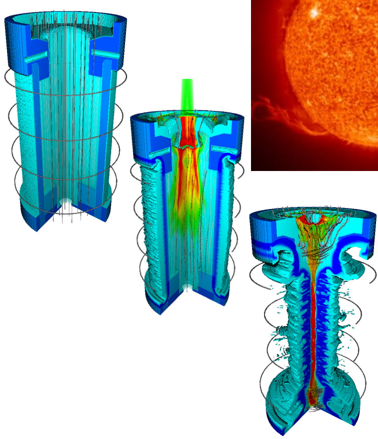
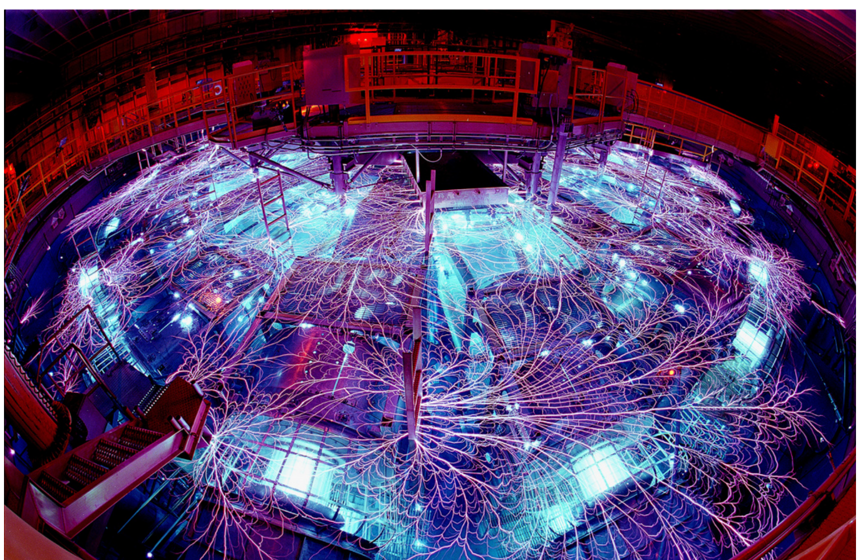
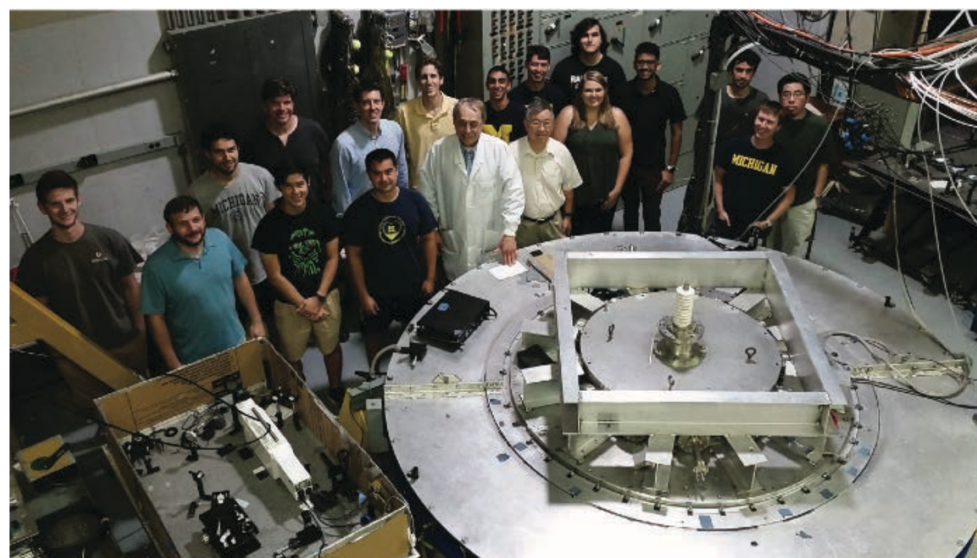
Magnetically driven implosions for nuclear fusion, radiation source development, laboratory astrophysics, and high-pressure material properties



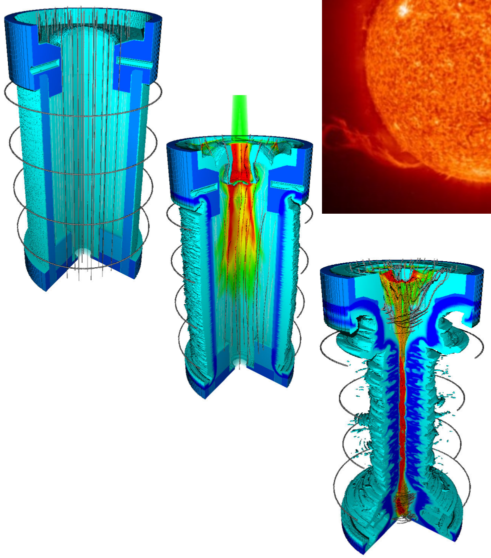
Ryan D. McBride
Associate Professor
Nuclear Engineering &
Radiological Sciences Department
Plasma, Pulsed Power, & Microwave Lab

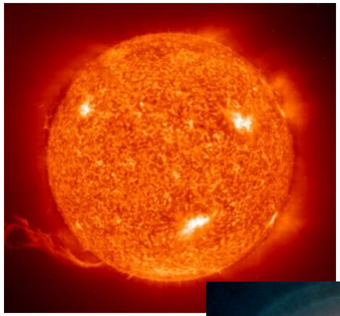


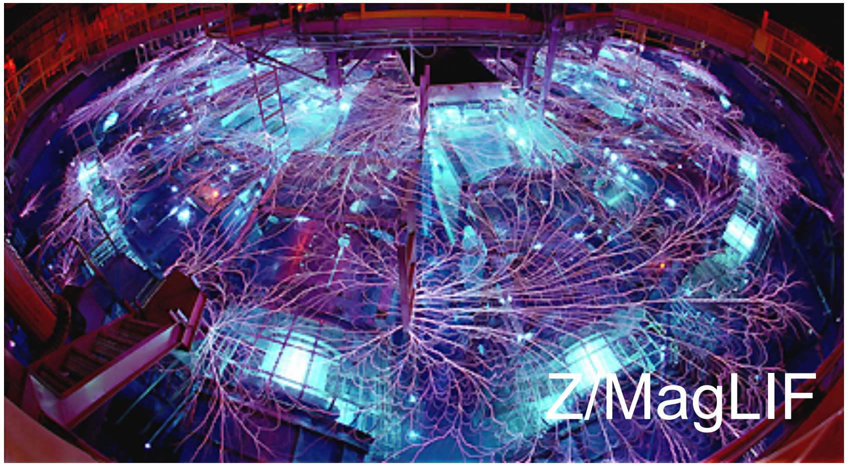


Overview

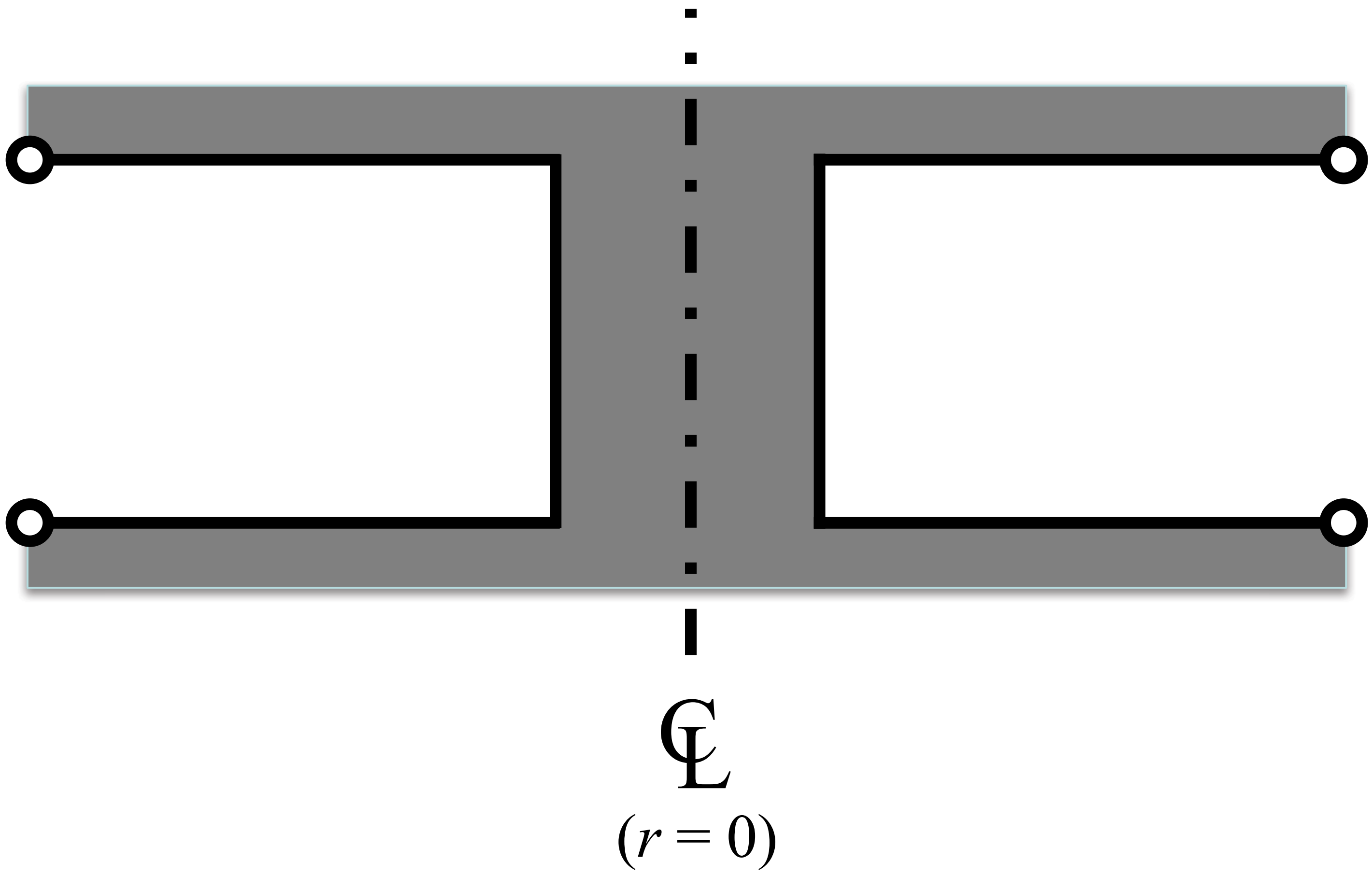
- What are magnetically driven implosions?
- What is pulsed power?
- How are magnetically driven implosions and pulsed power used to create HED matter?
- What is high-energy-density (HED) matter?
- What are some applications for magnetically driven implosions in HED physics?
- What research is presently underway at U-M and at the National Laboratories?



