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OXFORD, UK

30TH IEEE SYMPOSIUM ON FUSION ENGINEERING

From Z to a Next Generation Pulsed Power Facility

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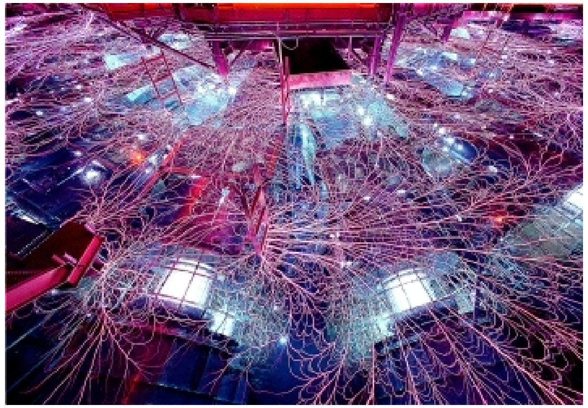
Sandia National Laboratories

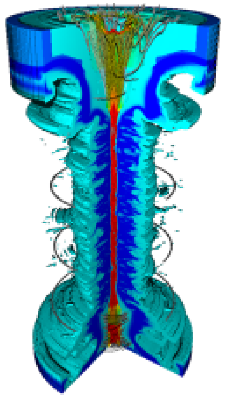
U.S. DEPARTMENT OF ENERGY NNSA

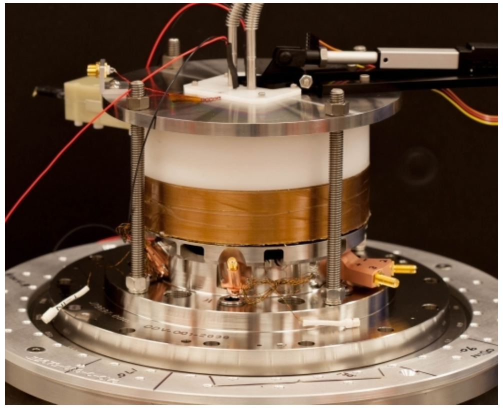
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories

From Z to a Next Generation Pulsed Power Facility







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PRESENTED BY

Daniel Sinars

Director, Pulsed Power Sciences Center

Sandia National Laboratories, Albuquerque, NM, USA

Oxford, UK

July 9-13, 2023

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These are exciting times to be working with pulsed power!

We support the security and prosperity of the United States and its allies by expanding the frontiers of high energy density science, fusion, and extreme radiation environments.

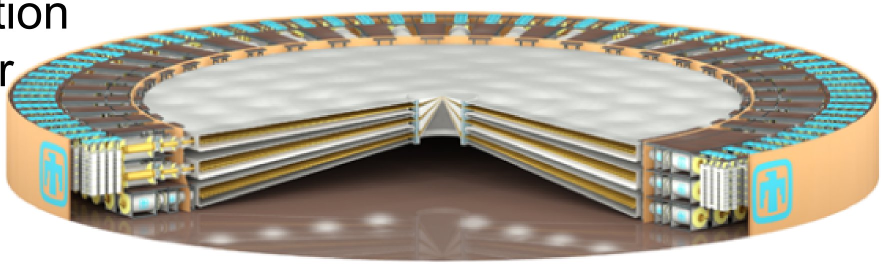
Using pulsed power technology, we

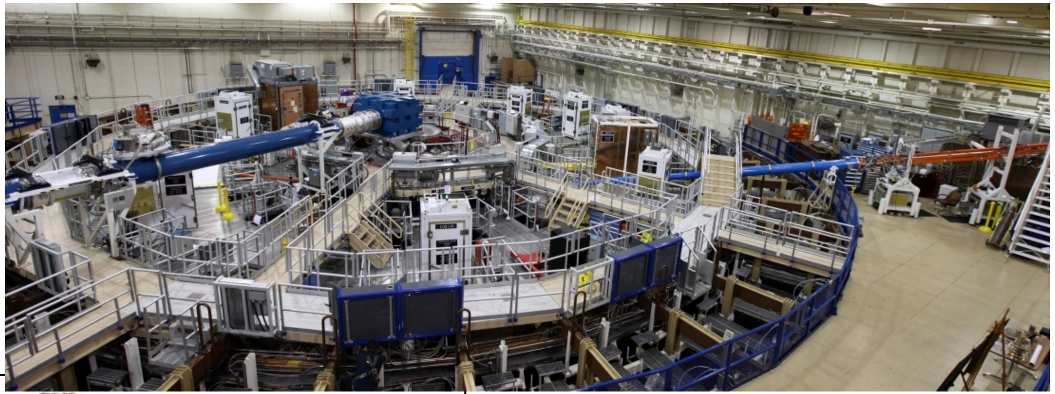
- Provide essential data for our nation's nuclear stockpile
- Provide an engine of discovery for national security

Sandia operates the world's largest pulsed power machine, Z.

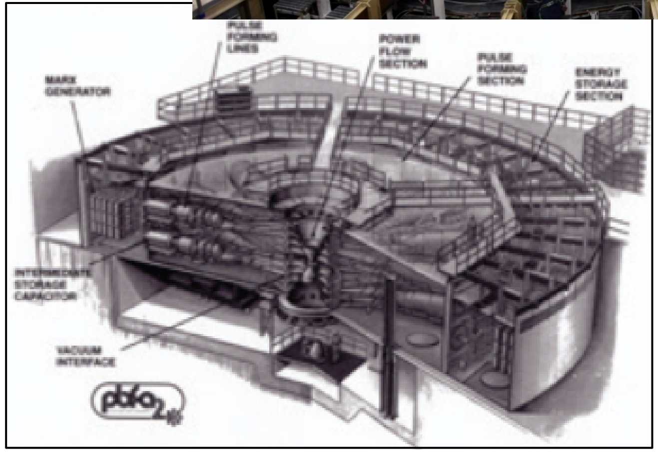
We are working with the NNSA on a Next-Generation Pulsed Power project that will go beyond Z's capabilities.

Next-Generation Pulsed Power (2030s)





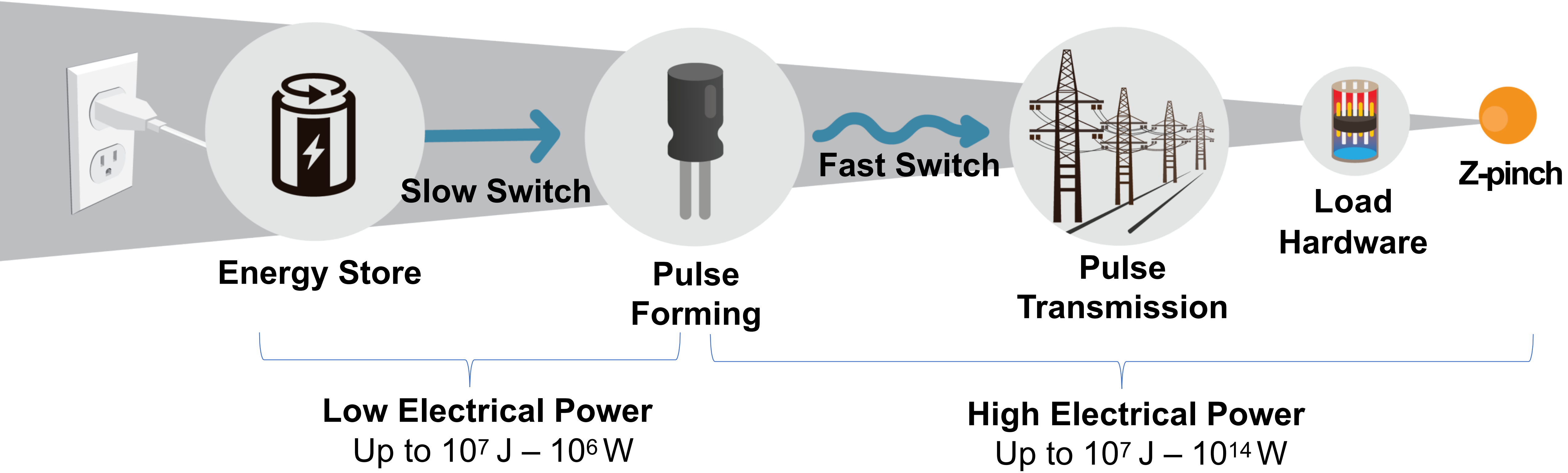
Z Machine (Today)



Particle Beam Fusion Accelerator 2 (1985)

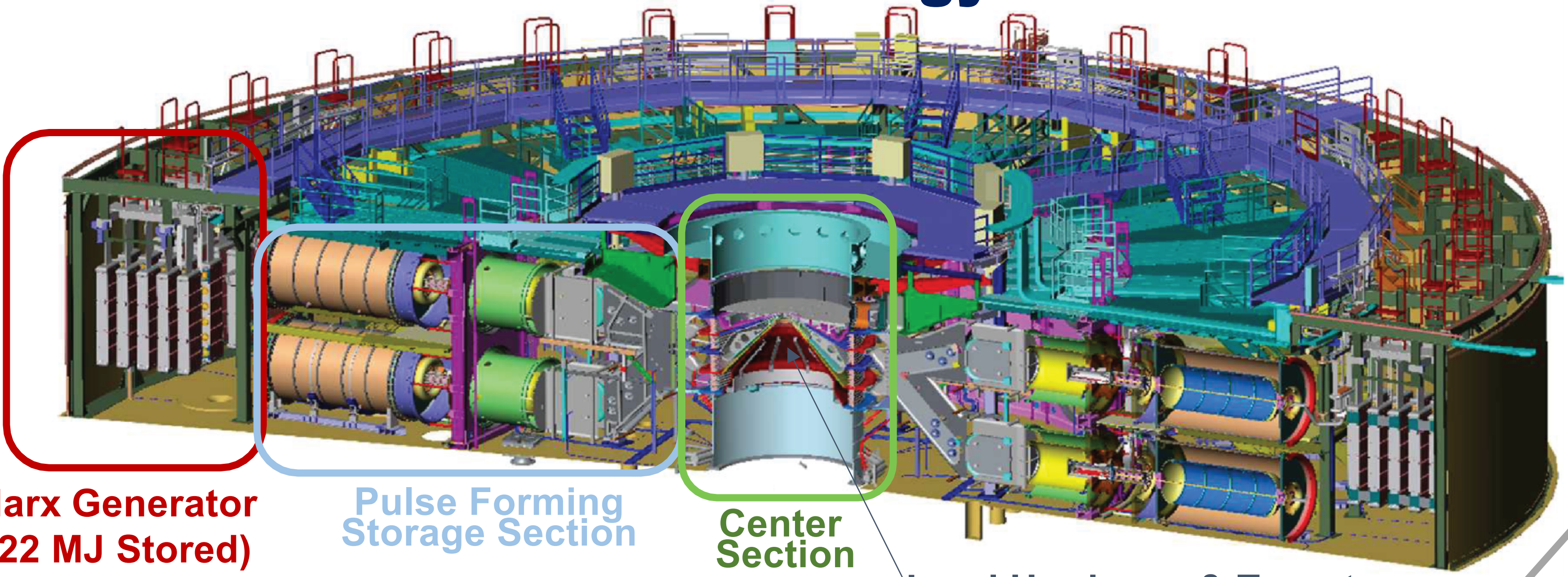
Introduction: Pulsed Power

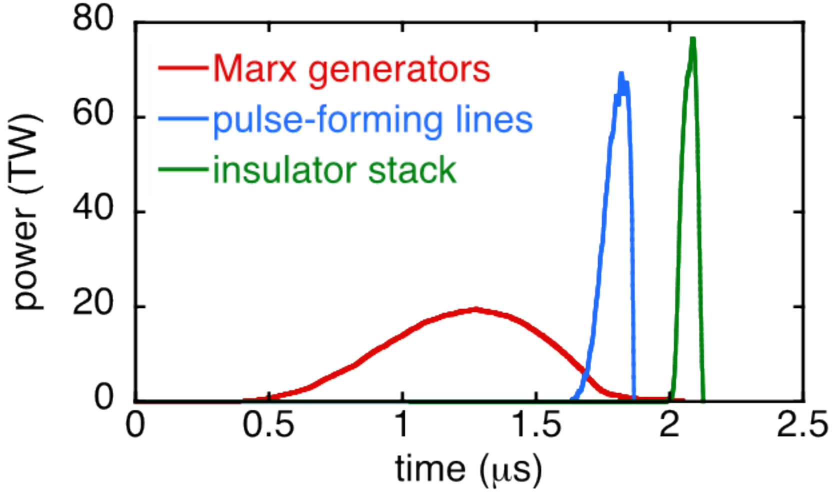
Z-pinch implosions are usually driven by pulsed power technology capable of creating bursts of high power



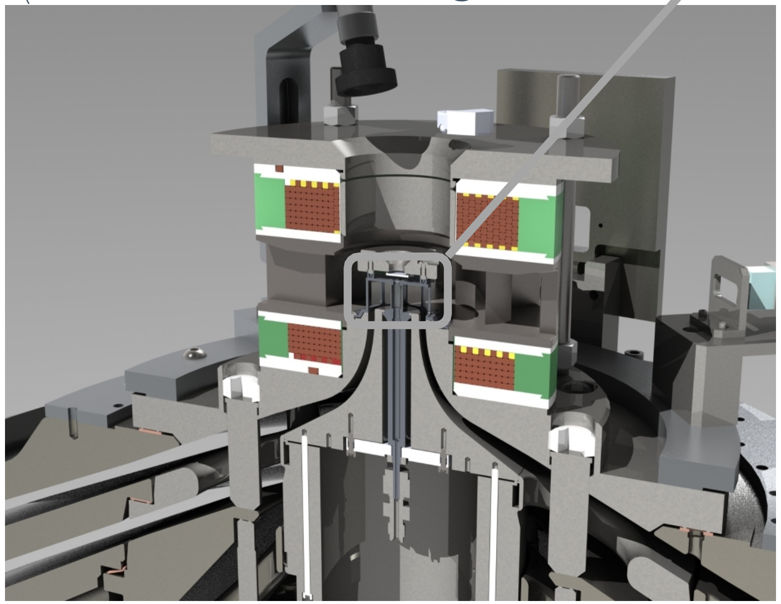
Pulsed power compresses electrical energy in both space and time to produce short bursts of high power.

