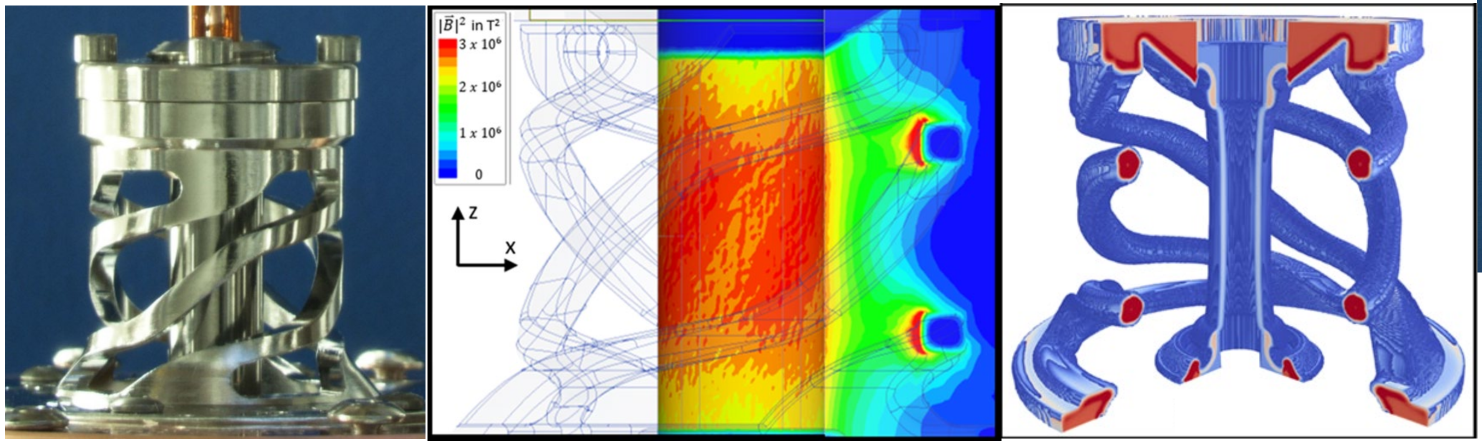
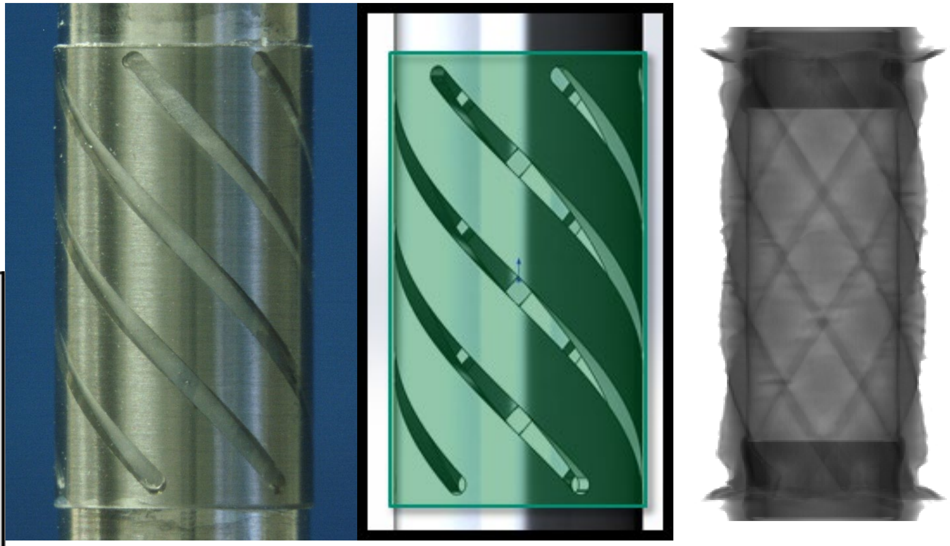
On the Dynamic Generation of Megagauss-Level Magnetic Fields to Magnetize and Stabilize Pulsed-Power-Driven Implosions





Gabriel Shipley

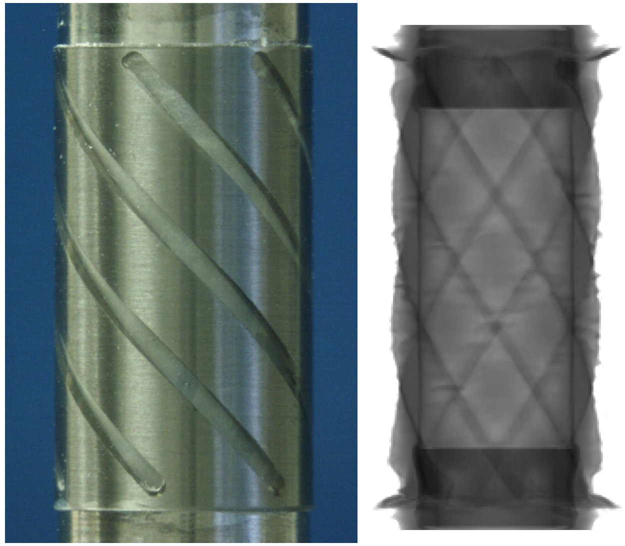
2021 DOE NNSA Stewardship Science Graduate Fellowship Program Review

STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP

SAND2021-7453 C

SSGF-funded research directly resulted in two novel, unique z-pinch target concepts and 6 successful experiments on the Z accelerator

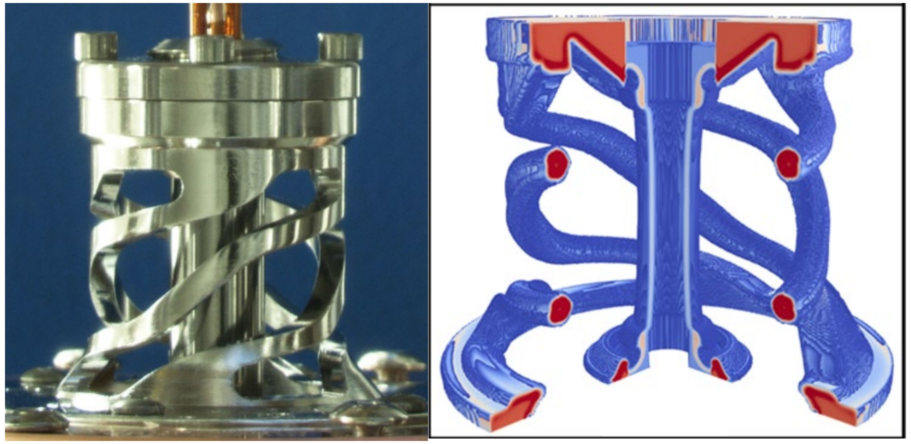
Auto-magnetizing Liners (AutoMag)



G. A. Shipley et al., *Physics of Plasmas* **25**, 052703 (2018)
G. A. Shipley et al., *Physics of Plasmas* **26**, 052705 (2019)

Principal investigator on Z accelerator

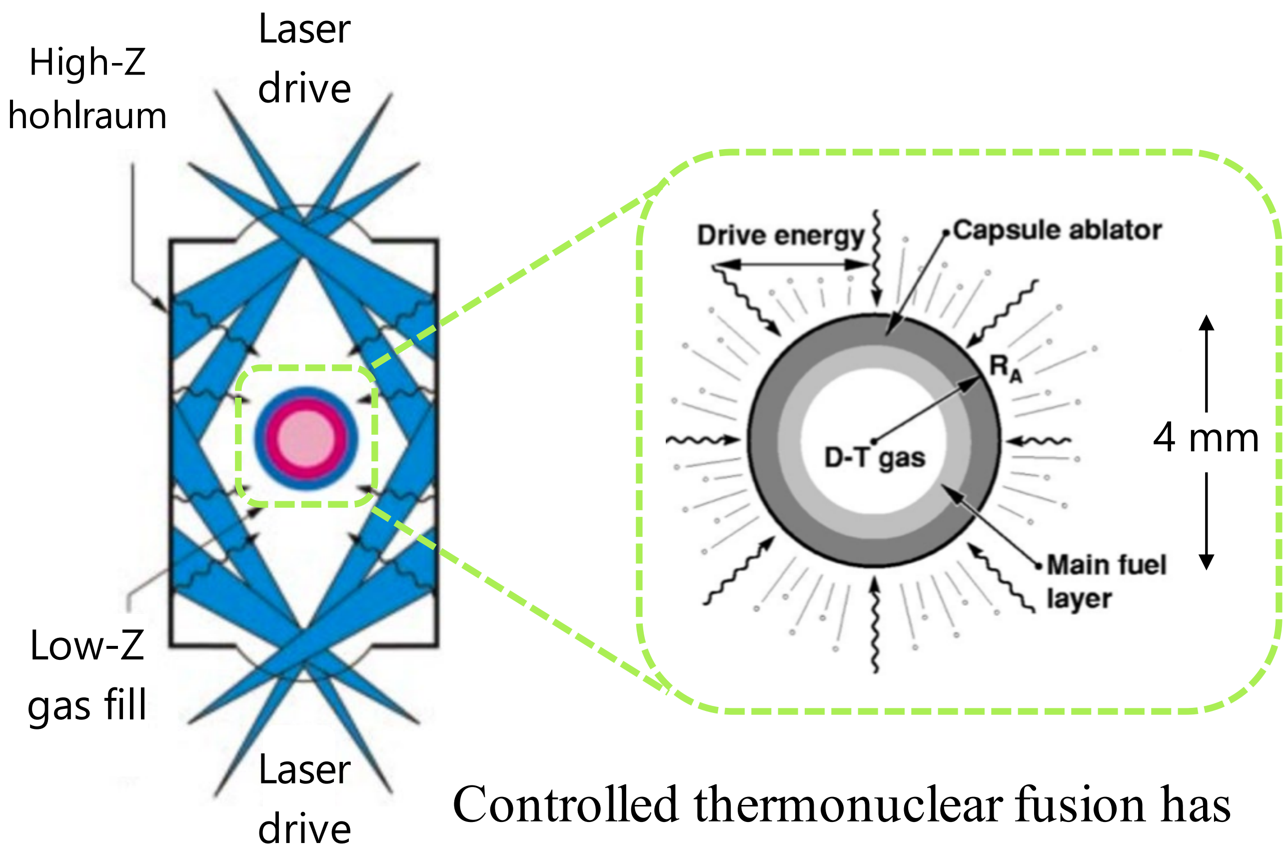
Magnetohydrodynamic (MHD) Instability Mitigation