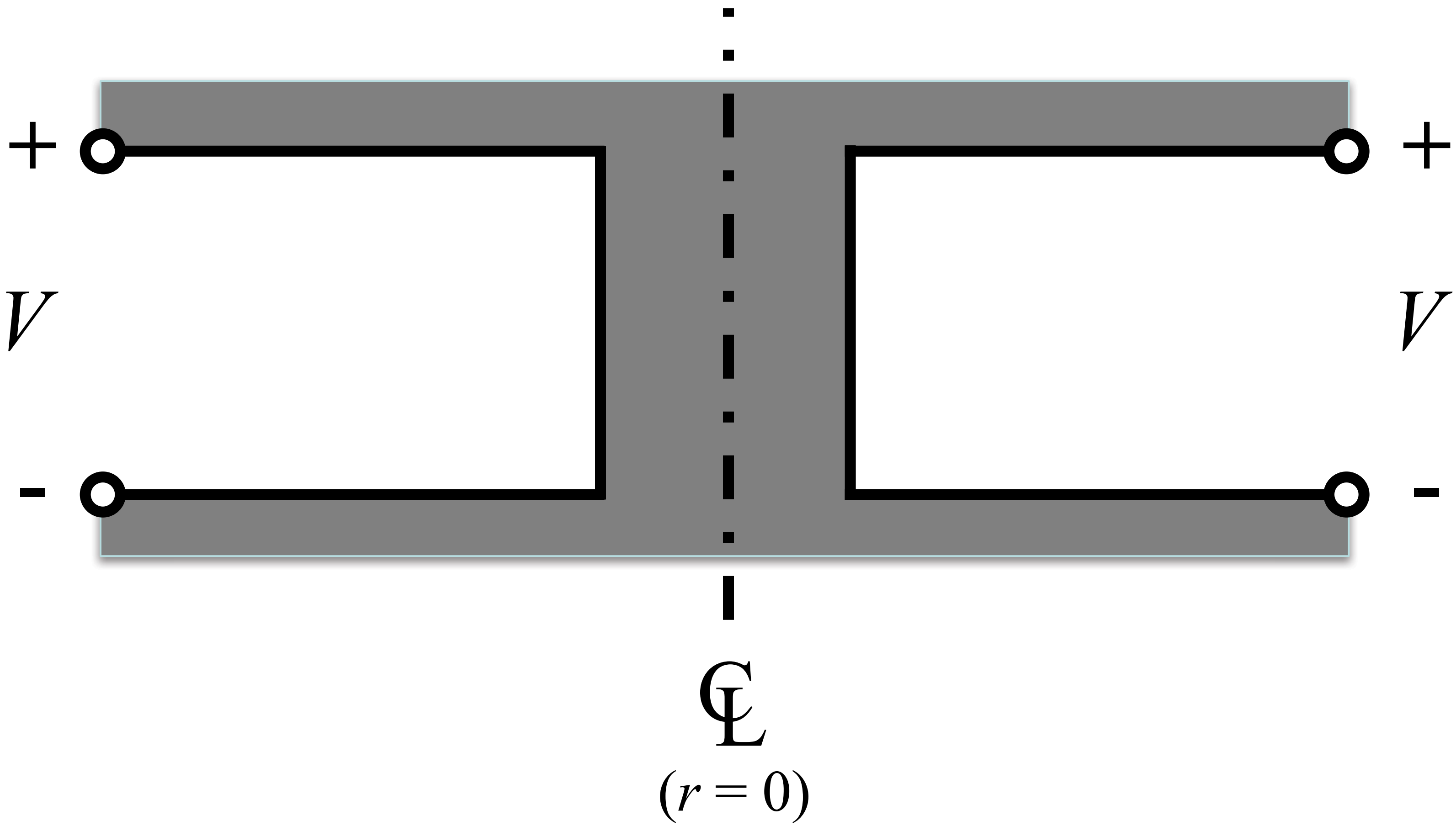




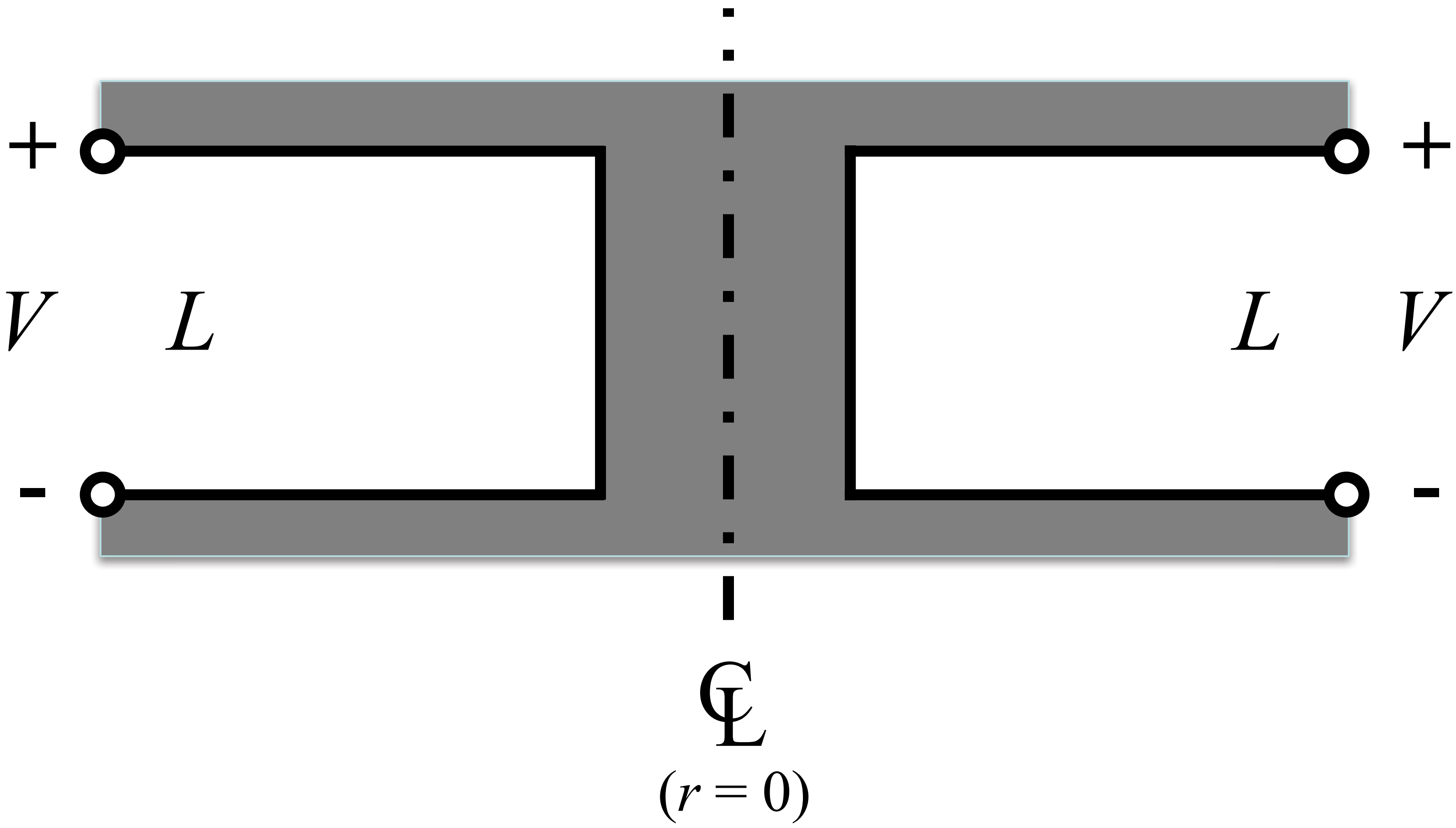
Basic Pulsed Power Experimental Setup



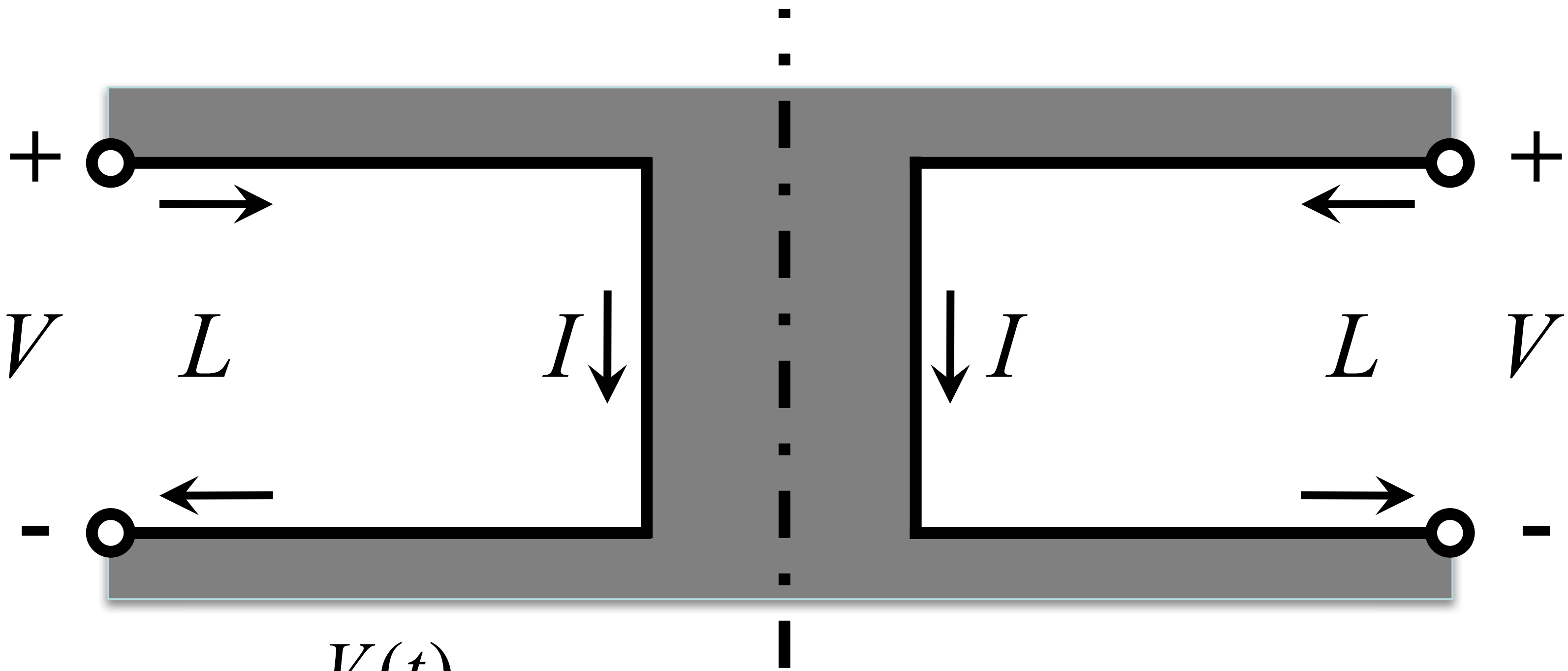
Basic Pulsed Power Experimental Setup



Basic Pulsed Power Experimental Setup

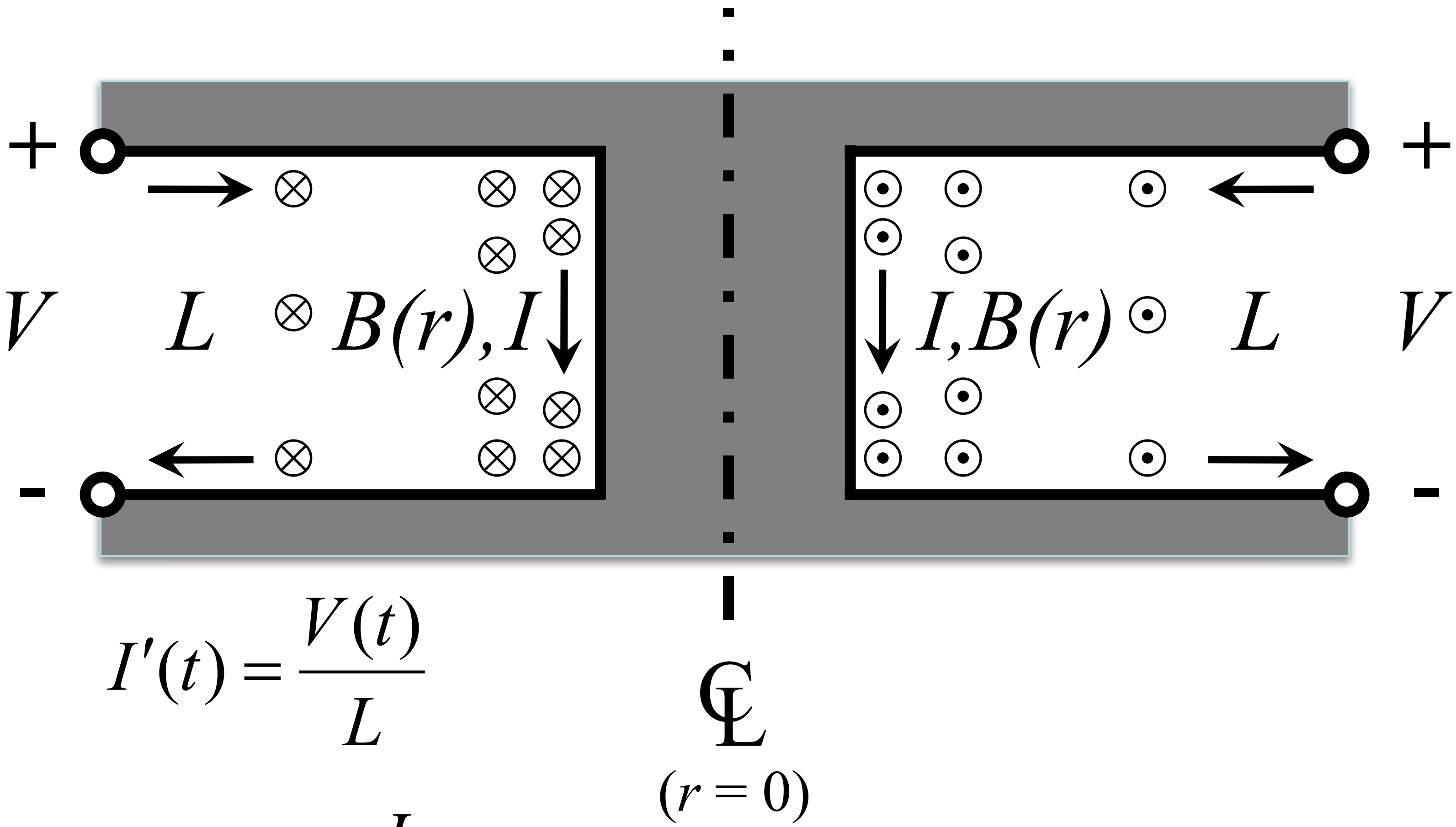


Basic Pulsed Power Experimental Setup



$$I'(t) = \frac{V(t)}{L}$$

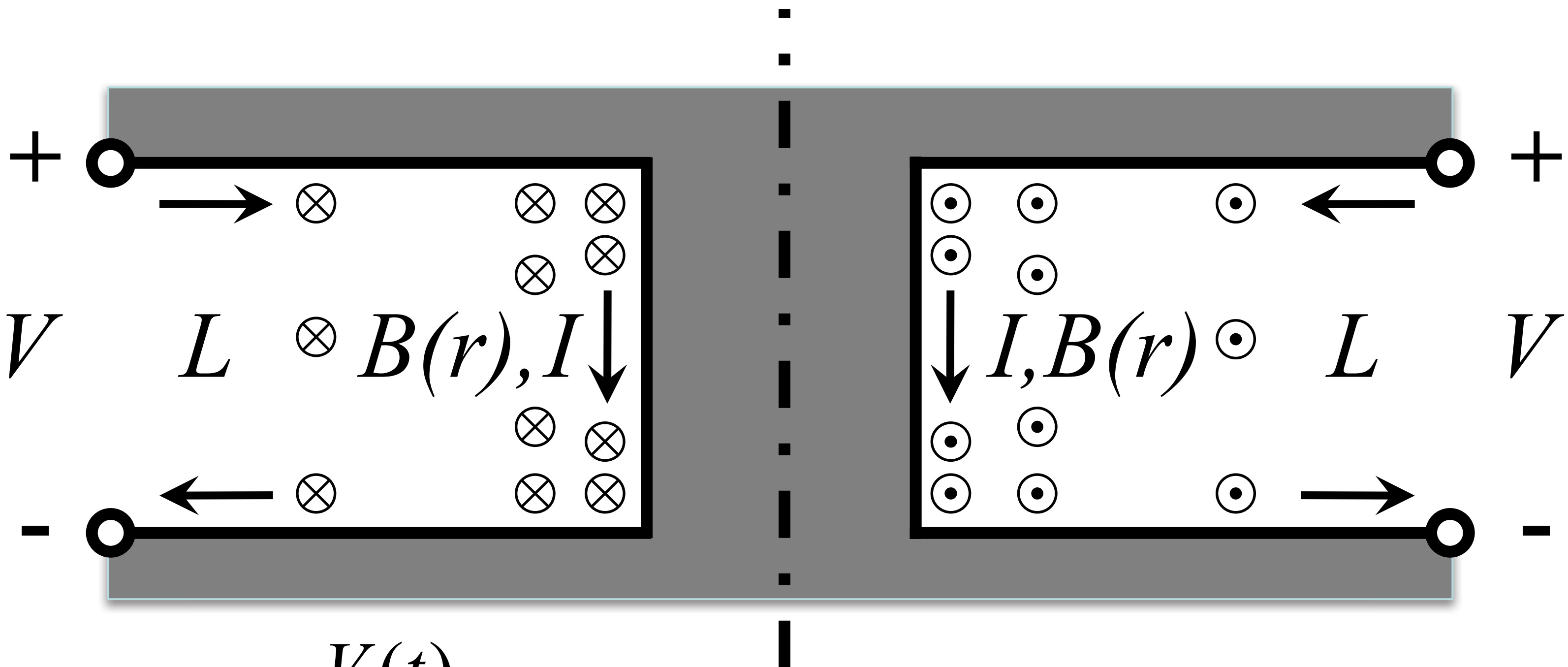
Basic Pulsed Power Experimental Setup



$$I'(t) = \frac{V(t)}{L}$$

$$B(r) = \frac{\mu_0 I}{2\pi r}$$

Basic Pulsed Power Experimental Setup



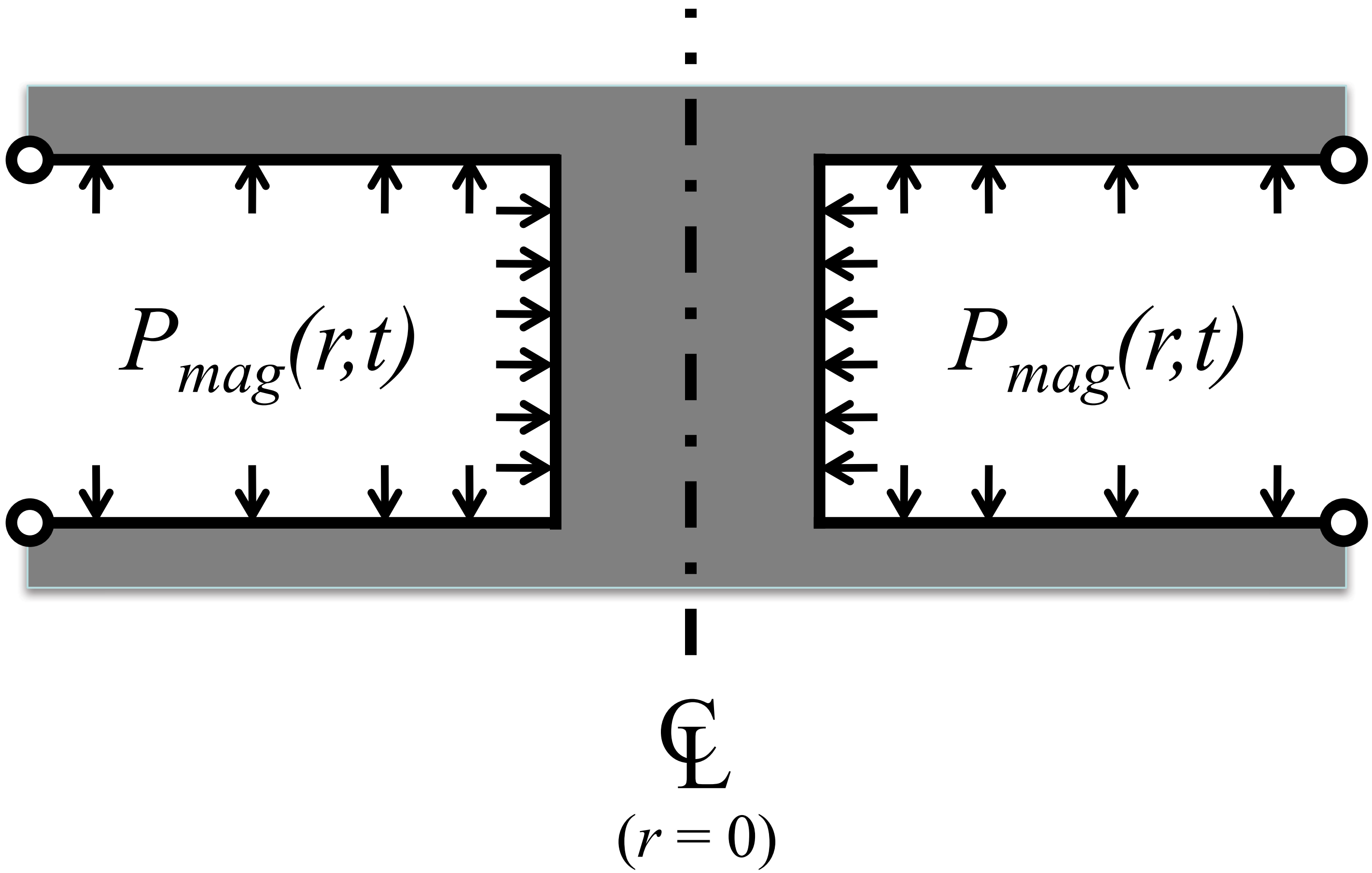
$$I'(t) = \frac{V(t)}{L}$$

$$B(r) = \frac{\mu_0 I}{2\pi r}$$

