Sandia National Laboratories

Exceptional service in the national interest

Innovation and Advancement of the MagLIF Concept on Z

Gabriel Shipley

in close collaboration with

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S. A. Slutz, D. J. Ampleford, L. Shulenburger, and the MagLIF team

June 29th, 2023

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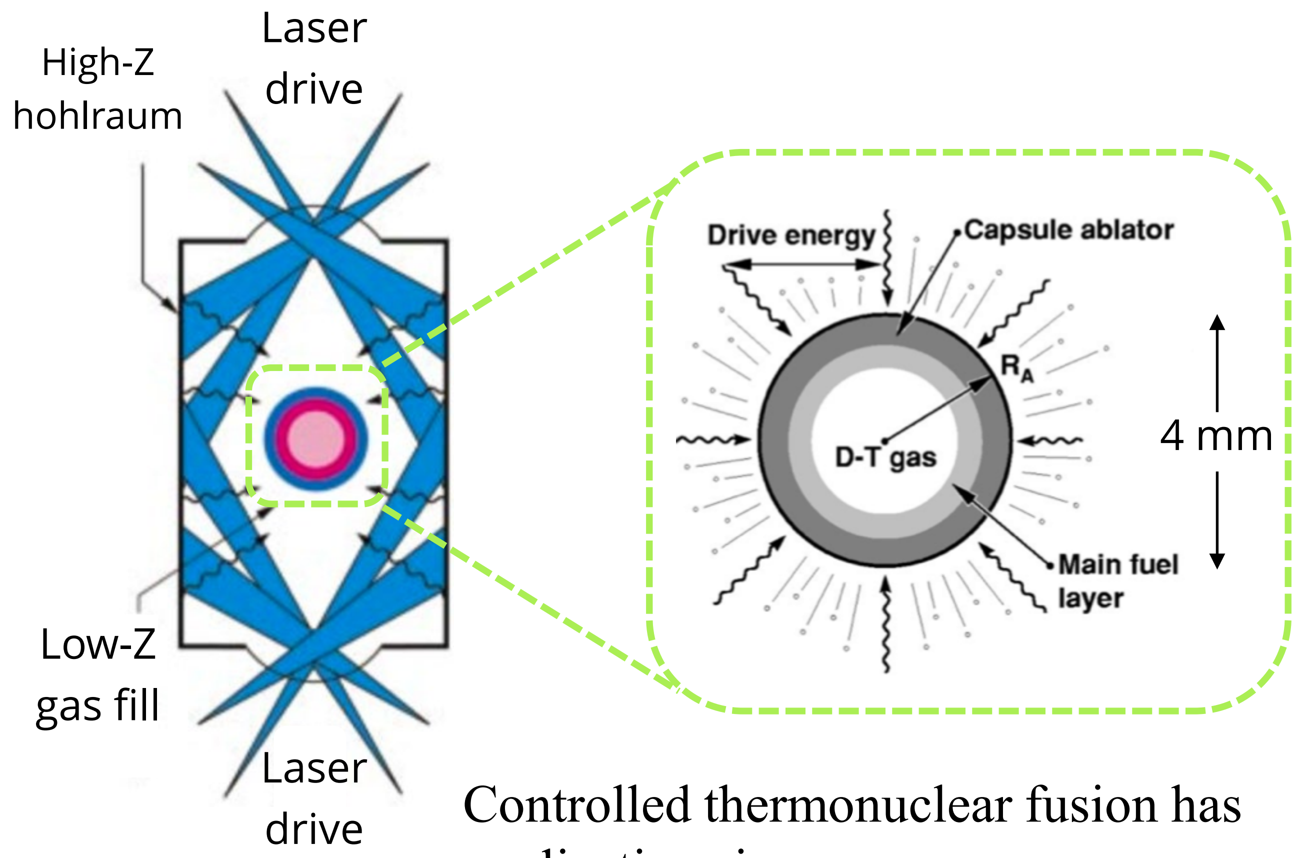
Inertial Confinement Fusion (ICF) is an exciting field of research and one of high importance to the DOE/NNSA mission space



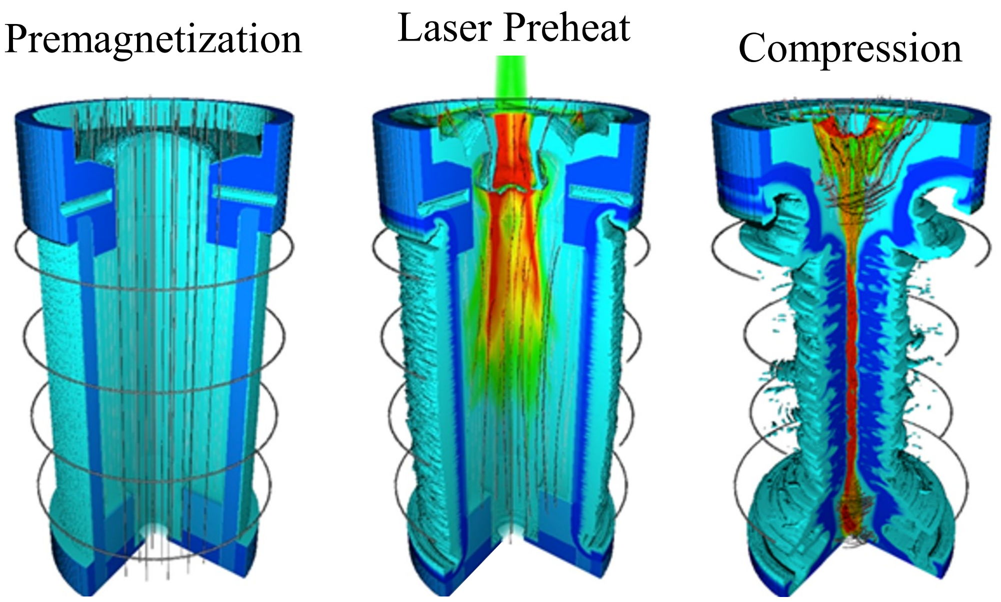
Controlled thermonuclear fusion has applications in:

Nuclear weapons stockpile stewardship
Radiation effects science
Energy production

Lindl et al., POP 11, 339 (2004), Clark et al., PPCF 59, 055006 (2017)

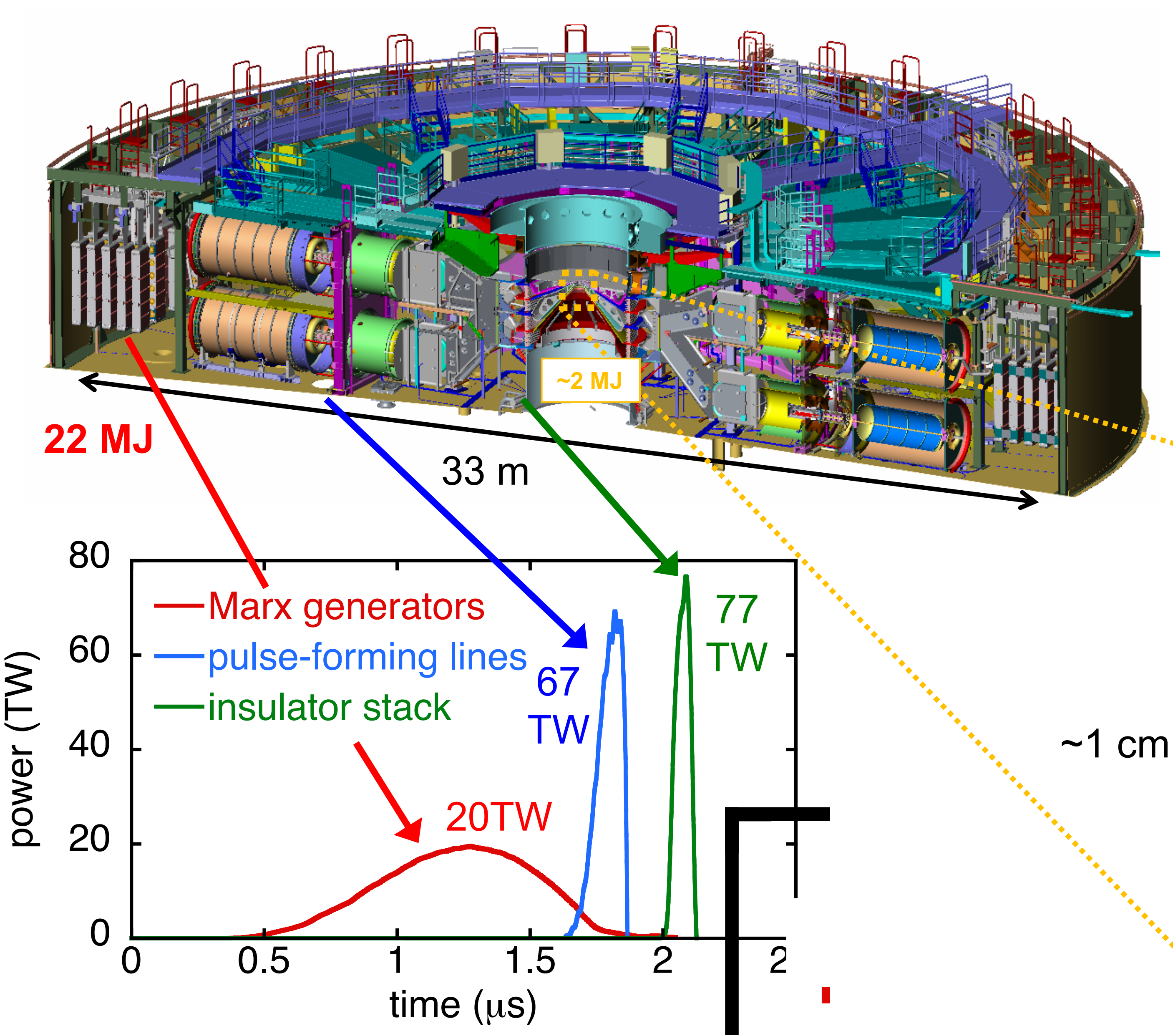
Sandia National Laboratories

- Long history of expertise and leadership in pulsed power accelerator science and technology.
- Sandia's Magnetized Liner Inertial Fusion approach seeks to achieve thermonuclear conditions in pulsed-power-driven cylindrical implosions.



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

The Z accelerator (the "Z Machine") is the largest and most powerful pulsed power accelerator in the world



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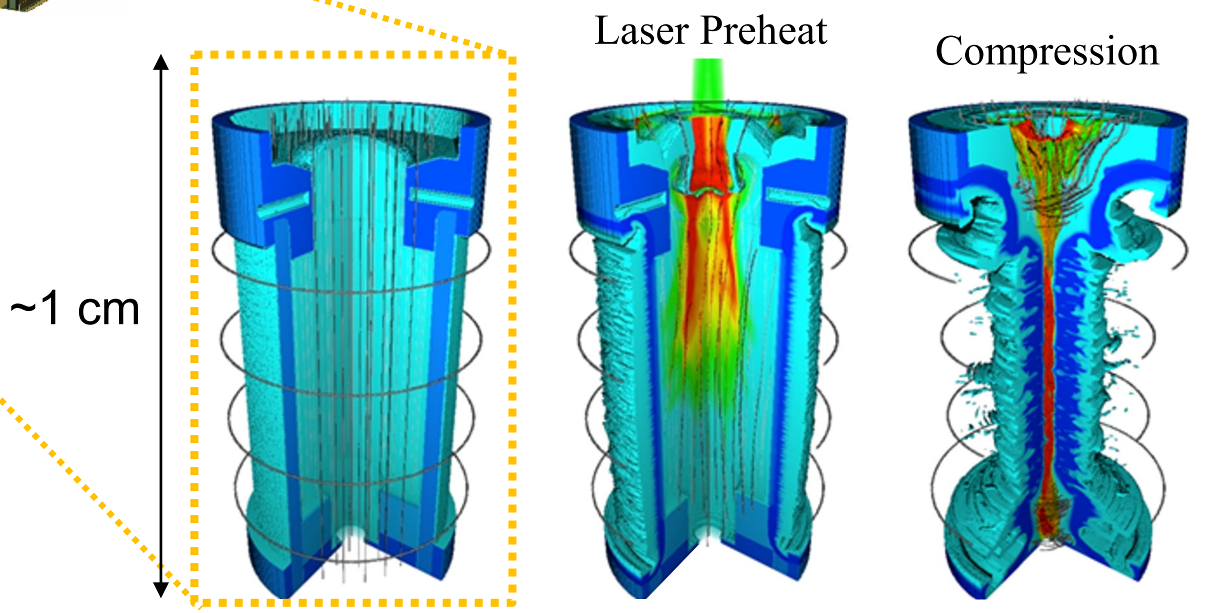
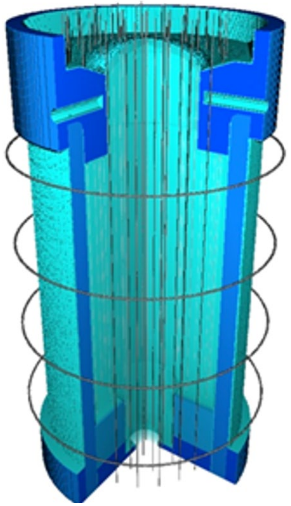


S. A. Slutz et al., Phys. Plasmas **17**, 056303 (2010).

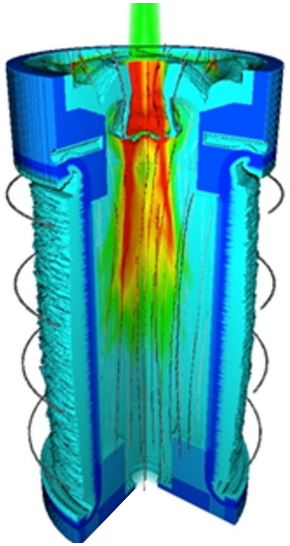
What is MagLIF?