G. A. Shipley et al., *Physics of Plasmas* **26,** 102702 (2019)

Co-principal investigator on Z
Principal designer on Z

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



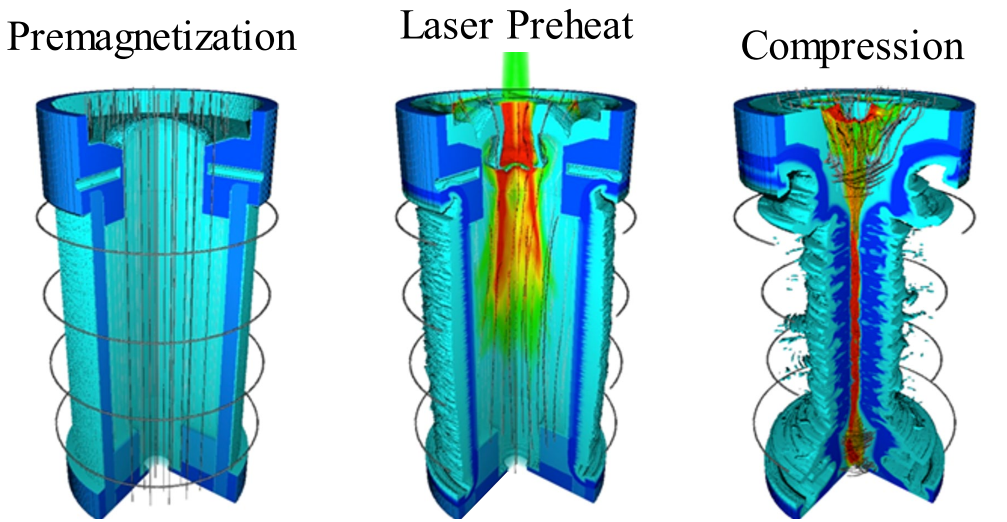
Controlled thermonuclear fusion has applications in:

Nuclear weapons stockpile stewardship
Radiation effects science
Energy production

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

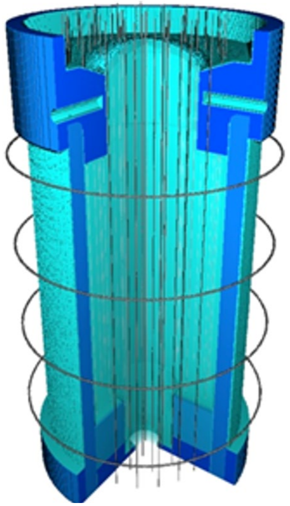
Sandia National Laboratories

- 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.



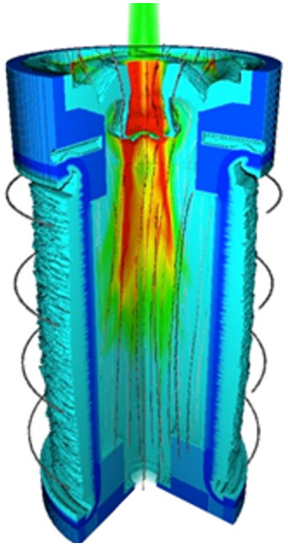
S. A. Slutz et al., Phys. Plasmas **17**, 056303 (2010).

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



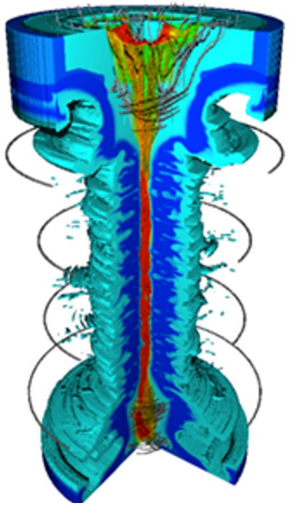
- **Premagnetization[2]: 10-20 T quasi-static axial magnetic field, $B_{z,0}$, is applied to thermally insulate fuel**

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)

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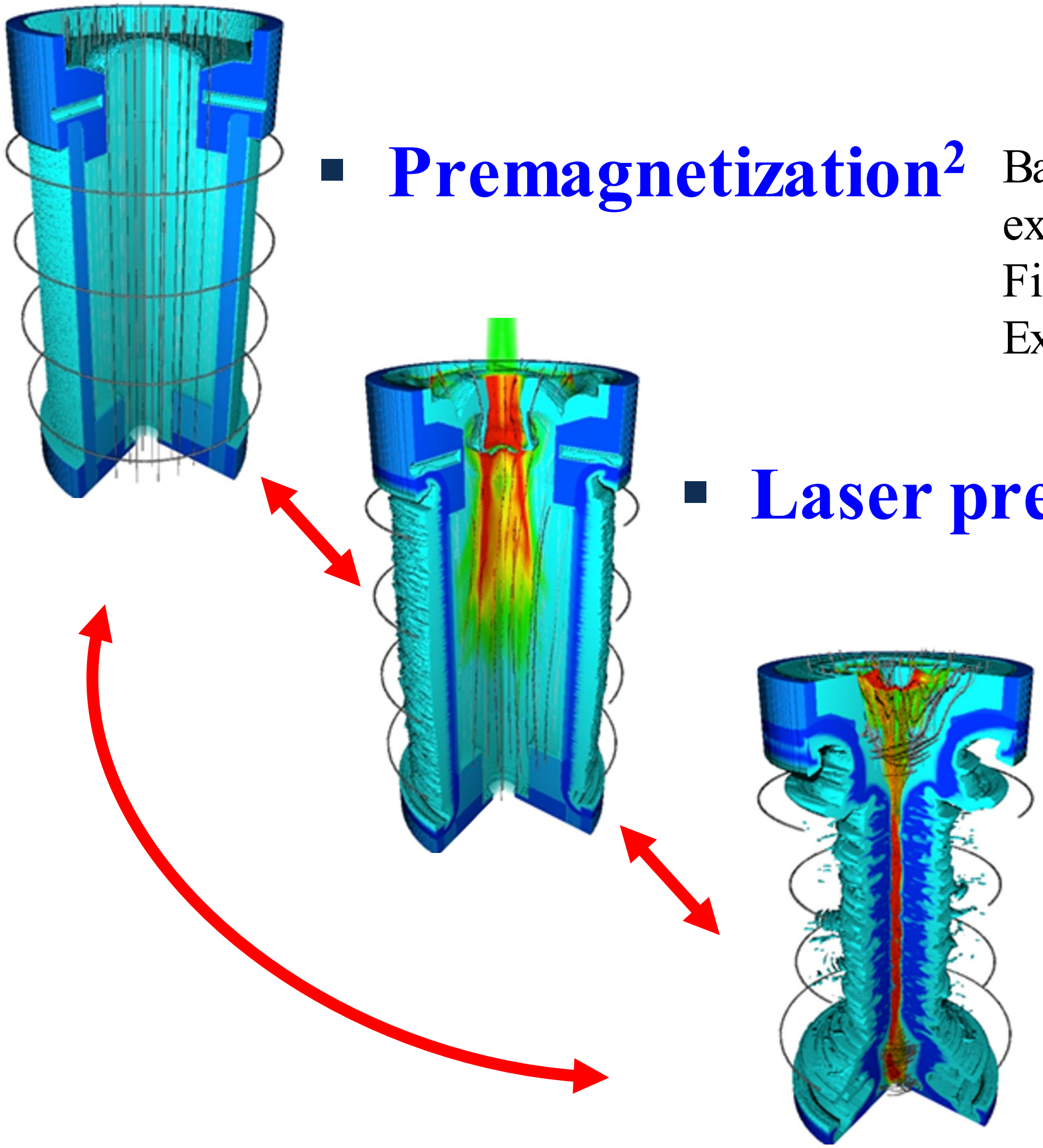
[1] S. A. Slutz et al., Phys. Plasmas **17**, 056303 (2010).