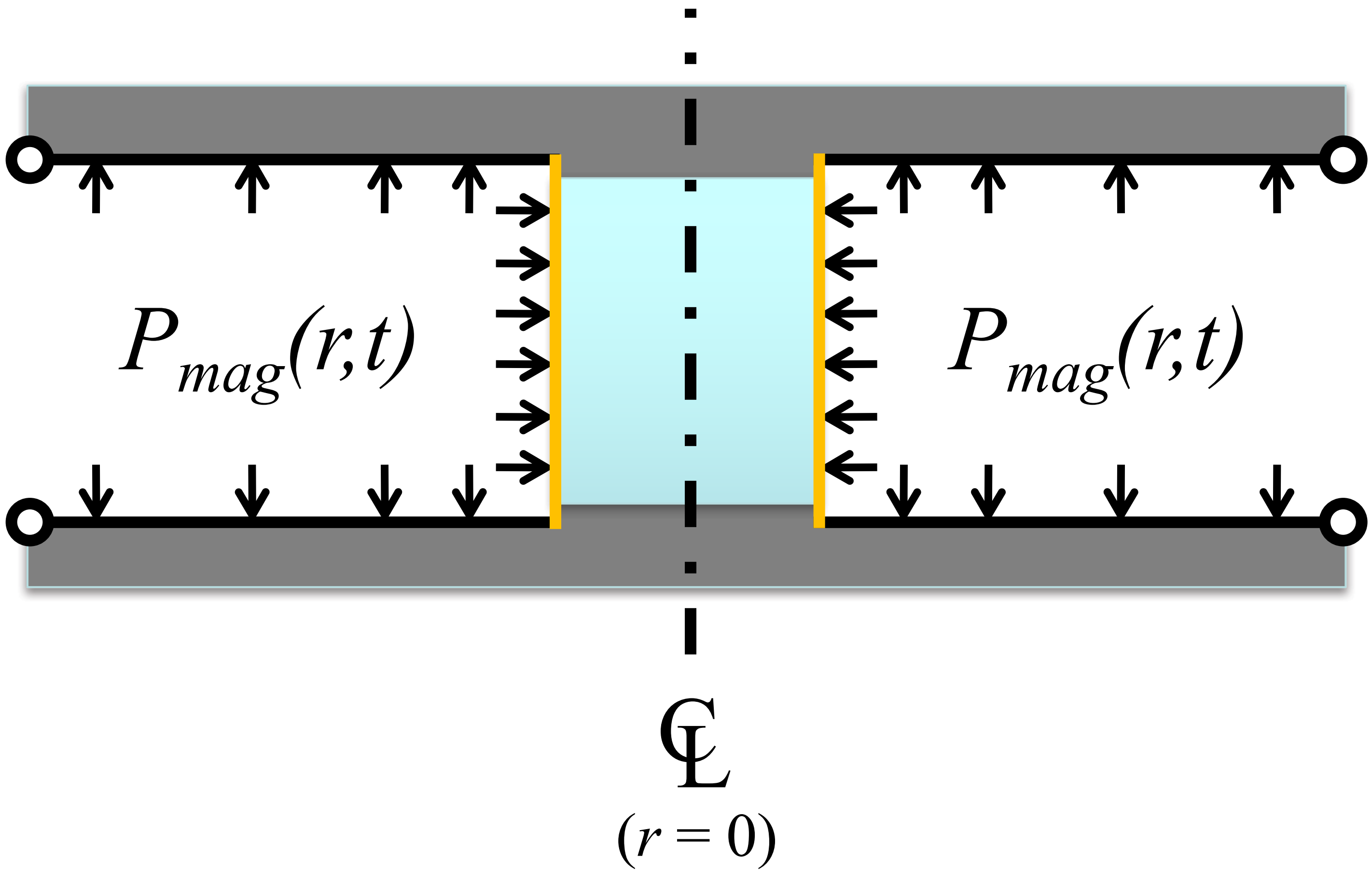
℄
$(r = 0)$

$$P_{mag}(r) = \frac{B^2(r)}{2\mu_0} \propto \frac{I^2}{r^2}$$

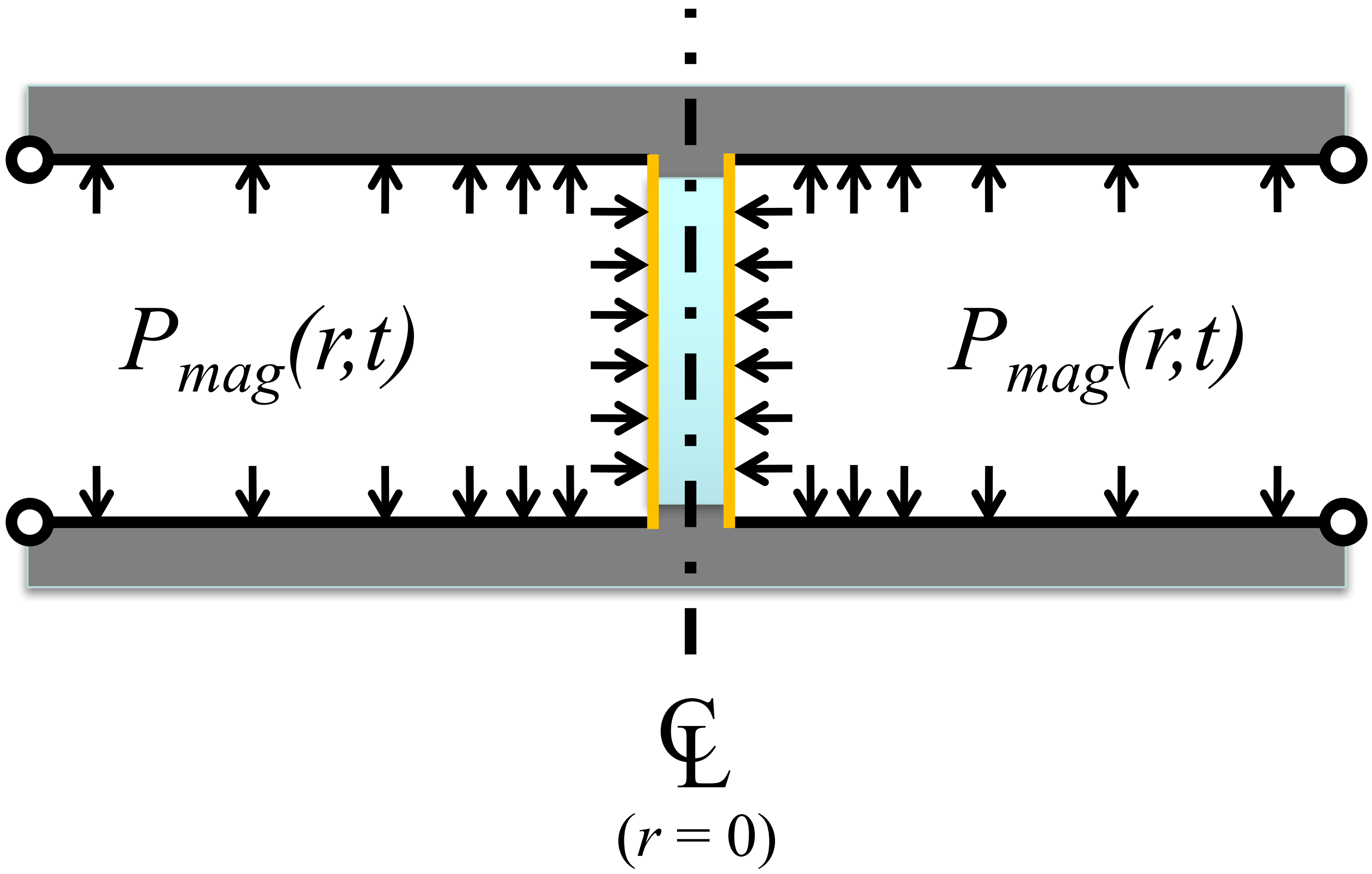
Basic Pulsed Power Experimental Setup



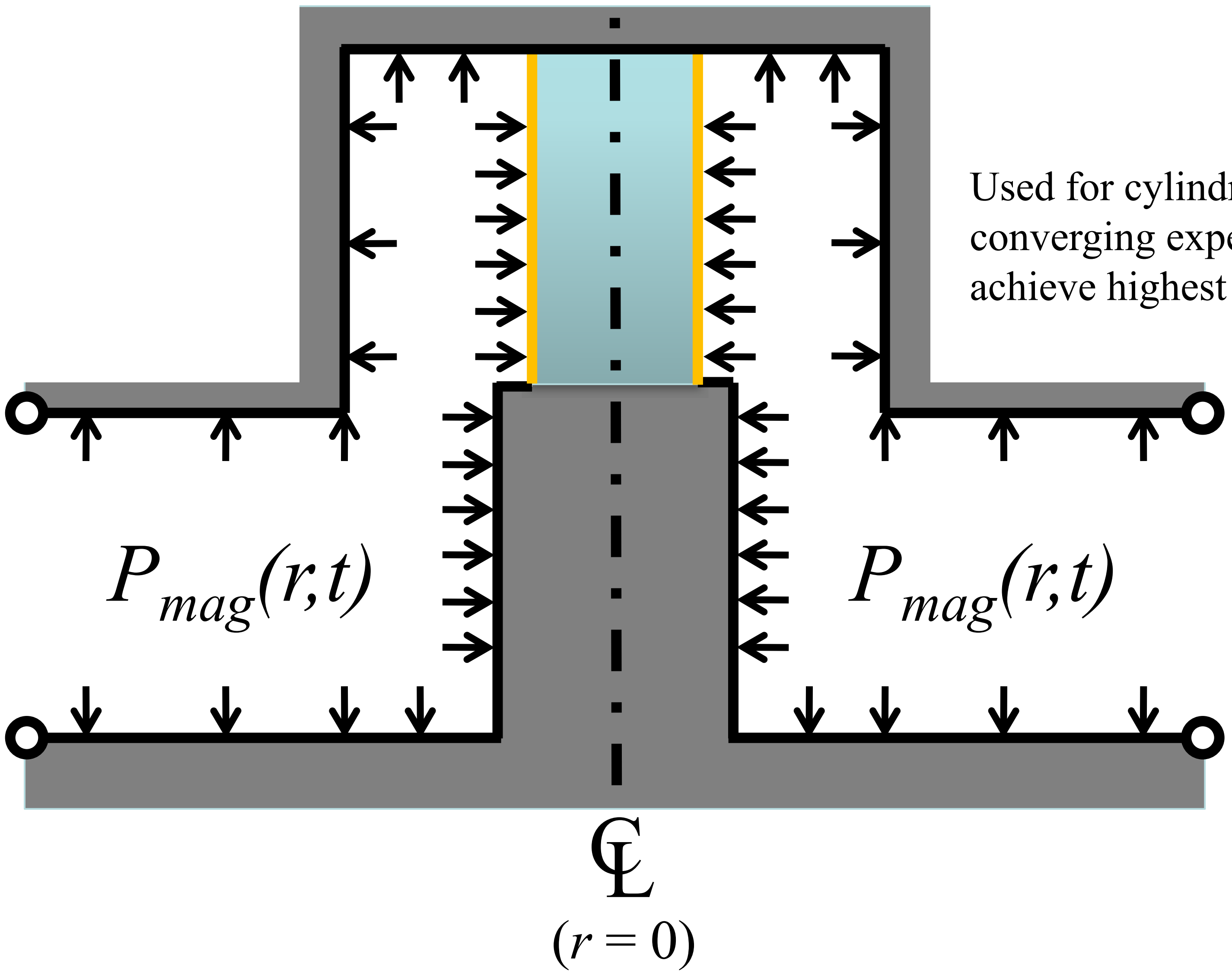
Imploding Geometry for Highest Pressures



Imploding Geometry for Highest Pressures

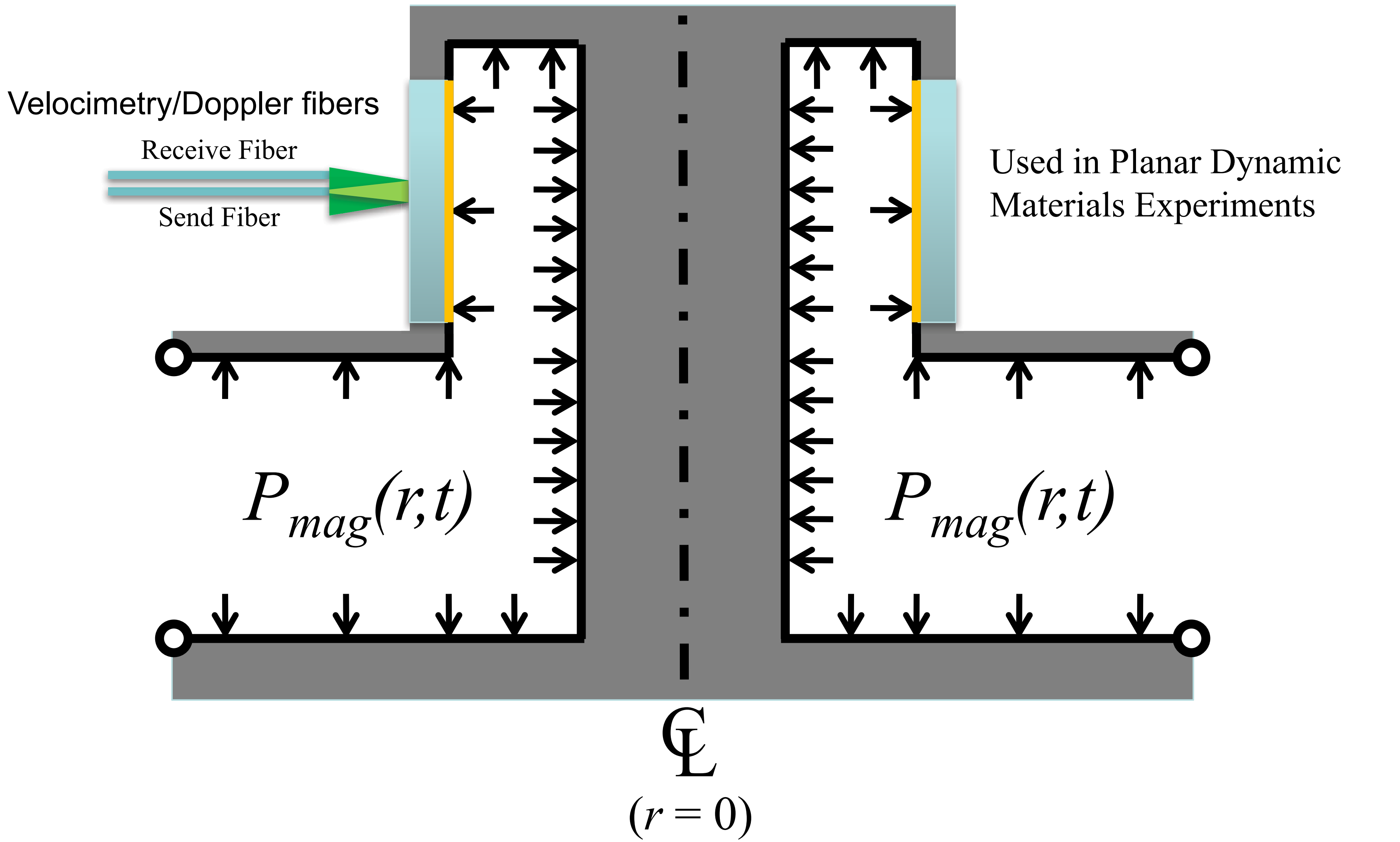


Imploding Geometry for Highest Pressures & Diagnostic Access

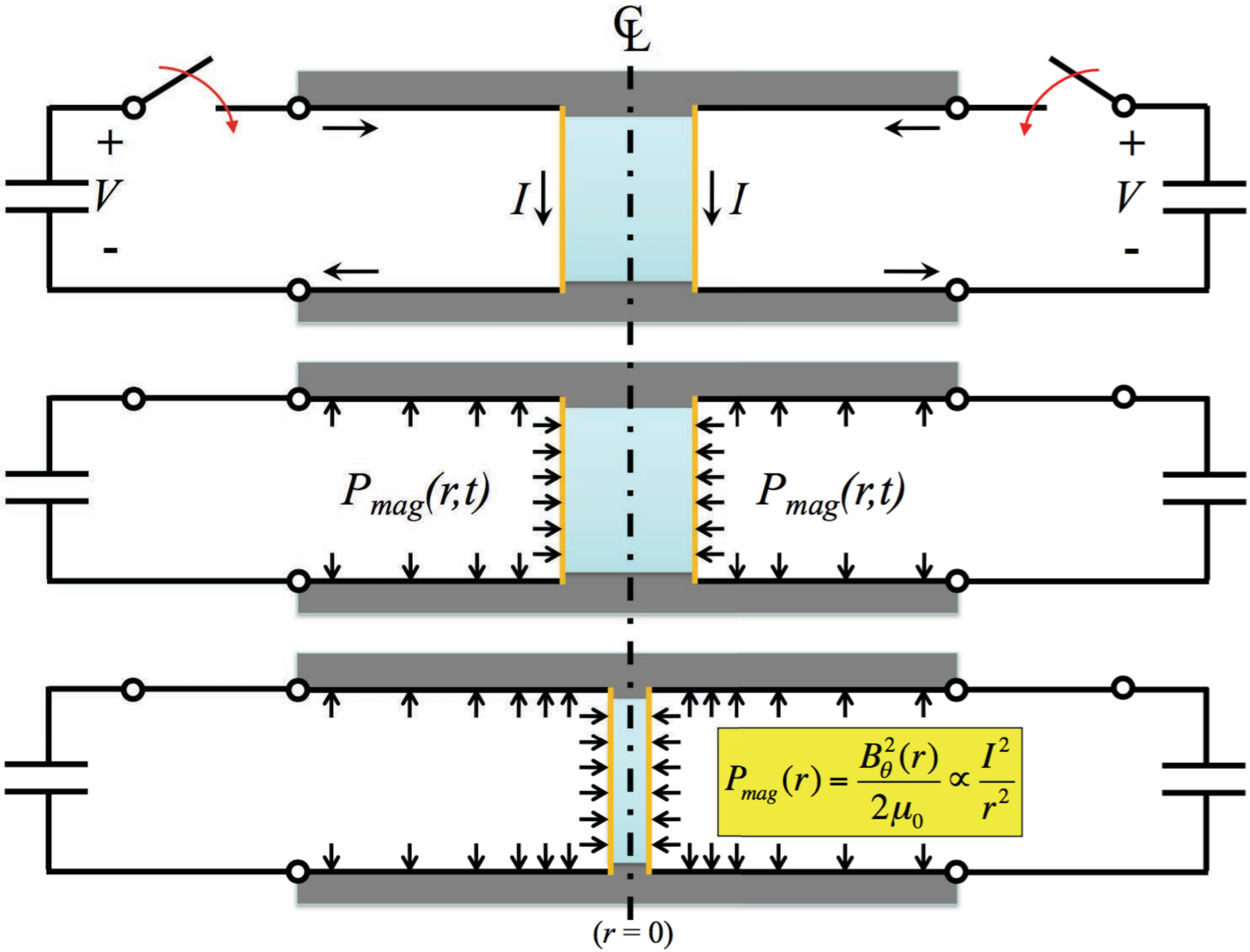


Used for cylindrically converging experiments to achieve highest pressures

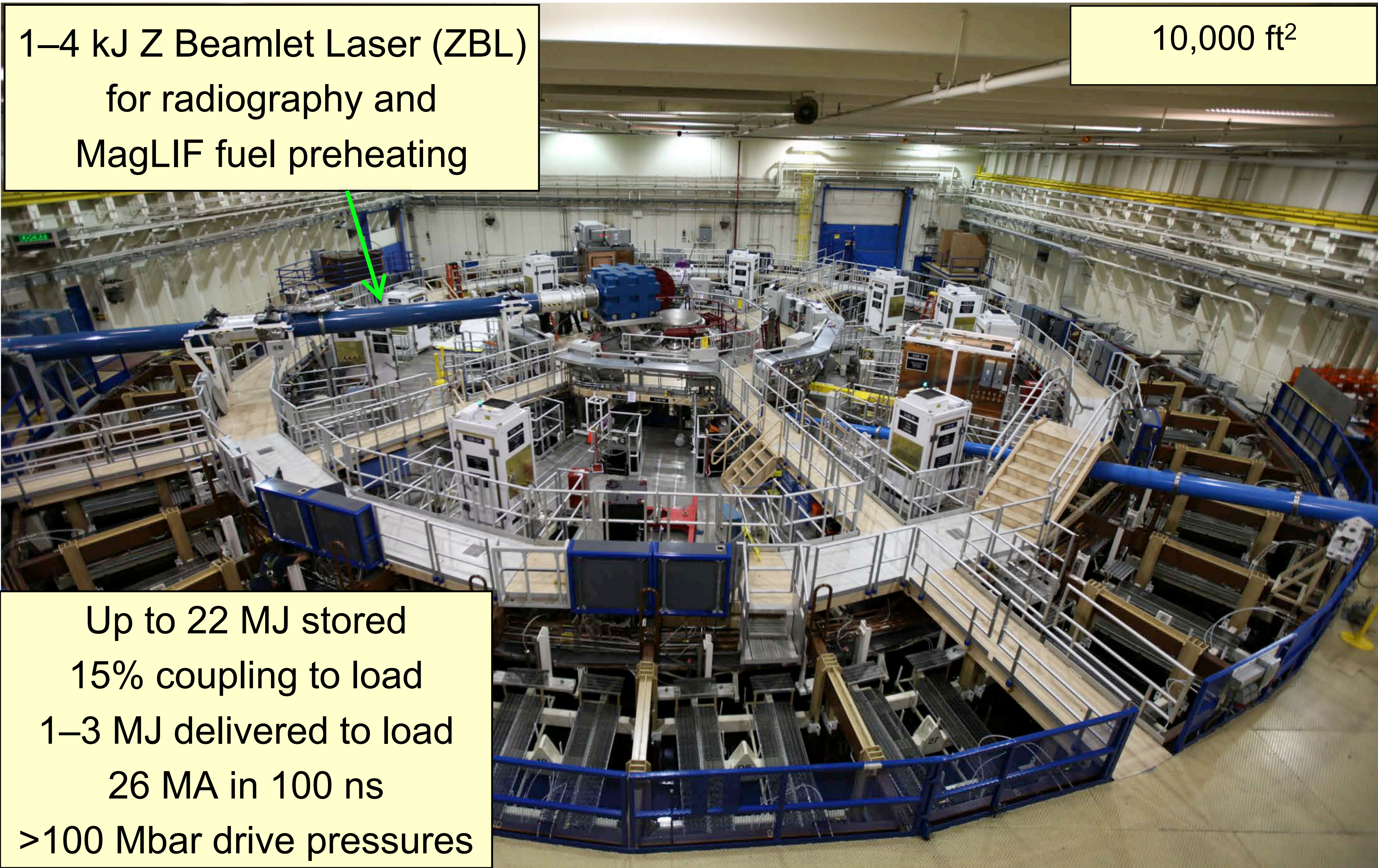
Exploding Geometry for Material Properties Experiments & Diagnostic Access