Magnetized Liner Inertial Fusion (MagLIF[1]): Magnetic compression of premagnetized, laser-preheated fusion fuel



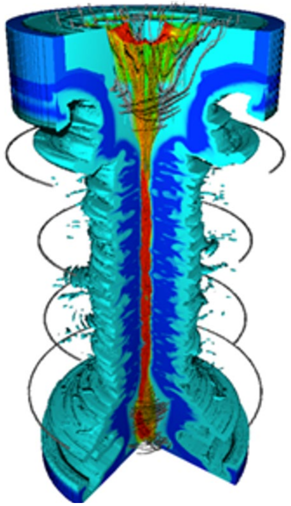
- **Premagnetization[2]: 10-20 T quasi-static axial magnetic field, $B_{z,0}$, is applied to thermally insulate fuel**

  Reduces required implosion velocity compared to laser ICF



- **Laser preheat[3]: The fuel is pre-heated using the Z-Beamlet Laser (4 kJ)**

  Reduces required compressive heating compared to laser ICF



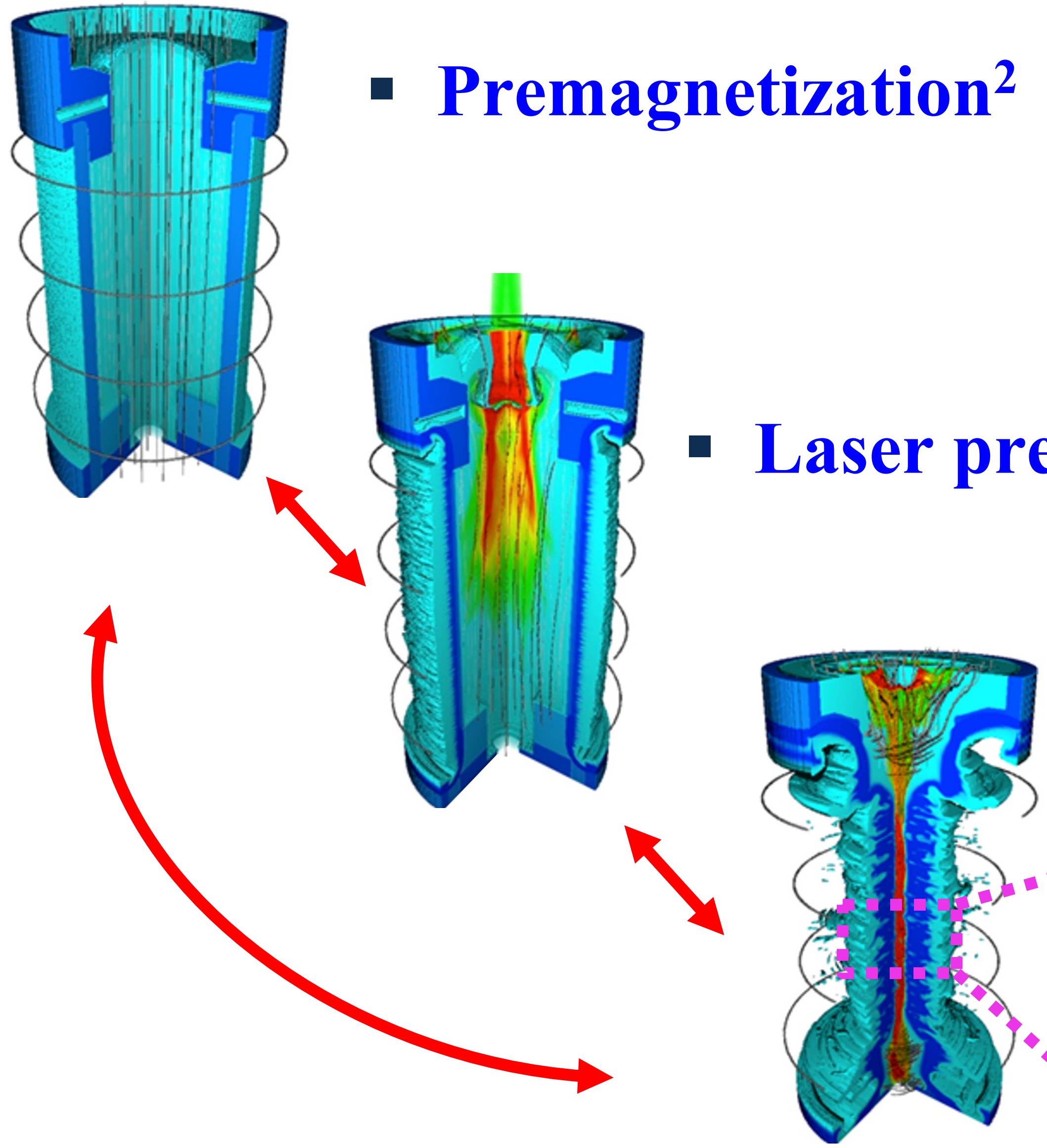
- **Compression: Z Machine drive current implodes liner, ~18 MA in 100 ns**

  Adiabatically compresses fuel to thermonuclear conditions

Deuterium-gas-filled beryllium liner (cylindrical tube)

[1] S. A. Slutz et al., Phys. Plasmas **17**, 056303 (2010). [2] Rovang et al., Rev. Sci. Instrum. **85**, 124701 (2014). [3] Harvey-Thompson et al., Phys. Plasmas **26**, 032707 (2019).

Each component of MagLIF[1] has unique challenges



- **Premagnetization[2]**

Background axial magnetic field provided by external field coil system.
Field strength is limited by coil technology.
External coils limit diagnostic access to target.

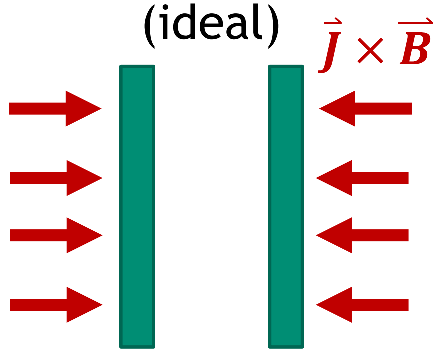
- **Laser preheat[3]**

Laser energy coupling to fuel suffers from losses.
Laser energy deposition can exacerbate liner-fuel material mix (radiative losses).

- **Compression**

Instabilities in imploding liner degrade compression of fuel, limiting fusion yield.

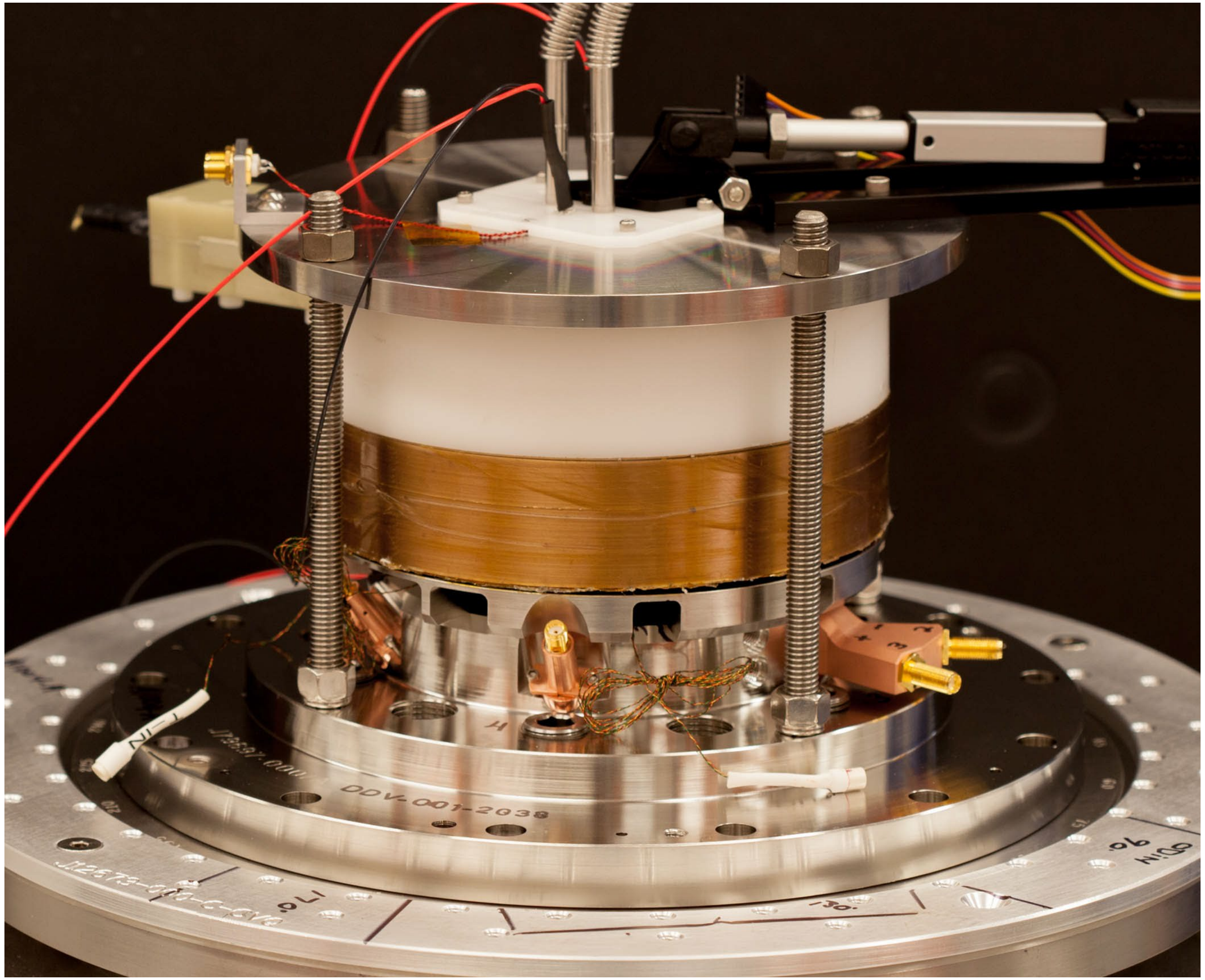
vs.



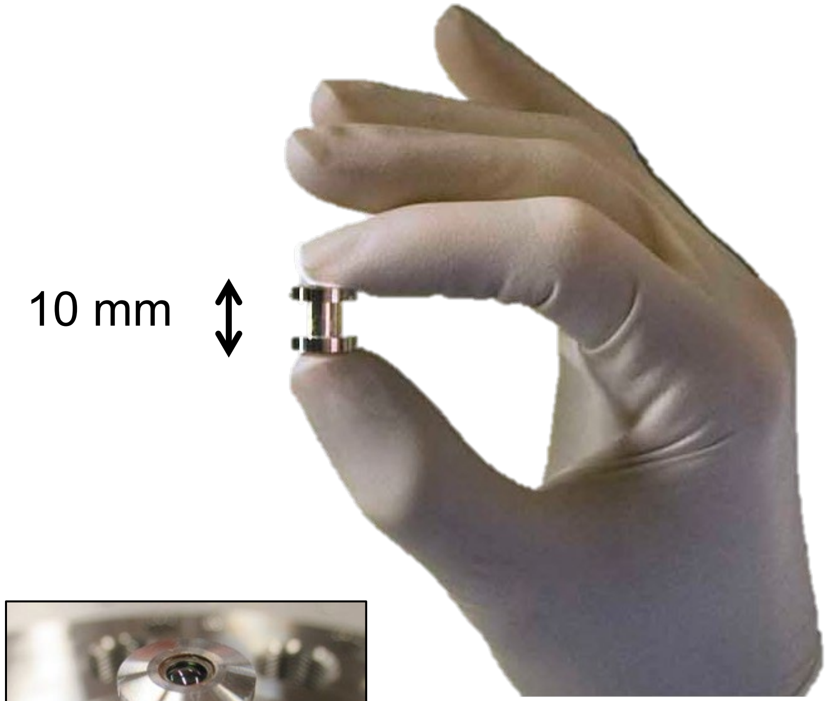
[1] S. A. Slutz et al., Phys. Plasmas **17**, 056303 (2010).
[2] Rovang et al., Rev. Sci. Instrum. **85**, 124701 (2014).
[3] Harvey-Thompson et al., Phys. Plasmas **26**, 032707 (2019).