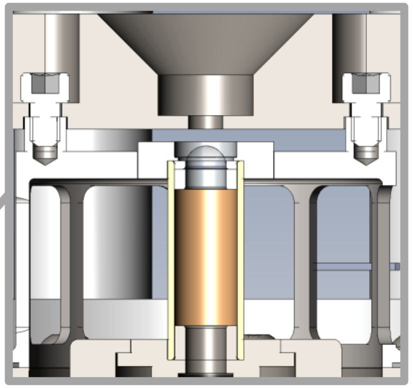
Z, the world's largest pulsed power machine, delivers 80 TW and 6 MJ of electrical energy to its center section





Load Hardware & Target





Z-pinch target

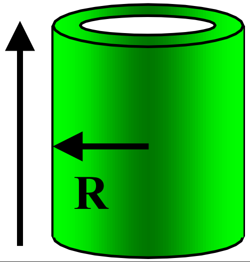
Z today couples several MJ out of 22 MJ stored to the load hardware region at the machine center.

The Z machine can generate ~100 Mbar drive pressures, which can be used to obtain the high pressures needed for fusion

Magnetically Driven Implosion

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

drive current *I*



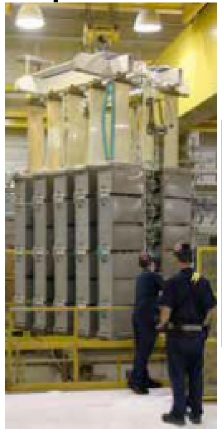
100 MBar at 26 MA and 1 mm

100 GPa = 1 Mbar ≈ 10^6 atm

Pressure equivalent to Energy Density (J/m^3)

1 Mbar = 10^{11} J/m^3, threshold of High Energy Density regime

Z Storage capacitor

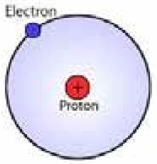


2e-6 Mbar

TNT

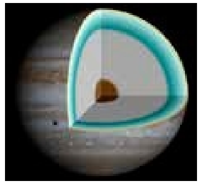
0.07 Mbar

Internal Energy of H atom



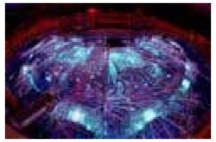
1 Mbar

Metallic H in Jupiter's core



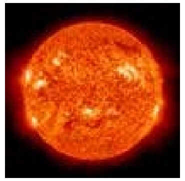
30 Mbar

Z Magnetic Drive Pressure



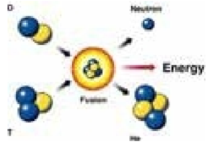
~100 Mbar

Center of sun



250,000 Mbar

Burning ICF plasma



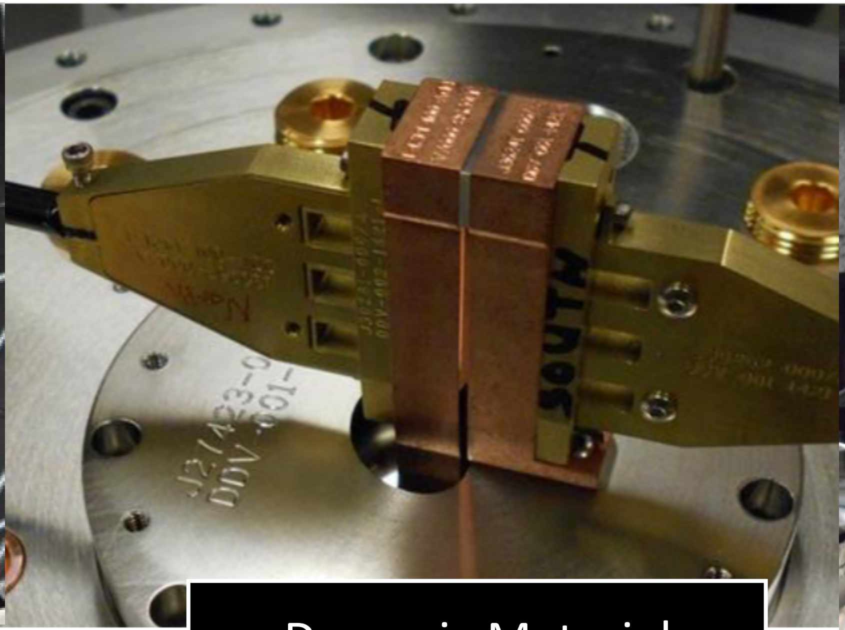
800,000 Mbar

Push on samples

Compress fuel at high velocity

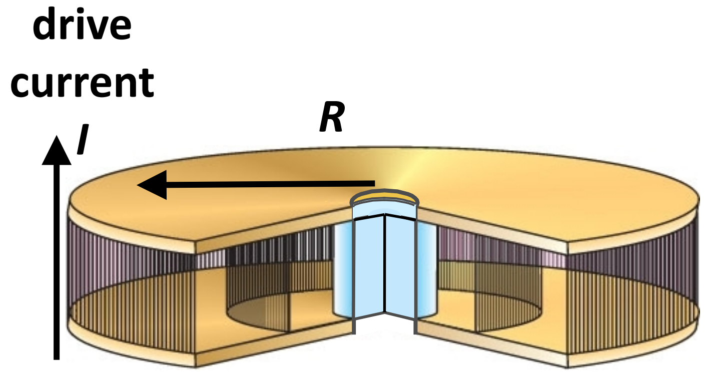
Z is a precision tool for high energy density science[1]

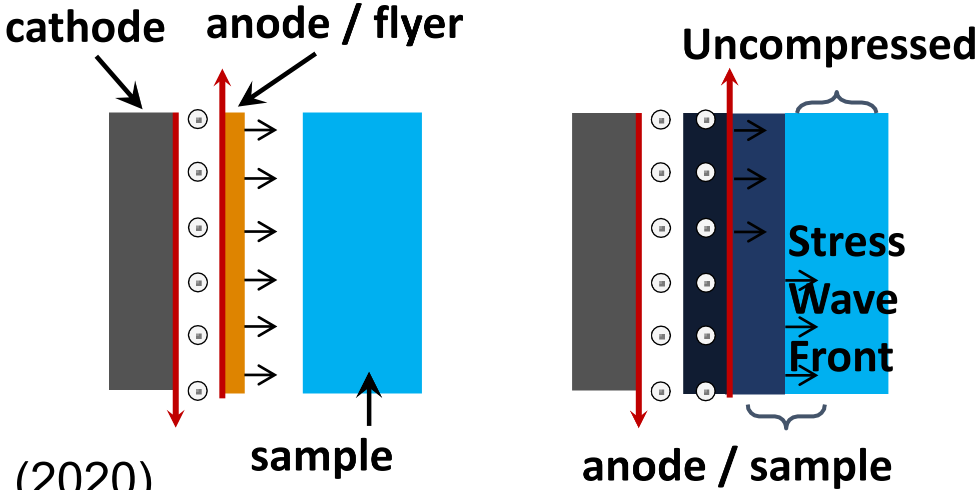
Radiation Science

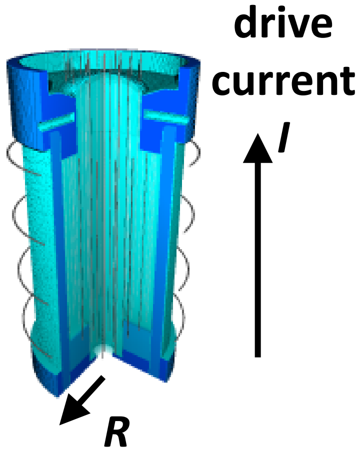


Dynamic Material Properties

Inertial Confinement Fusion



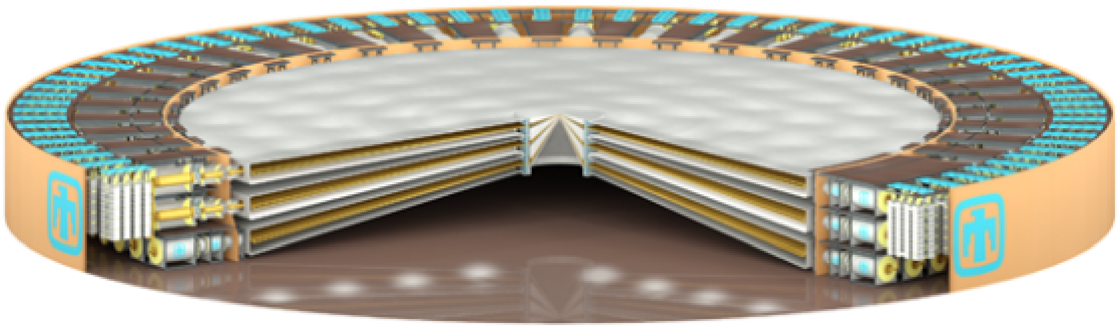




[1] D.B. Sinars *et al.*, Phys. Plasmas (2020).

Sandia is working with the NNSA on a Next Generation Pulsed Power (NGPP) project to address important HED capability gaps and provide needed agility and flexibility for the next phase of stockpile modernization/replacement

One example concept that would deliver 50-70 MA of electrical current depending on target



Parameter	Z	Ex. NGPP Option
Diameter	108’	300’
Marxes	36 @ 600 kJ (22 MJ)	75 @ 2400 kJ (180 MJ)
Capacitors	2,160 @ 2.65 μF	13,500 @ 2.95 μF
Power at Stack	85 TW	602 TW
Forward Energy at Stack	6 MJ (short pulse)	54 MJ (short pulse)
Energy to target	1-2 MJ	9-18 MJ

NGPP will:

Be the world’s most powerful warm x-ray source

Support fusion yields up to ~100 MJ

Provide advanced capability for high energy density physics (e.g., dynamic materials)

Advance the state-of-the-art for fast pulsed power technology

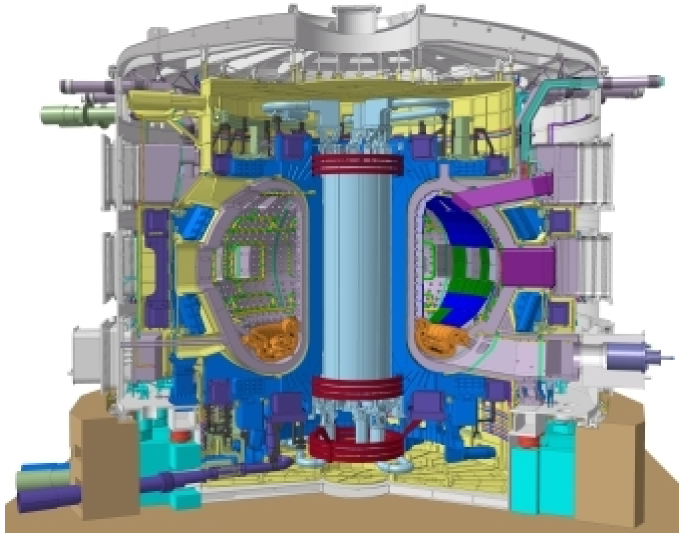
Provide a venue for scientific and technical innovation for national security

