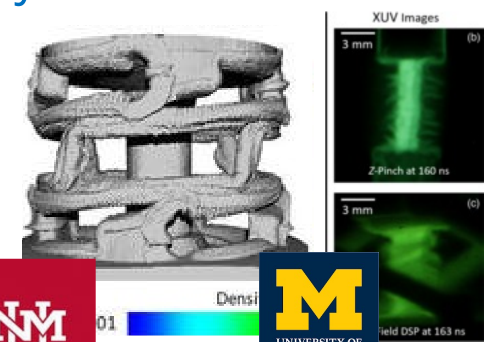


Implosion Stability and Mix

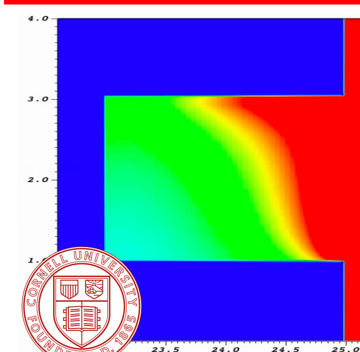
ETI experiments



Dynamic Screw Pinch



Current distribution within the target volume

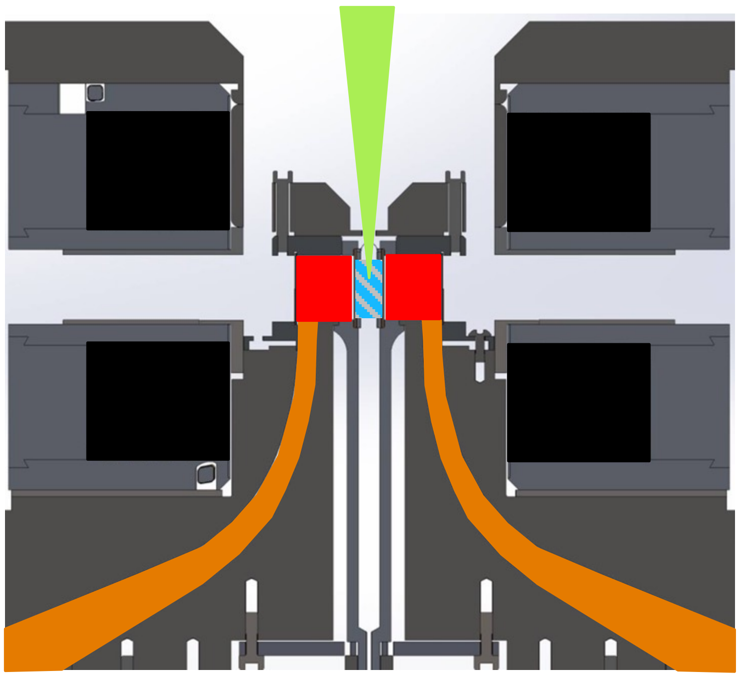


Hall MHD

Shipley et al., Physics of Plasmas **26**, 102702 (2019)
Campbell et al., PRL **125** 035001 (2020)
Seyler & M. R. Martin, Phys. Plasmas **18**, 012703 (2011).

Five key focus areas highlight the innovations, opportunities, and risks for MagLIF

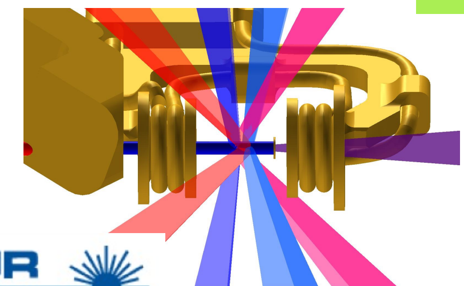
MagLIF Experimental Assembly



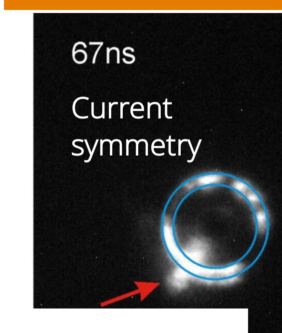
Performance and Physics Scaling

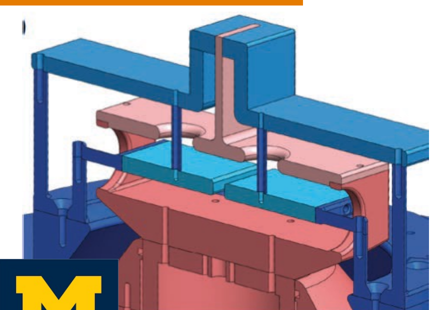
Mini MagLIF

Preheat Efficacy



Transmission line to the target





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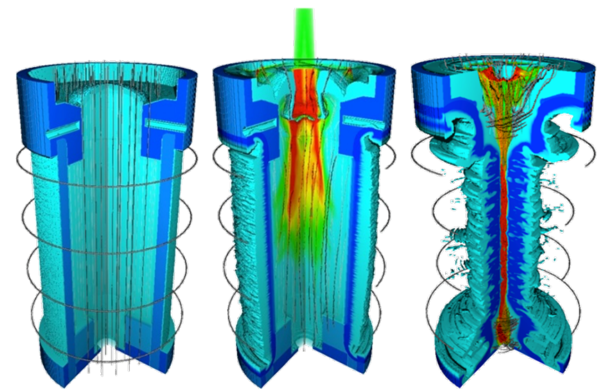
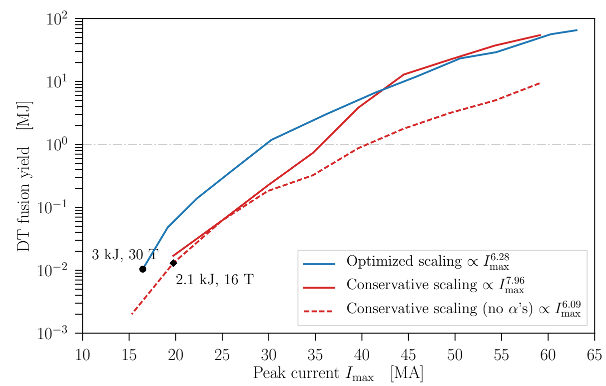
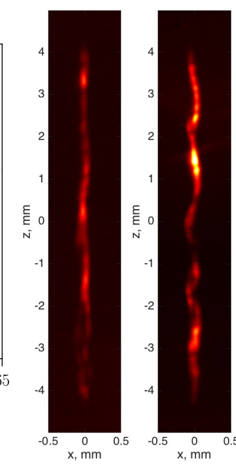
Summary

Summary: Magnetized Liner Inertial Fusion is a promising approach to reaching multi-MJ yields with pulsed power

- Magnetized Liner Inertial Fusion (MagLIF) is a Magneto-Inertial scheme that uses a combination of magnetic field coils, laser preheat and pulsed-power-driven compression to reach fusion conditions
- A self-similar scaling theory has been developed to set requirements for a MJ-class facility and guide target design
- Scaling risks have been identified in the areas of preheat, implosion stability and mix, and detailed physics studies are underway to address these
- Research efforts are currently concentrating on testing self-similar scaling, improving performance on Z and on focused physics studies







Questions?