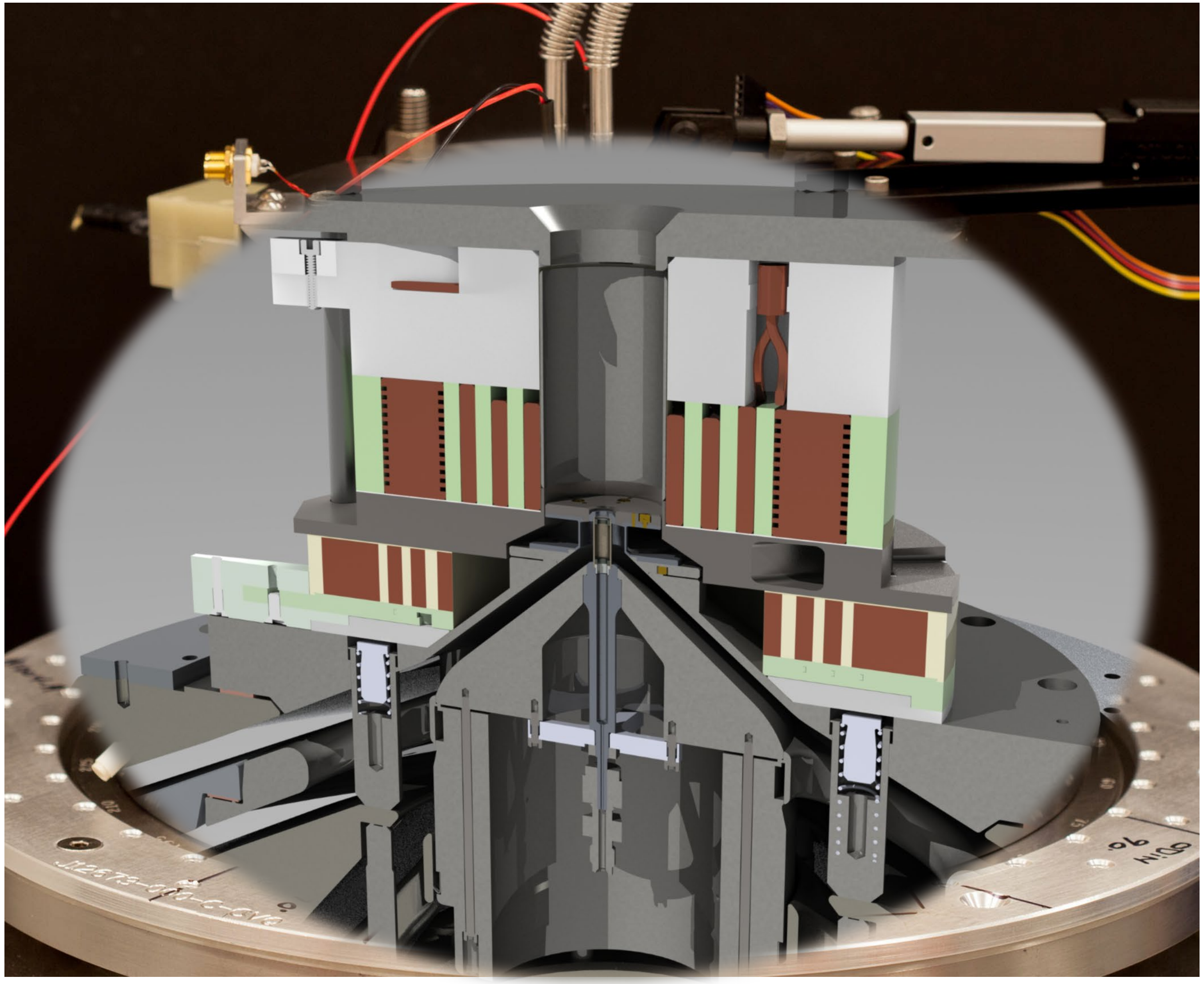
The anatomy of MagLIF

10 mm

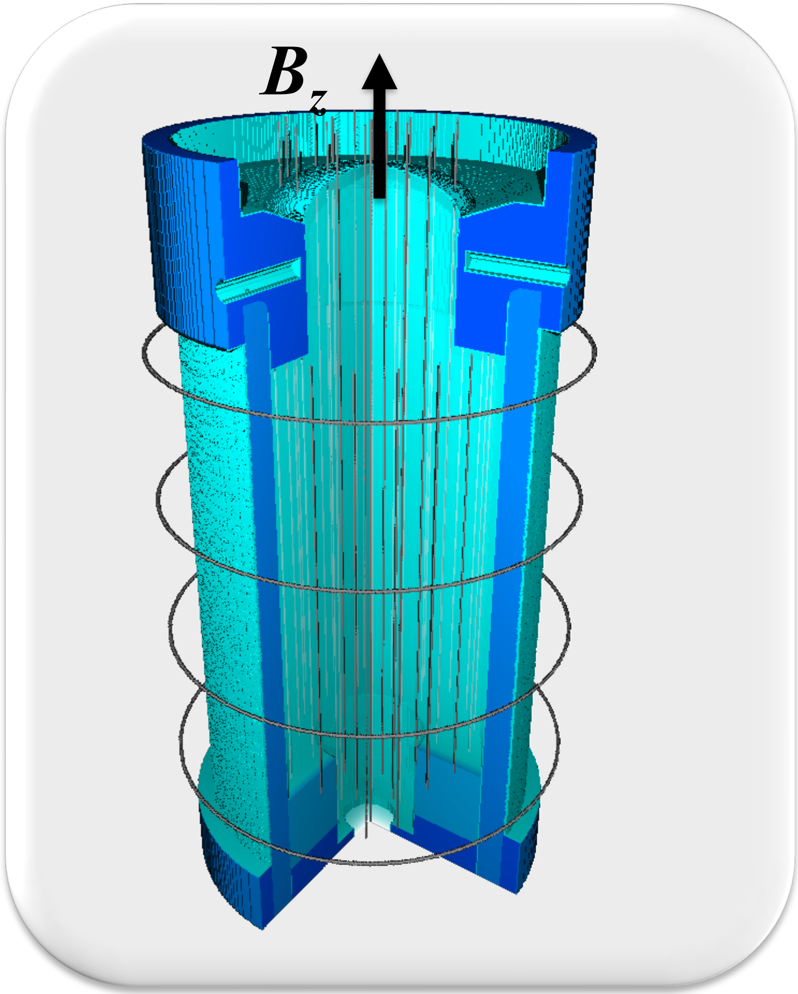


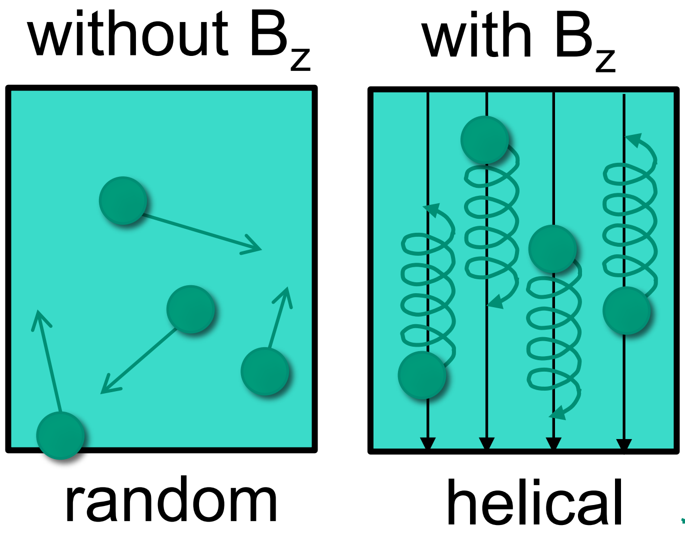
The anatomy of MagLIF



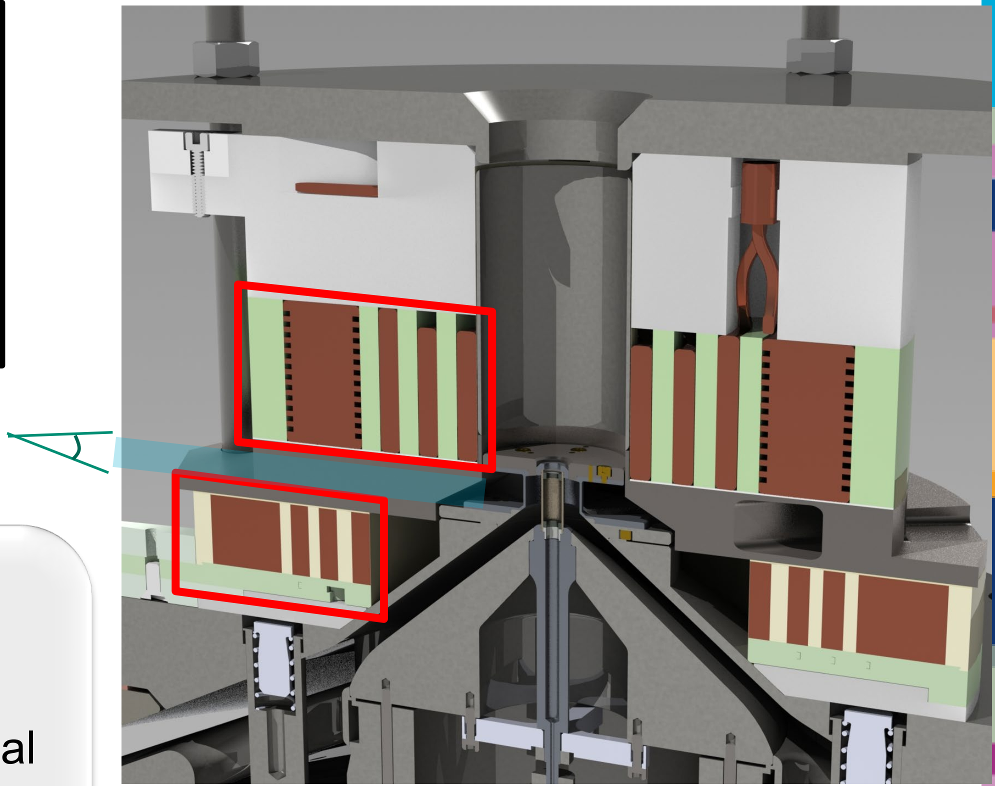


Helmholtz-like coils are used to premagnetize the MagLIF load[1]



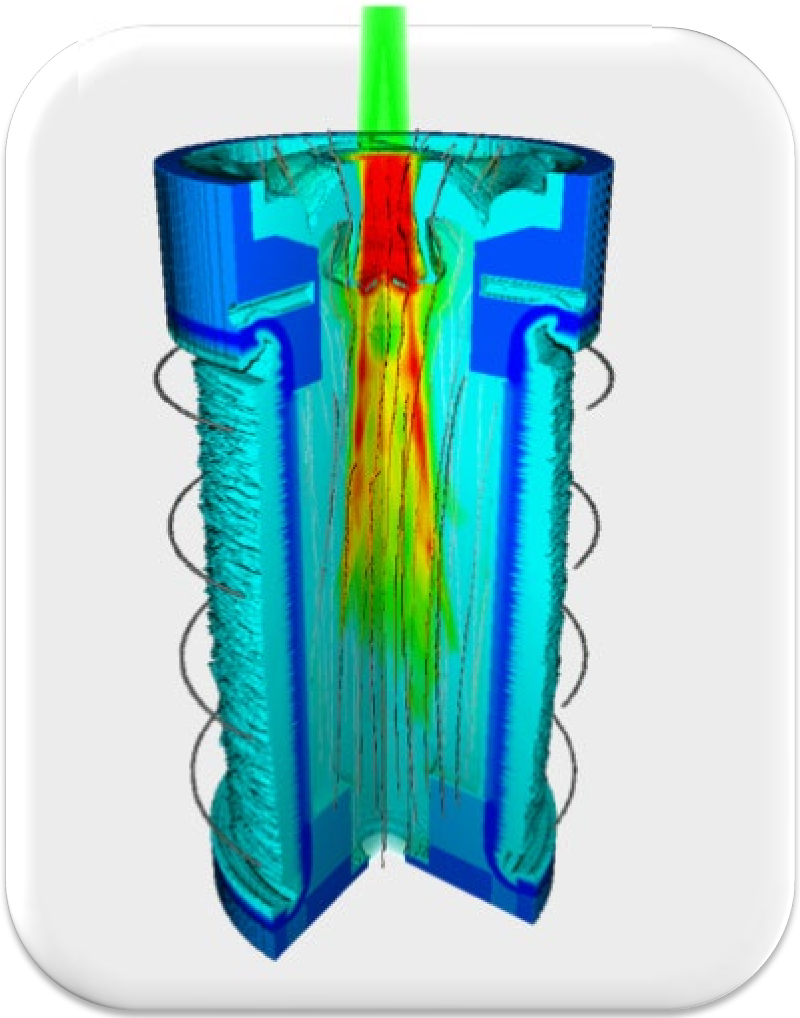


Premagnetize fuel
- Field coils embed 7-20 T field over millisecond timescale.
- Field suppresses radial thermal conduction.
- Compressed field at stagnation traps fusion products.



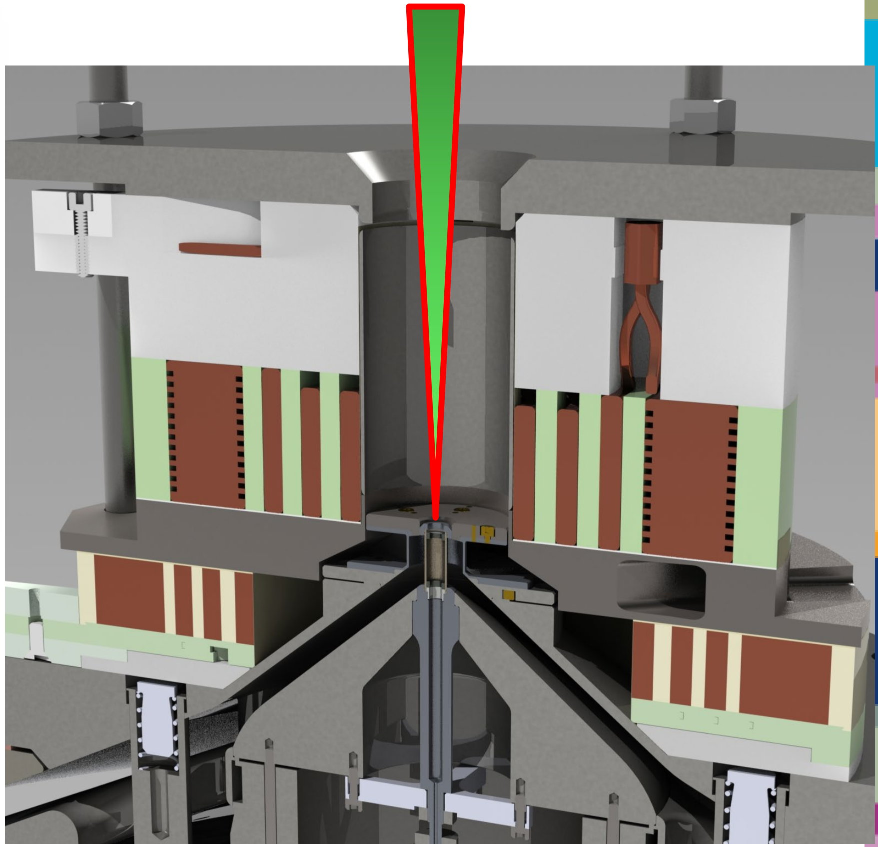
[1]D. C. Rovang *et al.*, Rev. Sci. Instrum. **85**, 124701 (2014).

To reduce the necessary convergence ratio to reach thermonuclear conditions, the Z Beamlet laser is used to preheat the fuel



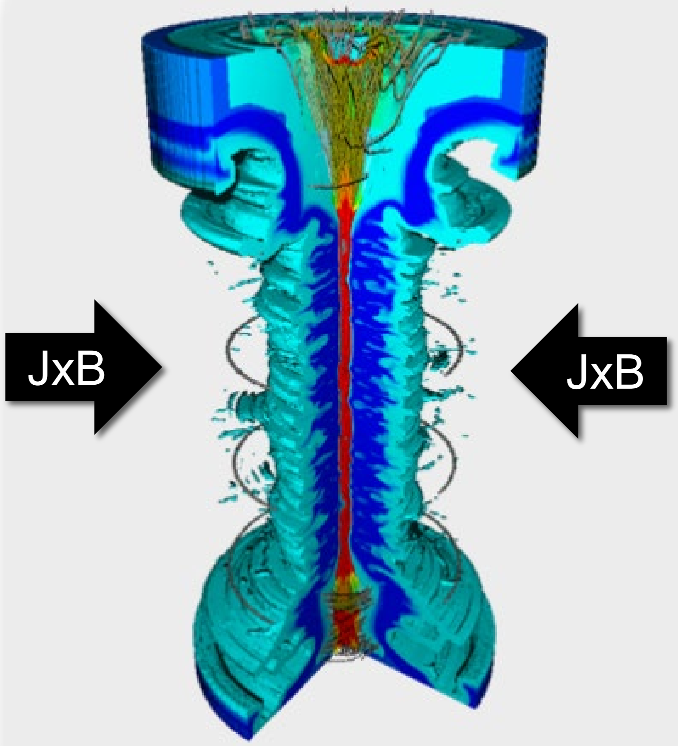
Preheat the fuel

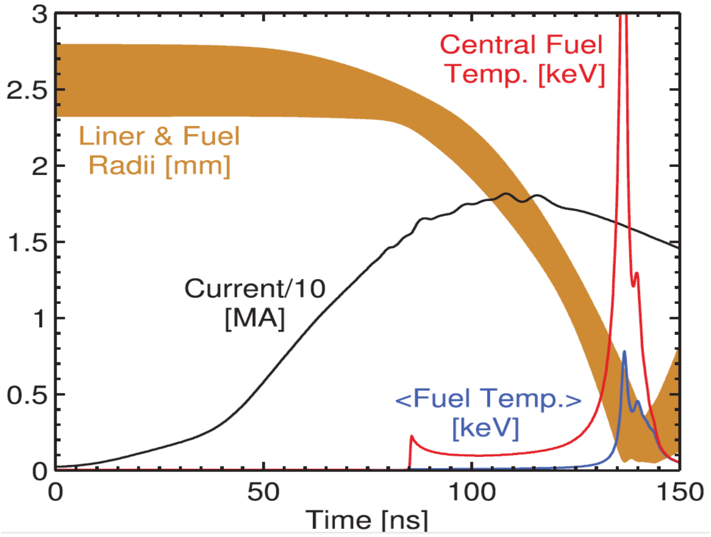
- Z-Beamlet laser delivers ~2-3 kJ to the Z chamber.
- Laser heats fuel through Inverse Bremsstrahlung (~100-200 eV, 1-2 kJ)
- Laser preheat sets the adiabat of the implosion.



M. R. Weis, et al., Phys. Plasmas **28,** 012705 (2021).
A. J. Harvey-Thompson, et al., Phys. Plasmas **27,** 113301 (2020).
A. J. Harvey-Thompson, et al., Phys. Plasmas **26**, 032707 (2019).
A. J. Harvey-Thompson, et al., Phys. Plasmas **25**, 112705 (2018).
M. Geissel, et al., Phys. Plasmas **25**, 022706 (2018).
A. J. Harvey-Thompson, et al., Phys. Rev. E **94**, 051201 (2016).
A. J. Harvey-Thompson, et al., Phys. Plasmas **22**, 122708 (2015).

~20 MA peak current from Z is used to compress the liner and fuel.