Mission need and requirements finalized in 2023
Main project funding beginning in ~2026
Project completion in the 2030s

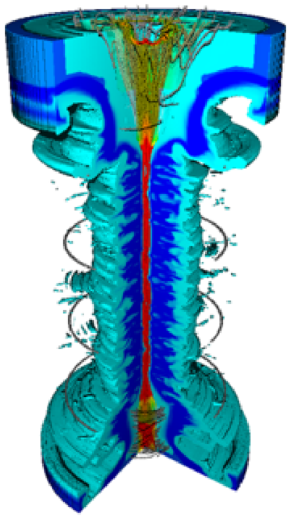
Magnetized Liner Inertial Fusion (MagLIF)

Magnetic inertial fusion (MIF) bridges the gap between magnetic confinement fusion (MCF) and inertial confinement fusion (ICF).[2]

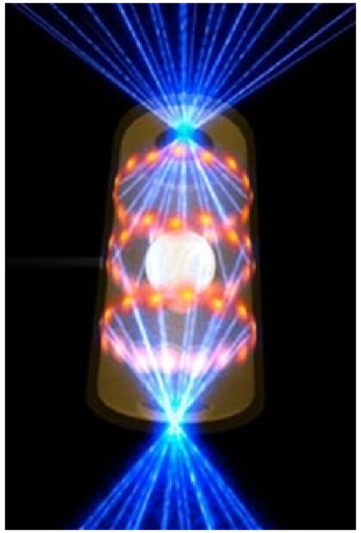
MCF (e.g. ITER)



MIF (e.g. MagLIF)



ICF (e.g. NIF)



MCF
- B field confines plasma
- B field traps α's

MIF
- B field reduces conduction losses during implosion
- B field increases path length of α's, reducing density reqts.

ICF
- Plasma inertially confined
- α's stopped by high density

	MCF	MagLIF	ICF
Density	1 x 10^{20} m^{-3}	1 x 10^{29} m^{-3}	2-20 x 10^{31} m^{-3}
Duration	300-500 s	1-2 x 10^{-9} s	5-10 x 10^{-11} s
Volume	8 x 10^{2} m^{3}	8 x 10^{-11} m^{3}	6 x 10^{-14} m^{3}
Magnetic field	100 kG	50-100 MG*	0 kG

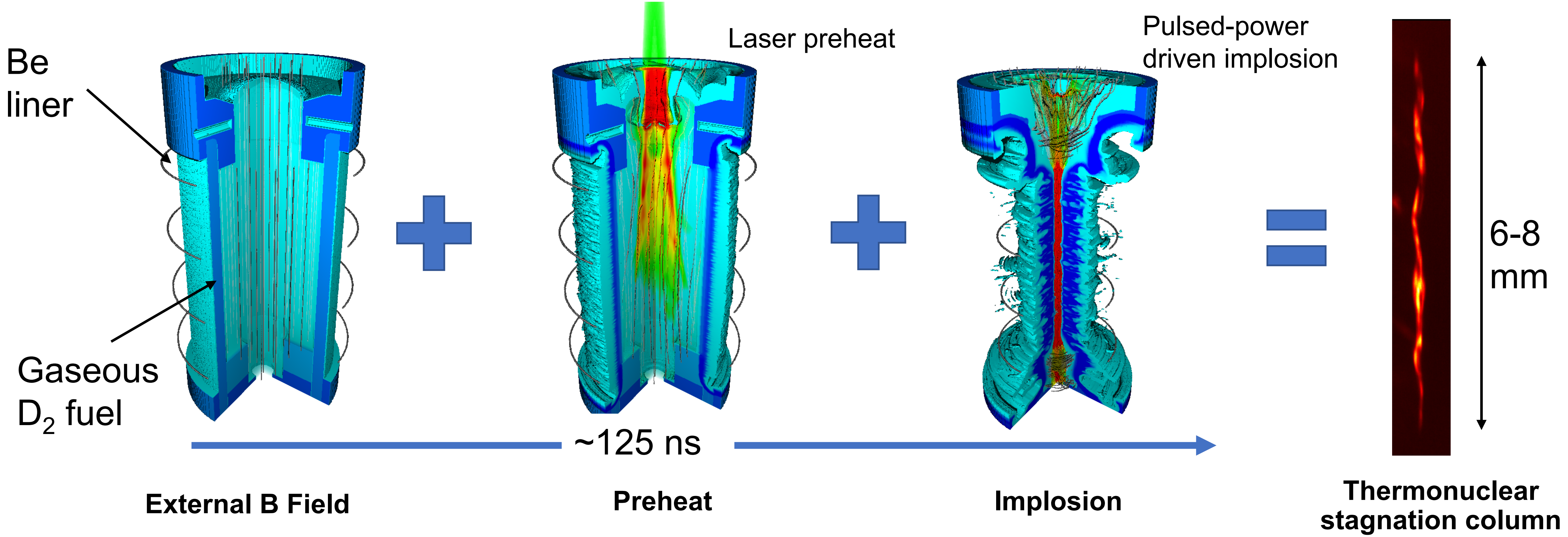
Lawson criterion (DT)

$$n\tau_E \geq 1.5 \cdot 10^{20} \frac{\mathrm{s}}{\mathrm{m}^3}$$

*Achieved by flux compression

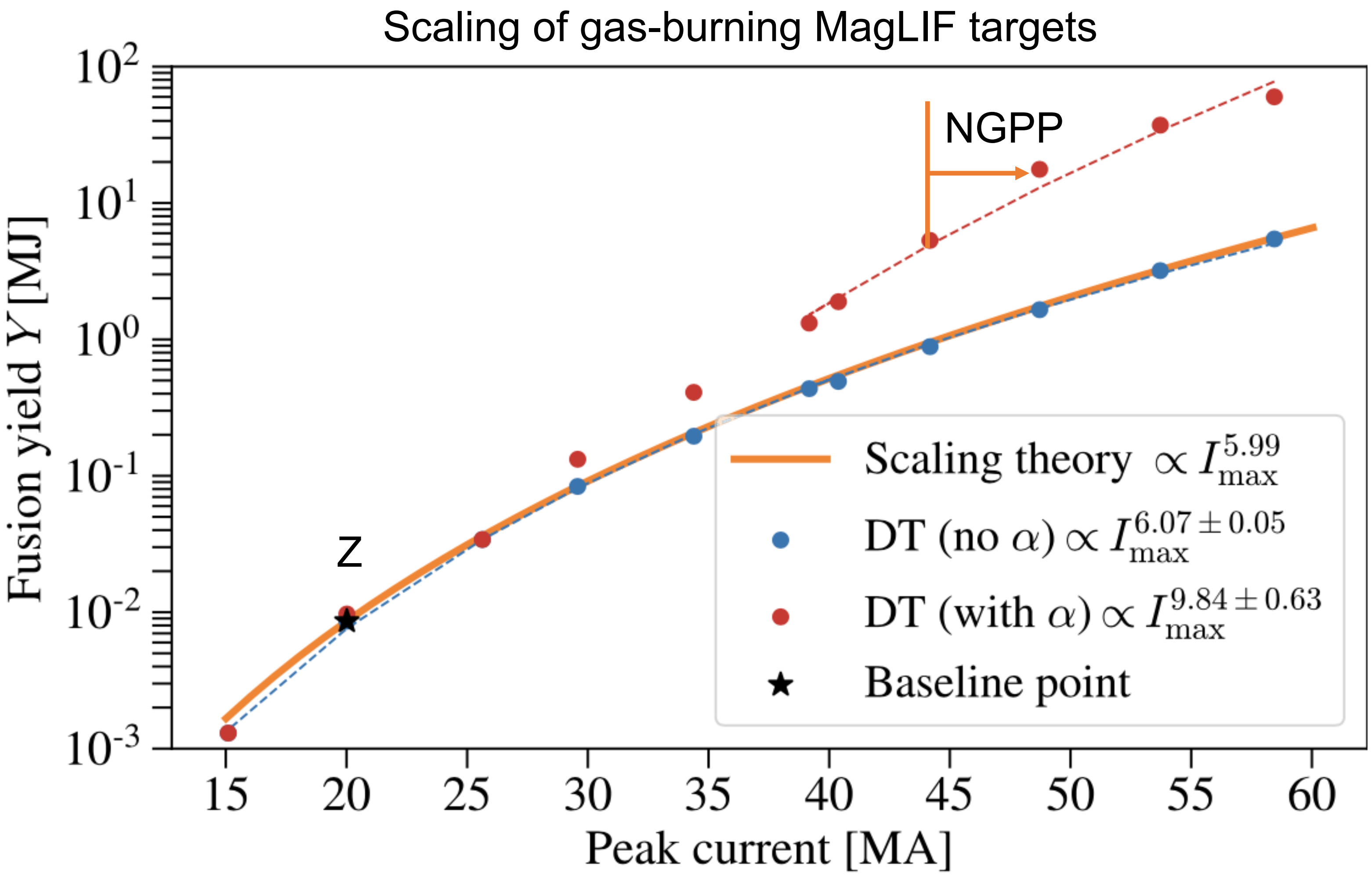
[2] Richard Siemon, et al., “Why Magnetized Target Fusion Offers A Low-Cost Development Path for Fusion Energy?” Comments on Plasma Physics and Controlled Fusion, December, 1997

Magnetized Liner Inertial Fusion (MagLIF) is a fusion concept combining external axial magnetic fields, laser preheat, and z-pinch implosions.[3,4,5]



[3] S. A. Slutz, M. C. Herrmann, R. A Vesey, *et al.*, Phys. Plasmas **17**, 056303 (2010).
[4] M. R. Gomez, S. A. Slutz, A. B. Sefkow, *et al.*, Phys. Rev. Lett. **113**, 155003 (2014).
[5] D.A. Yager-Elorriaga *et al.*, Nuclear Fusion (2022).

We are keenly interested in validating paths to ~100 MJ yields on future facilities with magnetic direct drive fusion targets[6,7]



[6] P.F. Schmit & D.E. Ruiz, Phys. Plasmas (2020).

[7] D. E. Ruiz, *et al.*, *"Exploring the parameter space of MagLIF implosions using similarity scaling. II. Current scaling"*, Phys. Plasmas (2023).

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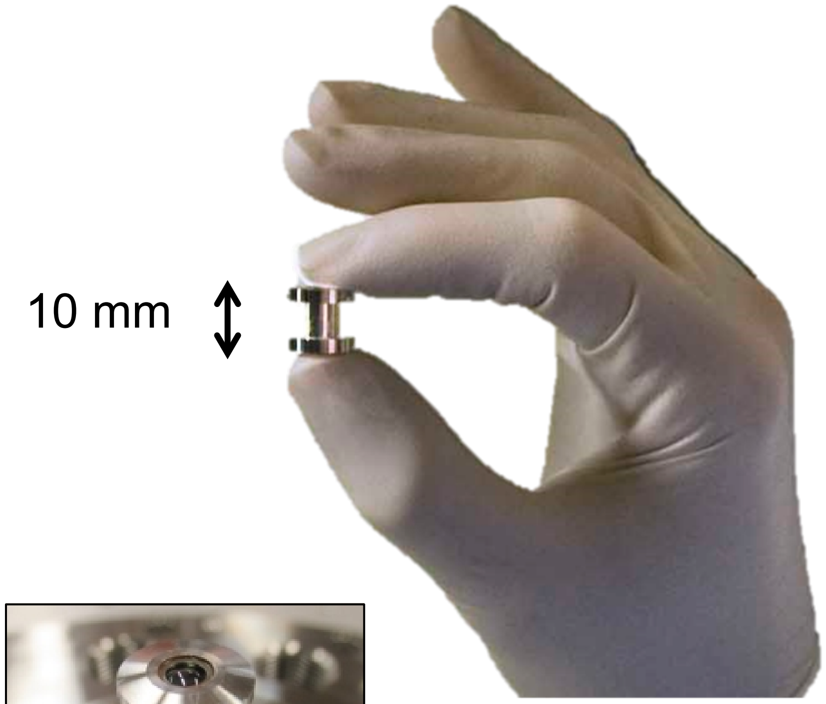