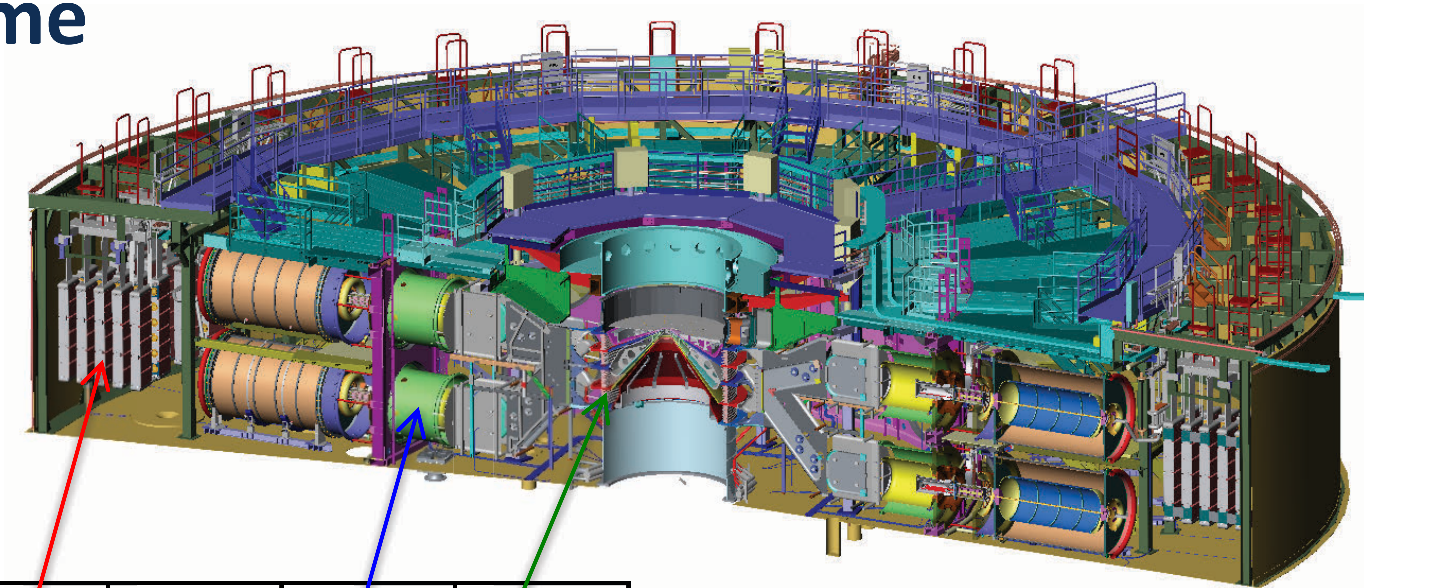
Apply Voltage using Capacitors and Switches

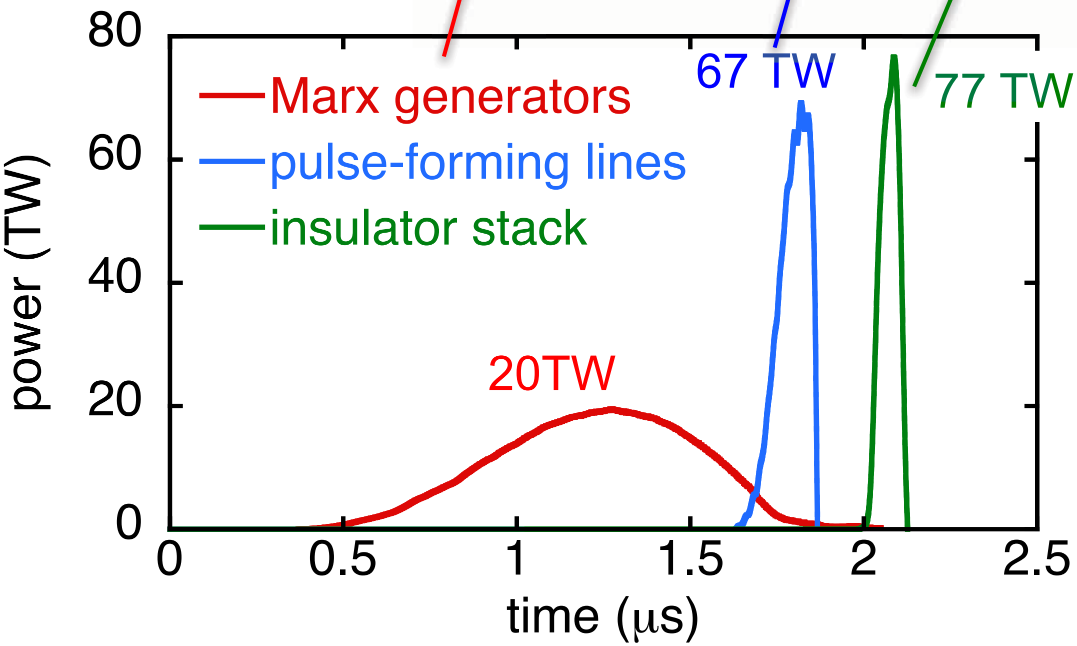


The Z Machine at Sandia National Laboratories



Pulsed-power is about energy compression in space and time

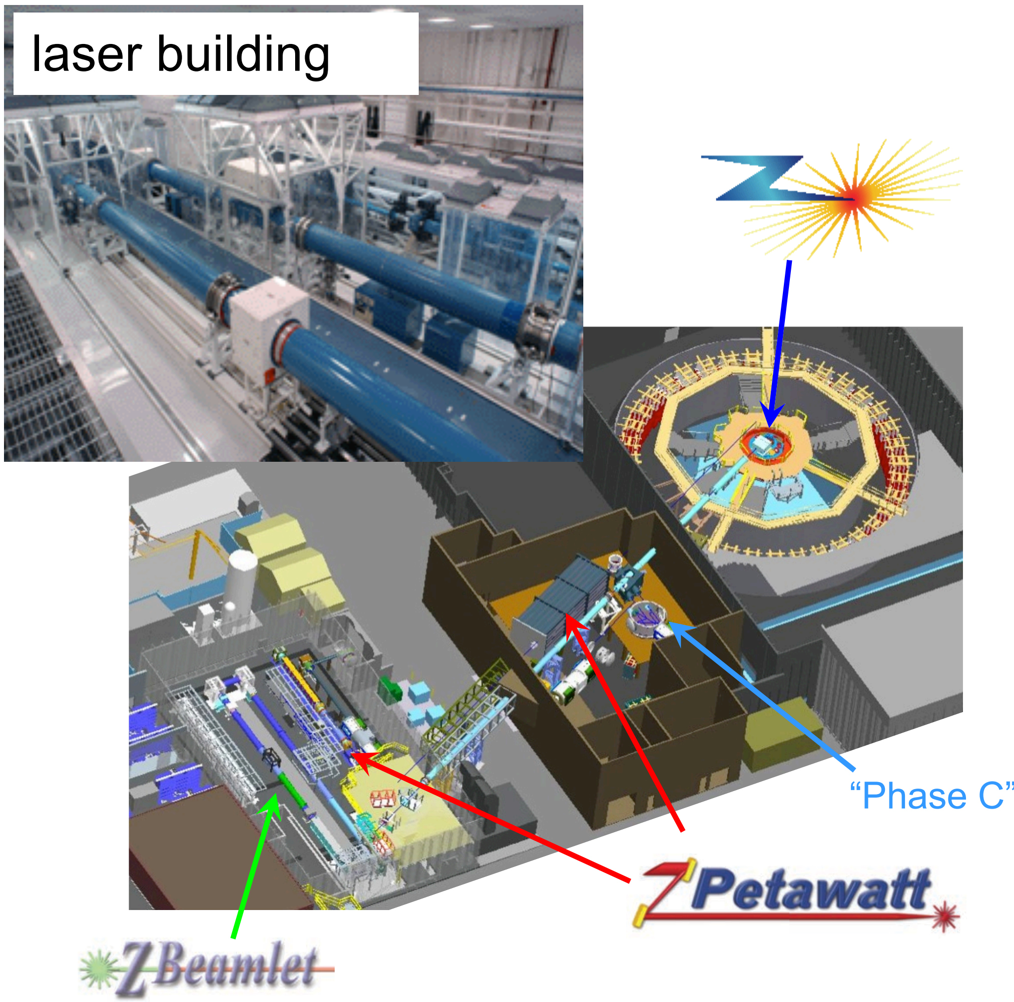




Energy compression achieved by a sequence of storage and switching techniques (energy stored over longer time scales and discharged over faster time scales):

- Voltages are combined in series for voltage addition
- Currents are combined in parallel for current addition
- Voltages and currents are increased together for power amplification

The Z Machine at Sandia National Laboratories: Overall Facility Scale Size



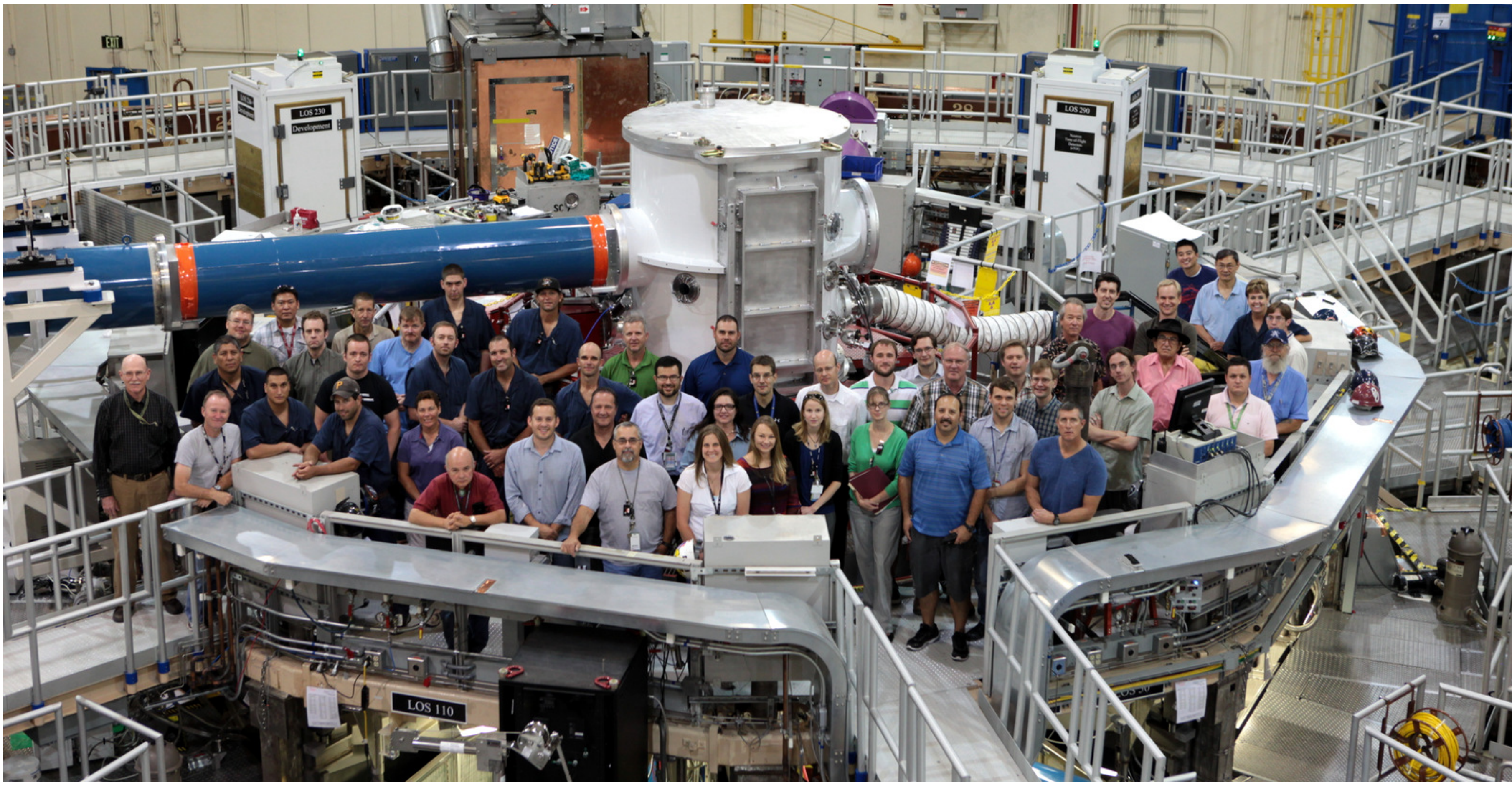
The Z-Beamlet (ZBL) and Z-Petawatt (ZPW) lasers at Sandia can be used to heat fusion fuel, radiograph experiments on Z, and perform standalone laser-only HEDP experiments

ZBL was originally a prototype laser for the National Ignition Facility (NIF)

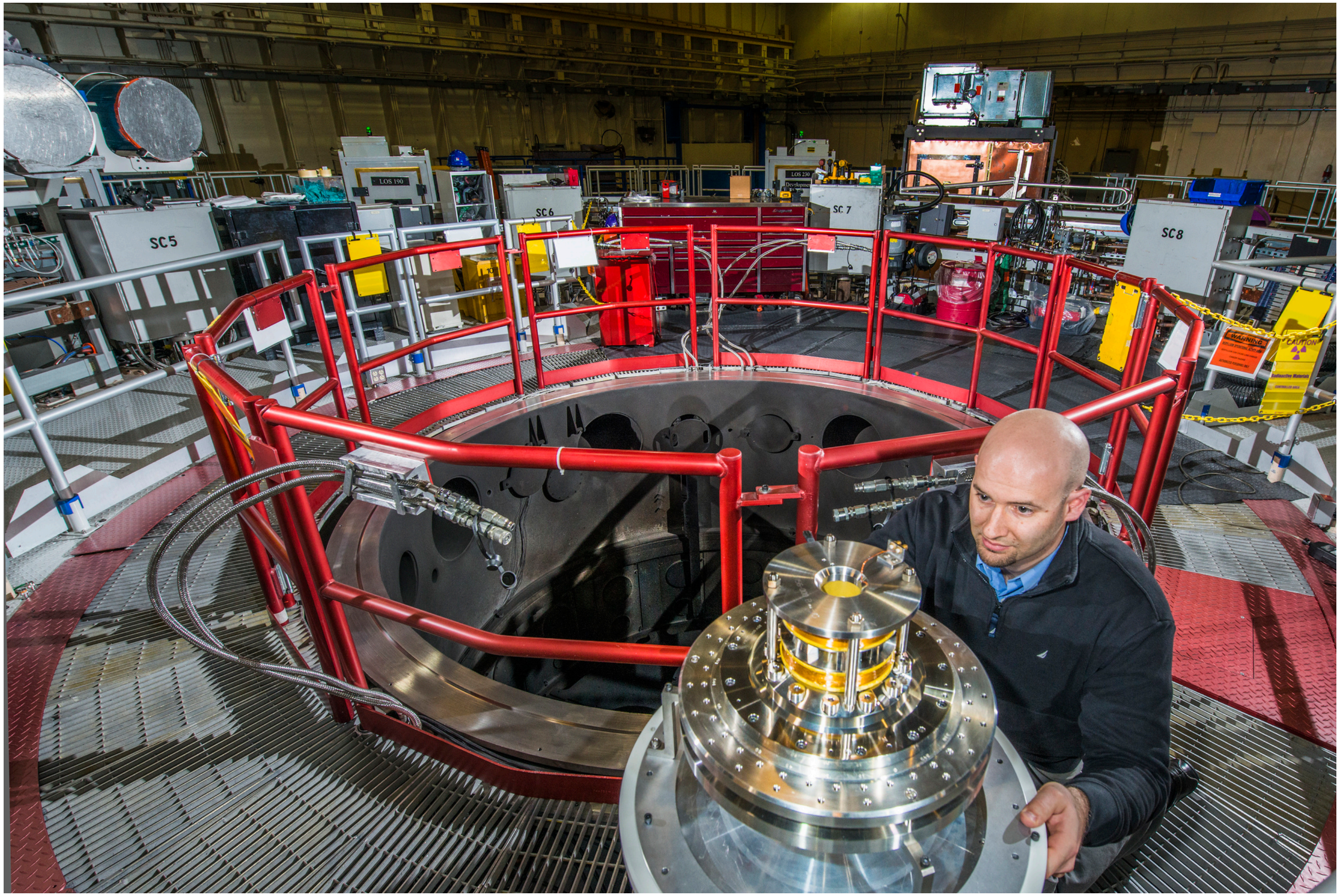
ZBL recently upgraded from 2 kJ in 2 ns to 4 kJ in 4 ns

UNIVERSITY OF MICHIGAN

The Z Machine at Sandia National Laboratories: Accelerator Scale Size (~100 feet)



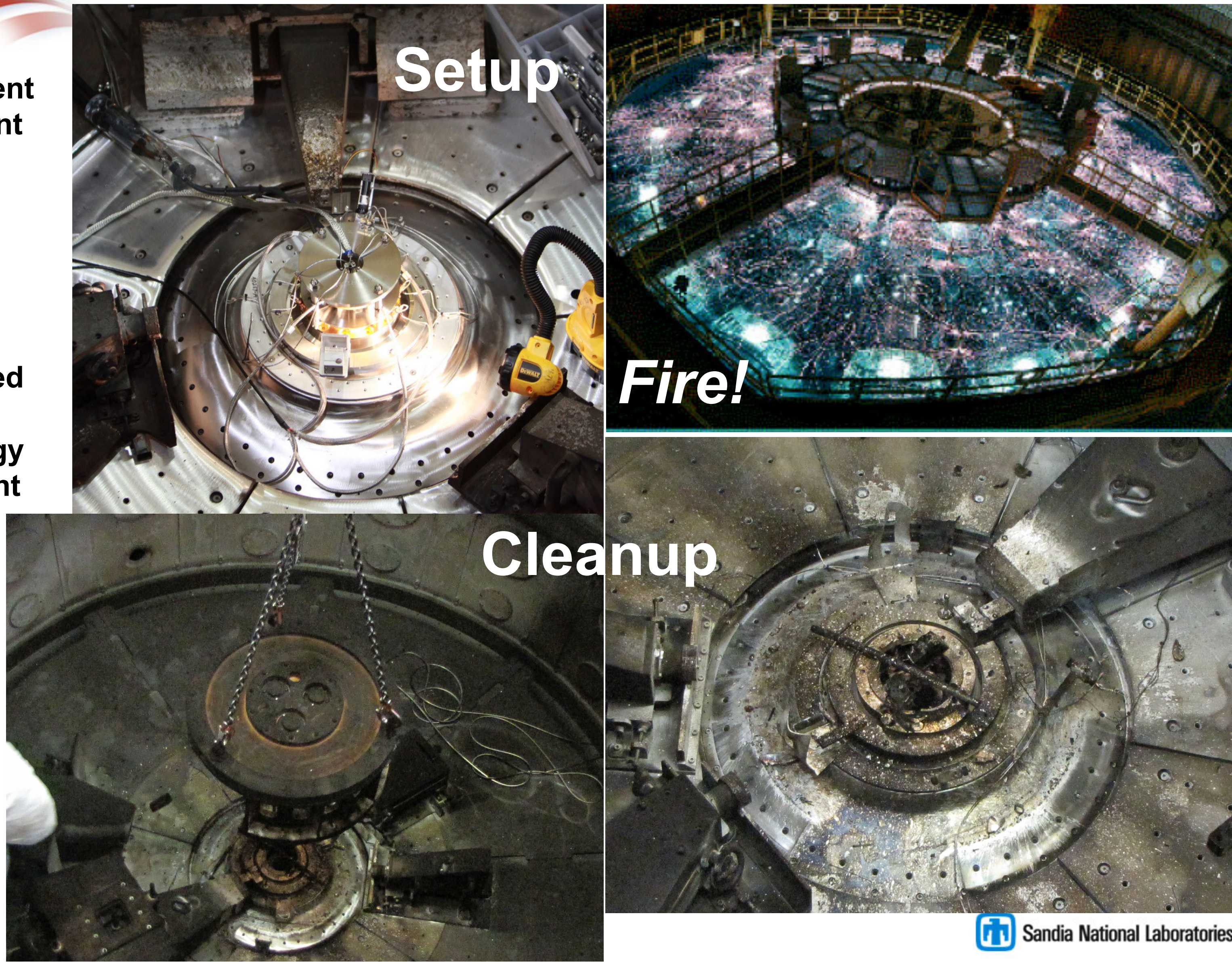
The Z Machine at Sandia National Laboratories: Load Hardware Scale Size (~1 foot)