Compress liner and fuel

- Lorentz force accelerated the liner.
- Fuel is then quasi-adiabatically compressed.
- Liner implosion leads to flux compression, amplifying B-field

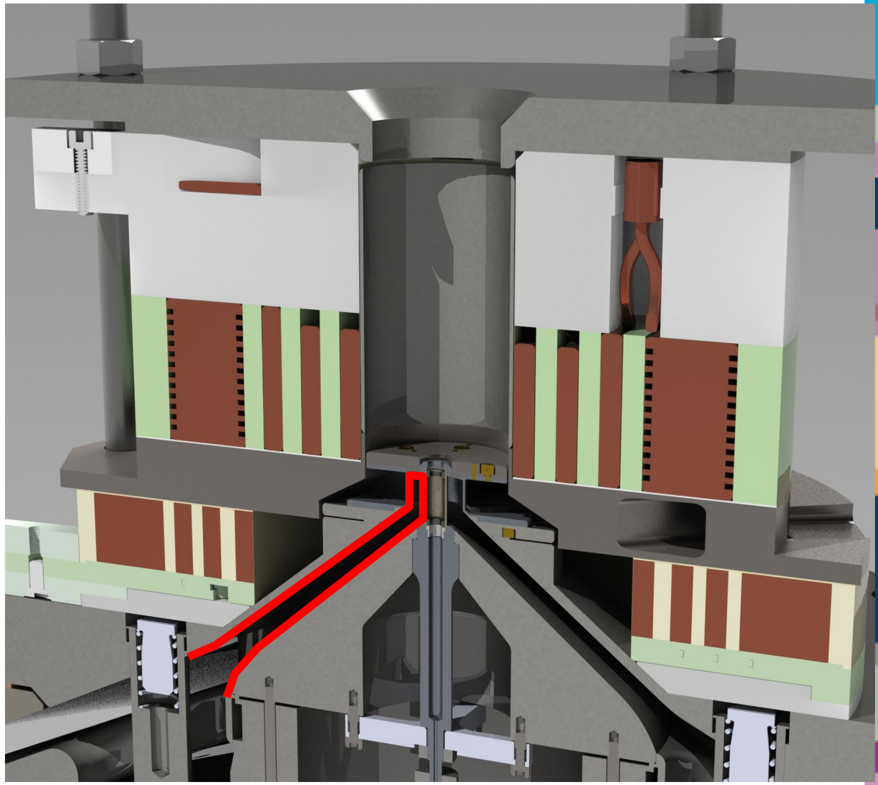
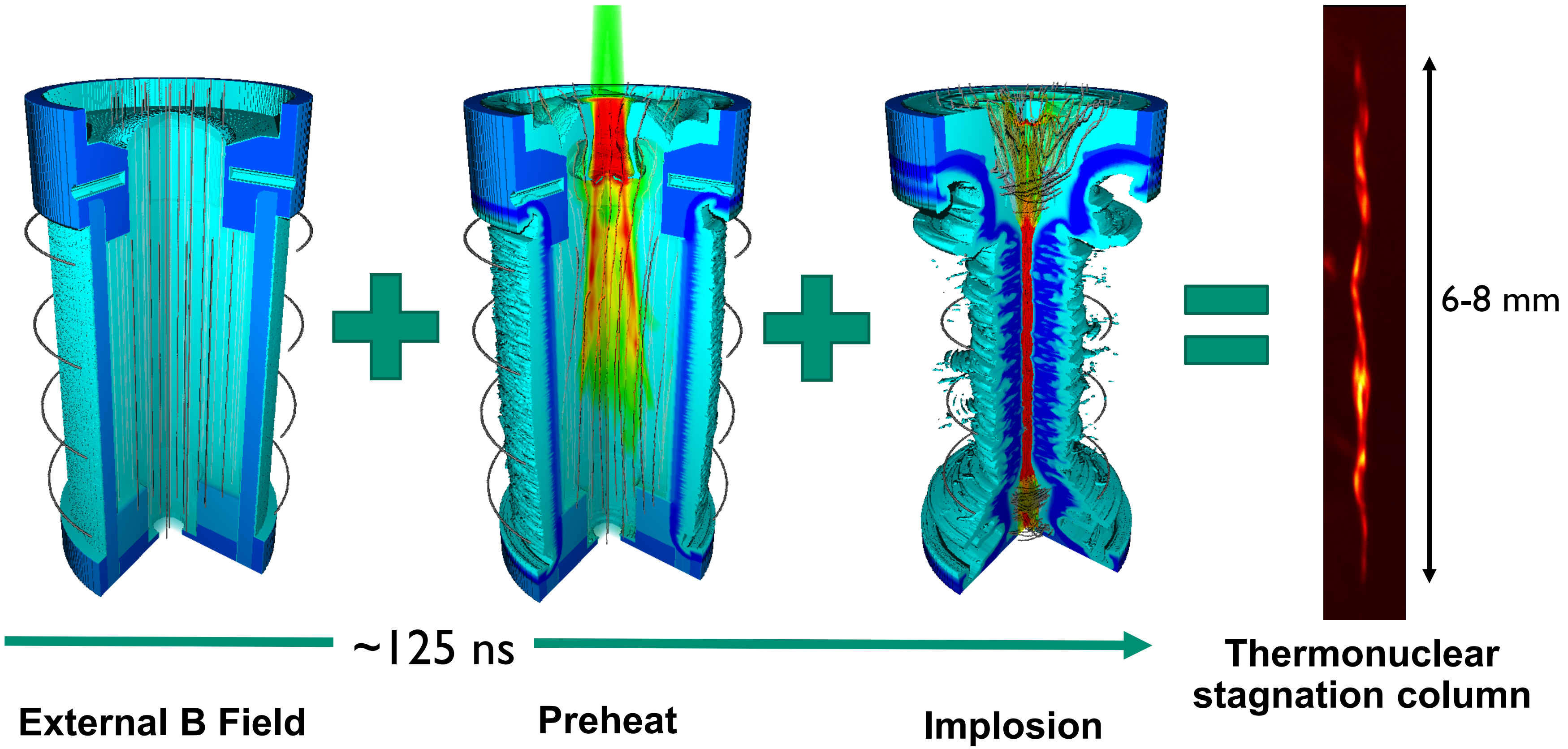


Image taken from R. McBride et al., Phys. Plasmas **23**, 012705 (2016).
3D implosion movie courtesy of C. Jennings.

Magnetized Liner Inertial Fusion (MagLIF[1,2]): Magnetic compression of premagnetized, laser-preheated fusion fuel



Shot ID	z3289
$\dot{R}_{max}$	70 km/s
R_{burn}	50 um
T_{burn}	2.7 keV
p_{burn}	1.9 Gbar
τ_{bw}	2 ns
Y (DT equivalent)	2 kJ

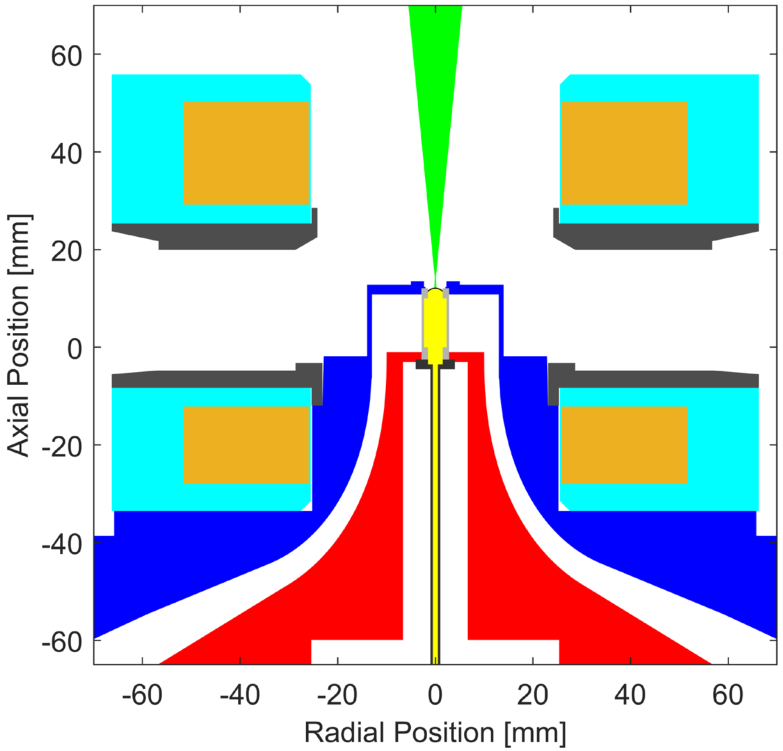
[1] S. A. Slutz, M. C. Herrmann, R. A Vesey, *et al.*, Phys. Plasmas **17**, 056303 (2010).
[2] M. R. Gomez, S. A. Slutz, A. B. Sefkow, *et al.*, Phys. Rev. Lett. **113**, 155003 (2014).

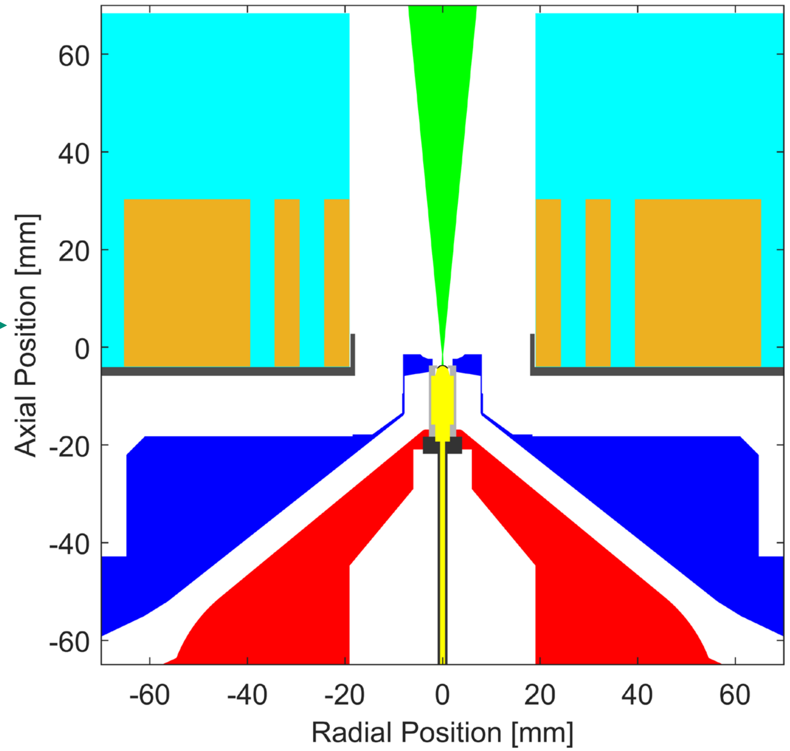
Advancements and Innovations in MagLIF

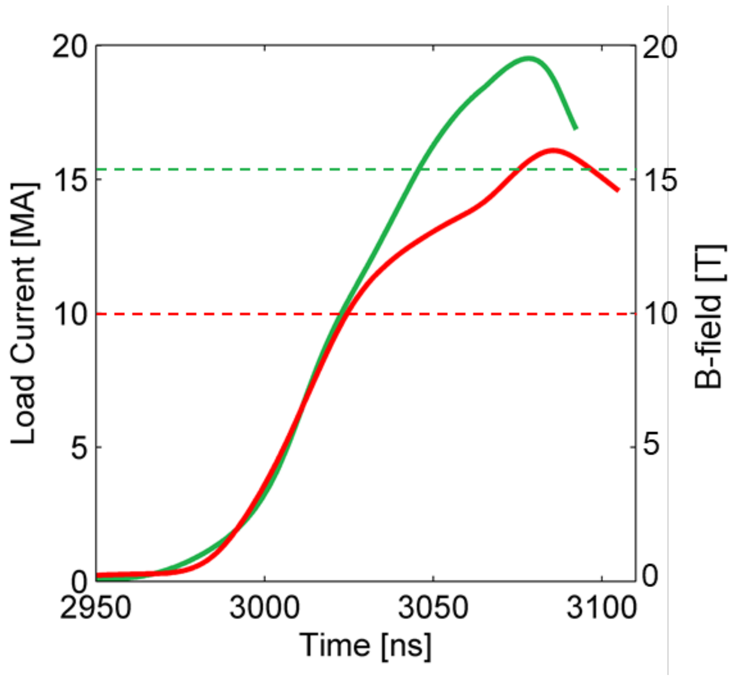
Magnetization

Magnetization and current coupling designs are linked through geometry so they were optimized simultaneously

- Conical transmission line with lower inductance and larger anode-cathode gaps reduced current losses allowing 19.5 MA to be delivered to the target
- Single, high performance coil delivered 15 T average field to the target while maintaining radial diagnostic access

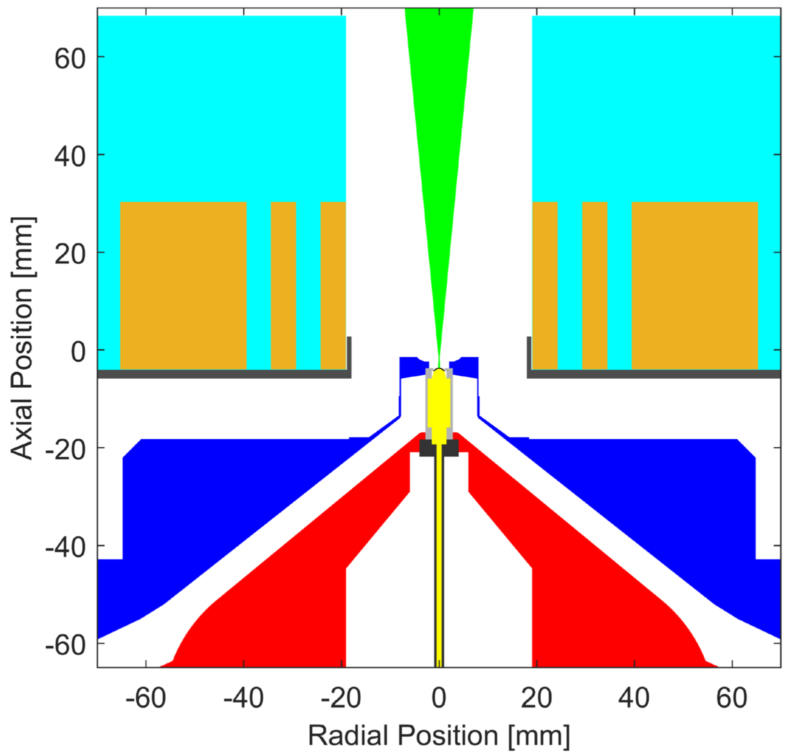


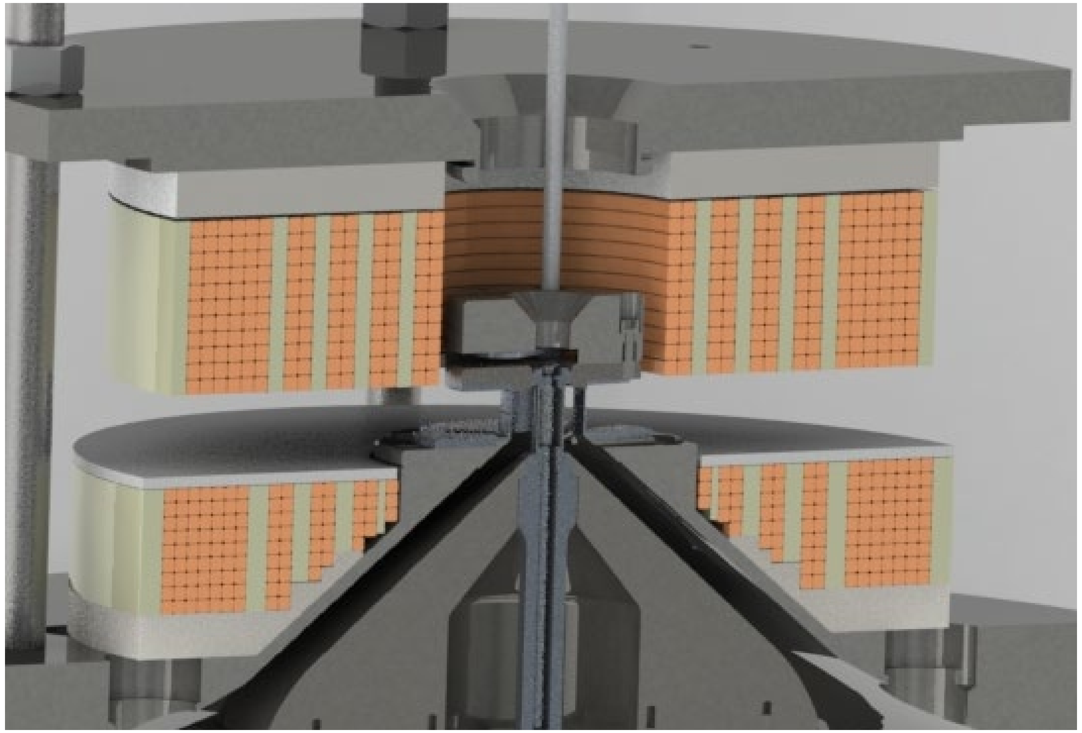




>15 T would improve MagLIF performance: Coil development continues

- Advanced coil fabrication techniques are being pursued to enable not standard coil cross section for bottom coil
- Calculations suggest that 25-30 T represents a technological "ceiling" for external field coils