[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.

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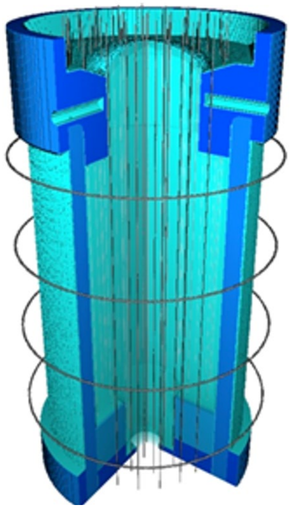
[1] S. A. Slutz et al., Phys. Plasmas **17**, 056303 (2010).

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

[3] Harvey-Thompson et al., Phys. Plasmas **26**, 032707 (2019).

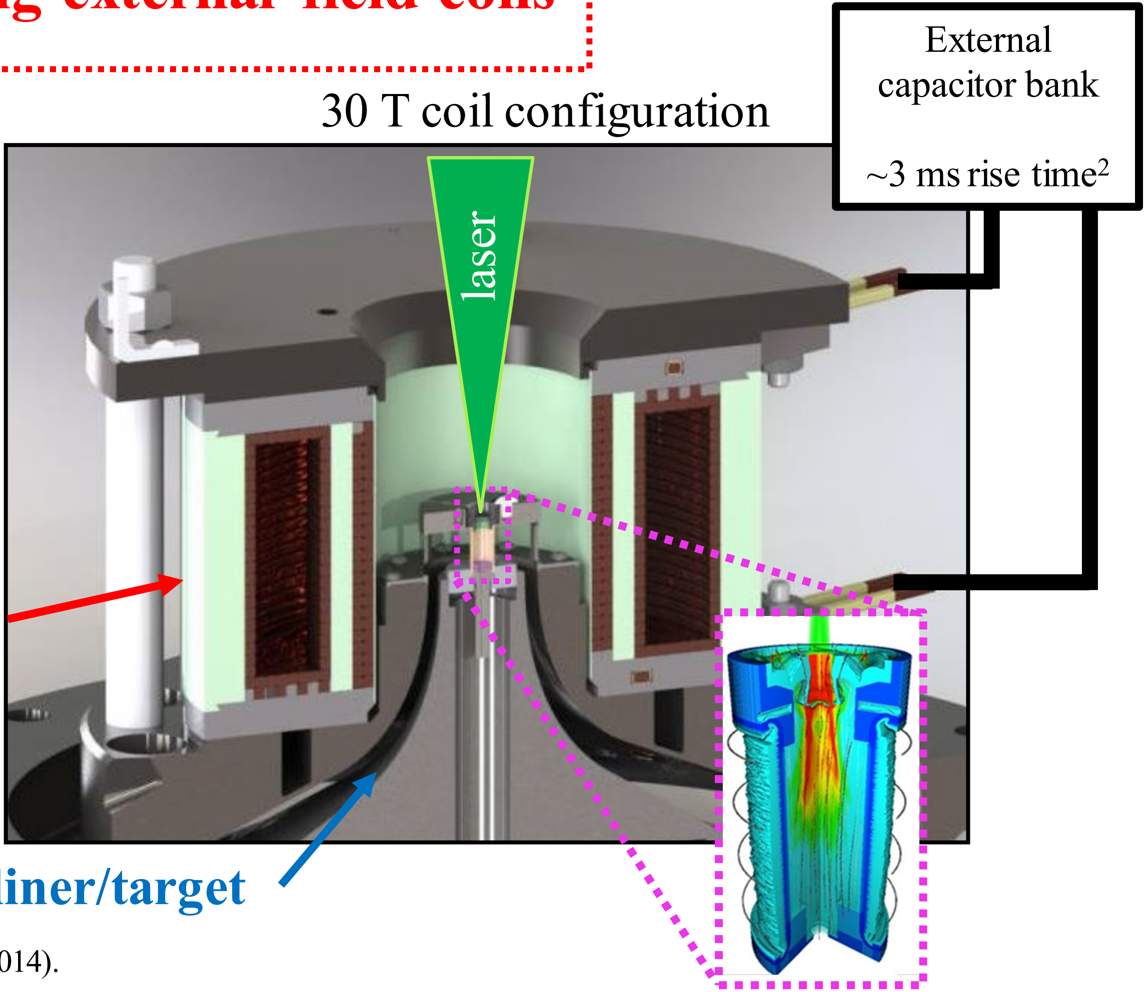
Magnetized Liner Inertial Fusion (MagLIF[1]): Magnetic compression of premagnetized, laser-preheated fusion fuel



Nearing upper limit using coils

- **Premagnetization[2]: 10-$\overbrace{\text{20 T}}$ quasi-static[2] axial magnetic field, $B_{z,0}$, is applied using external field coils**

Calculations[1] indicate that $B_{z,0}$ = 30-50 T would improve thermal insulation of fuel and increase fusion yield



30 T coil configuration

External capacitor bank

~3 ms rise time[2]

Copper coils block radial x-ray diagnostic access

Extended pulsed power feed reduces current coupling to liner/target

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

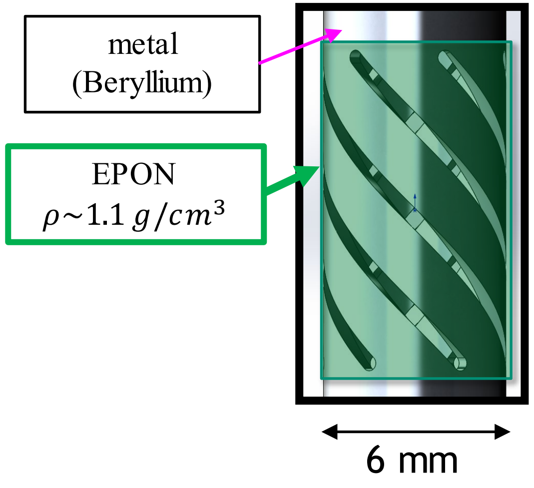
[2] Rovang et al., Rev. Sci. Instrum. **85**, 124701 (2014).