The Z Machine at Sandia National Laboratories: Fusion Target Scale Size (~1 cm)

Z is a fun place to conduct experiments

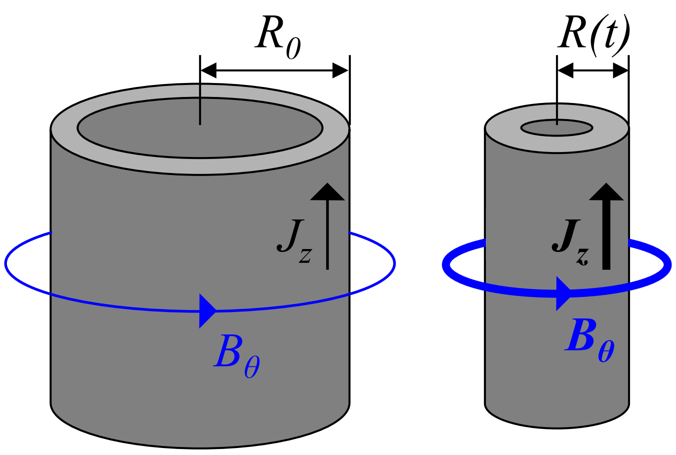
- Harsh environment makes experiment design and diagnostics development challenging
- Debris must be carefully managed
- Several MJ energy release equivalent to few sticks of dynamite

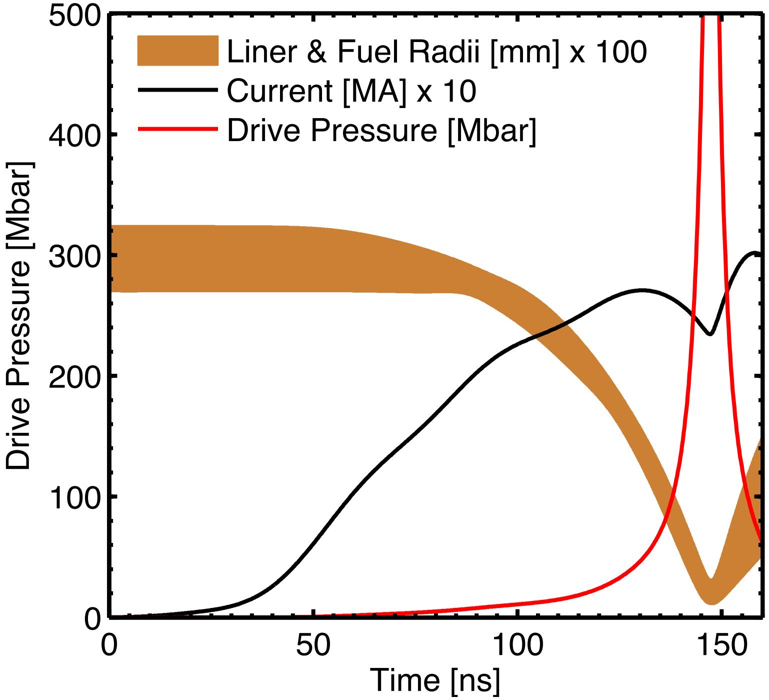


Magnetically-Driven Cylindrical Implosions are Efficient: Implosion Drive Pressure is Divergent!

$$P = \frac{B^2}{2\mu_o} = \boxed{140} \cdot \left(\frac{I_{[MA]}/30}{R(t)_{[mm]}} \right)^2 \quad [\text{Mbar}]$$

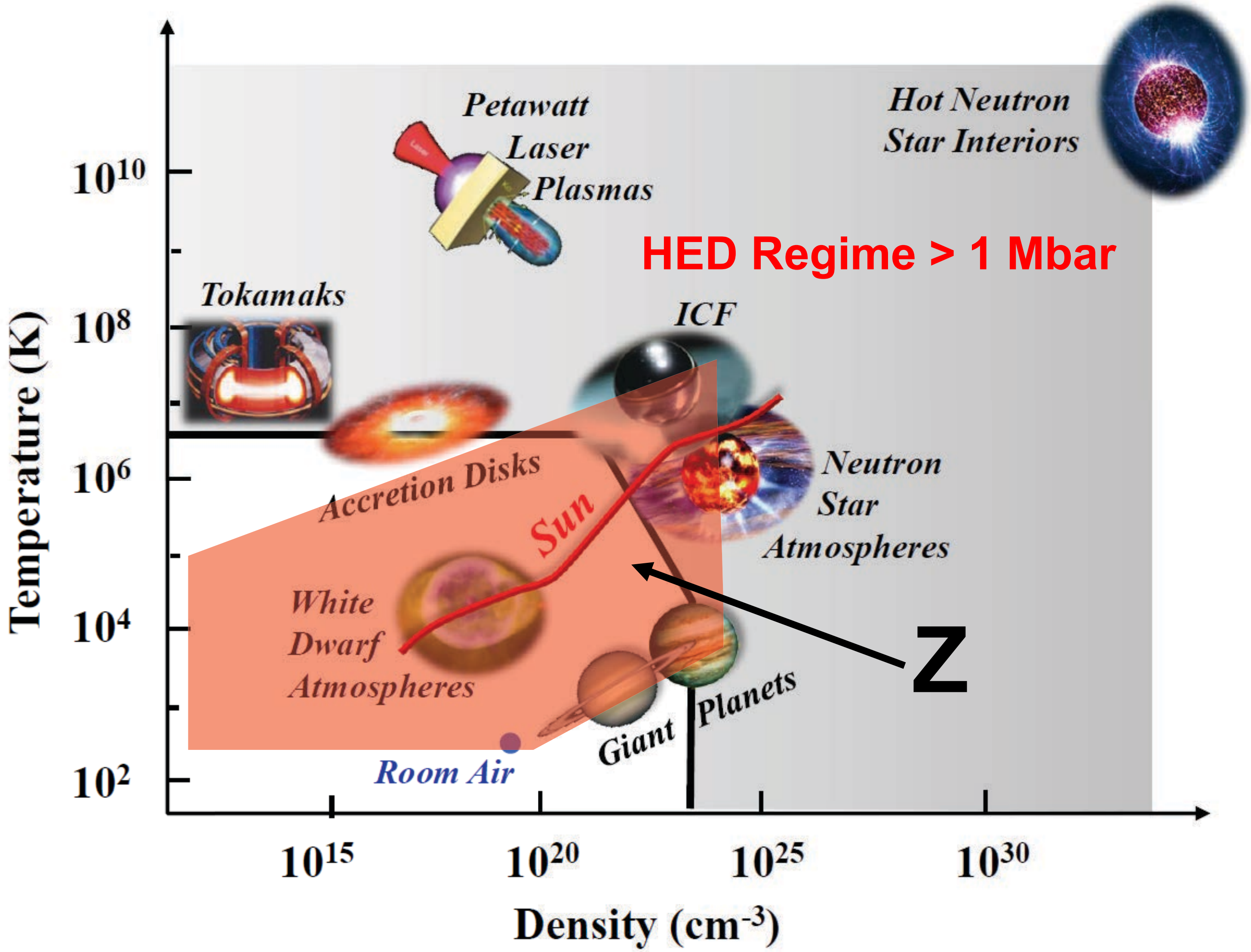
140 Mbar is the radiation drive pressure produced on the NIF!





1 bar ≈ 1 atmosphere

Z can access a large portion of the energy density phase-space for stockpile stewardship applications and high-impact fundamental science

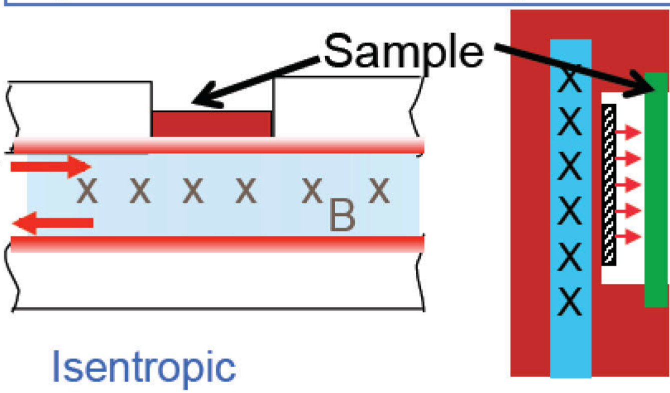


1 bar ≈ 1 atmosphere   4 keV ≈ 50 million K   Solid density ~ $10^{23}/cm^3$

Z & ZBL are used to create HED matter for stockpile stewardship applications and fundamental science

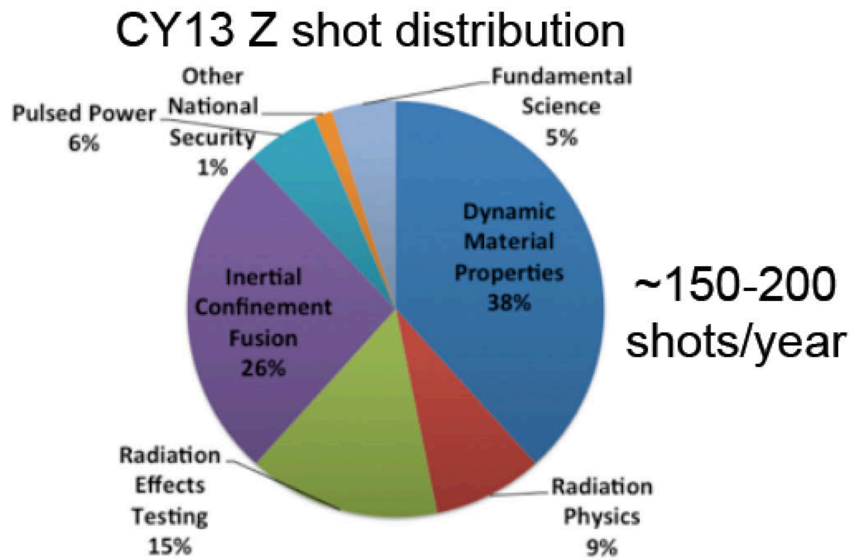
Sandia National Laboratories

Dynamic Material Properties



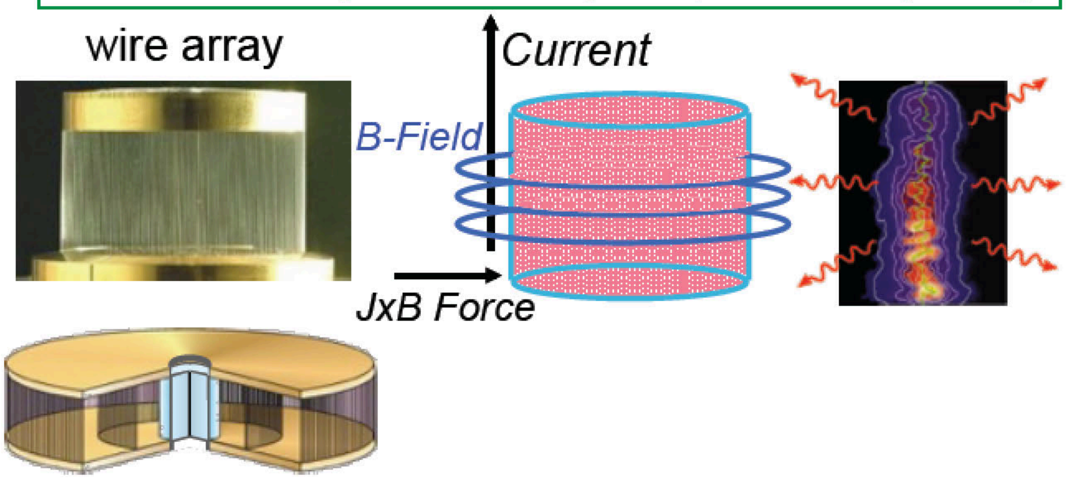
Isentropic Compression

Flyer Plate

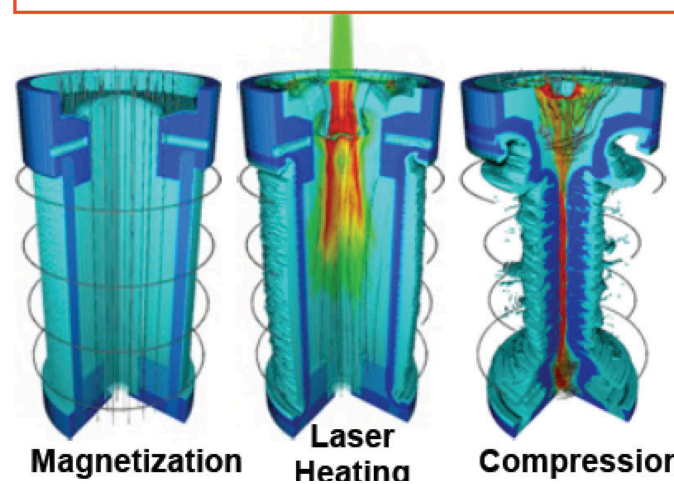


~150-200 shots/year

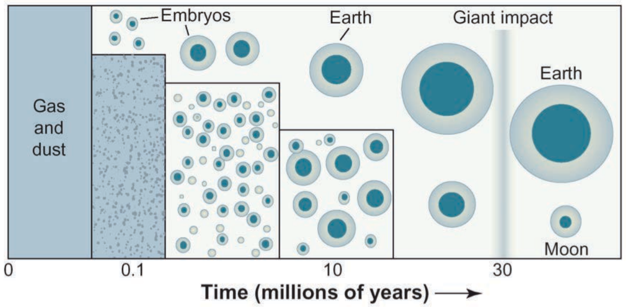
Z-Pinch X-ray Sources (RES, Rad. Physics)



Inertial Confinement Fusion



Sandia has established a fundamental science program on Z and has awarded time to university users



Earth formation

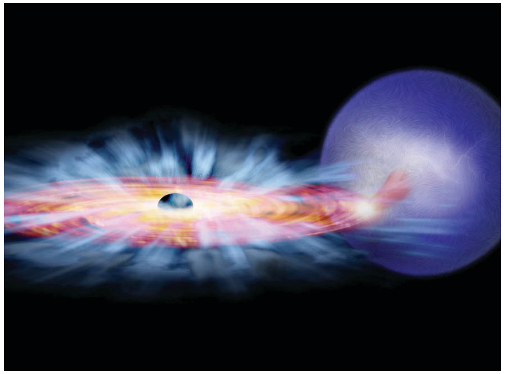
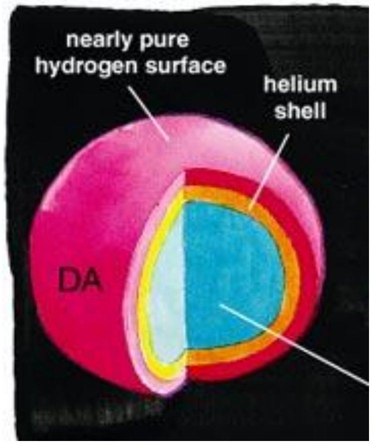
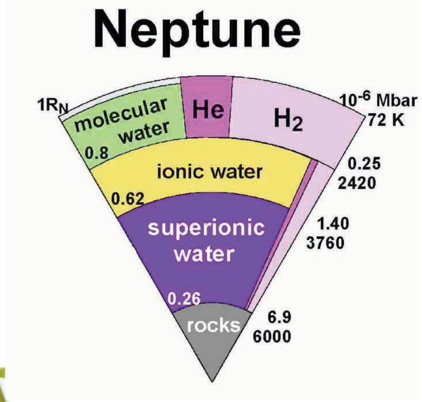


Photo-ionized plasmas

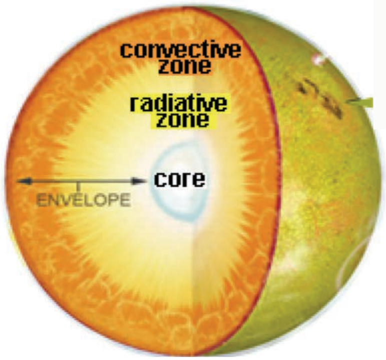
- Use high magnetic pressures and intense x-ray bursts to create unique matter and plasmas on Z that can help address astrophysical questions
- Addressing exciting scientific questions like:
  - Do we understand the structure of the sun?
  - Can we use white dwarfs as cosmic chronometers?
  - How does the accretion disk around a black-hole behave?
  - What is the structure of the planets in our solar system (and beyond)?
  - How did the Earth and the Moon form?



White Dwarfs



Planetary structure



Solar Opacities

The Z Fundamental Science Program engages a broad international community and has advanced HED science

???