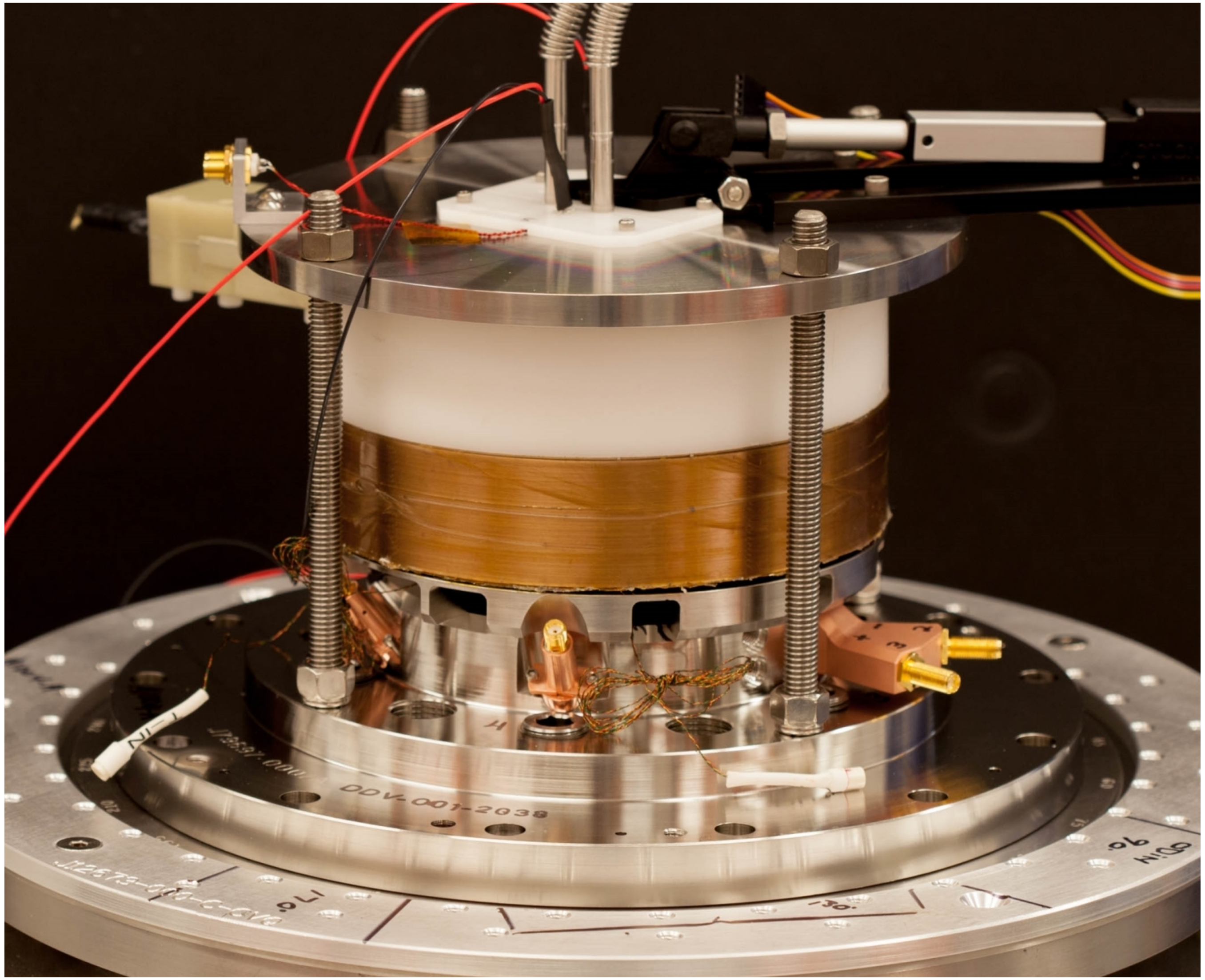

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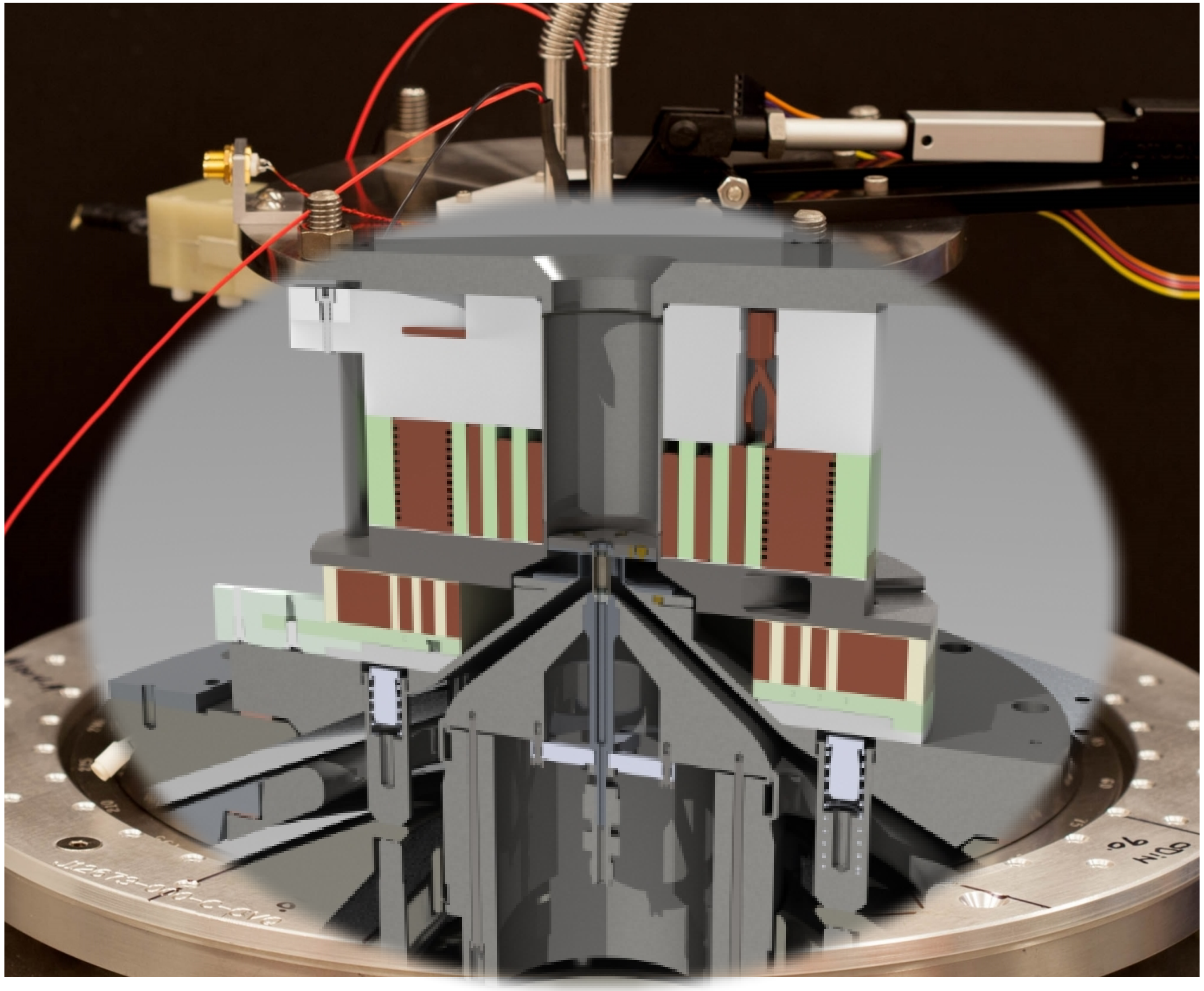
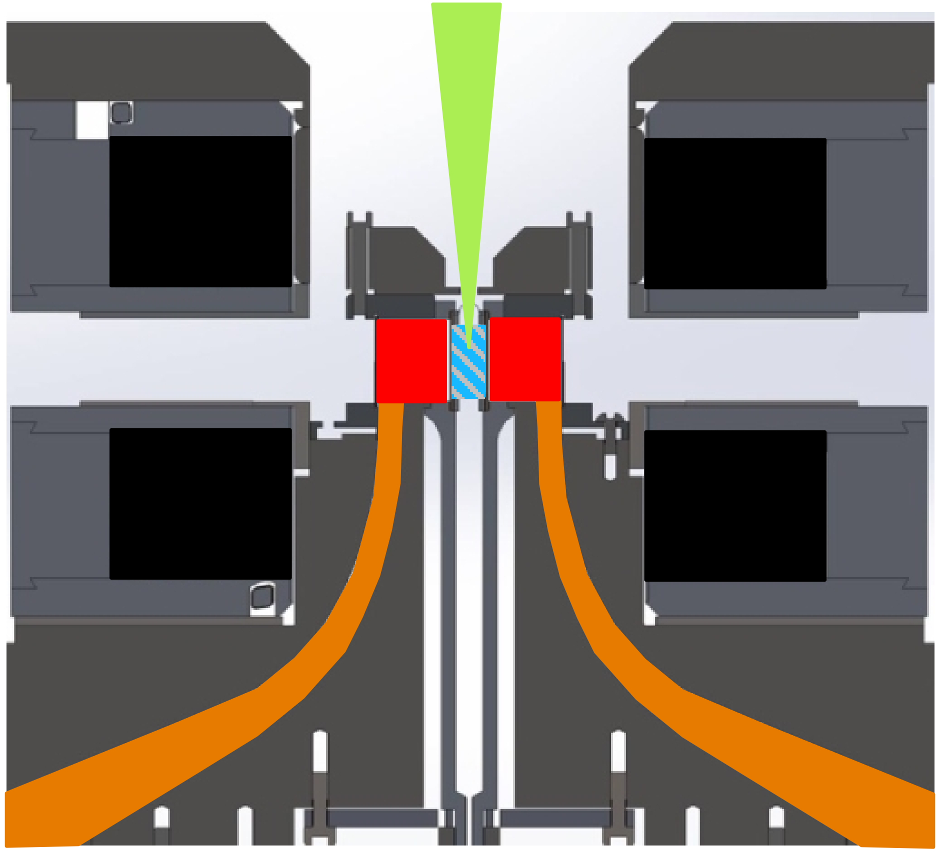
10 mm



Magnetized Liner Inertial Fusion (MagLIF)

We are actively engaged in building a deep understanding of the physics underpinning MagLIF[5]

MagLIF Experimental Assembly



Performance and Physics Scaling

Implosion Stability — * Examples today

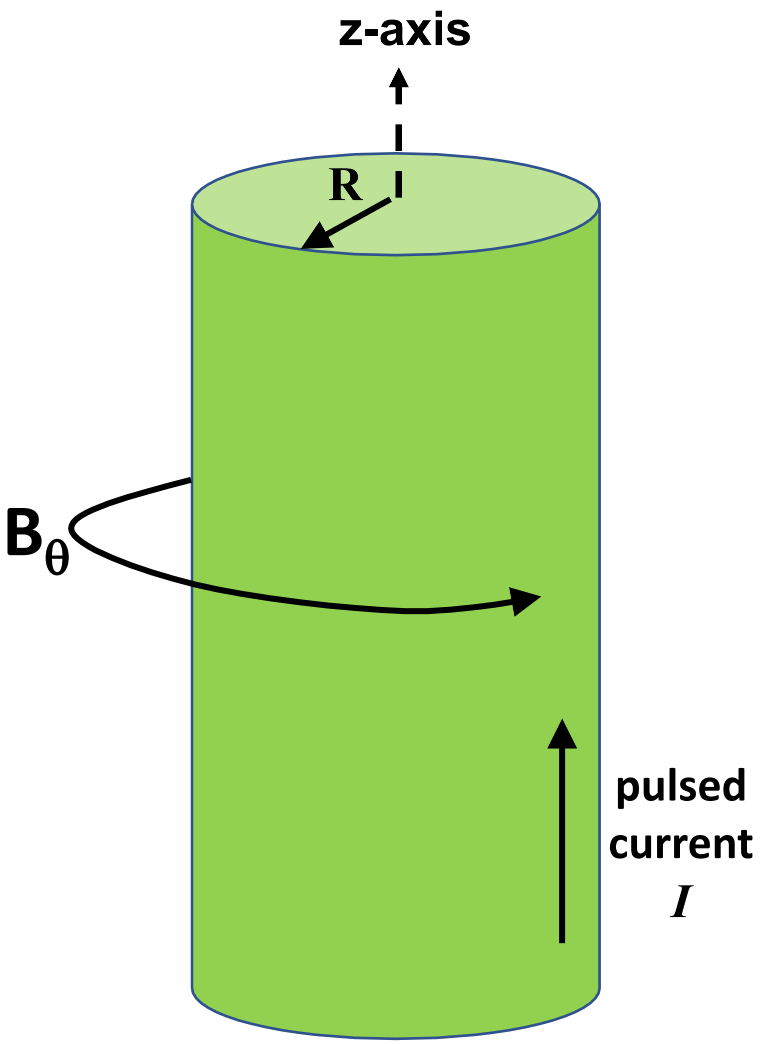
Stagnation pressure and confinement time

Transmission line to the load — * Example today

Laser preheat

[5] D.A. Yager-Elorriaga *et al.*, Nuclear Fusion (2022).