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

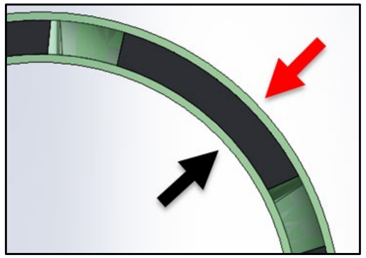
Eliminate coils

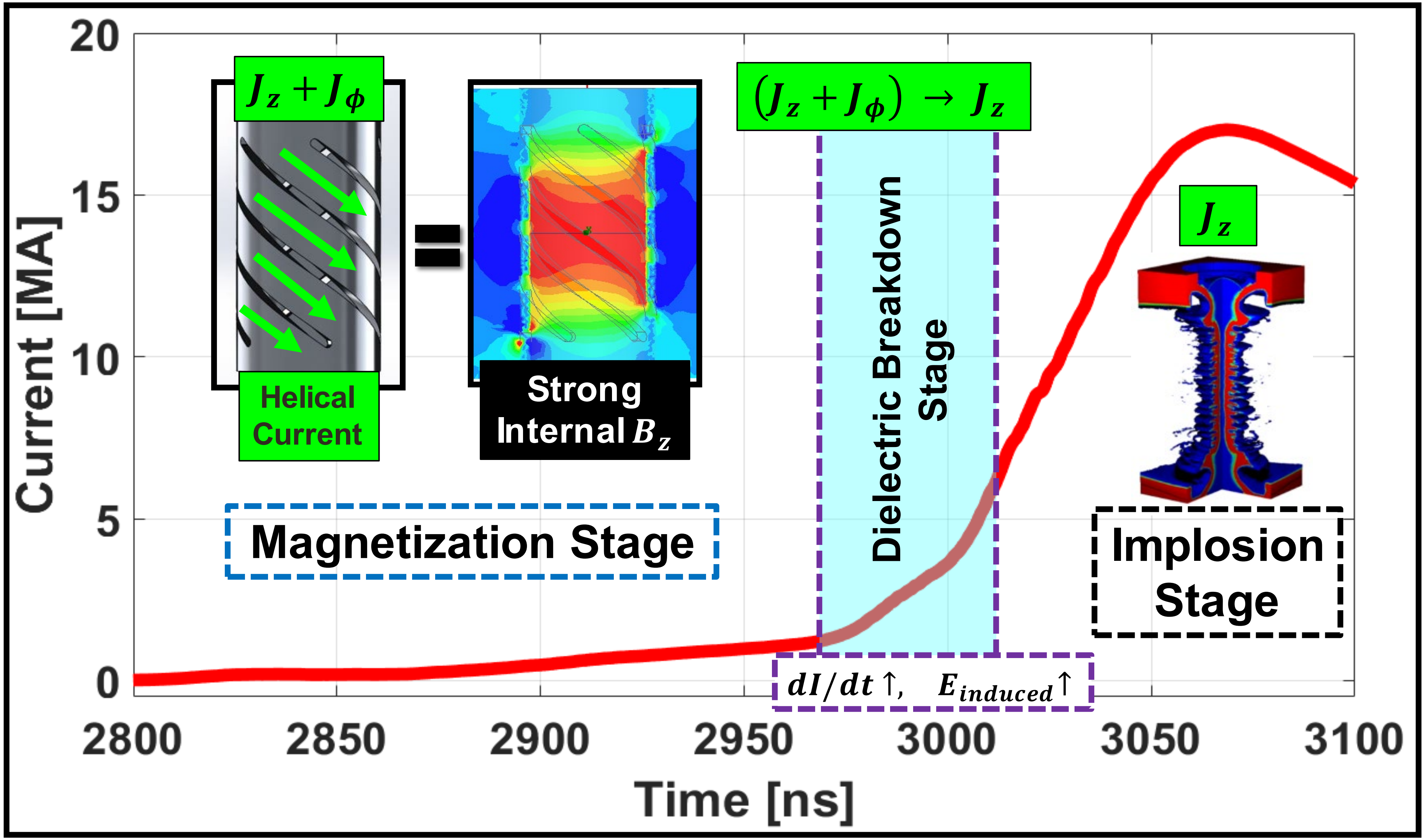
Magnetize the target using the pulsed power driver

AutoMag liner



top view





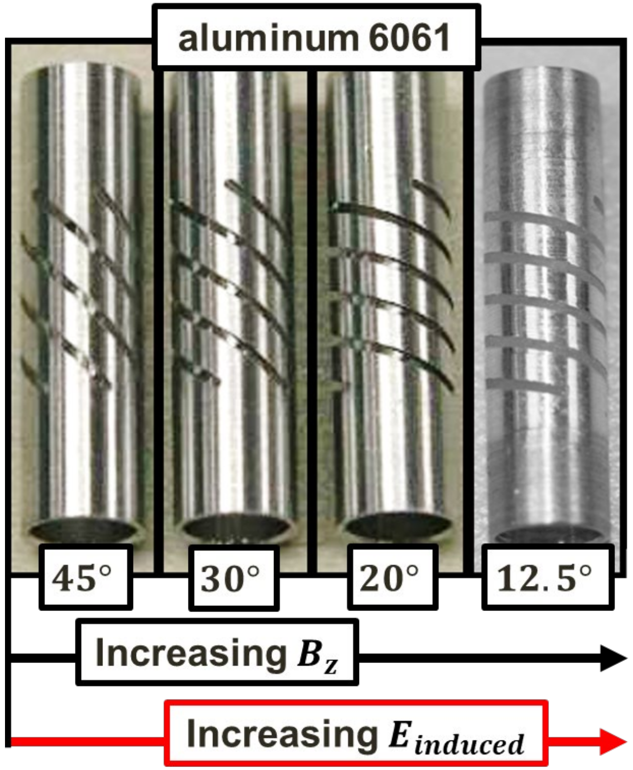
G. A. Shipley et al., *Physics of Plasmas* **25**, 052703 (2018).

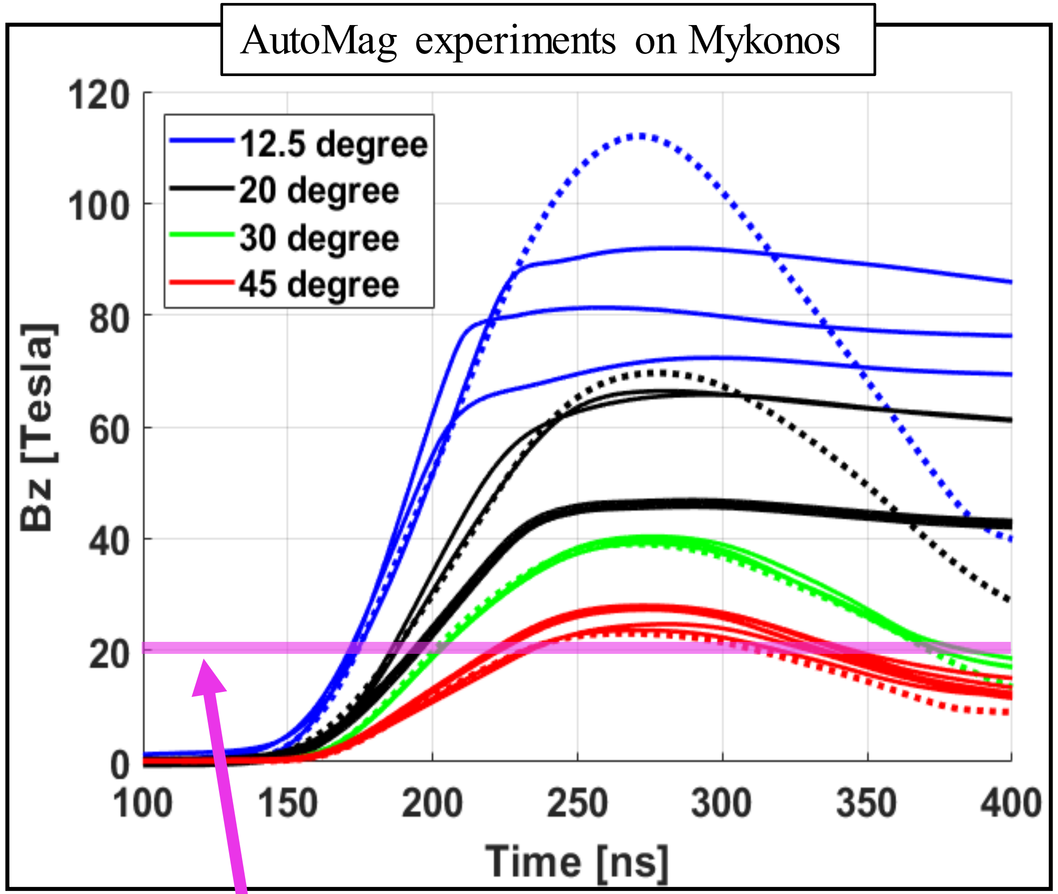
S. A. Slutz et al., *Phys. Plasmas* **24**, 012704 (2017).