- **Resources/shots on Z over 5 years**
  - 50+ dedicated ZFS shots (~5% of all Z shots)
  - Ride-along experiments on program shots
- **Science with far-reaching impact**
  - 1 Nature, 1 Nature Geoscience, 1 SCIENCE
  - 1 Phys. Rev. Lett, 3 Physics of Plasmas, 2 Physical Review (A,B) , 9 others
- **Popular outreach**
  - National Public Radio, "All things considered", Joe Palca 3/6/2014
  - MIT Technology review, 10/4/2012
  - Discover Magazine, 9/16/2012
  - Local TV coverage (7-KOAT, 13-KRQE) in early 2015
- **New external funding won**
  - DOE/OFES/HEDLP
- **Students and postdocs**
  - 4 M.Sc. Exam, 2 Ph.D. exams
  - 5 postdocs

The Z Fundamental Science Program is resulting in high-impact scientific publications:

White Dwarf Photospheres
R. E. Falcon et al. Astrophys. J. 2015

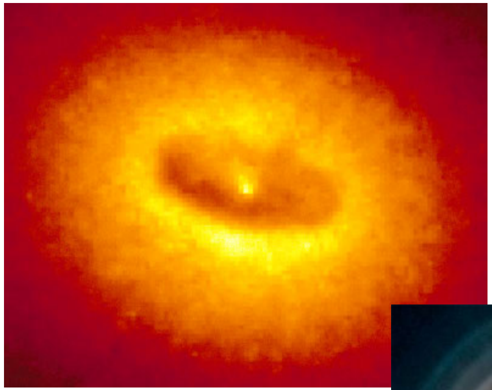
Active Galactic Nuclei & X-ray Binary Systems
M. Hall et al. Phys. Plasmas 2014

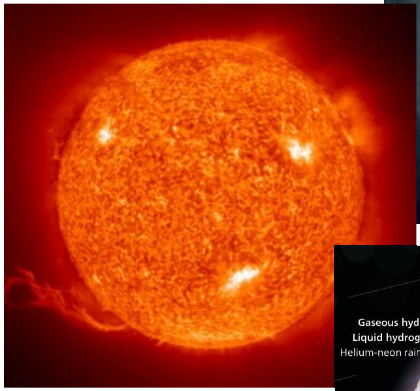
Black Hole Accretion Disks
G. A. Rochau et al. Phys. Plasmas 2014

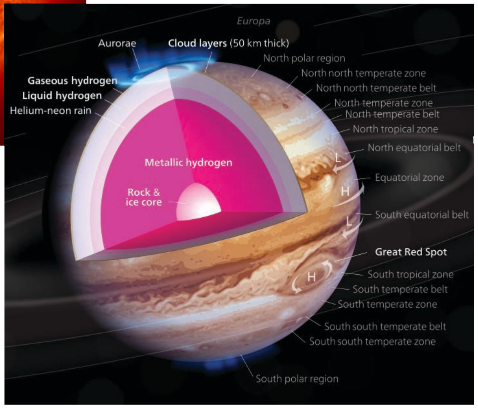
Earth and Super Earths
R. G. Kraus et al. Nature Geoscience 2015

Solar Opacity for Structure of Sun
J. E. Bailey et al., ***Nature 2015***

Gas Giant Planets/Metallic Hydrogen
M. D. Knudson, ***Science 2015***







Z experiments are informing *and challenging* the interpretation of spectral data from the world's multi-billion dollar x-ray observatories.

NATURE Editorial: November, 2013

THIS WEEK

EDITORIALS

MENTORING The heavy responsibility to the next generation p.438

WORLD VIEW Beware the real risk of World Cup fever p.439

POISON Strawberry-frog parents give protection to kids p.441

Nailing fingerprints in the stars

Laboratory-based experiments are sorely needed to complement the rapidly proliferating spectral data originating from observations by the latest space telescopes.

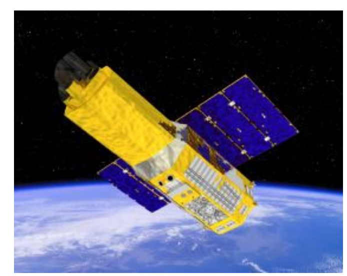
What are stars made of? After astronomers detected a bright-yellow, unknown spectral line in sunlight in 1868, they named the new element helium after the Greek Sun god Helios. But it was some 30 years before physicists on Earth managed to detect — and so confirm the discovery of — helium in a laboratory.

It is a pattern that has been repeated many times since: the indirect detection of elements and molecules through spectral signatures in

quantum mechanics. But heavier elements have many electrons that can participate in transitions — iron has 26, making the probabilities of possible transitions between levels too complex to calculate accurately. Measuring emissions in the lab is the only alternative. Physicists can use tunable lasers to excite electrons into more levels and measure further transitions. This information can then feed back to the astronomical observations. Extra funds would significantly improve this

Chandra
$2.8B

XMM-Newton
$1.1B



Suzaku
$0.5B

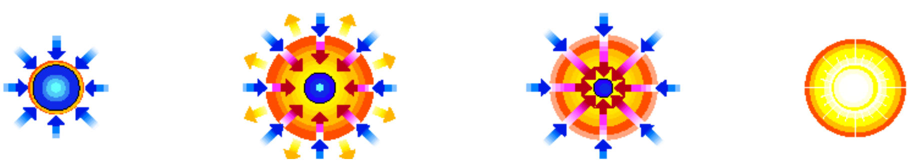
"Laboratory-based experiments are sorely needed to complement the rapidly proliferating spectral data originating from the latest [~$1B] space telescopes"

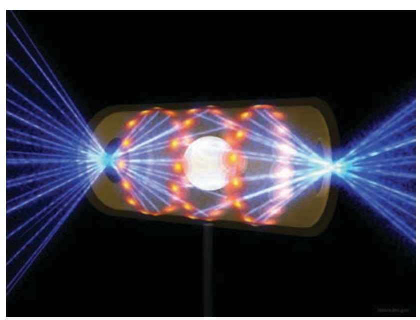
*Nature editor, Nature 503 (2013)

Nuclear fusion: traditionally, two approaches:

Inertial Confinement Fusion (ICF): Laser-driven

- National Ignition Facility (NIF), USA; Omega laser, USA
- Laser Megajoule (LMJ), France
- Typically associated with Nuclear Weapons (NW) & Stockpile Stewardship Program (SSP)

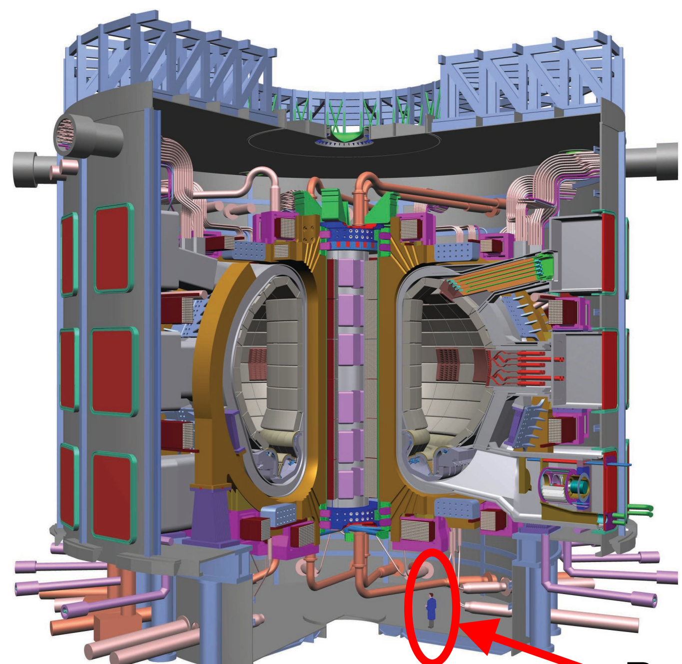




NIF ~ $4 billion

Magnetic Confinement Fusion (MCF):

- ITER (EU, India, Japan, China, Russia, South Korea, and the USA)
- JET (UK/EU), DIII-D (USA/Int.), etc.
- Typically associated with fusion energy



Person size!

ITER ~ $20 billion

Recent big news in ICF: NIF

Scientific breakeven in late 2013 – first time in history!

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CNN Tech

Laser bombardment yields energy milestone

By **Matt Smith**, CNN
updated 6:13 AM EST, Tue March 4, 2014 | Filed under: Innovations

The New York Times

SCIENCE

Giant Laser Complex Makes Fusion Advance, Finally

By KENNETH CHANG and WILLIAM J. BROAD FEB. 12, 2014

THE WALL STREET JOURNAL.

U.S. NEWS

A Star Is Born: U.S. Scores Fusion-Power Breakthrough

Experimental Reaction Yields Energy, but Sustainability Still Proves Elusive

By GAUTAM NAIK
Updated Feb. 12, 2014 6:13 p.m. ET

LETTER

doi:10.1038/nature13008

Fuel gain exceeding unity in an inertially confined fusion implosion

O. A. Hurricane[1], D. A. Callahan[1], D. T. Casey[1], P. M. Celliers[1], C. Cerjan[1], E. L. Dewald[1], T. R. Dittrich[1], T. Döppner[1], D. E. Hinkel[1], L. F. Berzak Hopkins[1], J. L. Kline[2], S. Le Pape[1], T. Ma[1], A. G. MacPhee[1], J. L. Milovich[1], A. Pak[1], H.-S. Park[1], P. K. Patel[1], B. A. Remington[1], J. D. Salmonson[1], P. T. Springer[1] & R. Tommasini[1]

400 MJ stored in NIF, ~10 kJ into fuel, ~20 kJ out in fusion yield (good, but should be ≥1 MJ yield if capsule ignites)

Other recent big news: MagLIF (Nature, 12/31/13)

NEWS IN FOCUS

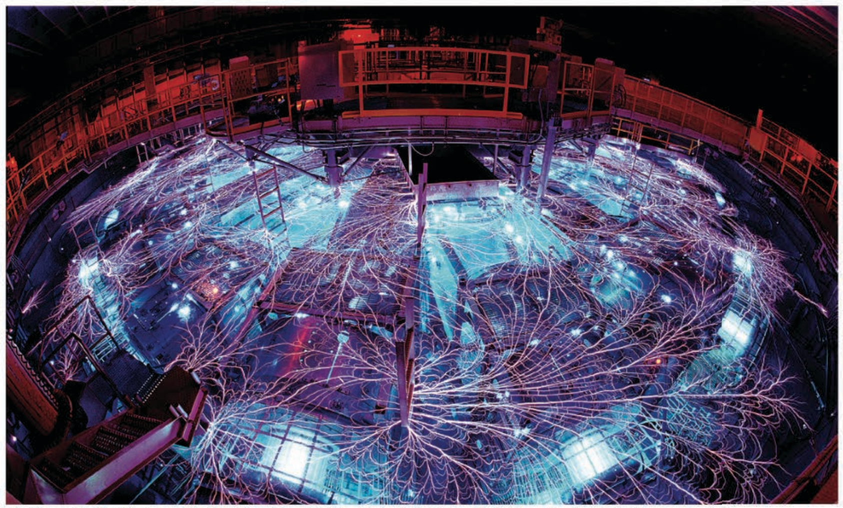
CLIMATE Water will be scarce in warmer world, huge study says **p.10**

PHYSICS With $50 million spent, X-ray source is now out in the cold **p.11**

2014 Transgenic monkeys, comets and more will make the news this year **p.13**

EPIGENETICS A scientist's bid to track down the roots of aggression **p.14**

RANDY MONTOYA/SANDIA NATL LAB.



The intense electrical discharge of the Z machine at Sandia National Laboratories in New Mexico is used in attempts to trigger nuclear fusion.

PLASMA PHYSICS

Triple-threat method sparks hope for fusion

The secrets to its success are lasers, magnets and a big pinch.

BY W. WAYT GIBBS

The Z machine at Sandia National Laboratories in New Mexico discharges the most intense pulses of electrical current on Earth. Millions of amperes can be sent towards a metallic cylinder the size of a pencil eraser, inducing a magnetic field that creates a force — called a Z pinch — that crushes the cylinder in a fraction of a second.

Since 2012, scientists have used the Z pinch to implode cylinders filled with hydrogen isotopes in the hope of achieving the extreme temperatures and pressures needed for energy-generating nuclear fusion. Despite their efforts, they have never succeeded in reaching ignition — the point at which the energy gained from fusion is greater than the energy put in.

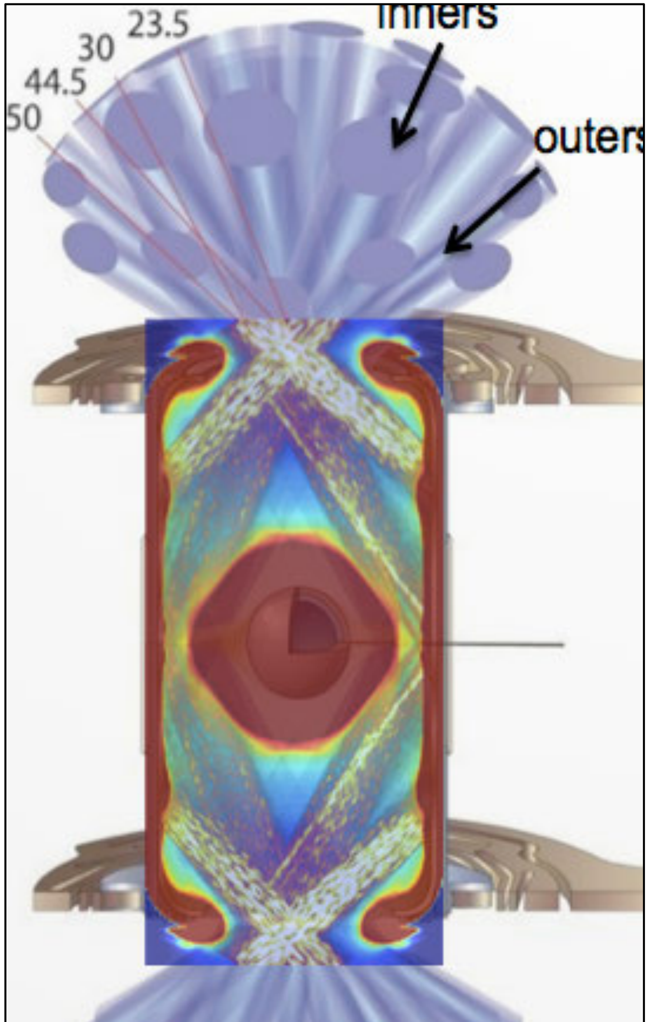
But after tacking on two more components, physicists think they are at last on the right path.

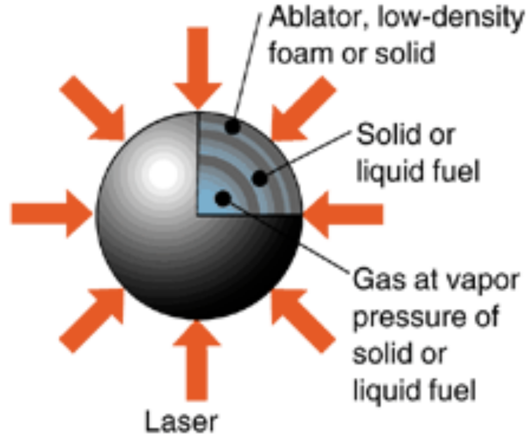
Researchers working on Sandia's Magnetized Liner Inertial Fusion (MagLIF) experiment added a secondary magnetic field to thermally insulate the hydrogen fuel, and a laser to pre-heat it (see 'Feeling the pinch'). In late November, they tested the system for the first time, using 16 million amperes of current, a 10-tesla magnetic field and 2 kilojoules of energy from a green laser.

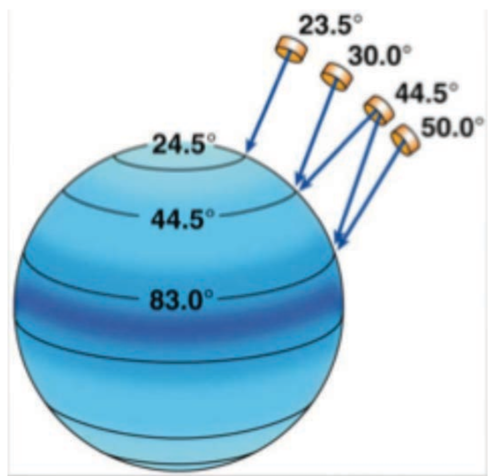
"We were excited by the results," says ▸

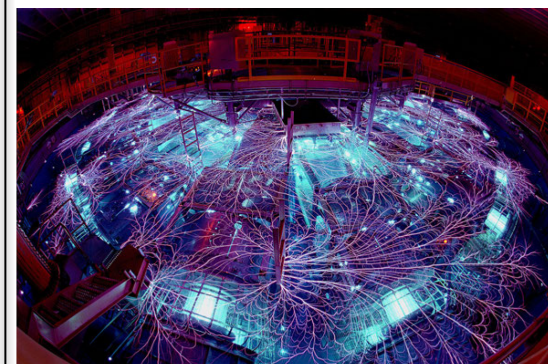
Recently, the U.S. National ICF Program added pulsed-power and magnetically driven implosions (energy rich & efficient)

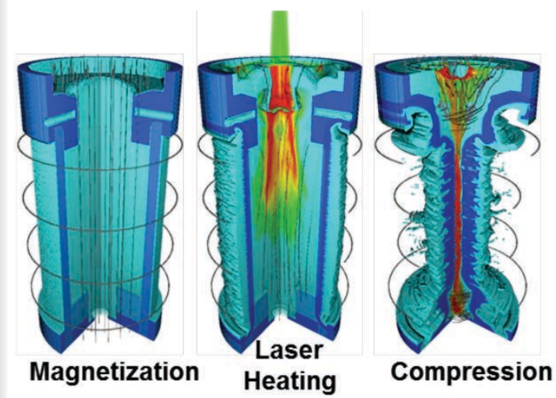
Indirect-drive ICF (NIF)	Direct-drive ICF (OMEGA)	Magnetic-drive ICF (Z)







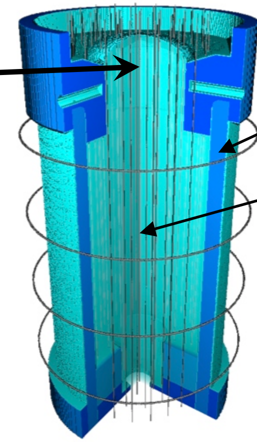


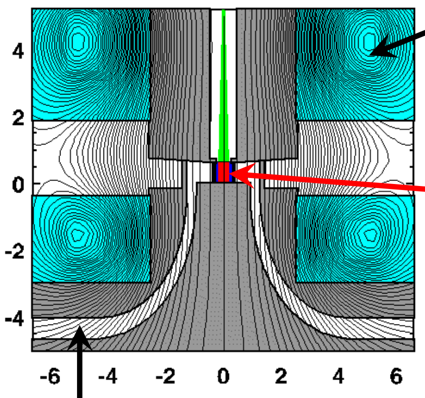


Z ~ $0.1 billion

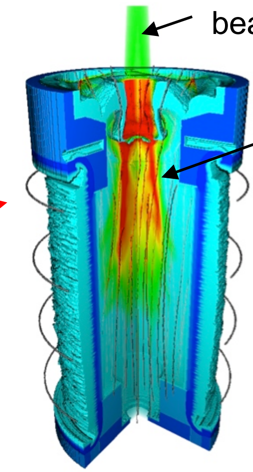
Sandia National Labs is using the Z facility to study the Magnetized Liner Inertial Fusion (MagLIF) concept

1. Magnetization: 10–50 T B_z applied (ms timescale) to insulate hot fuel from cold liner wall and to trap charged fusion products in the fuel