Implosion stability is dominated by the magneto-Rayleigh-Taylor instability[10], an interchange instability between the z-pinch mass and the magnetic pressure

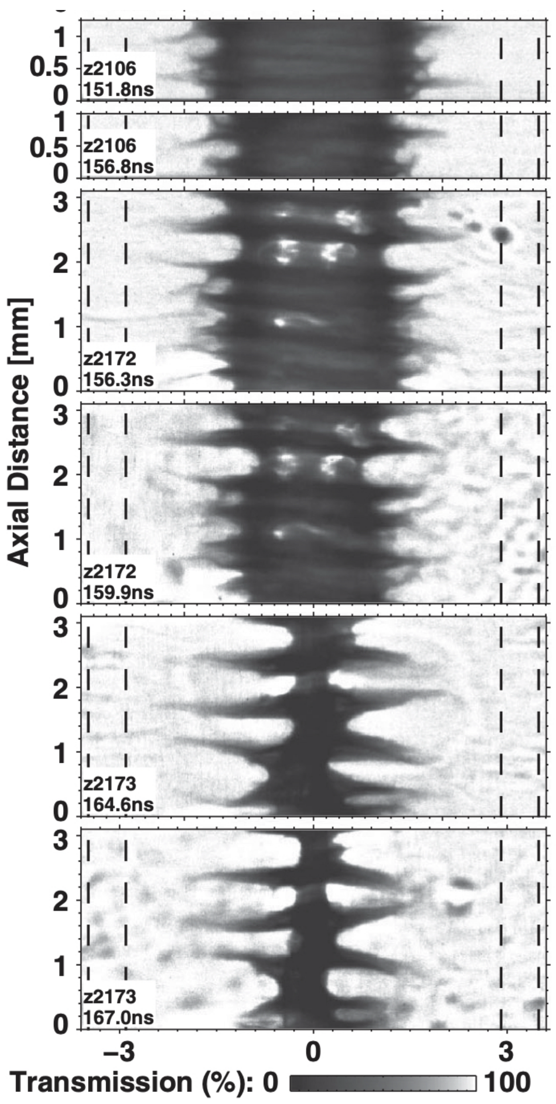


A small perturbation with amplitude η will grow as

$$\frac{d^2\eta}{dt^2} = \gamma^2(t)\eta$$

$$\gamma^2 = kg(t)$$

$$g = -\frac{\mu_0}{4\pi m_L}\frac{I^2(t)}{R(t)}$$

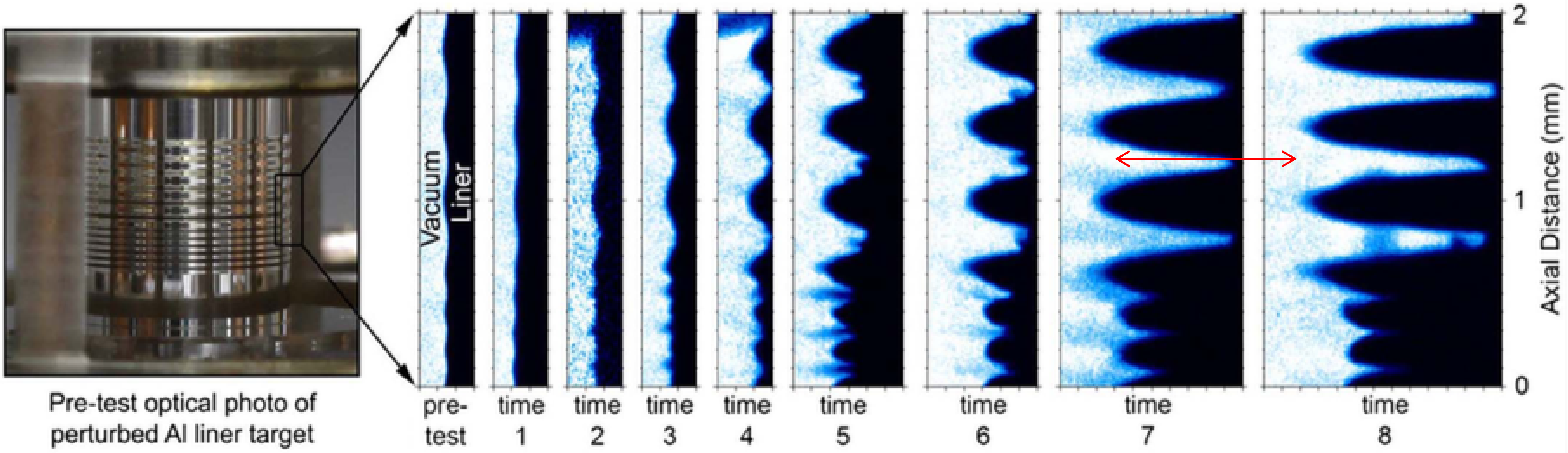


[11] R.D. McBride *et al.*, Phys. Rev. Lett. (2012).

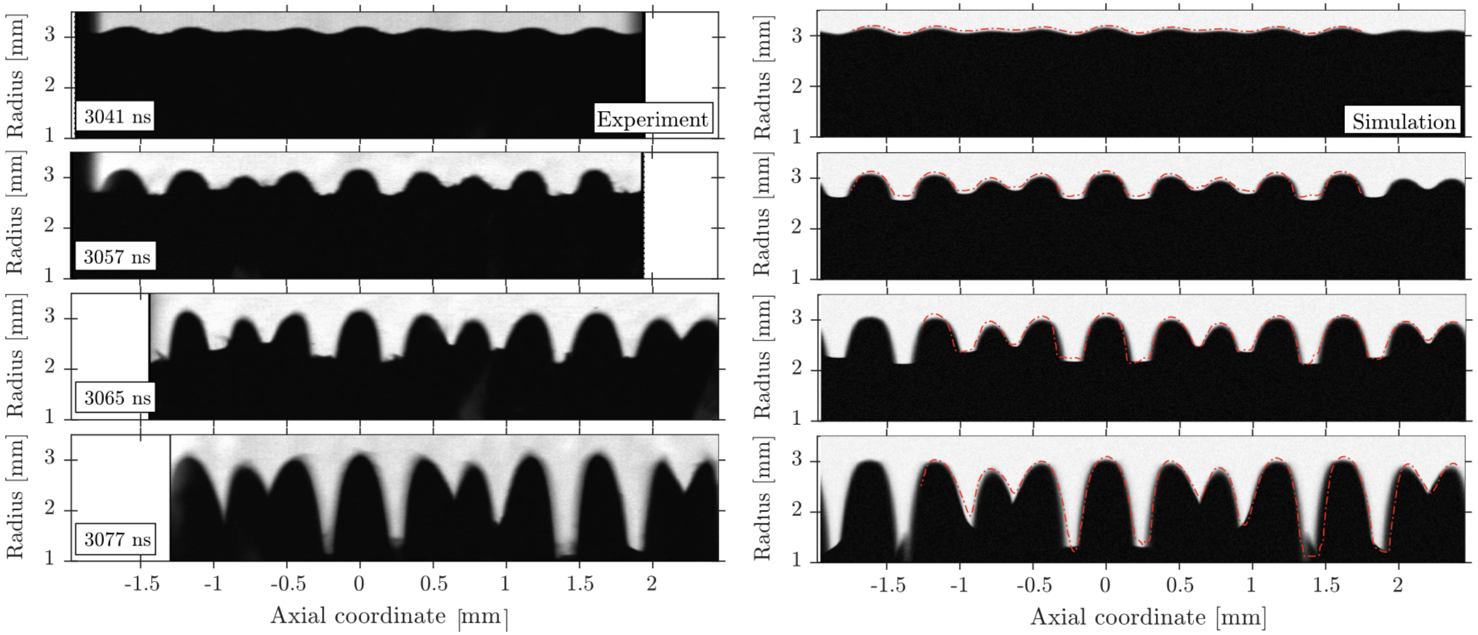
[10] E.G. Harris, Phys. Fluids 5, 1057 (1962).

To validate our understanding, we did many controlled instability studies to benchmark our predictive capabilities.[11-13]

Single-mode MRT growth[12]

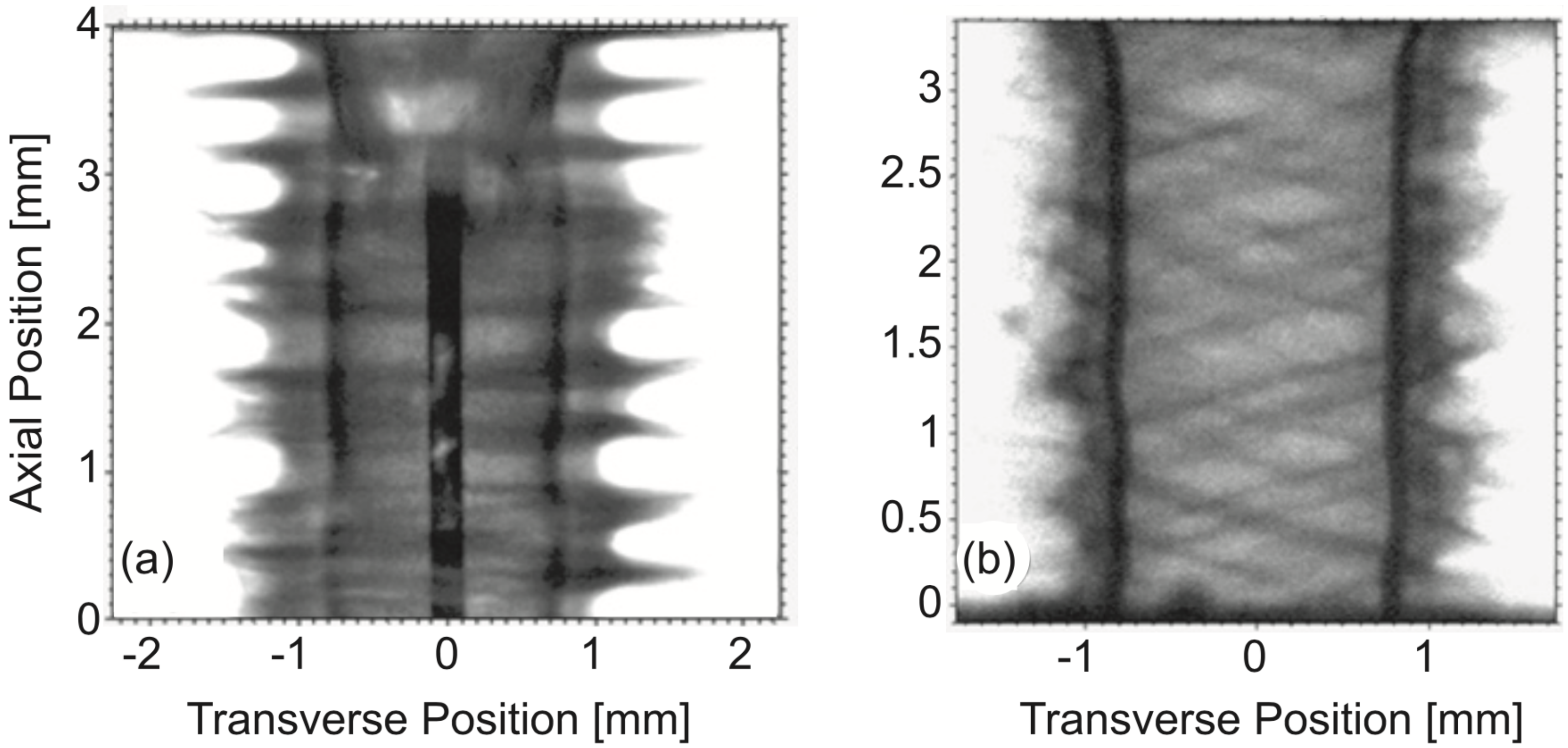


Harmonic generation and inverse cascade in two-wavelength MRT growth[13]