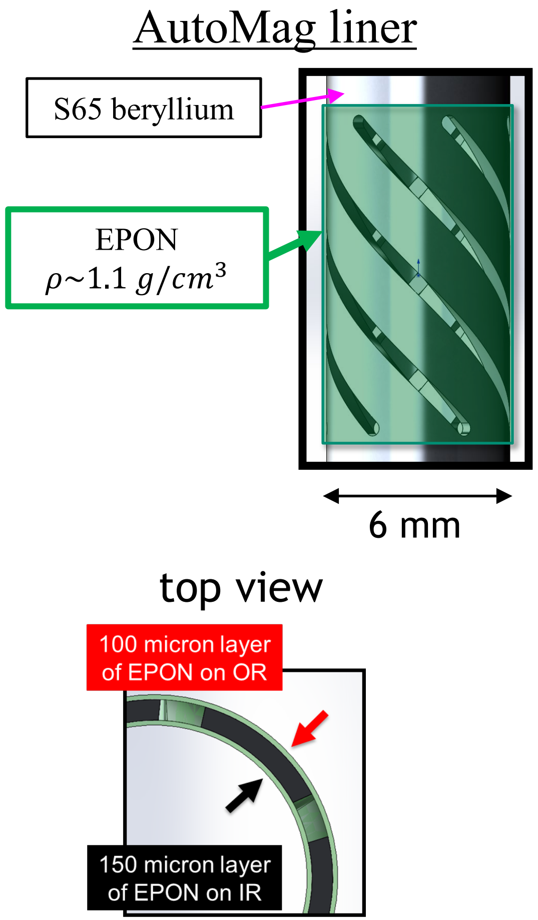


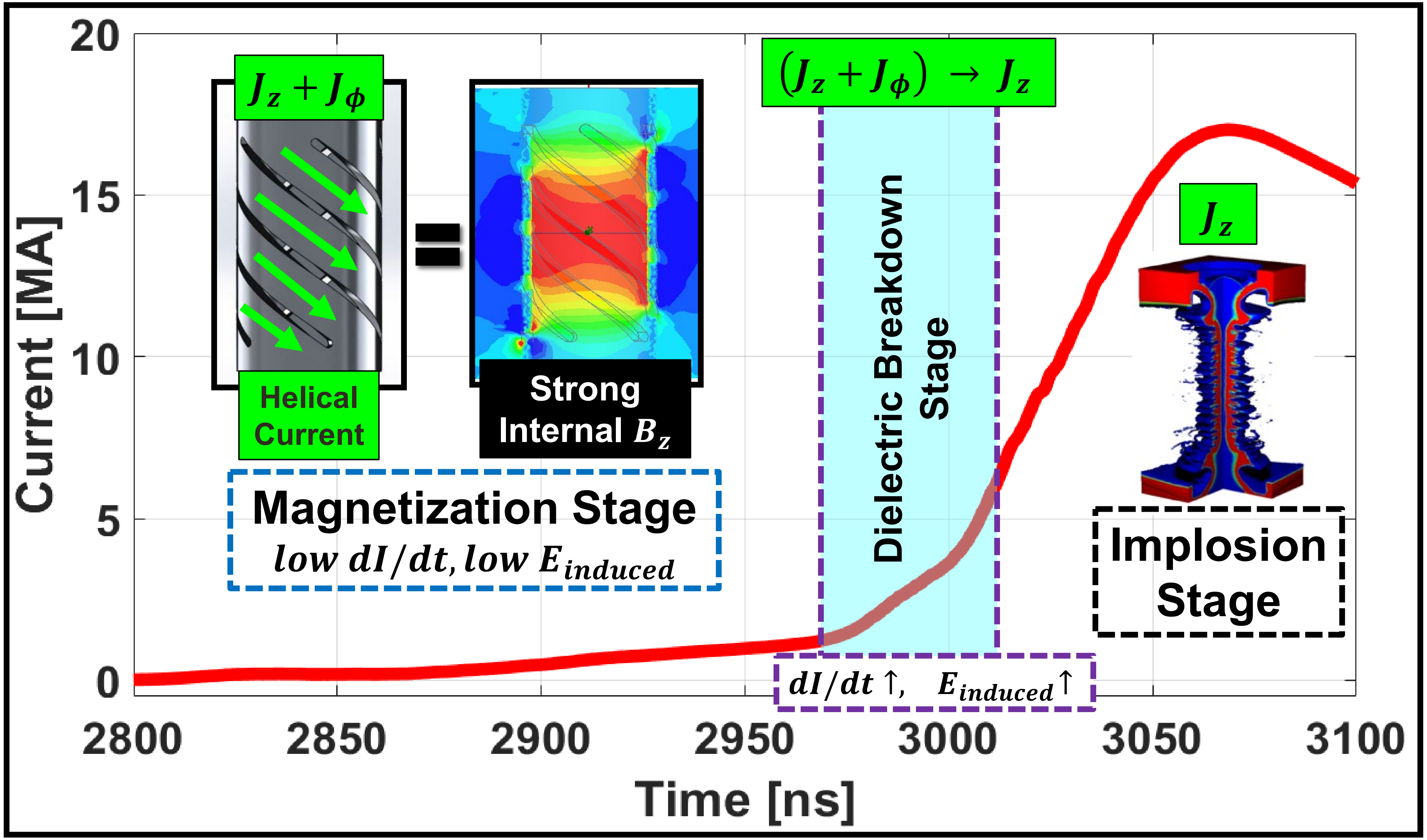


A path towards magnetization *without* coils

If coils represent a technological challenge/barrier,
let’s get rid of them!

Auto-magnetizing (AutoMag*) liners offer an alternative to external coils with several potential advantages



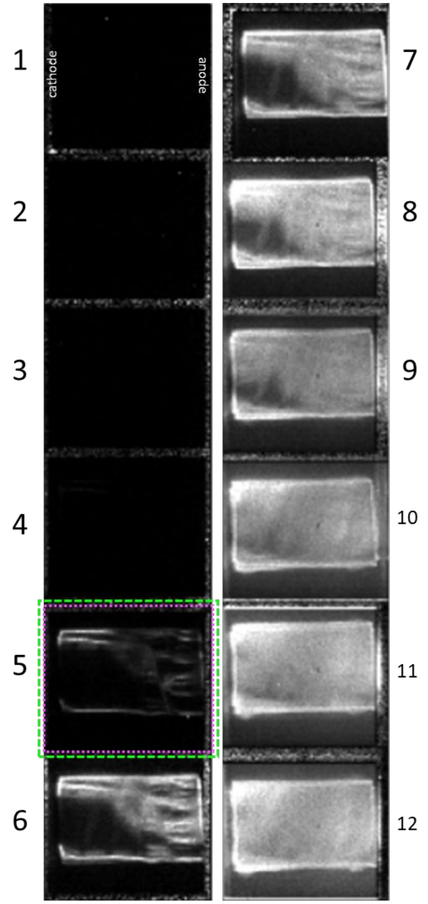


* Slutz et al., Phys. Plasmas 24, 012704 (2017).

Work has focused on <1 MA testing on Mykonos, implosion experiments on Z, and 3D modeling in ALEGRA

Mykonos experiments[2]

12 frame gated imaging of dielectric breakdown process
(EPON-encapsulated target shown)

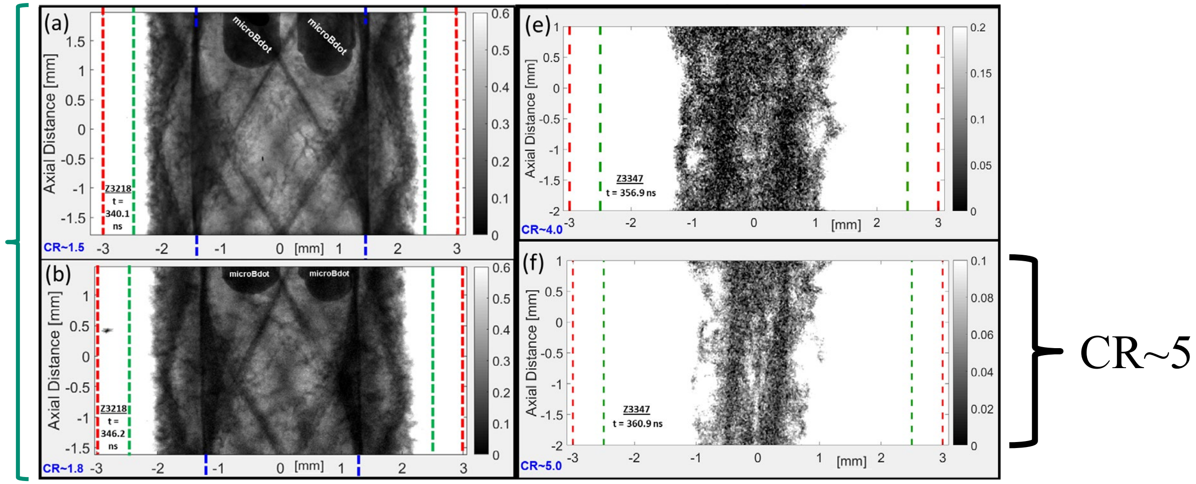


5 ns frames | ~50 micron resolution

[2]G. A. Shipley et al., *Physics of Plasmas* **29**, 032701 (2022).

Z experiments[1] (Z3218, Z3219, and Z3347)

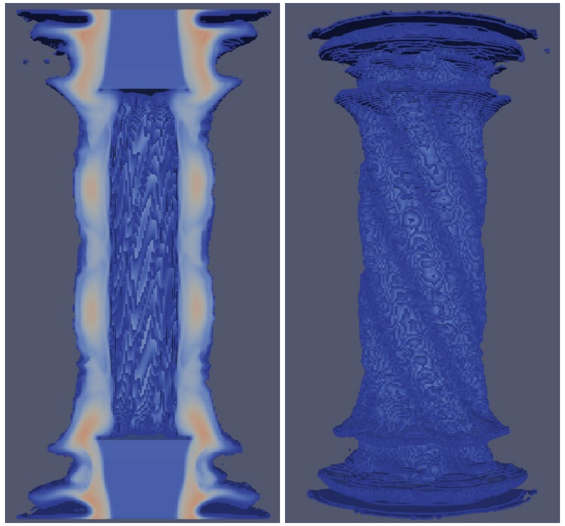
Radiographic data from AutoMag on Z



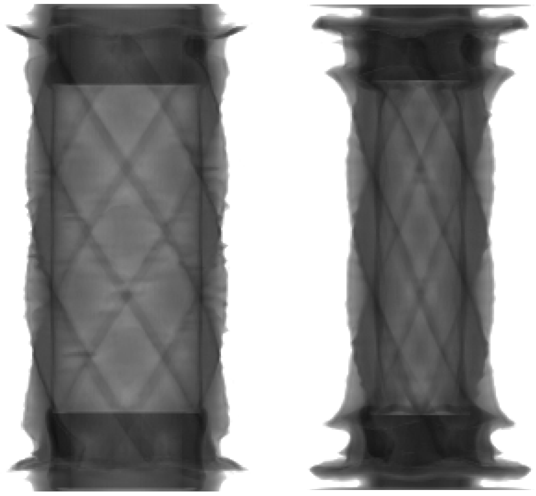
[1]G. A. Shipley et al., *Physics of Plasmas* **26**, 052705 (2019).