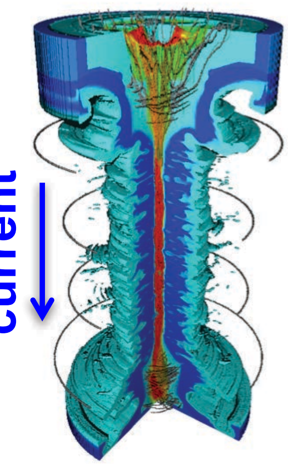




2. Preheating: ZBL laser preheats fuel to 100–250 eV to reduce required compression ratio to CR≈20–30



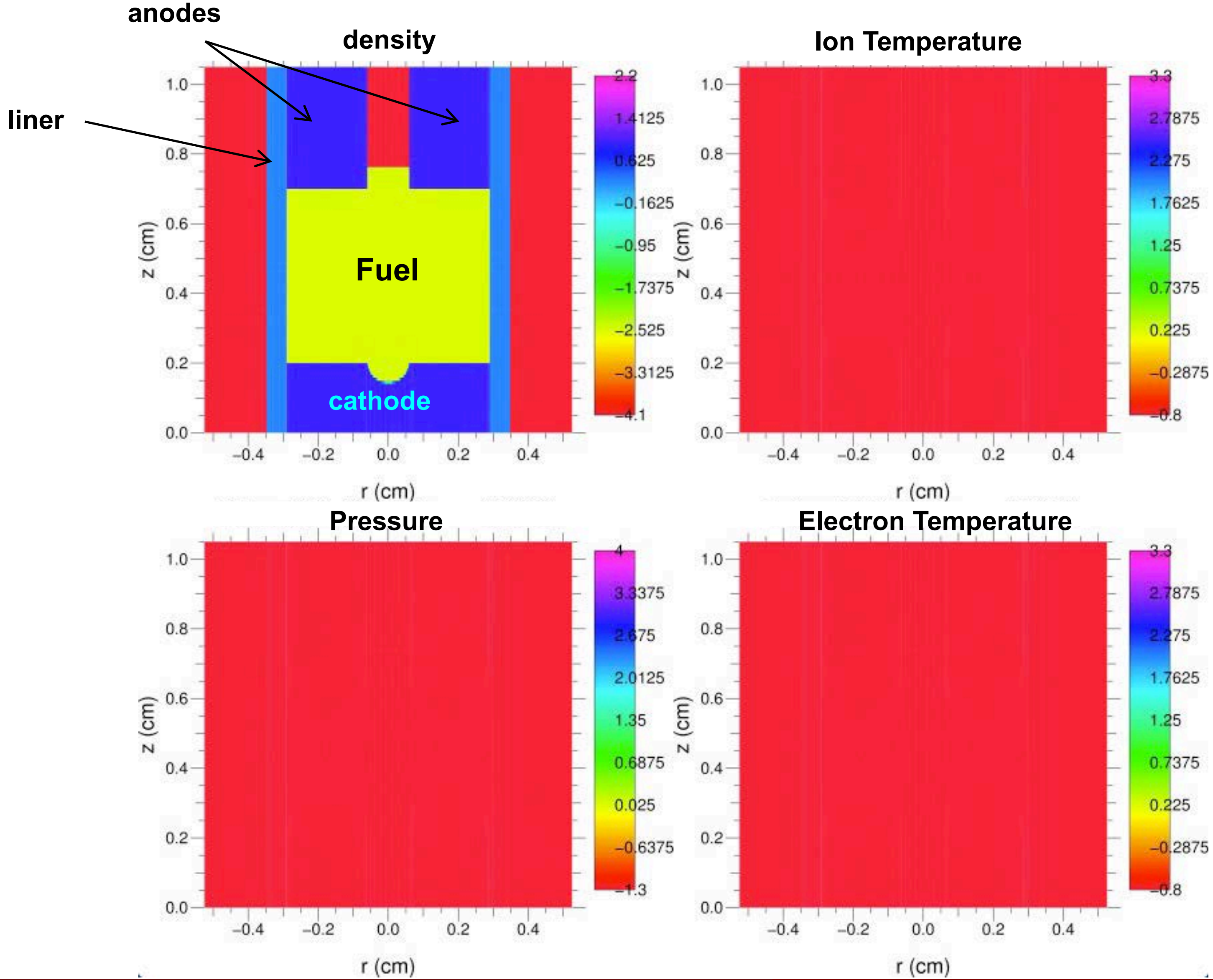
3. Implosion & Flux Compression: Z drive current & B_θ field implode liner (via z-pinch) at 50–100 km/s, compressing fuel and B_z field by 1000x



With DT fuel, simulations indicate scientific breakeven may be possible on Z (fusion energy out = energy deposited in fusion fuel)

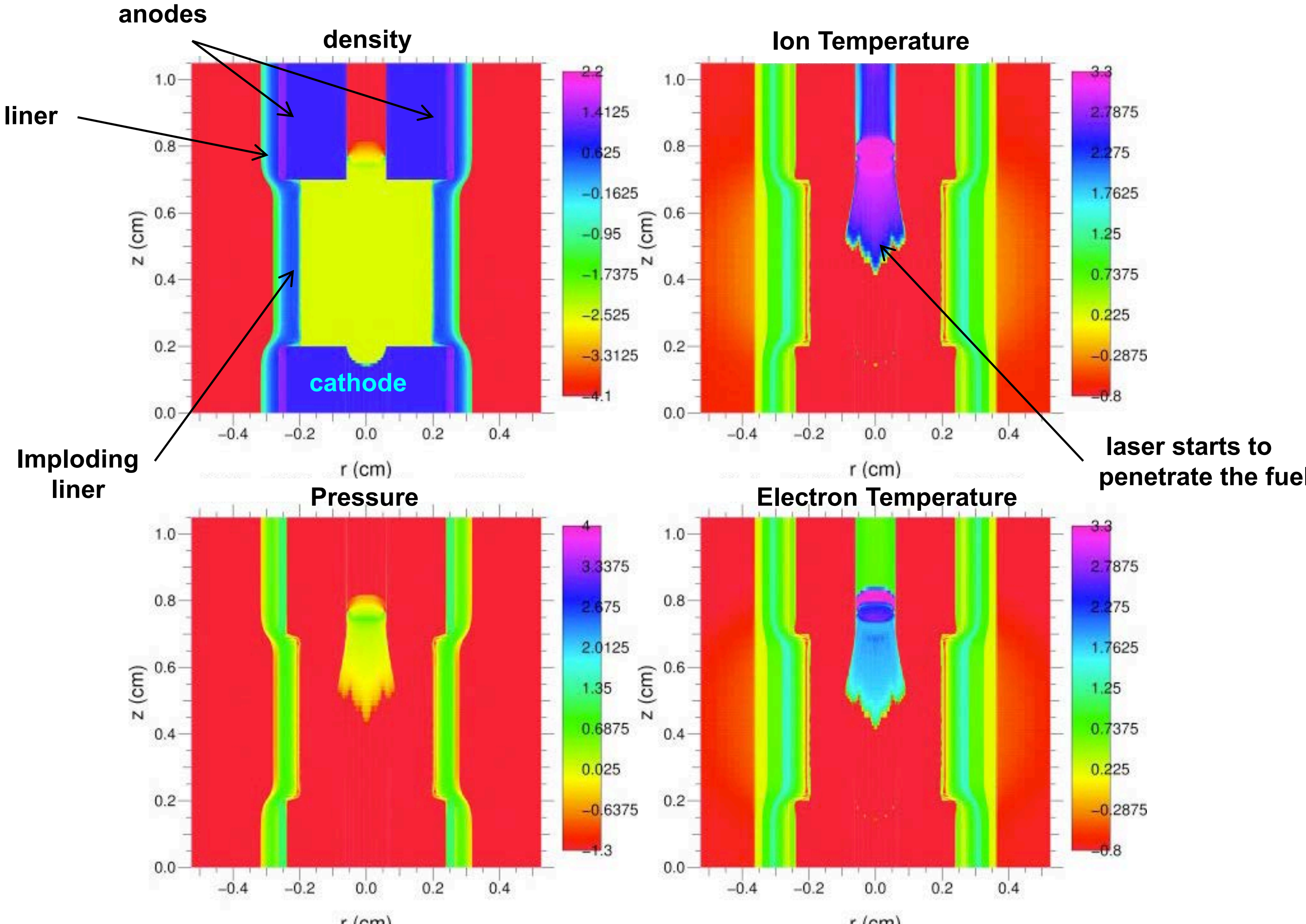
S. A. Slutz *et al.*, PoP **17**, 056303 (2010). S. A. Slutz and R. A. Vesey, PRL **108**, 025003 (2012).

HYDRA Simulation MagLIF Movie
time = 0.0 ns



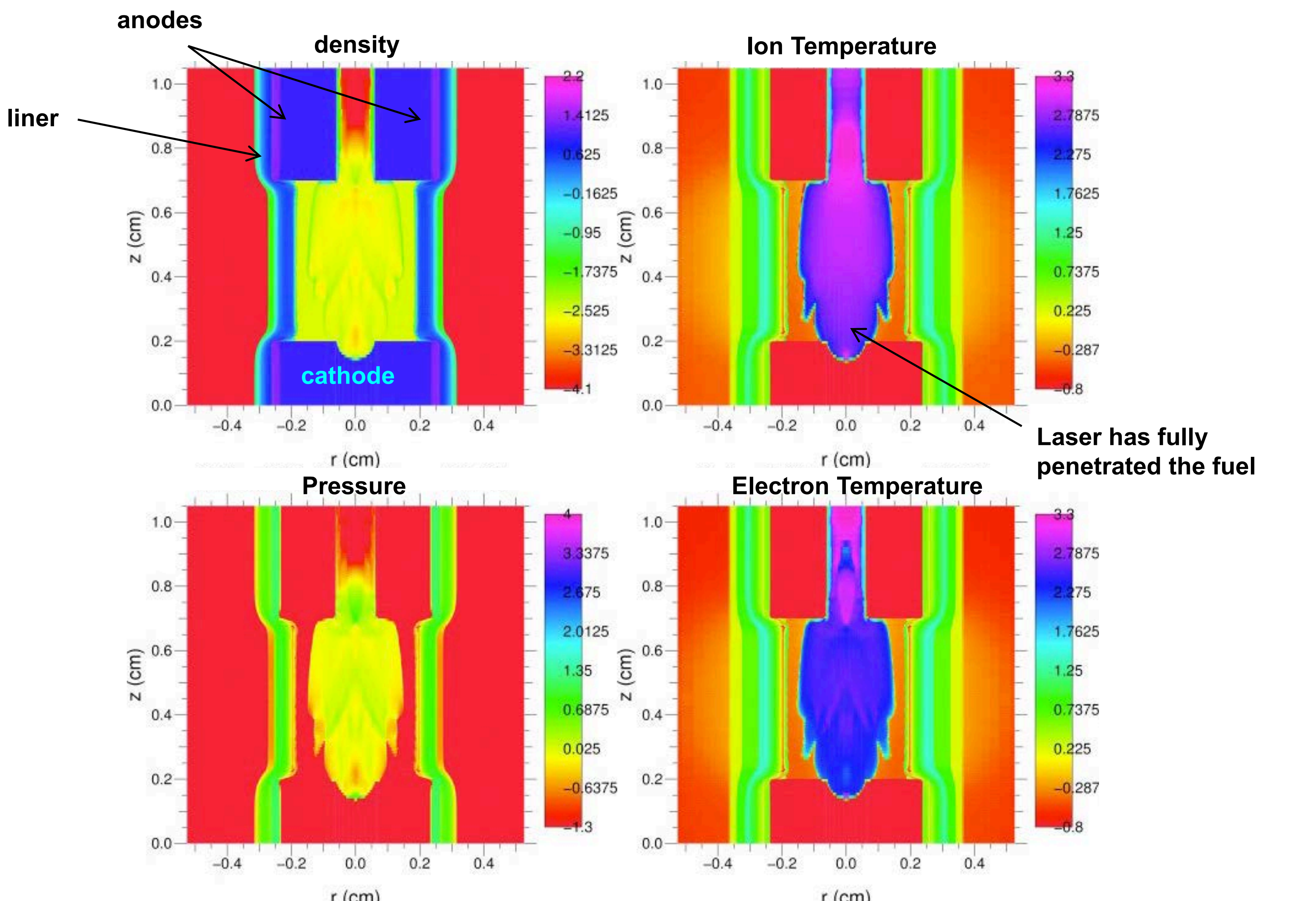
A. B. Sefkow *et al.*, Phys. Plasmas **21**, 072711 (2014).

HYDRA Simulation MagLIF Movie
time = 120.0 ns

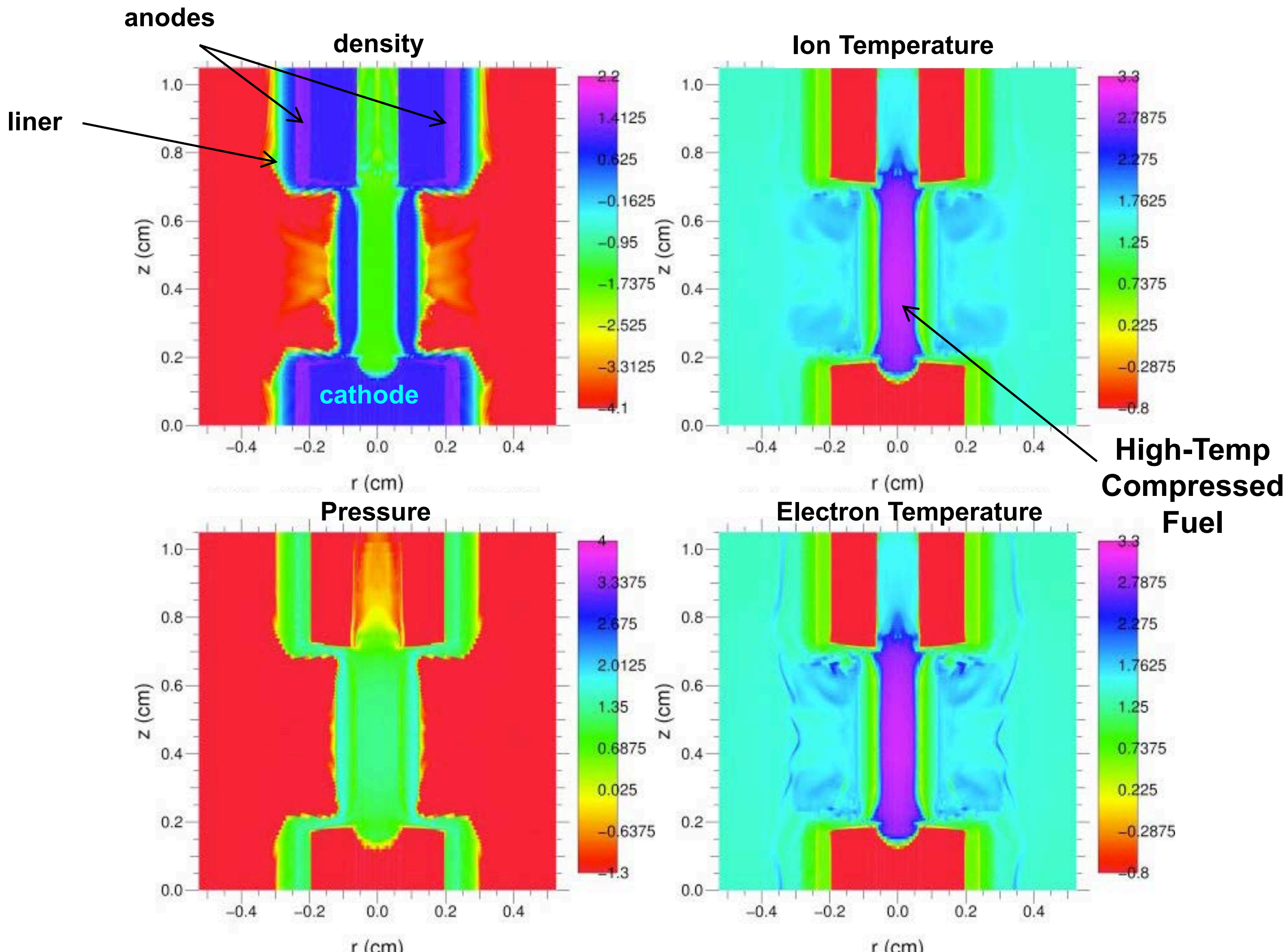


A. B. Sefkow *et al.*, Phys. Plasmas **21**, 072711 (2014).

HYDRA Simulation MagLIF Movie
time = 123.0 ns



HYDRA Simulation MagLIF Movie
time = 144.0 ns



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

HYDRA Simulation MagLIF Movie
time = 153.0 ns

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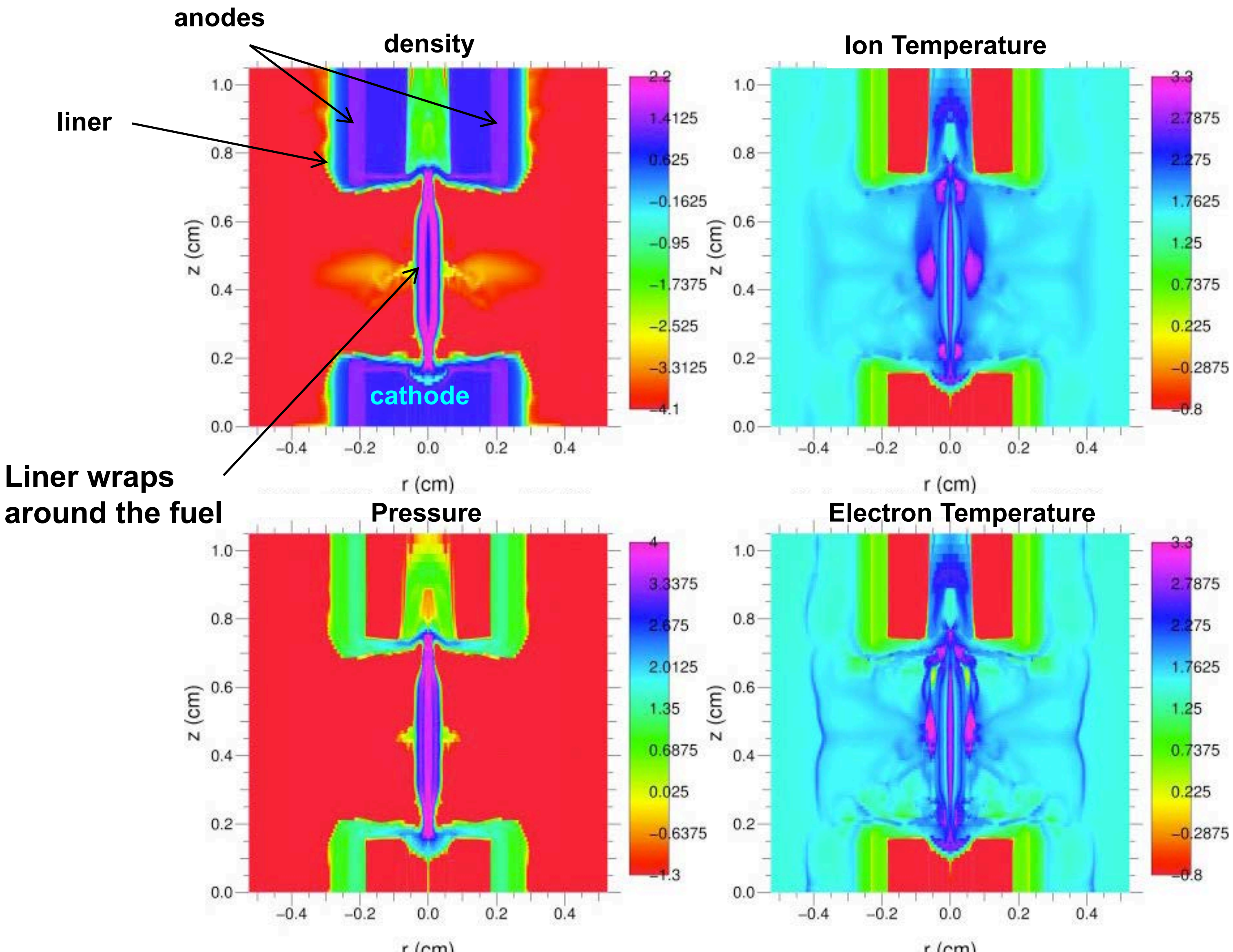