[11] R.D. McBride *et al.*, Phys. Rev. Lett. (2012).
[12] D.B. Sinars *et al.*, Phys. Rev. Lett. (2010);
D.B. Sinars *et al.*, Phys. Plasmas (2011).
[13] D.E. Ruiz *et al.*, Phys. Rev. Lett. (2022).

growth from cylindrical to helical[14], the origin of which remains an active area of research

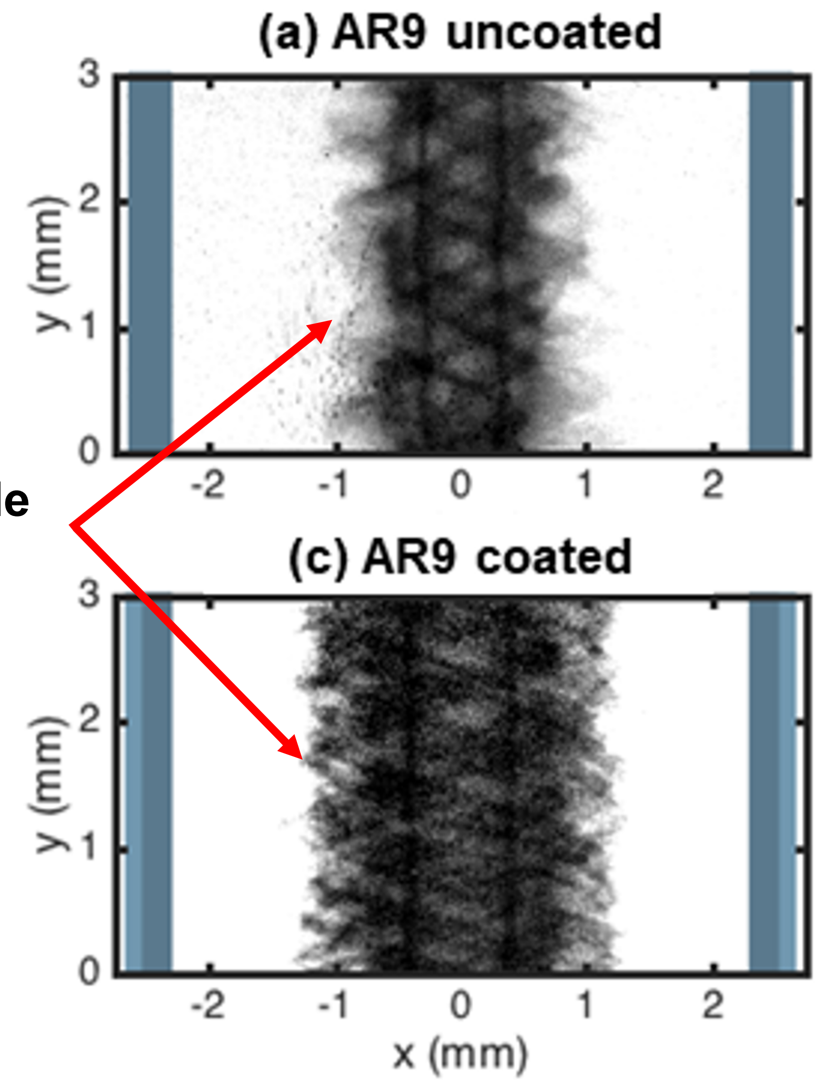


Physics that may be contributing to helical structure:

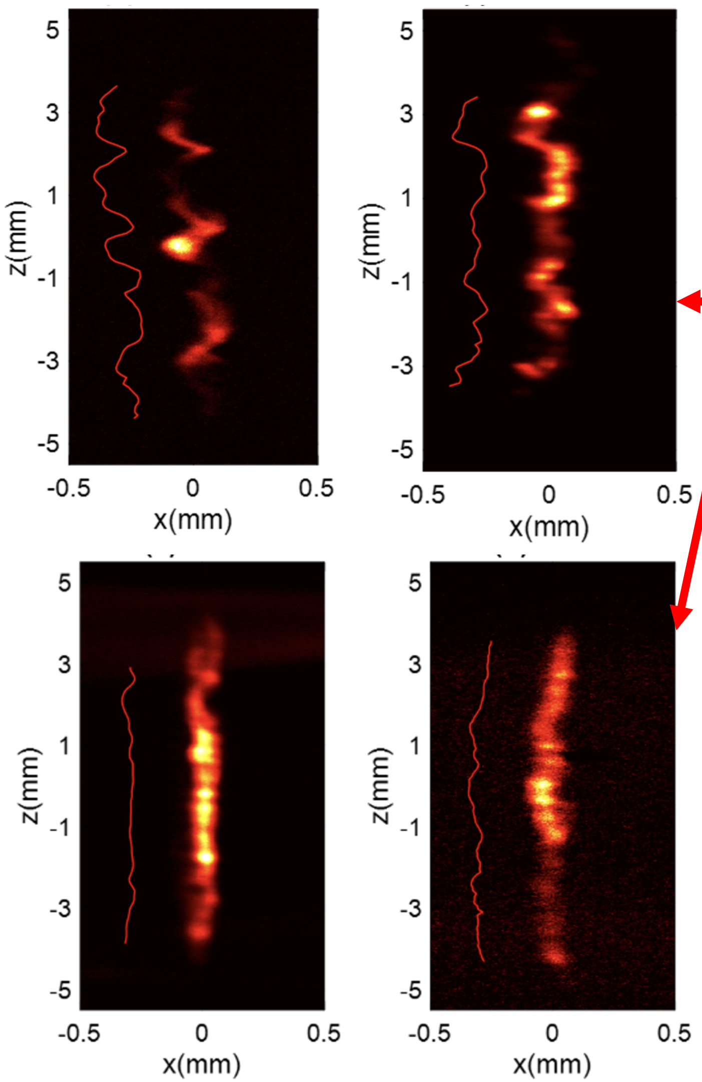
- Electrothermal Instability[15-18]
- Compression of axial flux in the feed onto the liner surface[19]
- Hall interchange instability in low-density plasma around the liner[20]

[14] T.J. Awe *et al.*, Phys. Rev. Lett. (2013).
[15] K.J. Peterson *et al.*, Phys. Plasmas (2012).
[16] K.J. Peterson *et al.*, Phys. Plasmas (2013).
[17] E.P. Yu, T.J. Awe, K.R. Cochrane et al., Phys. Plasmas **27**, 052703 (2020).
[18] T.J. Awe, E.P. Yu, M.W. Hatch et al., Phys Plasmas (2021).
[19] C.E. Seyler, M.R. Martin, & N.D. Hamlin, Phys. Plasmas (2018).
[20] J.M. Woolstrum *et al.*, Phys. Plasmas (2022).

We have been looking at the use of dielectric coatings to improve the stability and reproducibility of MagLIF implosions.[21]



Radiography shows pitch angle and amplitude growth change

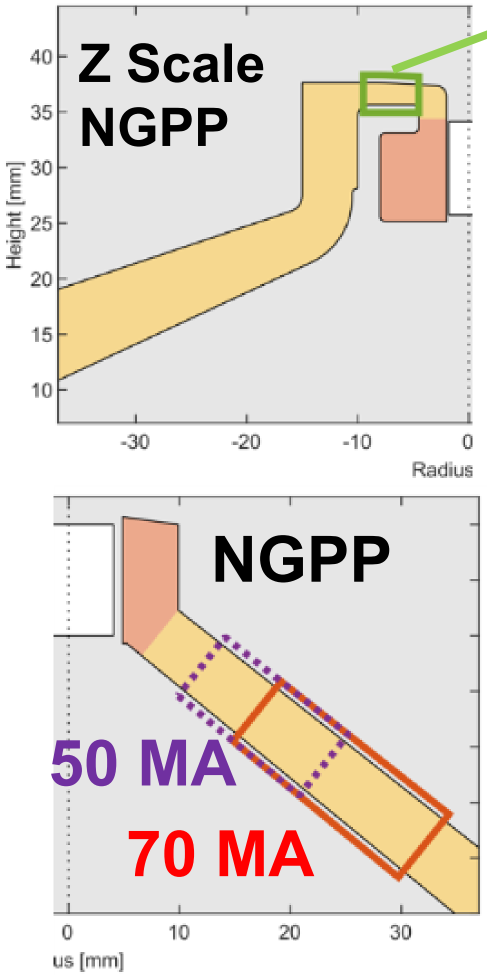


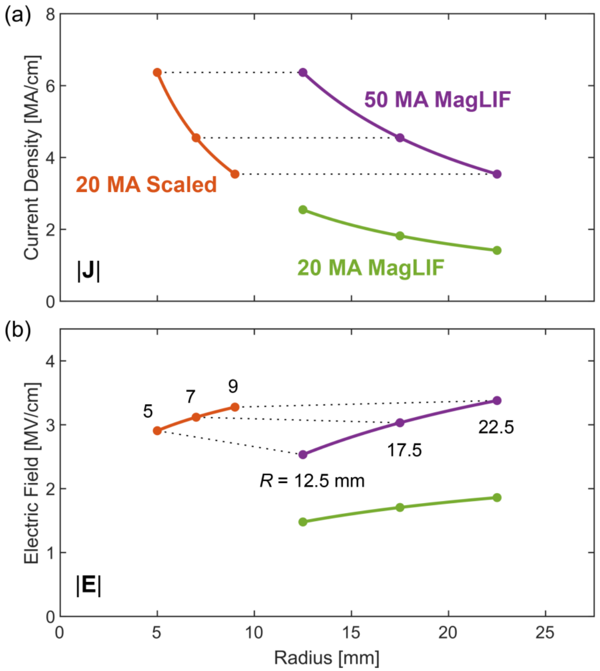
Multi-keV self-emission images show more uniform emission and are straighter in coated case.

Secondary DT neutrons may also imply improved magnetization (BR) at stagnation

[21] D.J. Ampleford *et al.*, *Controlling Morphology and Improving Reproducibility of Magnetized Liner Inertial Fusion Experiments*, submitted for publication.

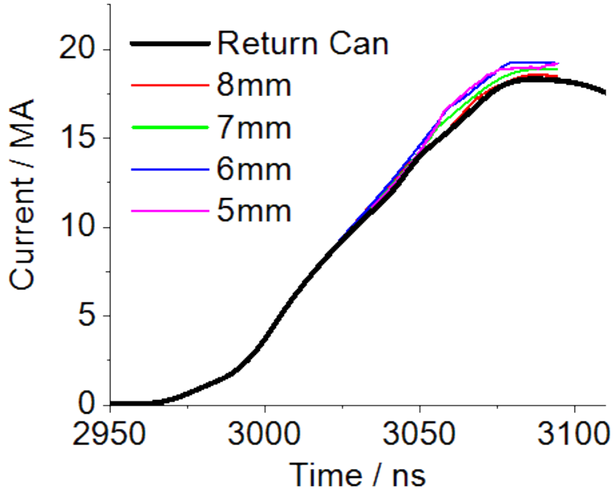
We have done scaled experiments on Z that replicate conditions representative of those found on NGPP to test the power flow[22]





Conditions match nominal current density and electric fields

Z Line VISAR measurements show identical currents at different radial locations



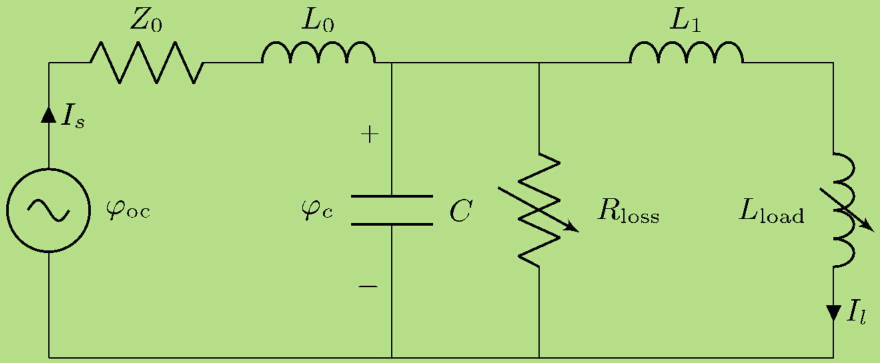
Ongoing work[23] is directly measuring plasma conditions in the power flow region

[22] C.E. Myers *et al.*, PRAB (accepted, 2023).
[23] N. Bennett *et al.*, PRAB (2023).