3D MHD simulations (ALEGRA)[3]

Simulation of Z3347 implosion



density maps

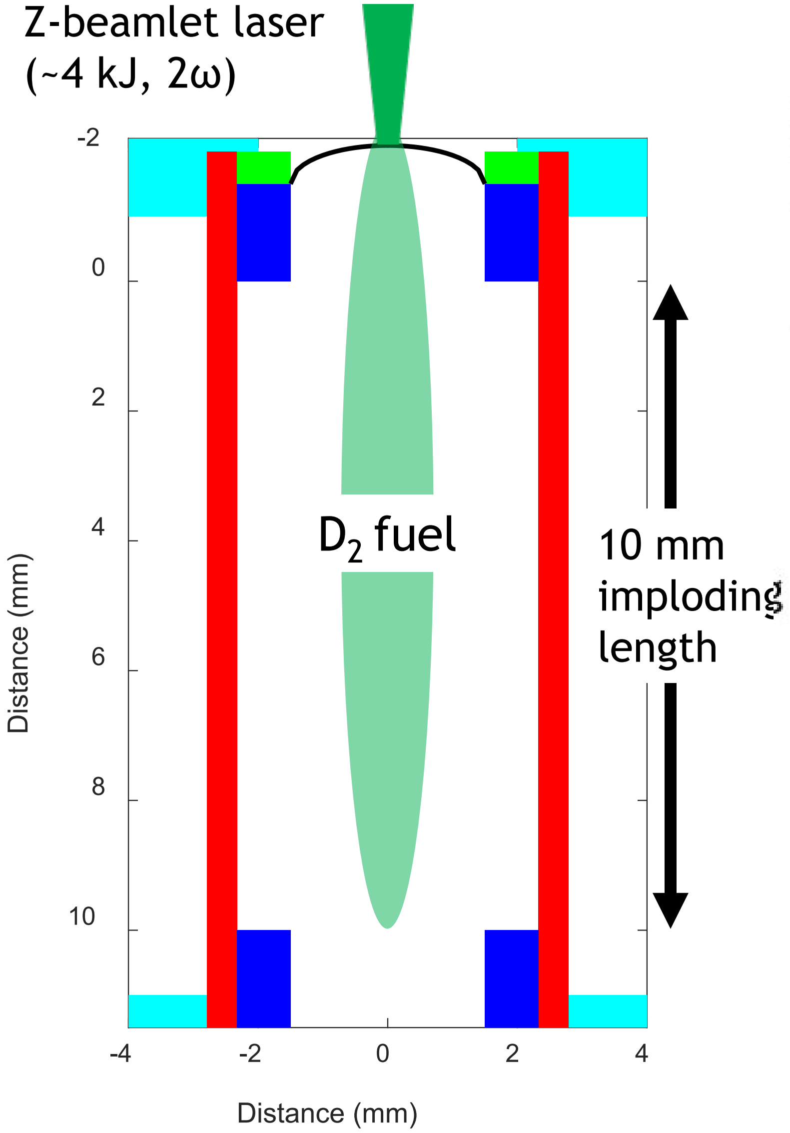


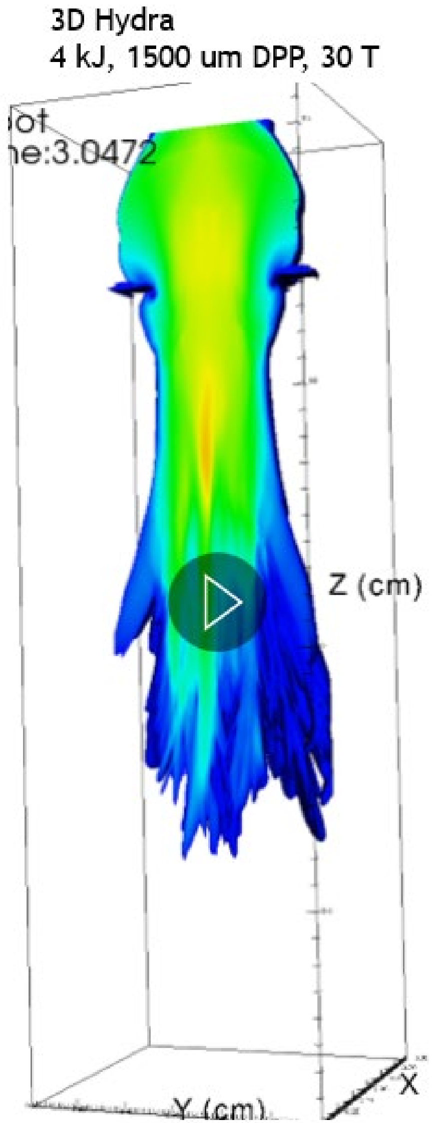
synthetic radiographs

[3]G. A. Shipley et al., *Physics of Plasmas* (submitted)

Laser preheat

MagLIF preheat challenge: Couple sufficient energy into underdense D_2 fuel without creating mix

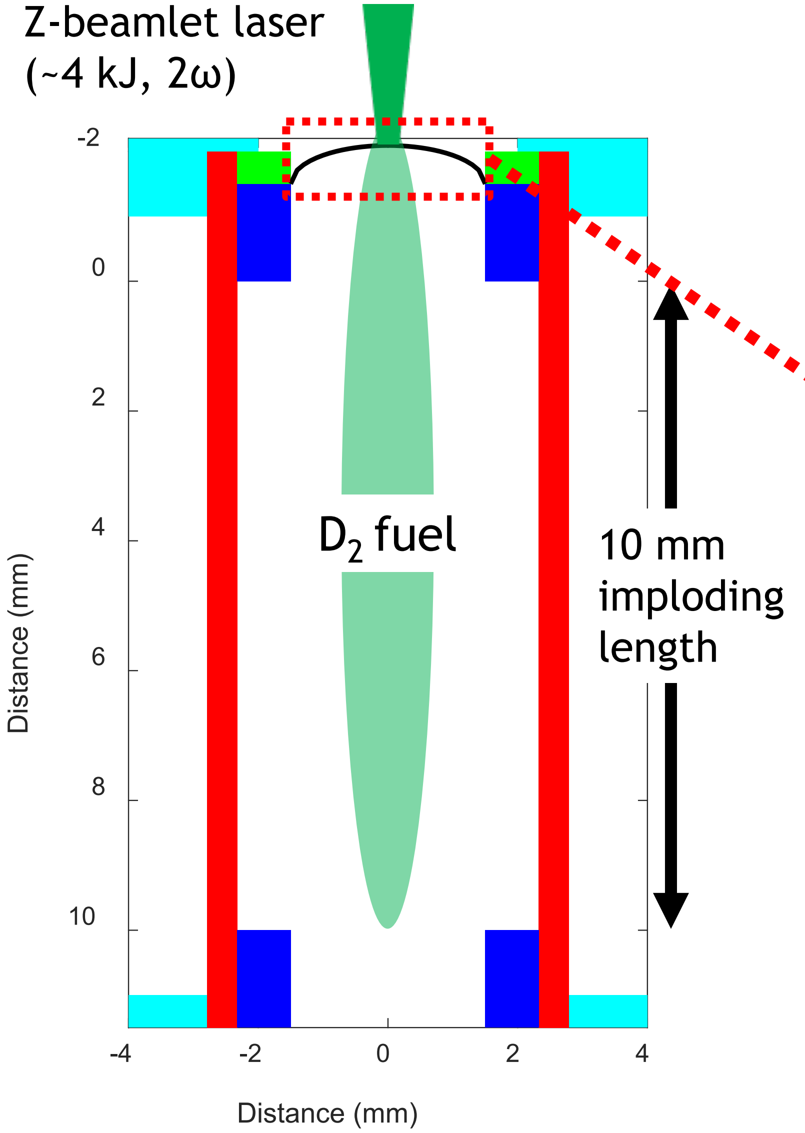




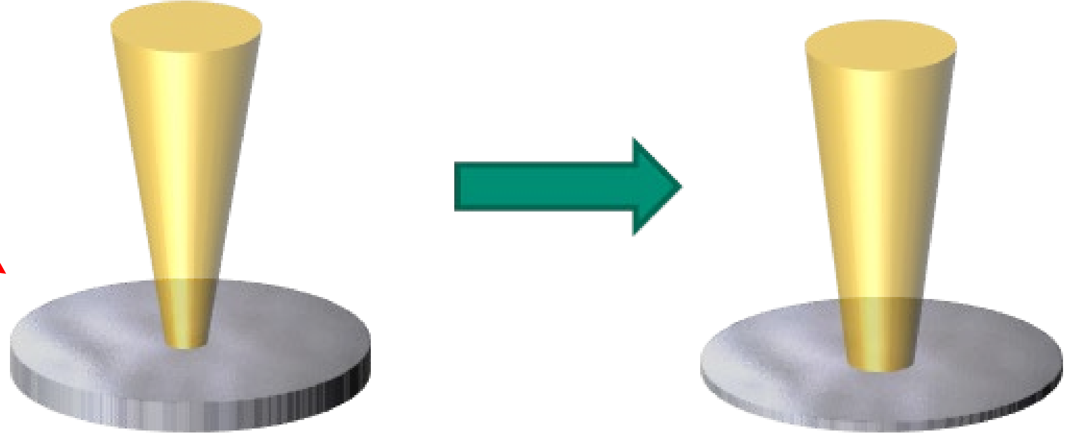
- Laser preheat occurs by inverse Bremss. absorption of laser energy in the gas
- The laser must penetrate an LEH foil
  - Laser entrance hole (LEH) foil interactions reduce energy, generate mix and are hard to model

How can we reduce losses, increase energy deposited in D2 gas?

Method 1: Reduce the window thickness via cryogenic cooling



Lowering the fuel temperature to 25% also lowers the pressure to 25% and allows for a ¼ window thickness.



1.1mm spot, 1.56μm window

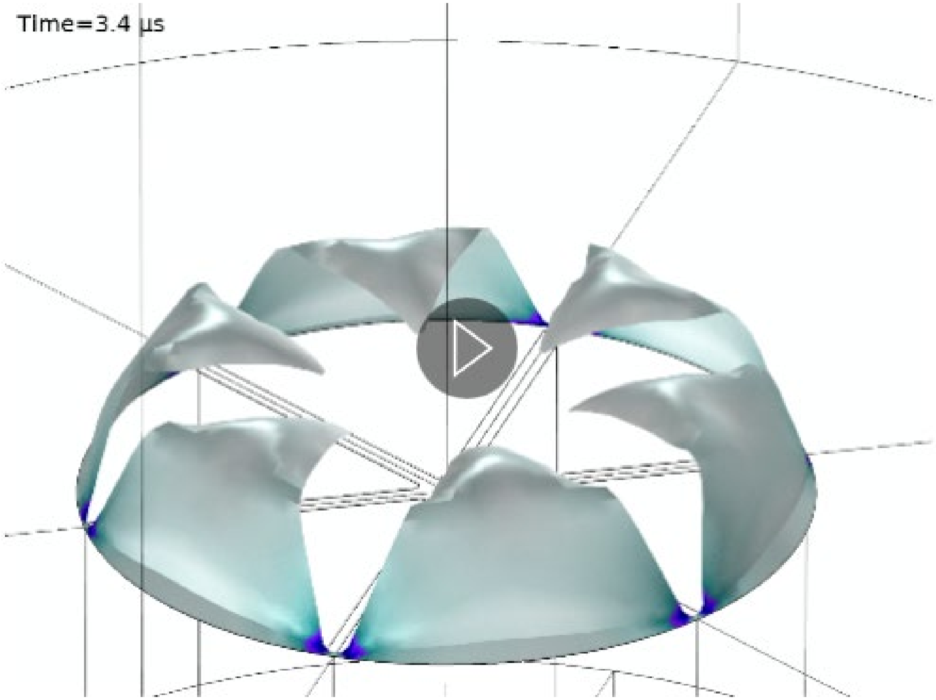
295K

1.5mm spot, 0.5μm window

75K

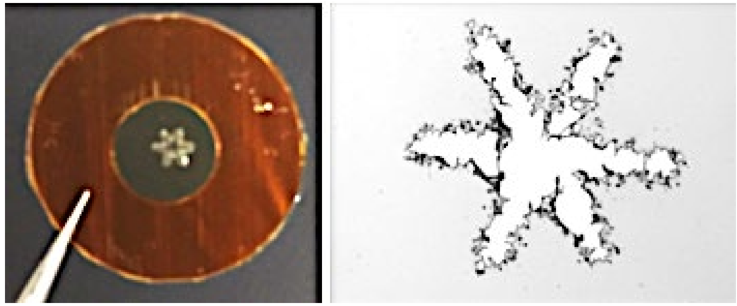
Method 2: Just get rid of the window before the implosion!

"Lasergate"



COMSOL simulations performed by Veryst Engineering, LLC

A laser prepulse with 'snowflake' pattern weakens window, and fuel pressure pushes LEH window out of laser path.



actual laser-cut snowflake

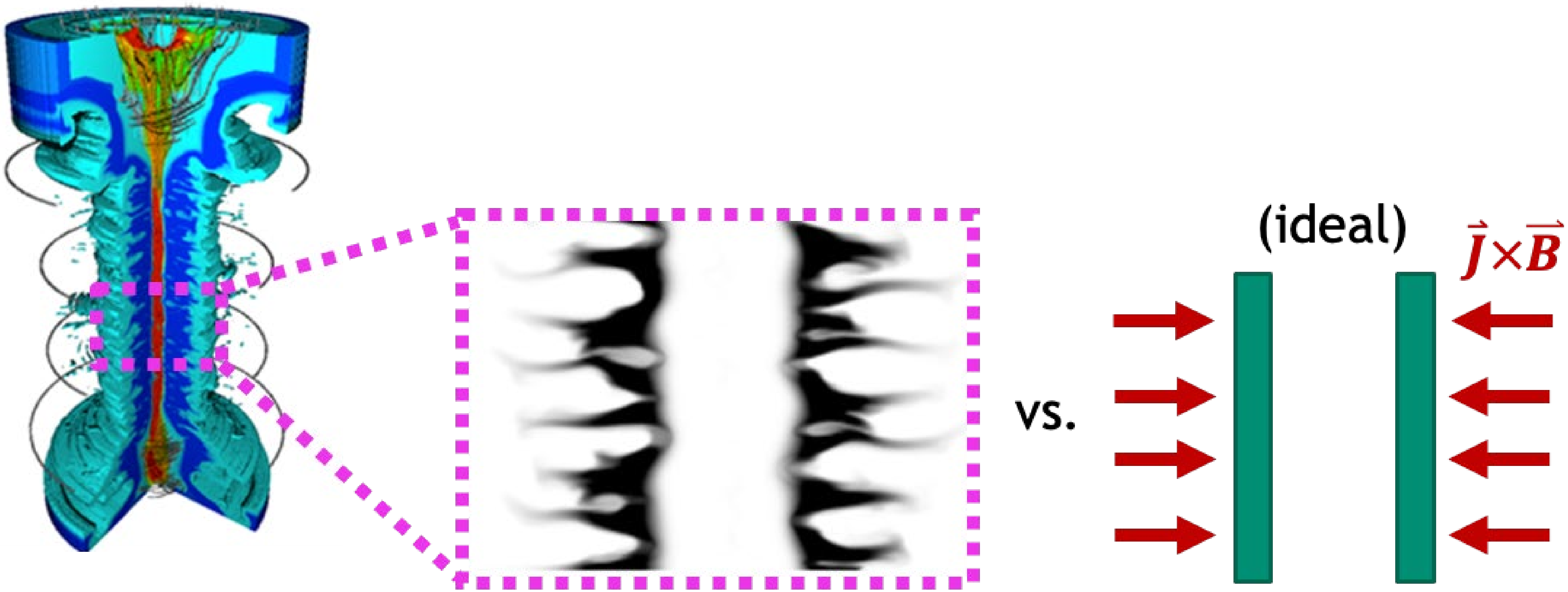
LEH foil material moves on well-understood hyrodynamic timescale of the ruptured gas cell!

B. R. Galloway et al.: Phys. Plasmas **28**, 112703 (2021)

S. M. Miller et al.: Rev. Sci. Instruments **91**, 063507 (2020)

Implosion

Compression of the liner is not ideal → instabilities limit performance!