B_z=30-100 T internal axial field is easily attainable in AutoMag liners

92 T was measured during experiments* on Mykonos accelerator (<1 MA, ~100 ns rise time)

Surrogate for O(1 MA, 100 ns) prepulse on Z





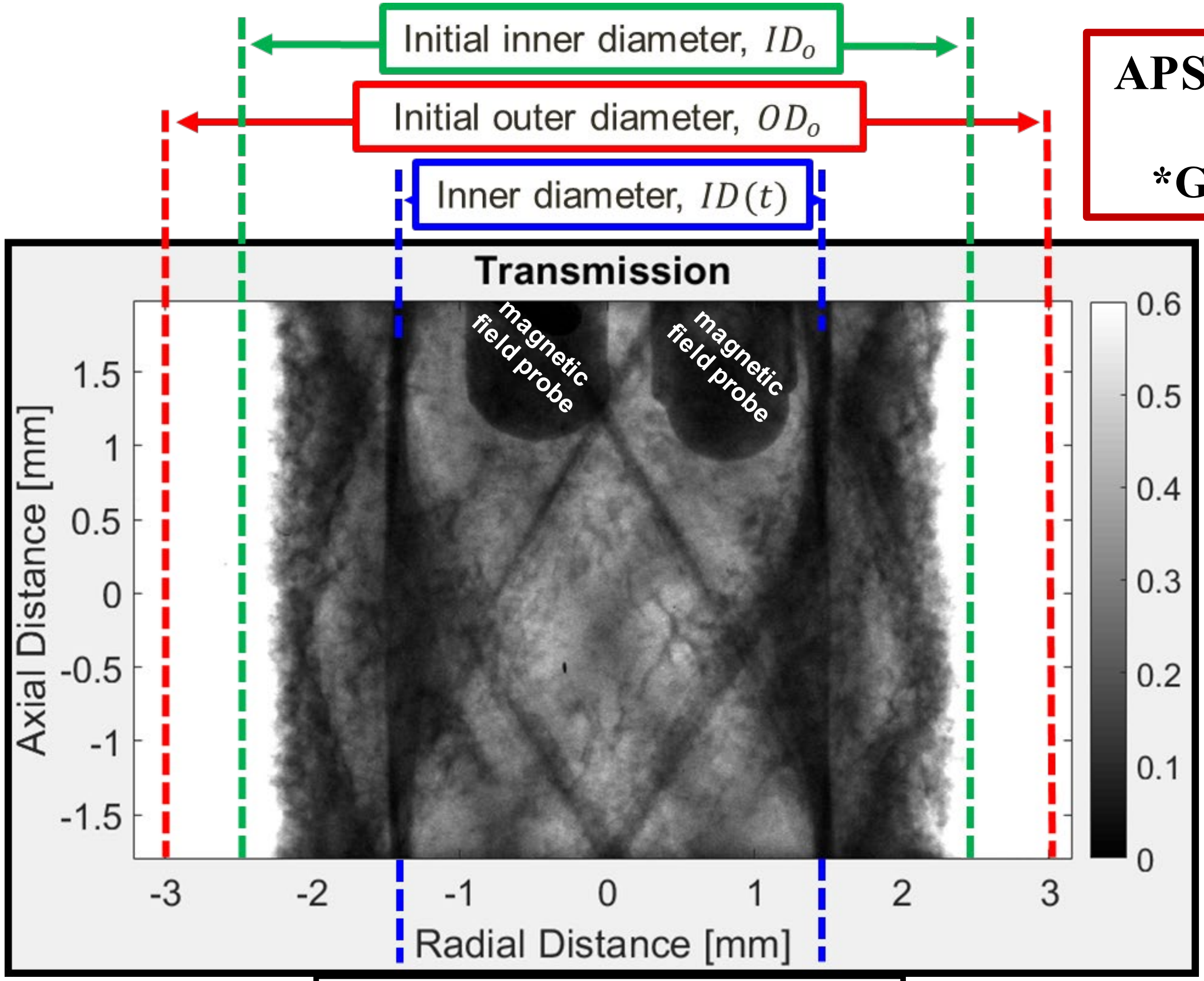
External coils are limited to B_z ~ 20 T

* G. A. Shipley et al., *Physics of Plasmas* **25**, 052703 (2018).

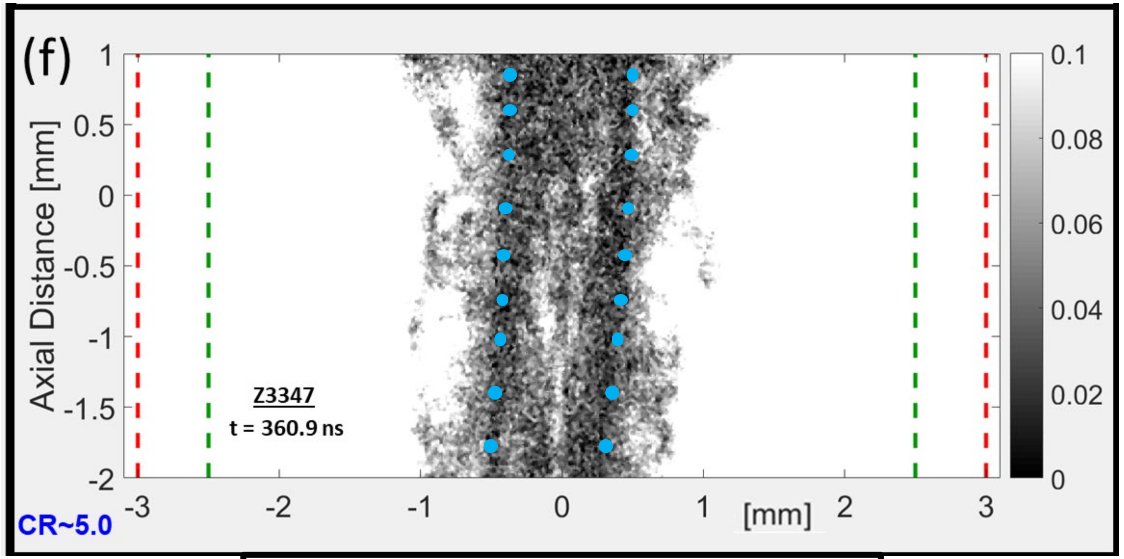
Radiography* diagnosed implosion dynamics of first ever AutoMag liners on Z, a unique dataset for code validation