Physics scaling of MagLIF from Z to a future facility

Similarity scaling of MagLIF loads rests upon 4 theoretical models.[24]

Circuit model

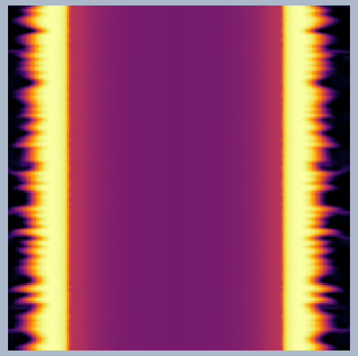


R. D. McBride, et al., Phys. Rev. ST Accel. Beams **13**, 51 (2010).

Liner stability and IFAR modeling

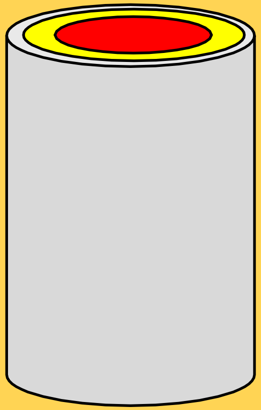
$$\Gamma_{\rm max}(t) \simeq \frac{1}{4}\frac{\rm IFAR(t)}{R_{\rm out}(t)}\left(\int_0^t \sqrt{|\ddot{R}_{\rm out}|}\,{\rm d}t'\right)^2$$

$$\mathrm{IFAR}(t) \simeq \frac{2\pi R_{\rm out}^2(t)\rho_{\rm ref}}{\widehat{m}}\left(\frac{p_{\rm mag}(t)}{2p_{\rm ref}}\right)^{1/\gamma}$$



R. Nora, et al., Phys. Plasmas **21**, 056316 (2014).

Two-interface shell model

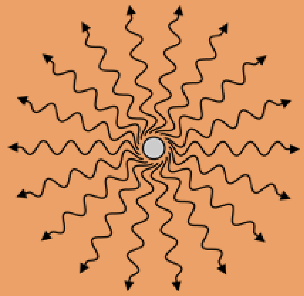


$$\frac{\widehat{m}}{2}\frac{{\rm d}^2}{{\rm d}t^2}R_{\rm out} = 2\pi R_{\rm out}\left(p_{\rm liner} - p_{\rm mag}\right),$$

$$\frac{\widehat{m}}{2}\frac{{\rm d}^2}{{\rm d}t^2}R_{\rm in} = 2\pi R_{\rm in}\left(p_{\rm fuel} - p_{\rm liner}\right).$$

Fuel energetics

$$\frac{{\rm d}\widehat{U}}{{\rm d}t} = \widehat{P}_{\rm preheat} + \widehat{P}_{\rm PdV} + \widehat{P}_{\alpha} - \widehat{P}_{\rm rad} - \widehat{P}_{\rm c} - \widehat{P}_{\rm end}$$



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

[24] D. E. Ruiz, P.F. Schmit, D. A. Yager-Elorriaga *et al.*, *"Exploring the parameter space of MagLIF implosions using similarity scaling. I. Theoretical Framework", Phys. Plasmas (2023).*

When writing these equations, we identify the key dimensionless parameters characterizing a MagLIF implosion.[24]

Circuit model

$$\Sigma \propto \frac{L_1}{L_0} + \frac{h}{L_0} \ln\left(\frac{R_{\mathrm{can}}}{R_0}\right)$$

Circuit-target coupling and delivery of electrical energy

Liner stability and IFAR modeling

$$\Psi \propto \frac{R_0^2}{\widehat{m}} p_{\mathrm{mag}}^{1/\gamma} \propto \mathrm{AR} \left(\frac{I_{\mathrm{max}}}{R_0}\right)^{2/\gamma}$$

Robustness of the liner against instabilities

Two-interface thin-shell model

$$\Pi \propto \frac{I_{\mathrm{max}}^2 t_{\mathrm{rise}}^2}{\widehat{m} R_0^2} \qquad \Phi \propto \frac{\widehat{E}_{\mathrm{preheat}} t_{\mathrm{rise}}^2}{\widehat{m} R_0^2}$$

Magnetic drive and compression of fuel

Fuel energetics

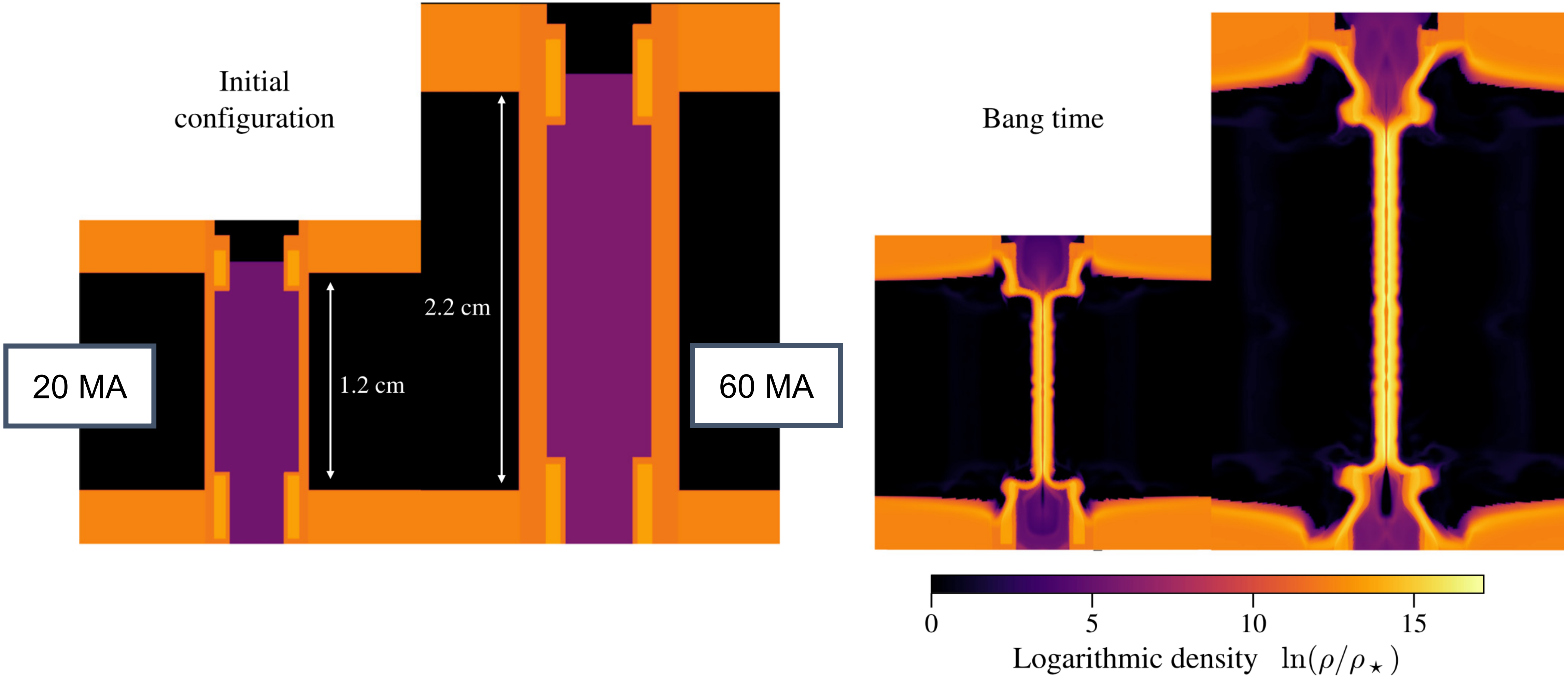
$$\Upsilon_{\mathrm{rad}} \propto \frac{(\rho_0 R_0)^2 T_0^{1/2} t_{\mathrm{rise}}}{\widehat{E}_{\mathrm{preheat}}} \qquad \Upsilon_{\mathrm{ci}} \propto \frac{\rho_0 T_0^2 t_{\mathrm{rise}}}{\widehat{E}_{\mathrm{preheat}} B_0}$$

$$\Upsilon_{\mathrm{cc}} \propto \frac{\rho_0^2 T_0^{1/2} t_{\mathrm{rise}}}{\widehat{E}_{\mathrm{preheat}} B_0^2} \qquad \Upsilon_{\mathrm{cnd}} \propto \frac{\rho_0 T_0^{3/2} R_0^2 t_{\mathrm{rise}}}{\widehat{E}_{\mathrm{preheat}} h}$$

Confinement of assembled hot fuel

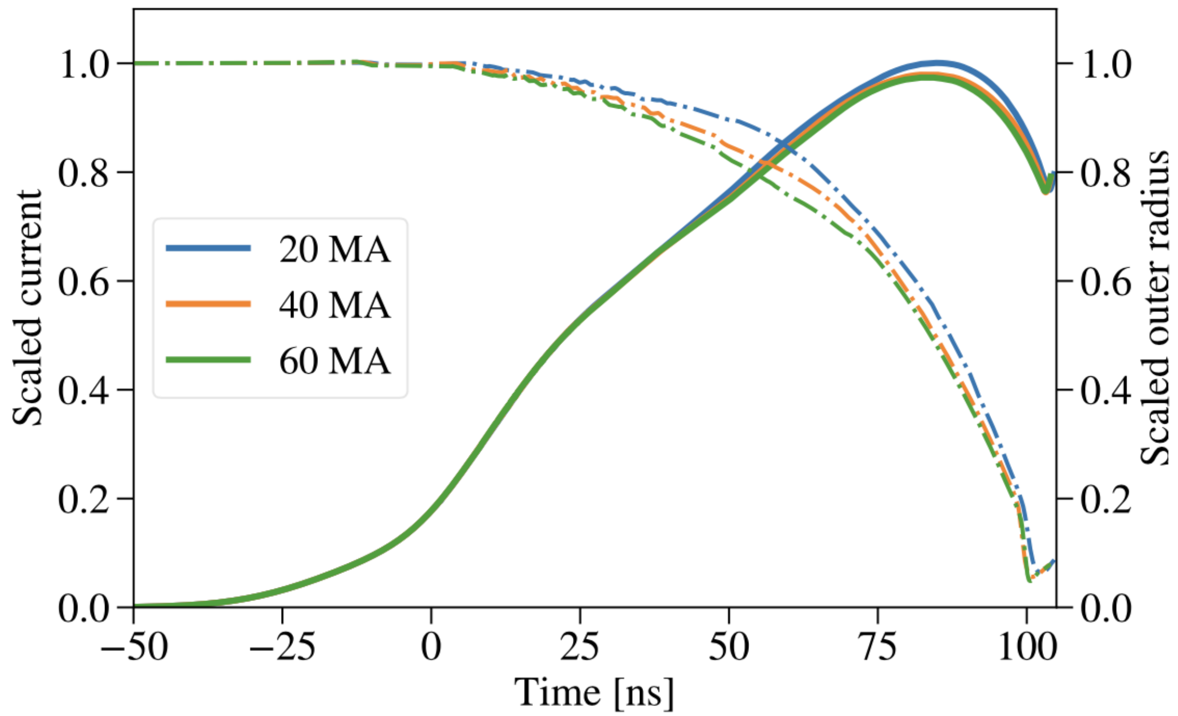
[24] D. E. Ruiz, P.F. Schmit, D. A. Yager-Elorriaga *et al.*, *"Exploring the parameter space of MagLIF implosions using similarity scaling. I. Theoretical Framework", Phys. Plasmas (2023).*

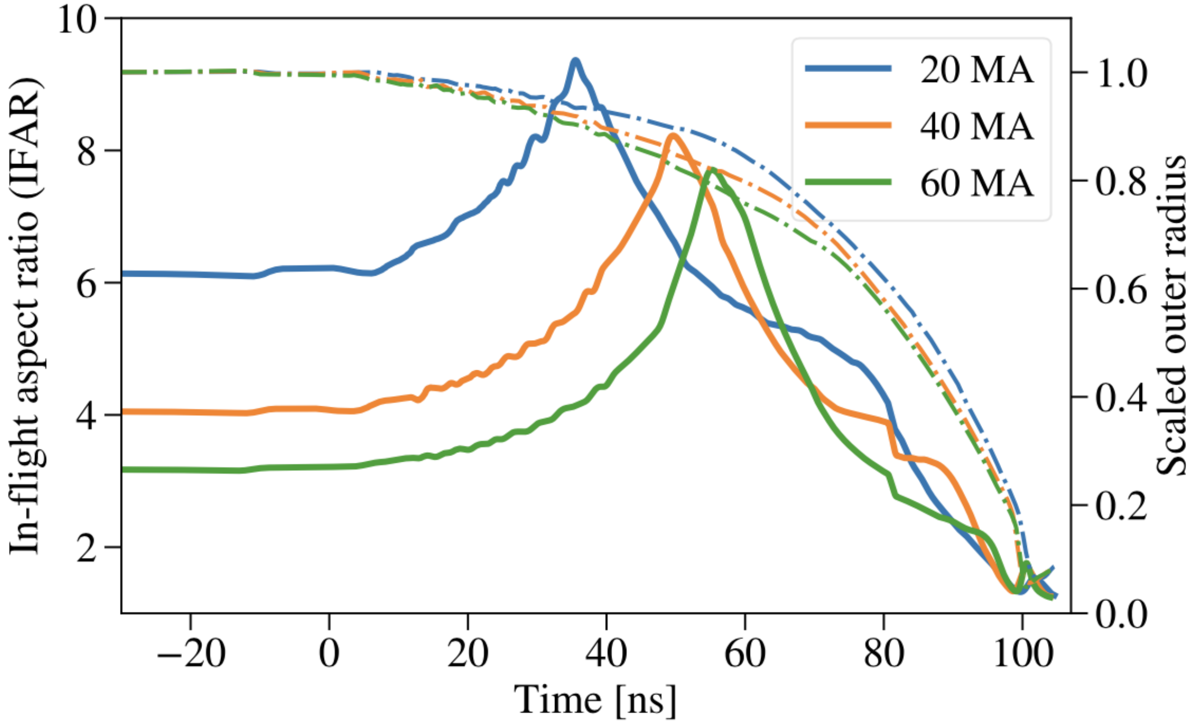
When scaling up in current, MagLIF liners become larger in radius, taller, and thicker.[7]