<u>Magneto-Rayleigh-Taylor Instability (MRTI)</u>

Analogous to the Rayleigh-Taylor instability in hydrodynamics:

“Heavy fluid” = liner material, “light fluid” = drive magnetic field

Implosion instabilities evolve differently for various target types – and they can be mitigated with dielectric coatings

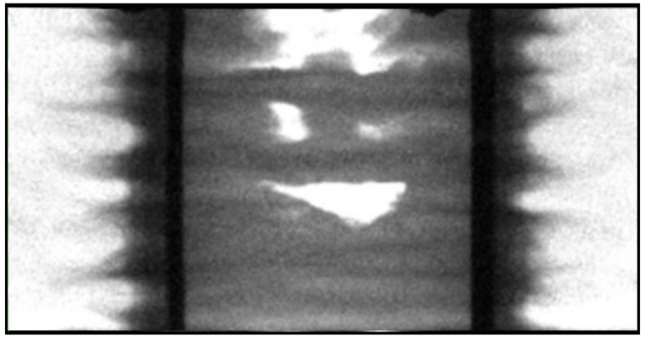
Azimuthally-correlated for non-magnetized liners

Helical for magnetized liners with reduced time integrated self-emission

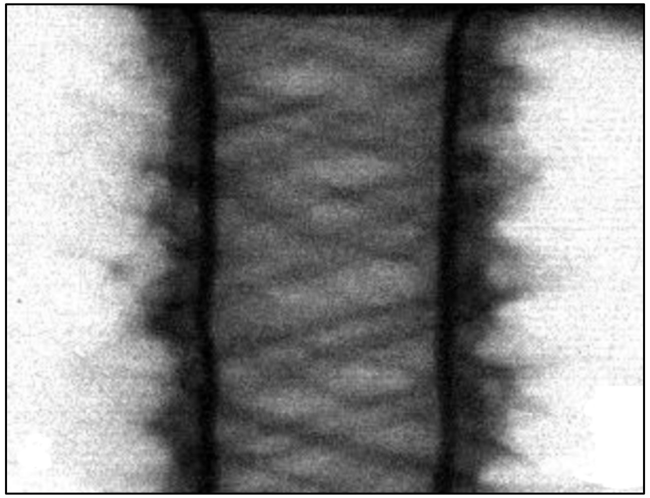
Dielectric coatings dramatically reduce instability development

Coated, magnetized liners have a very stable inner surface at high convergence

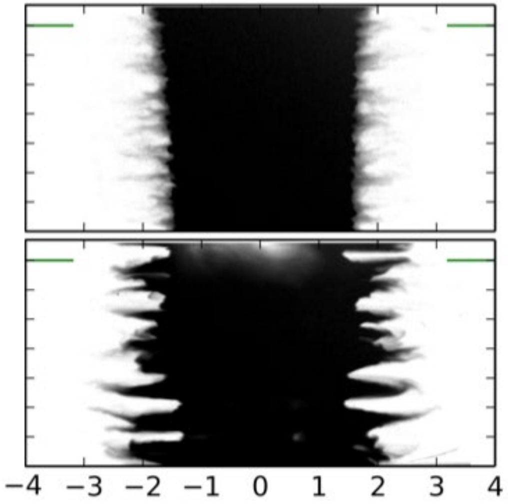
Standard



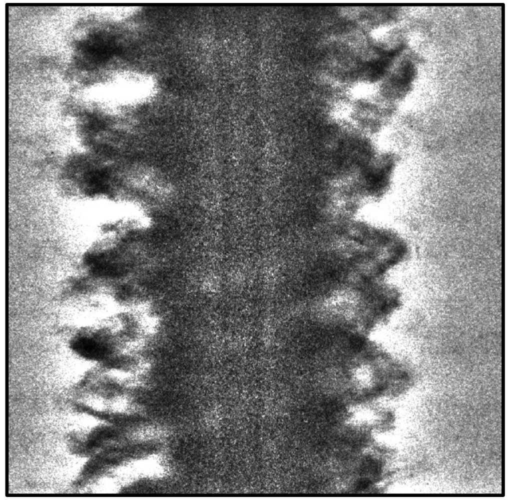
Magnetized



Coated



Coated + Magnetized



T. J. Awe, et al., Phys. Rev. Lett. 111, 235005 (2013).

T. J. Awe, et al., Phys. Rev. Lett. 116, 065001 (2016).

Implosion instabilities evolve differently for various target types – and they can be mitigated with dielectric coatings

Coatings work to mitigate instabilities, so we're done right?

- Dielectric coatings are difficult to model in multi-physics design simulation tools
- Dielectric coatings mitigate the *seed* of implosion instabilities, not the instabilities themselves

T. J. Awe, et al., Phys. Rev. Lett. 111, 235005 (2013). T. J. Awe, et al., Phys. Rev. Lett. 116, 065001 (2016).

Linear theory* suggests instability growth can be reduced *in flight* via dynamic drive field polarization

Drive Field Polarization

$$\theta_B(t) = \tan^{-1}[\Xi(t)] = \tan^{-1}\left[\frac{B_z(t)}{B_\phi(t)}\right]$$

$$B_z(t) \propto I(t)$$

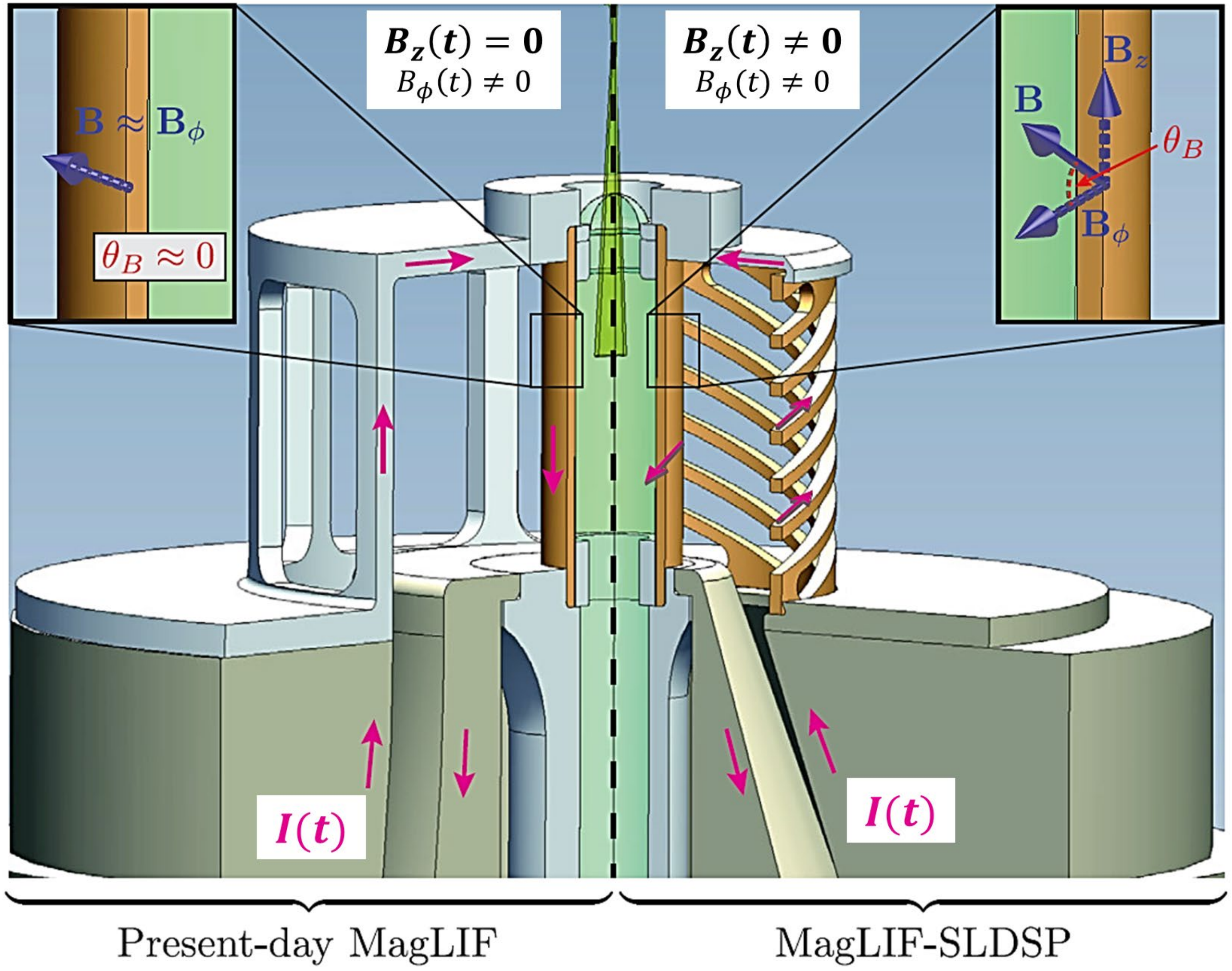
$$B_\phi(t) \propto \frac{I(t)}{r_l(t)}$$

$I(t)$ = current flowing through liner

$r_l(t)$ = liner outer radius at time t

Drive Field Ratio

$$\Xi(t) = \frac{B_z(t)}{B_\phi(t)}$$



Reproduced from *P. F. Schmit et al., *Phys. Rev. Lett.* **117**, 205001 (2016).

Linear theory* suggests instability growth can be reduced *in flight* via dynamic drive field polarization

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$B_z(t) \propto I(t)$

$$B_\phi(t) \propto \frac{I(t)}{r_l(t)}$$

$I(t)$ = current flowing through liner

$r_l(t)$ = liner outer radius at time t

Drive Field Ratio

$$\Xi(t) = \frac{B_z(t)}{B_\phi(t)}$$

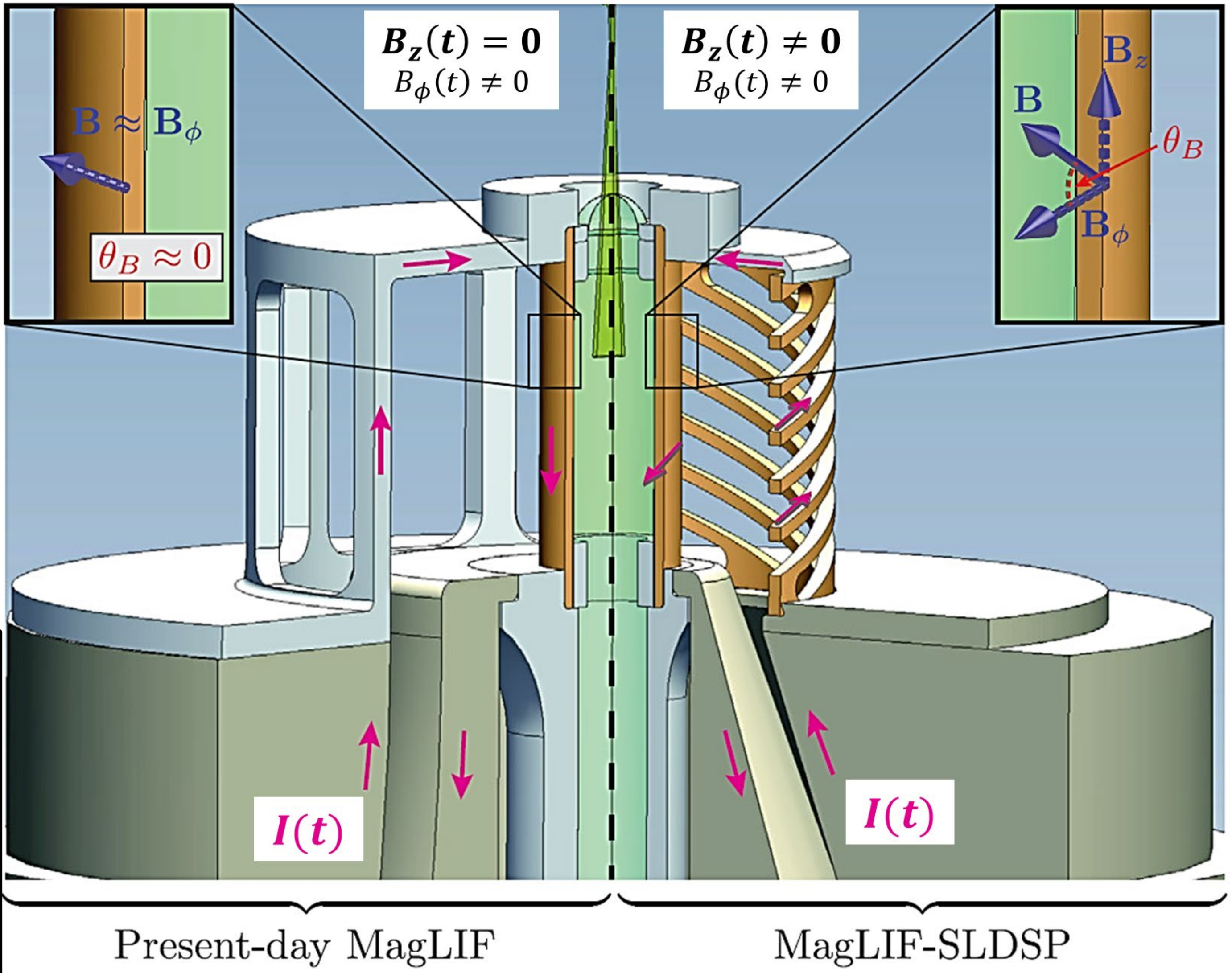
Liner implodes ($r_l(t)$ decreases), drive magnetic field polarization rotates

↓

Shifts fastest growing MRTI modes as a function of time and applies stabilizing magnetic tension

↓

MRTI growth is reduced *in flight* via a Solid Liner Dynamic Screw Pinch* (SLDSP)



Reproduced from *P. F. Schmit et al., *Phys. Rev. Lett.* **117**, 205001 (2016).

Initial 3D simulations* provided a qualitative estimate of MRTI mitigation via screw pinch mechanism