APS Division of Plasma Physics (DPP) 2018 invited talk

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



Z3218 Frame 1, CR ~ 1.5



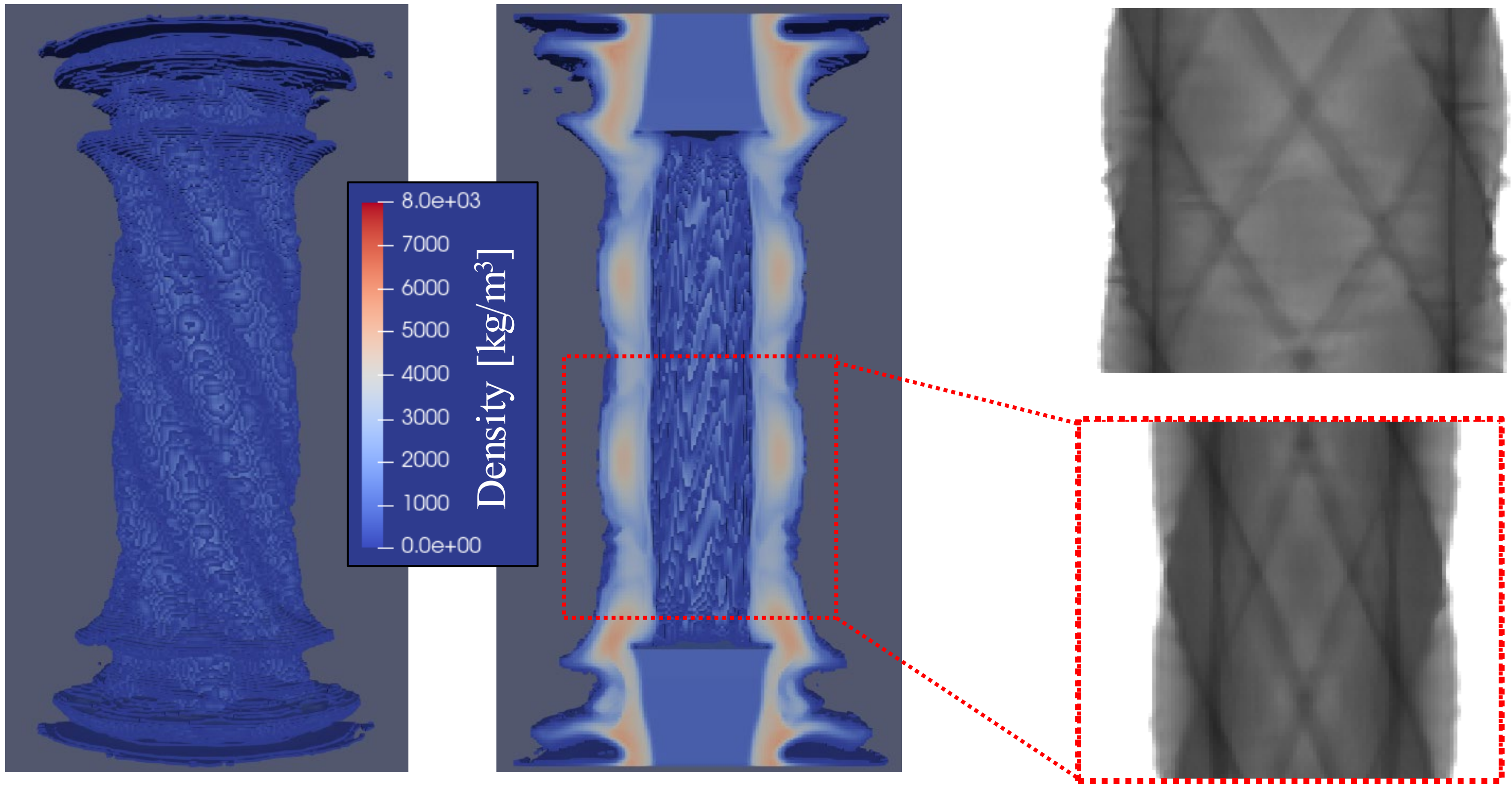
Z3347 Frame 2, CR ~ 5

Convergence Ratio

$$\text{CR} = \frac{ID_o}{ID(t)}$$

3D MHD ALEGRA was used to model AutoMag implosion dynamics

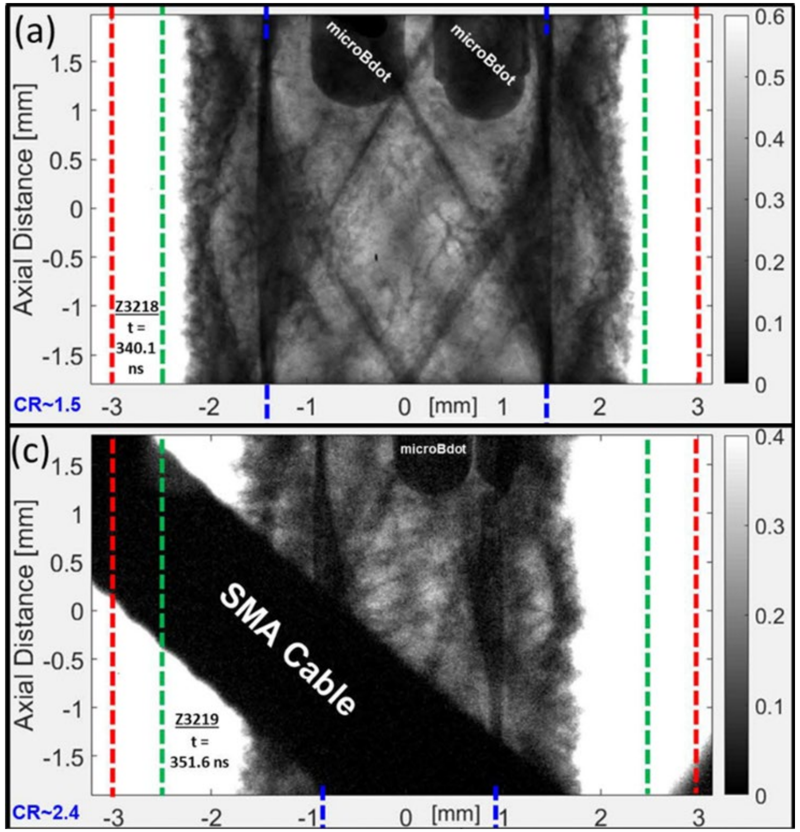
Post-shot 3D ALEGRA



density maps

opacity maps

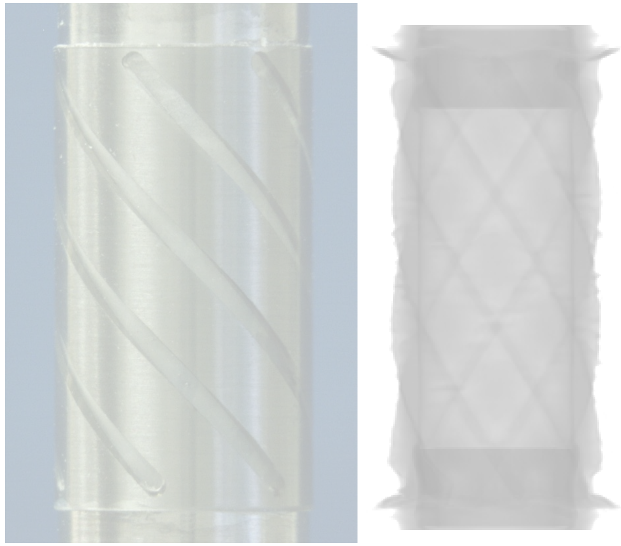
Z Radiography Data



3D modeling is computationally expensive, but helical symmetry of AutoMag prevents use of 2D.

Calculations suggest dielectric breakdown of insulating material heavily influences implosion dynamics.

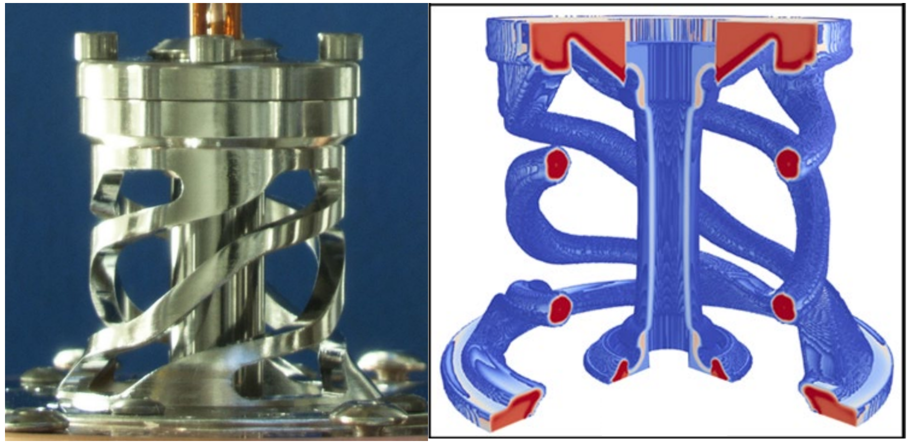
Auto-magnetizing Liners (AutoMag)



G. A. Shipley et al., *Physics of Plasmas* **25**, 052703 (2018)
G. A. Shipley et al., *Physics of Plasmas* **26**, 052705 (2019)

Principal investigator on Z

Magnetohydrodynamic (MHD) Instability Mitigation

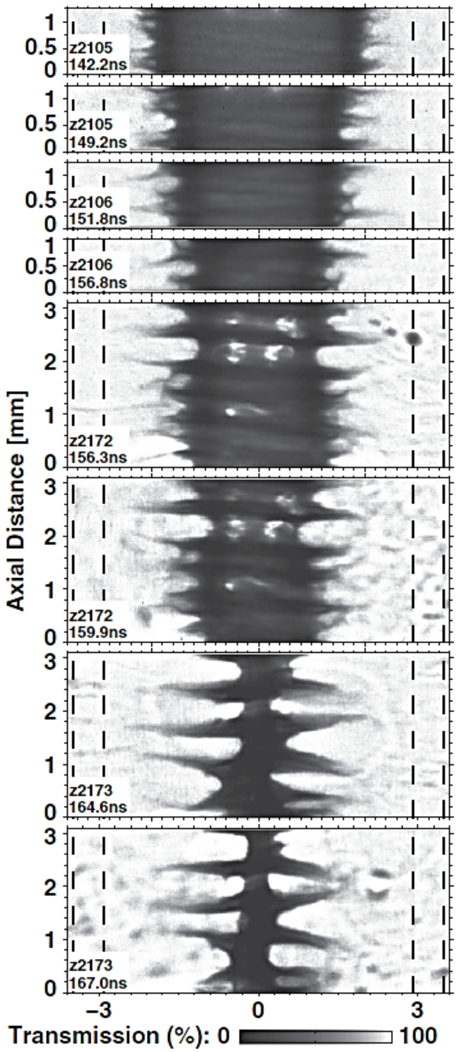


G. A. Shipley et al., *Physics of Plasmas* **26,** 102702 (2019)

Co-principal investigator on Z
Principal designer on Z

Liner implosions suffer from magneto-Rayleigh-Taylor instabilities (MRTI)

$B_{z,0} = 0$



R. D. McBride et al., *Phys. Rev. Lett.* **109**, 135004 (2012).

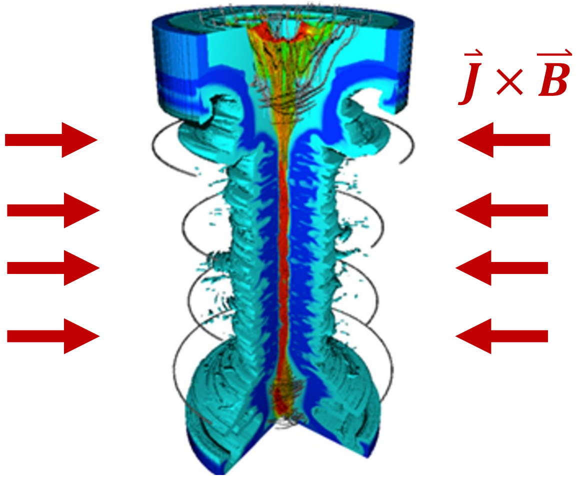
Unmagnetized implosions

azimuthally oriented instability structures

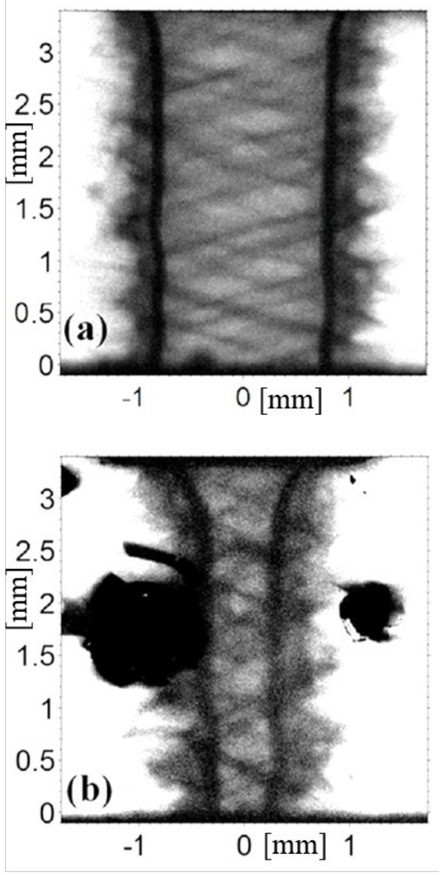
Magnetized implosions

helically oriented instability structures

Solid metallic tube (liner)