[7] D. E. Ruiz, *et al., "Exploring the parameter space of MagLIF implosions using similarity scaling. II. Current scaling", Phys. Plasmas (2023).*

By design, the implosion trajectories scale similarly and the in-flight aspect ratios improve at higher current.[7]

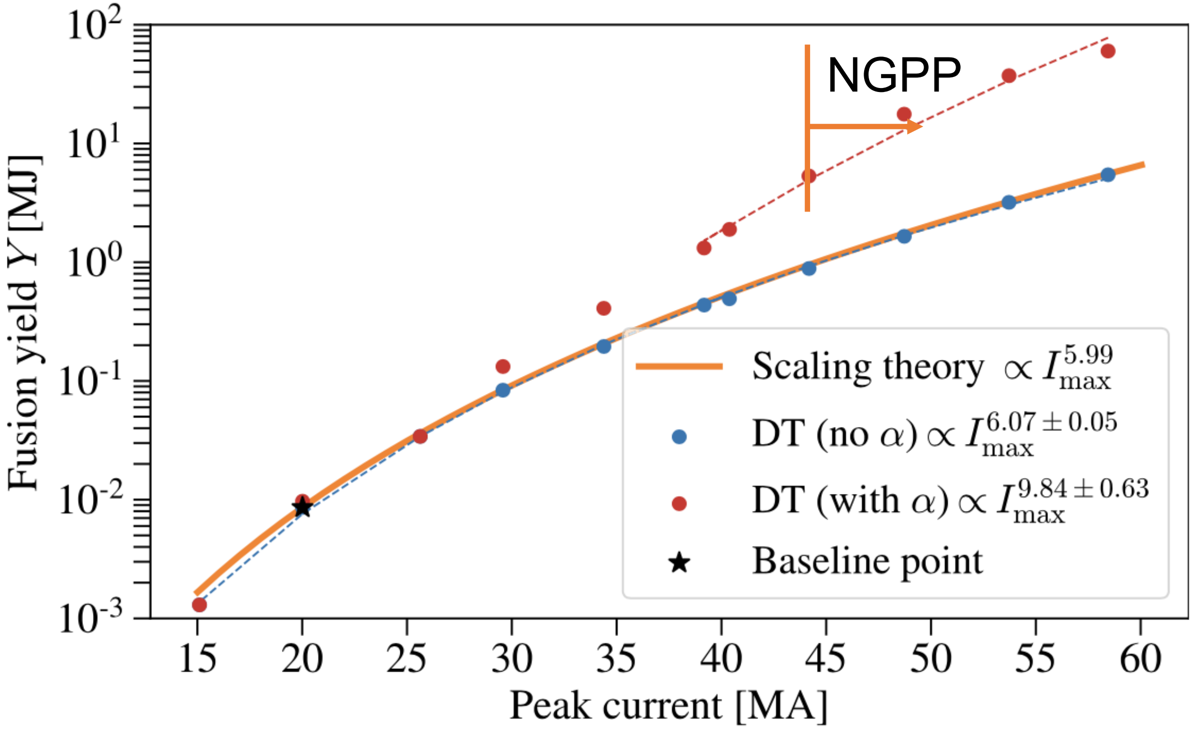




[7] D. E. Ruiz, *et al., "Exploring the parameter space of MagLIF implosions using similarity scaling. II. Current scaling", Phys. Plasmas (2023).*

We are keenly interested in validating paths to ~100 MJ yields on future facilities with magnetic direct drive fusion targets[6,7]

Scaling of gas-burning MagLIF targets



[6] P.F. Schmit & D.E. Ruiz, Phys. Plasmas (2020).
[7] D. E. Ruiz, *et al.*, *"Exploring the parameter space of MagLIF implosions using similarity scaling. II. Current scaling"*, Phys. Plasmas (2023).

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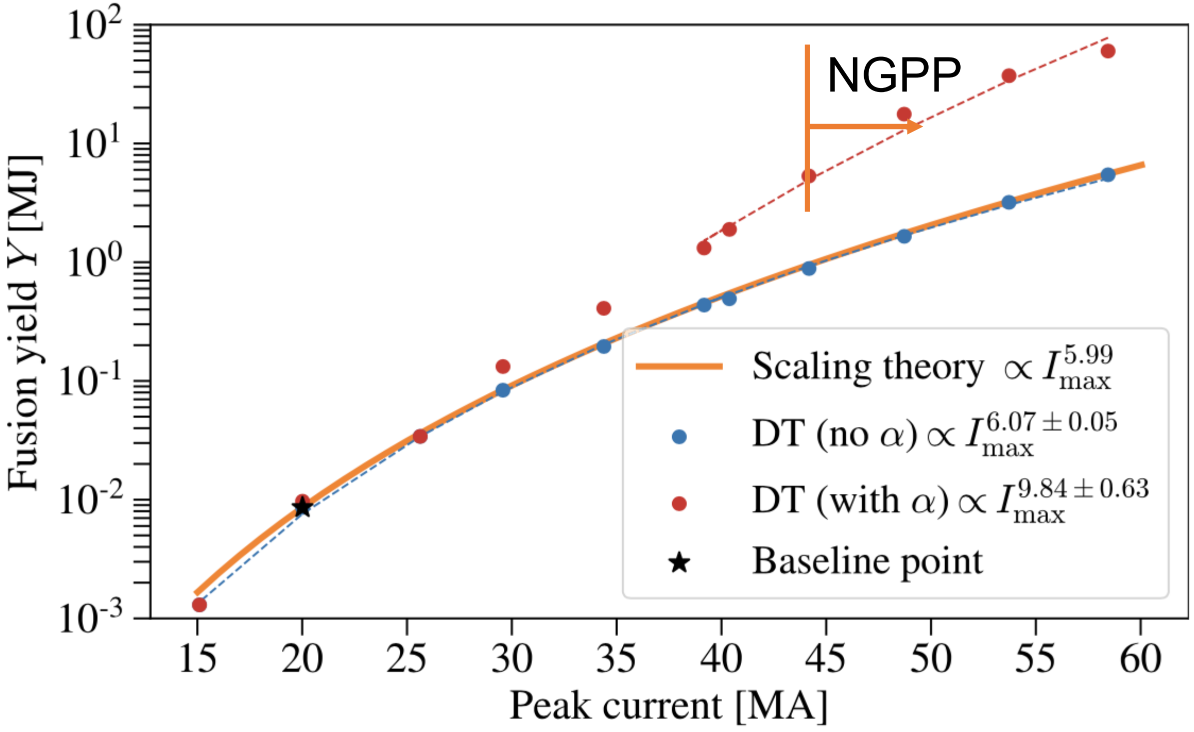
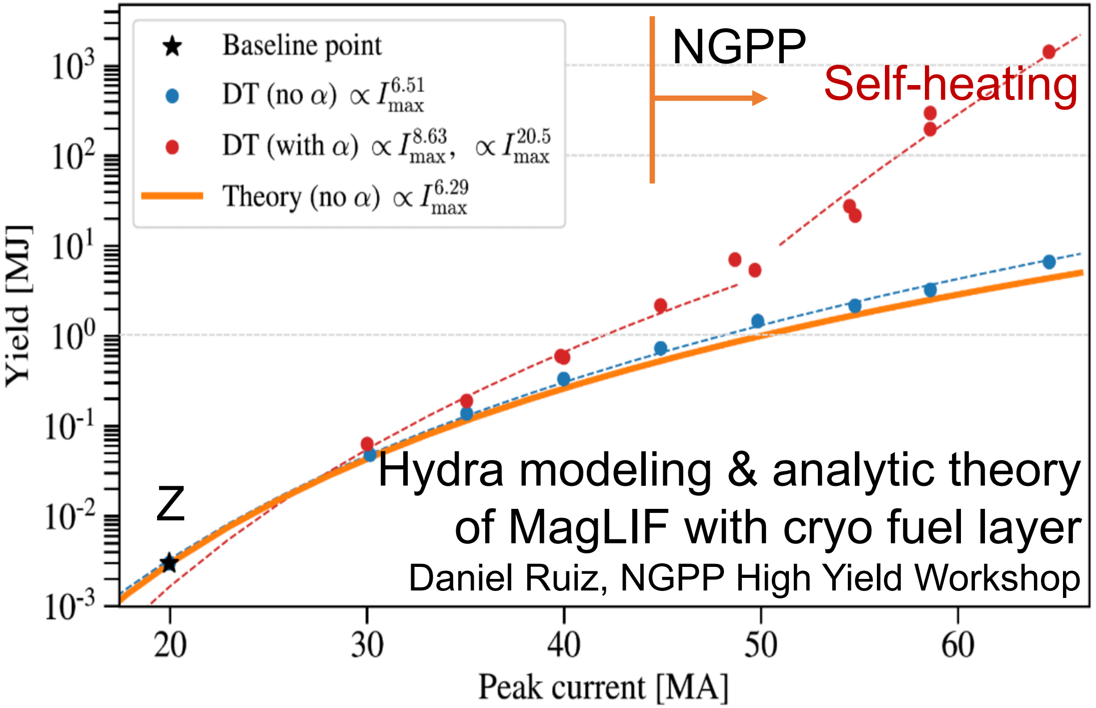


Ice-burning MagLIF targets might substantially increase fusion yields



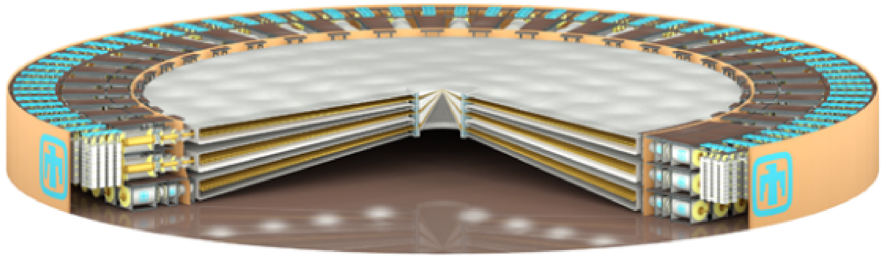
[6] P.F. Schmit & D.E. Ruiz, Phys. Plasmas (2020).

[7] D. E. Ruiz, *et al., "Exploring the parameter space of MagLIF implosions using similarity scaling. II. Current scaling",* Phys. Plasmas (2023).

These are exciting times to be working with pulsed power!

- Our fusion research program is organized around four pillars, only some of which I could cover today
  - **Scaling science**
    (understanding how our target performance scales up **and down** in current)
  - **Deep understanding**
    (e.g., implosion instabilities, stagnation conditions)
  - **Control and optimization**
    (e.g., how does MagLIF vary with current, magnetic field, laser energy)
  - **Innovation**
    (e.g., dynamic screw pinch, quasi-isentropic liner compression, ice-burning MagLIF)

- A Next-Generation Pulsed Power project will enable us to make transformative progress toward demonstrating pulsed-power-based approaches to inertial confinement fusion by demonstrating significant single-shot fusion yields
- Other technologies needed for repetitive fusion in pursuit of fusion energy[25] are also being examined. We are submitting funding proposals to look at these.



[25] D.B. Sinars *et al.*, J. Fusion Energy (2015).