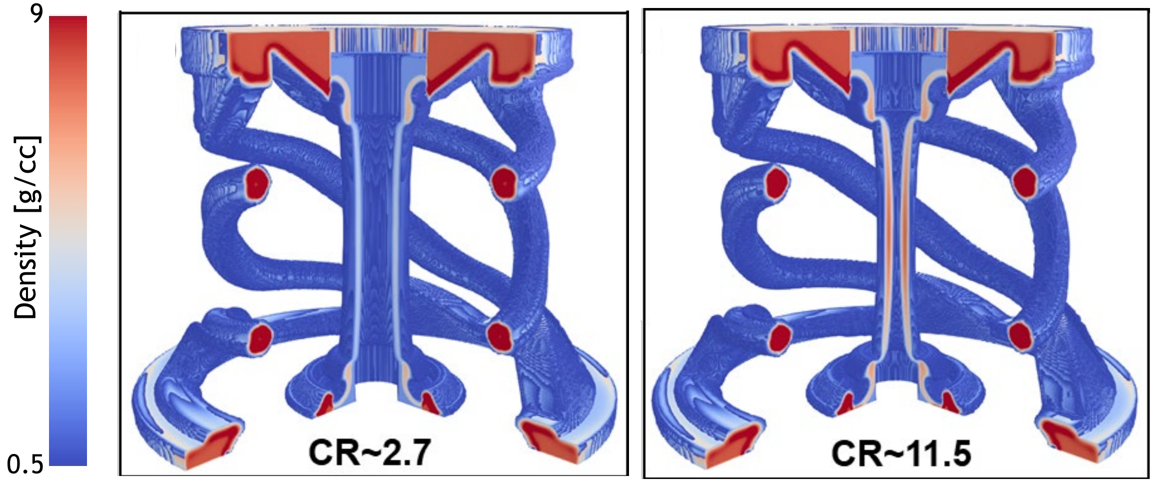
Azimuthal drive field implosion

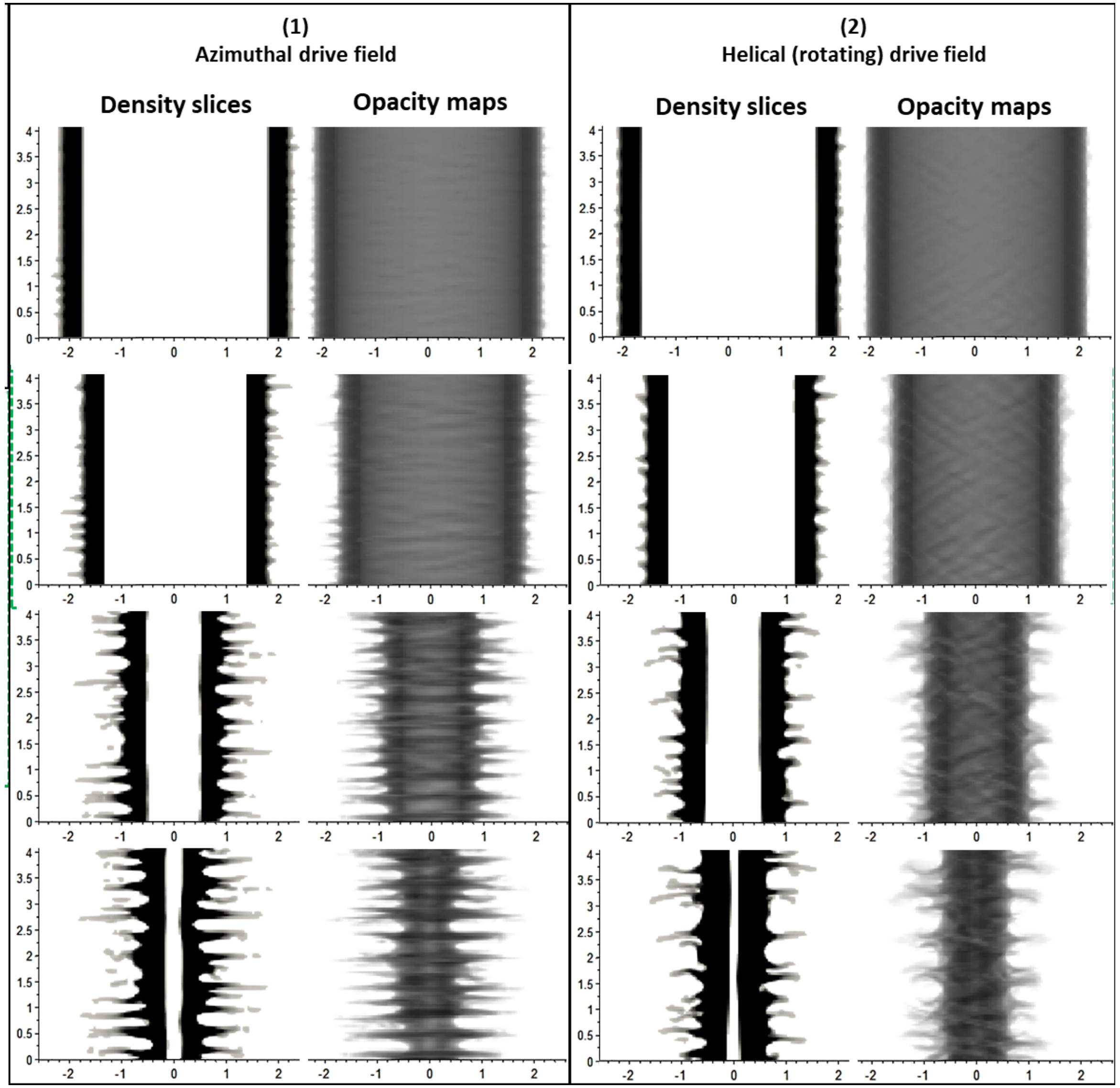
vs.

Helical (rotating) drive field produced by Z design return current structure

$$\Xi = \frac{B_z}{B_\phi} \sim 0.5$$

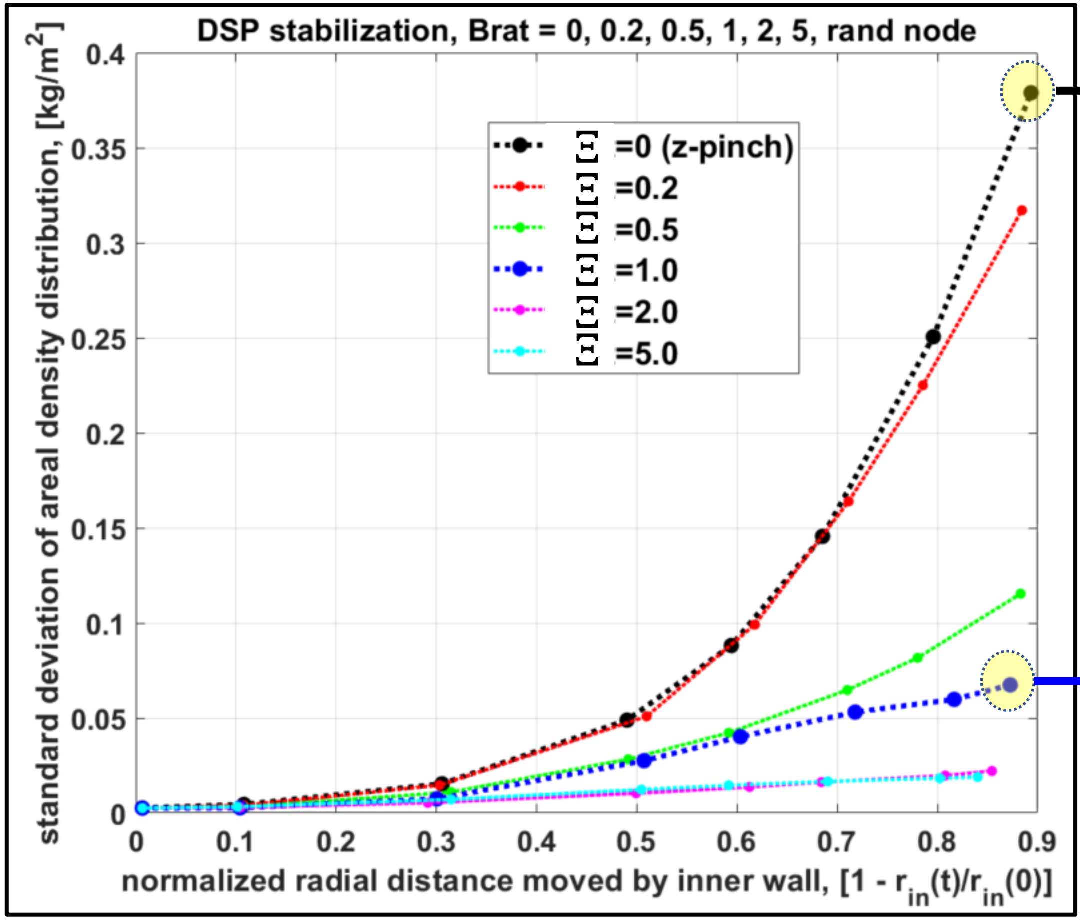
3D ALEGRA

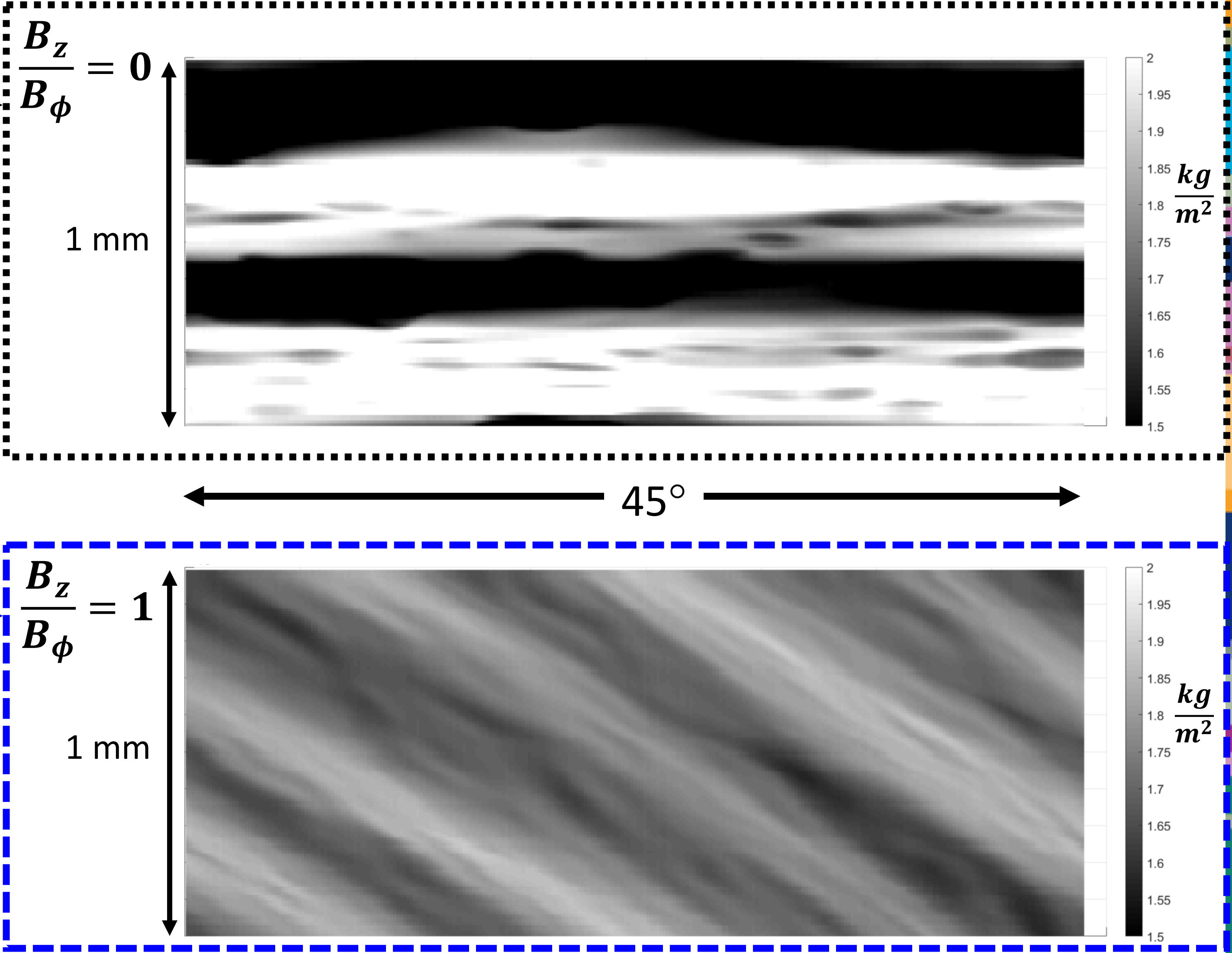




*G. A. Shipley, C. A. Jennings, and P. F. Schmit, *Physics of Plasmas* **26,** 102702 (2019).

Areal density analysis of high resolution 3D simulations provides higher fidelity assessment of MRTI development

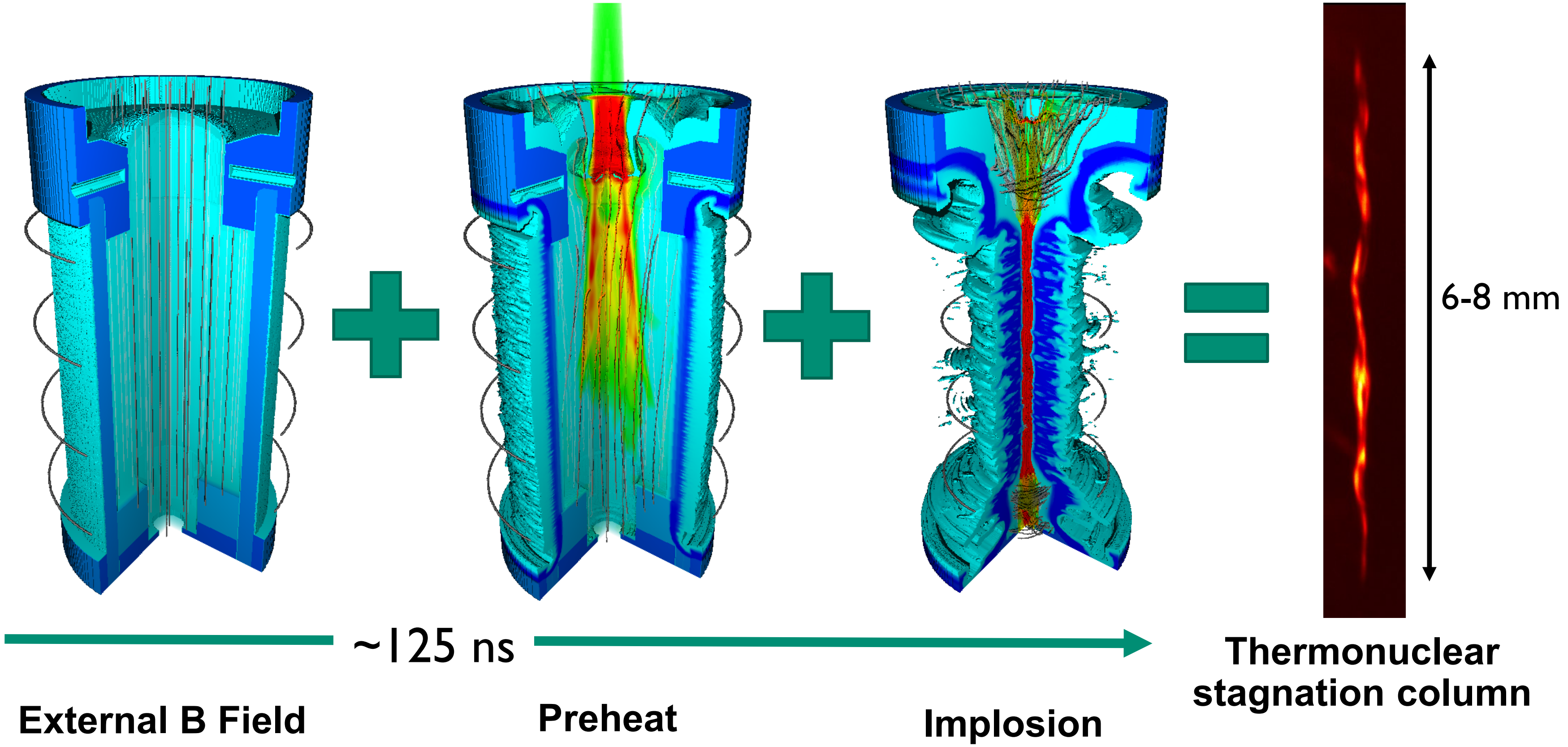




5x difference in $\sigma(\rho r)$ of Bz/Bphi = 0 and Bz/Bphi = 1 cases

3x difference in $\sigma(\rho r)$ of Bz/Bphi = 0 and Bz/Bphi = 0.5 cases

Magnetized Liner Inertial Fusion (MagLIF[1,2]): Magnetic compression of premagnetized, laser-preheated fusion fuel



Shot ID	z3289
$\dot{R}_{max}$	70 km/s
R_{burn}	50 um
T_{burn}	2.7 keV
p_{burn}	1.9 Gbar
τ_{bw}	2 ns
Y (DT equivalent)	2 kJ

[1] S. A. Slutz, M. C. Herrmann, R. A Vesey, *et al.*, Phys. Plasmas **17**, 056303 (2010).
[2] M. R. Gomez, S. A. Slutz, A. B. Sefkow, *et al.*, Phys. Rev. Lett. **113**, 155003 (2014).