$B_{z,0}$=7 T



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

Liner implosions suffer from magneto-Rayleigh-Taylor instabilities (MRTI)

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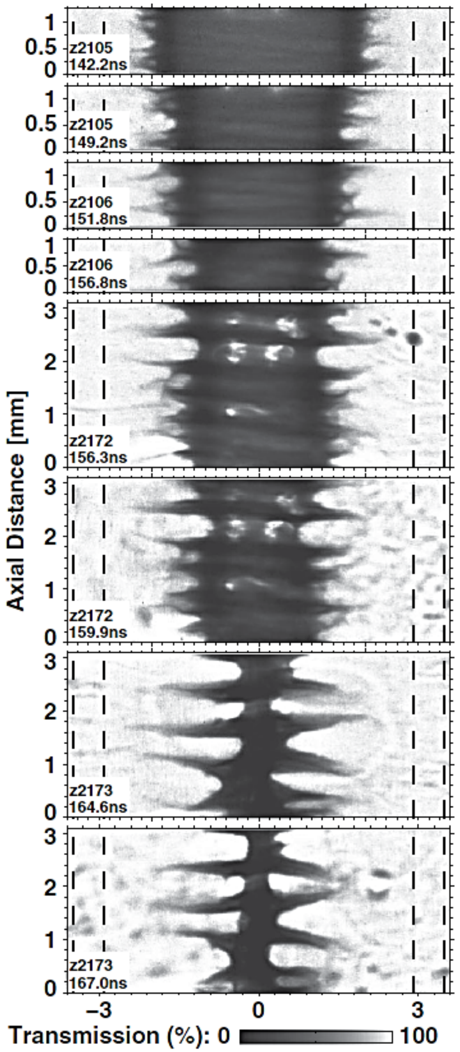


R. D. McBride et al., *Phys. Rev. Lett.* **109**, 135004 (2012).

Unmagnetized implosions

azimuthally oriented instability structures

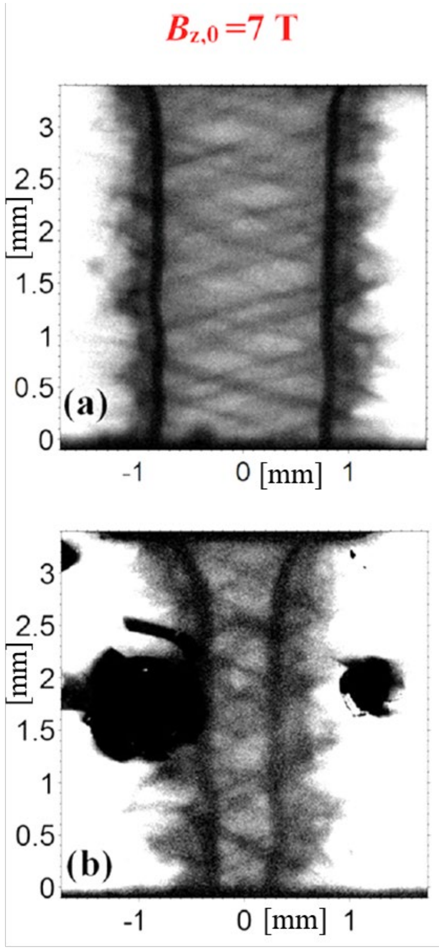
Magnetized implosions

helically oriented instability structures

For MagLIF, liner instabilities limit attainable fuel conditions (temperature, pressure, and density)

Instabilities degrade fusion yield and fuel confinement

$B_{z,0} = 7$ T



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

Linear theory* suggests instability growth can be reduced *in flight* via dynamic screw pinch effect

Magnetic Field Angle

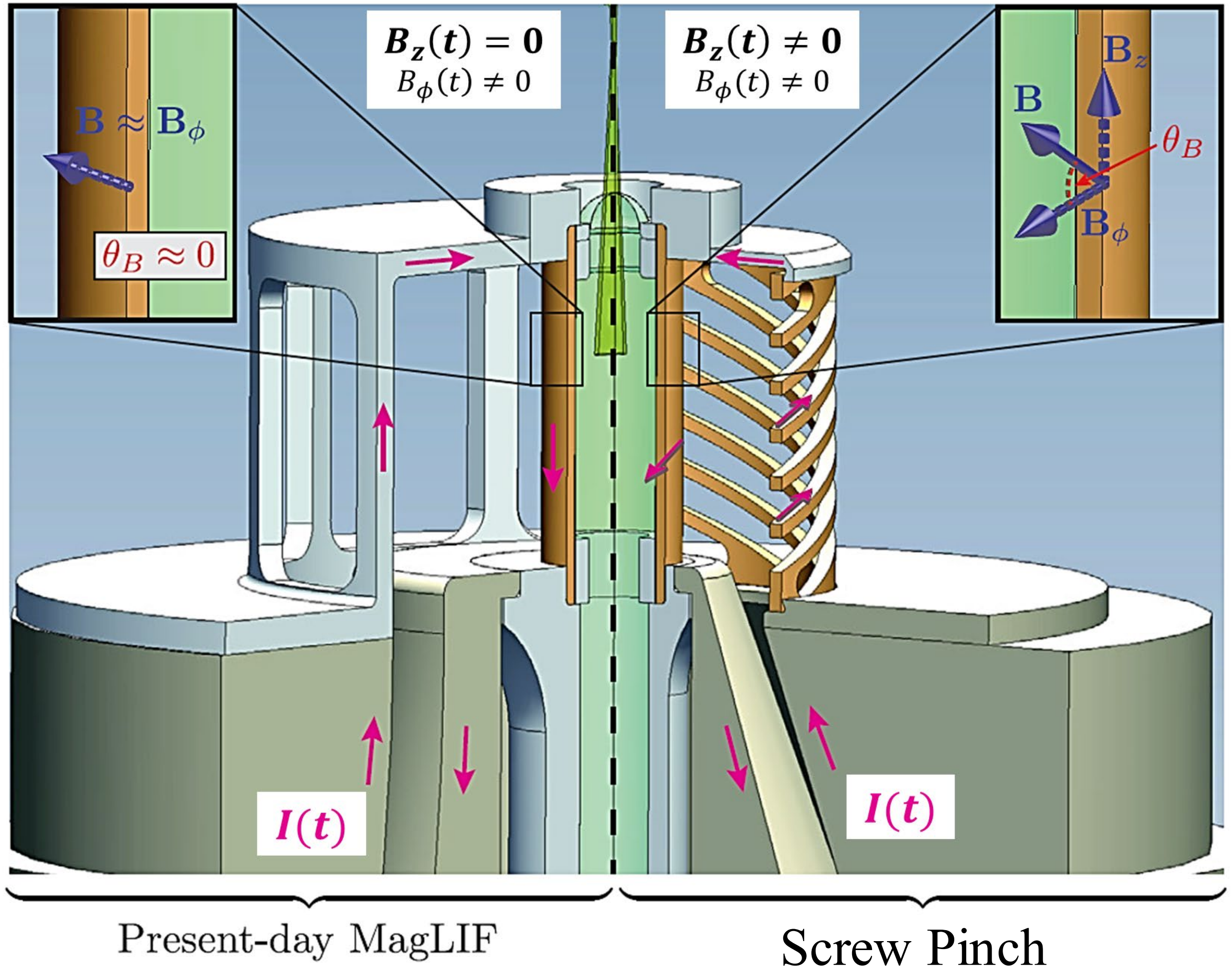
$$\theta_B(t) = \tan^{-1}\left[\frac{B_z(t)}{B_\phi(t)}\right]$$

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

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

$I(t)$ = current flowing through liner

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



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 screw pinch effect

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$I(t)$ = current flowing through liner

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

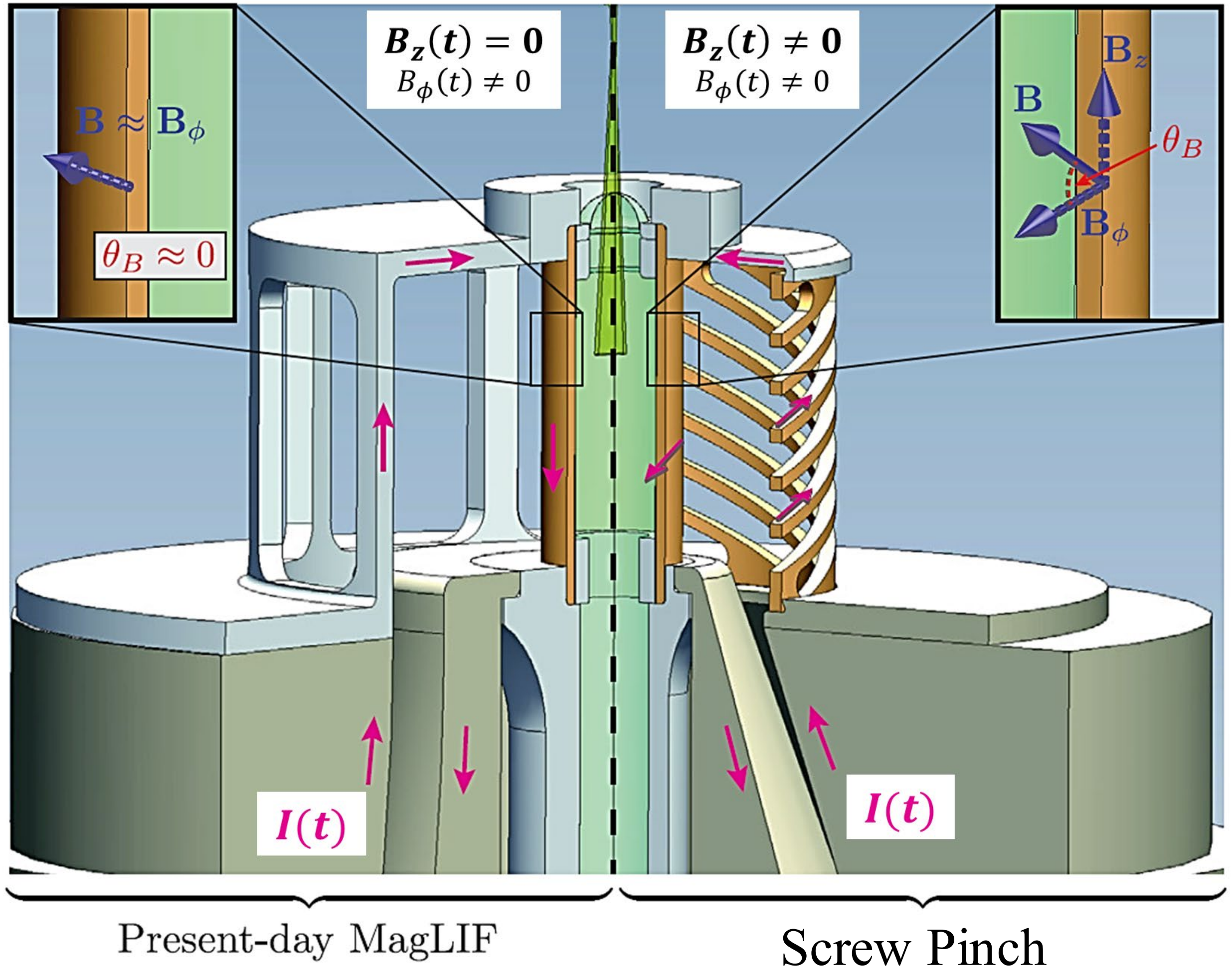
Liner implodes ($r_l(t)$ decreases), magnetic field angle rotates

↓

Applies stabilizing magnetic tension and shifts fastest growing MRTI modes as a function of time

↓

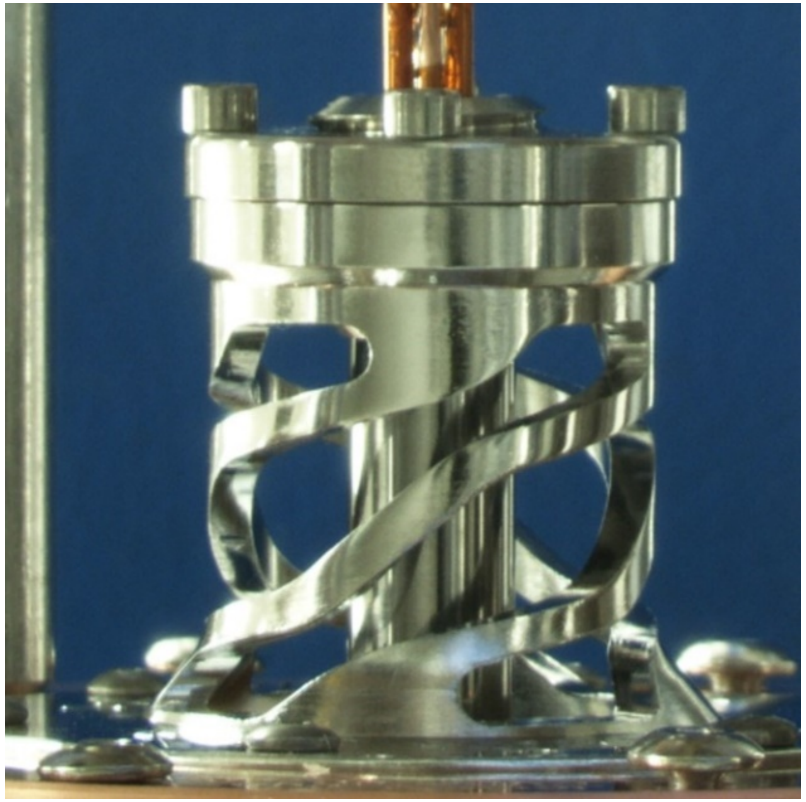
MRTI growth is reduced *in flight* via a Solid Liner Dynamic Screw Pinch* (SLDSP)



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

Radiography data from first DSP experiments on Z offers valuable opportunity for comparison to models

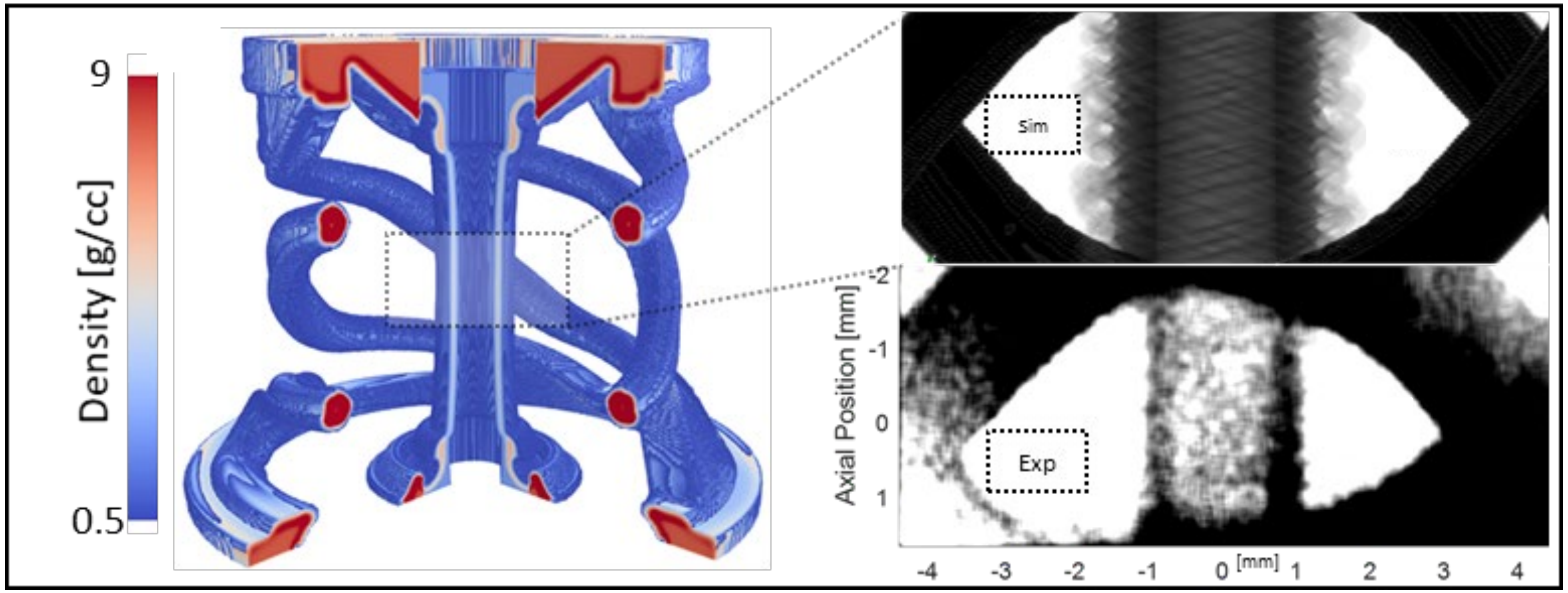
Hardware A0911 (Z3464 and Z3470)



Successfully fabricated and fielded
this complex target geometry

3D ALEGRA*

Predicted helical instability structures



Radiography “window” worked as designed (diagnostic access).

Implosion dynamics appear comparable, but radiography diagnostic performed poorly
→ Unable to resolve small scale structures (predicted helical instabilities).

*G. A. Shipley et al., *Physics of Plasmas* **26**, 102702 (2019)

Thank you for your attention! Questions?