A. B. Sefkow *et al.*, Phys. Plasmas **21**, 072711 (2014).

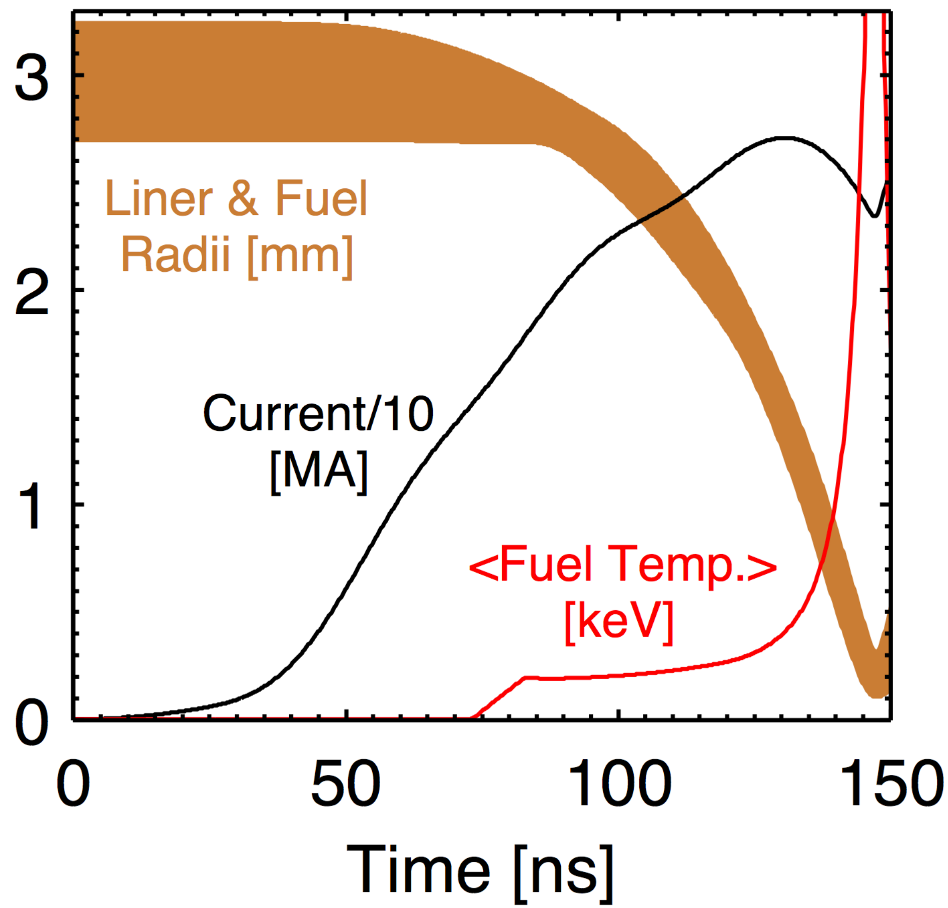
MagLIF Timing Overview:

~ 60–100-ns implosion times
~ adiabatic fuel compression (thus preheating the fuel is necessary)
~ 5-keV fuel stagnation temperatures (60 million degrees K)
~ 1-g/cc fuel stagnation densities
~ 5-Gbar fuel stagnation pressures

$$T \approx T_0 \left(\frac{\rho}{\rho_0} \right) \approx T_0 C_R^{4/3}$$

$$(C_R = R_0 / R_{stagnation})$$

- Typically for ICF (e.g., NIF), faster implosions shock-heat the fuel, not so for MagLIF
- Magnetization is used to keep the preheated fuel from cooling off during the implosion

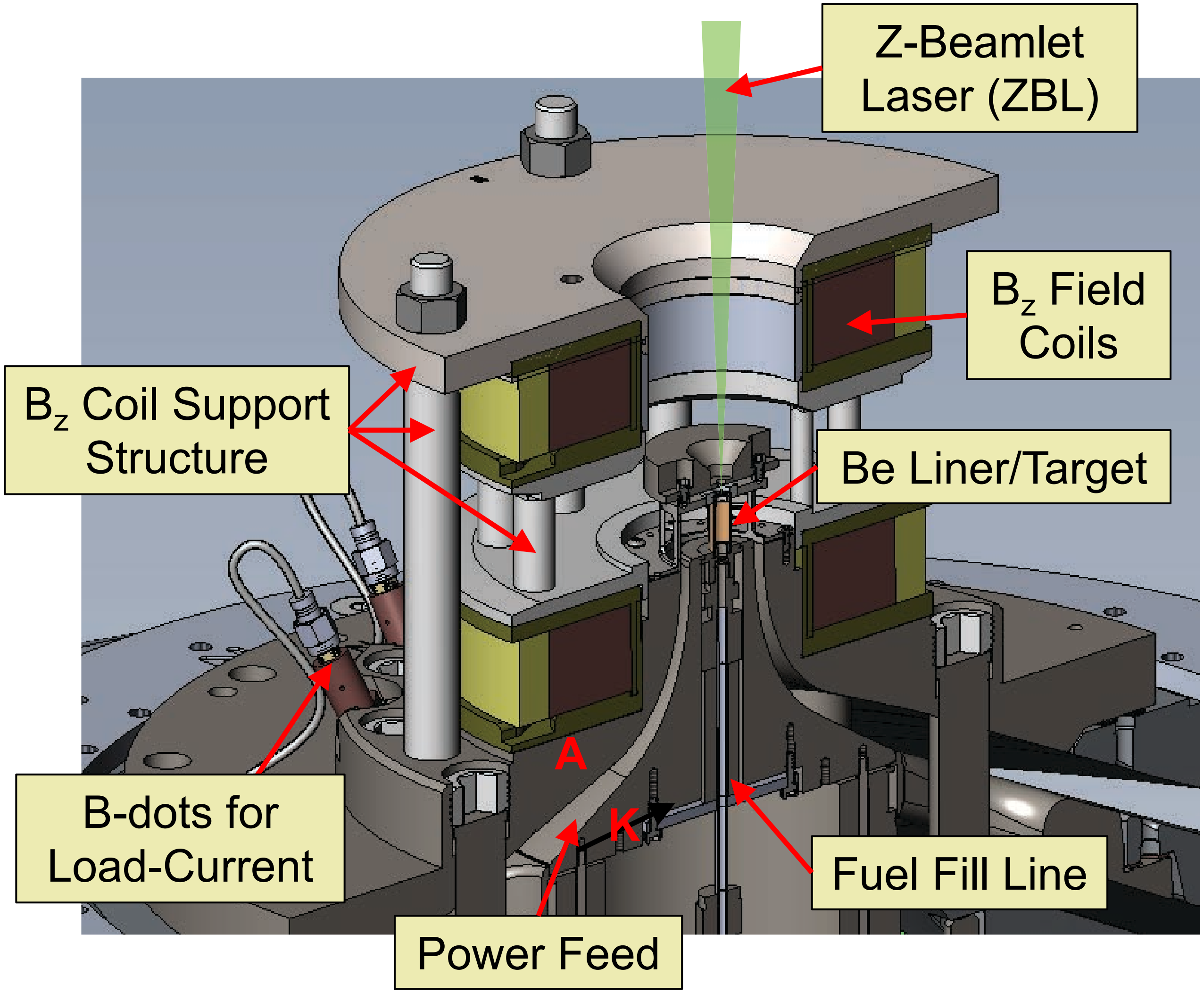


Semi-analytic simulation results from R. D. McBride and S. A. Slutz, PoP **22**, 052708 (2015).

Anatomy of a MagLIF Experiment:

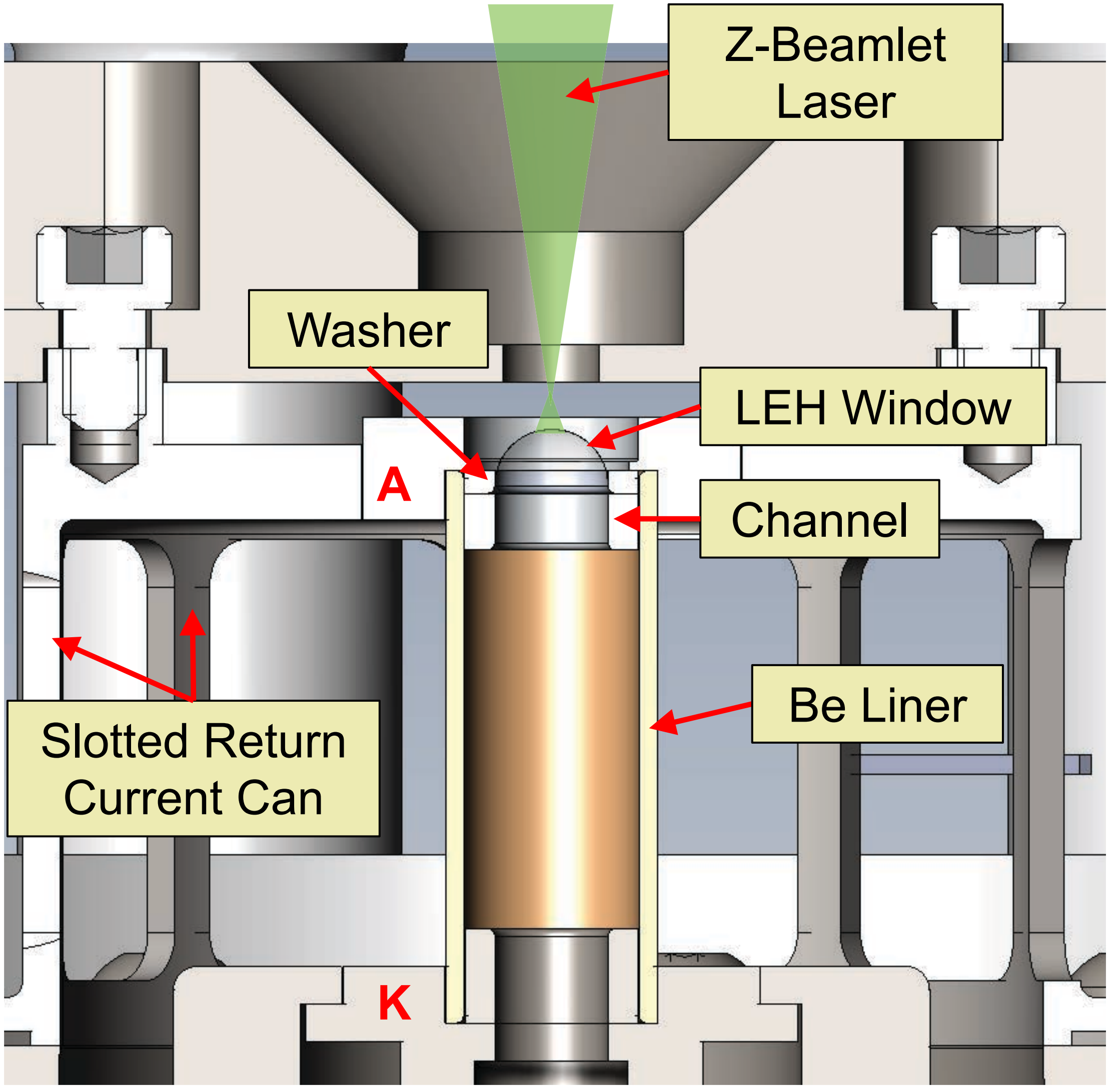
Sandia National Laboratories

- **Field Coils**: Helmholtz-like coil pair produce a 10-30 T axial field w/ ~3 ms rise time
- **ZBL**: 1-4 kJ green laser, 1-4 ns square pulse w/ adjustable prepulse (prepulse used to help disassemble laser entrance window)



Anatomy of a MagLIF Target:

- **Be Liner**: OD = 5.63 mm, ID = 4.65 mm, h = 5–10 mm
- **LEH Window**: 1-3 µm thick plastic window. Supports 60 PSI pure D2 gas fill.
- **Washer**: Metal (Al) washer supporting LEH window
- **Channel**: Al structure used to mitigate the "wall instability." Also reduces LEH window diameter to allow thinner windows
- **Return Can:** Slotted for diagnostic access



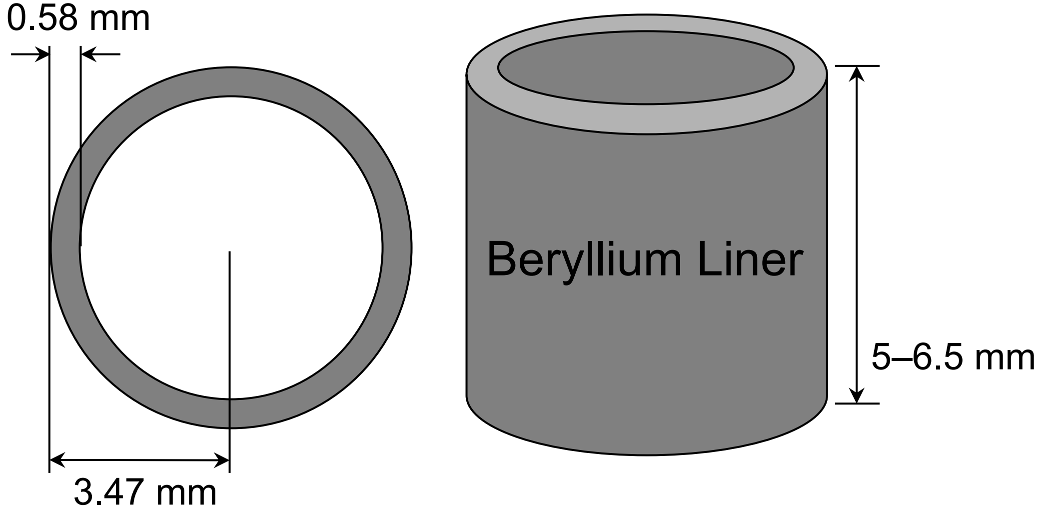
Many diagnostics used and continually being developed to study MagLIF and HEDP on Z

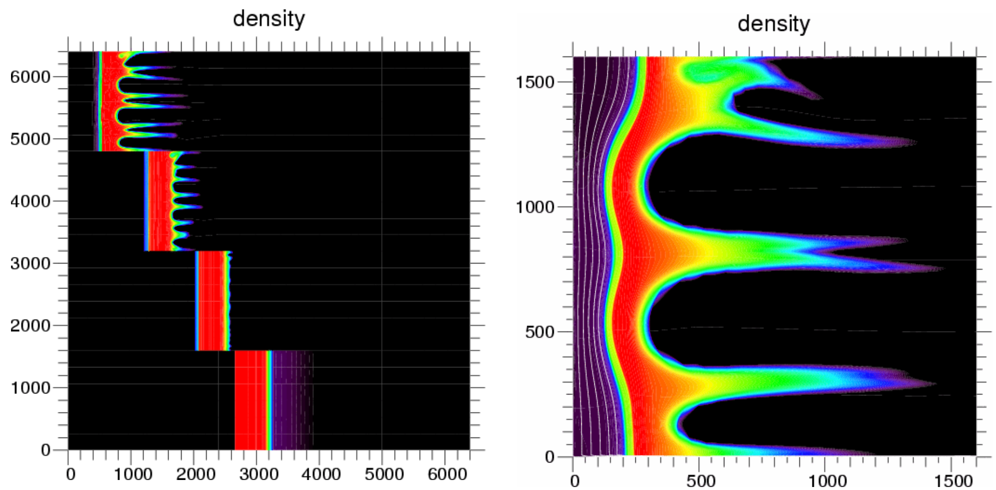
Z Target Diagnostics

- **Power & Energy**
  - X-ray Diodes
  - Photo Conducting Diamonds
  - Silicon Diodes
  - Bolometer
- **Spectroscopy**
  - Time-integrated 0.8-10 keV
  - Time-resolved 0.8-10 keV
  - Time-integrated 7-25 keV
  - Streaked Visible
- **X-ray Imaging**
  - 1.9 or 6.1 keV Backlighting
  - 277 or 528 eV Time-Gated Self-Emission
  - Filtered Self-Emission
- **Motion / Velocity**
  - VISAR
  - Photonic Doppler Velocimetry (PDV)
  - Passive Shock Breakout
- **Neutrons**
  - D-D Activation
  - D-T Activation
  - Time-of-Flight
  - Imaging

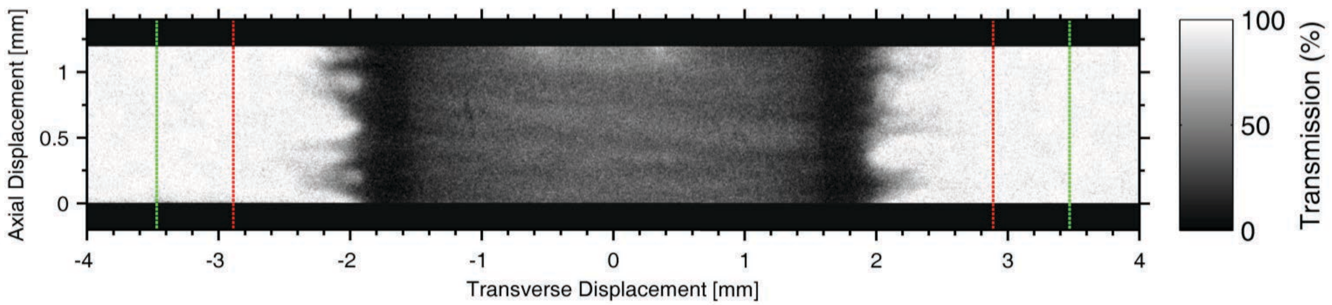
Implosion instabilities like the Magneto-Rayleigh-Taylor (MRT) instability could cause MagLIF to fail

Thus we use liners with thick walls to mitigate MRT feed-through





To study liner implosion instabilities, penetrating radiographs are taken to piece together implosion "movies":



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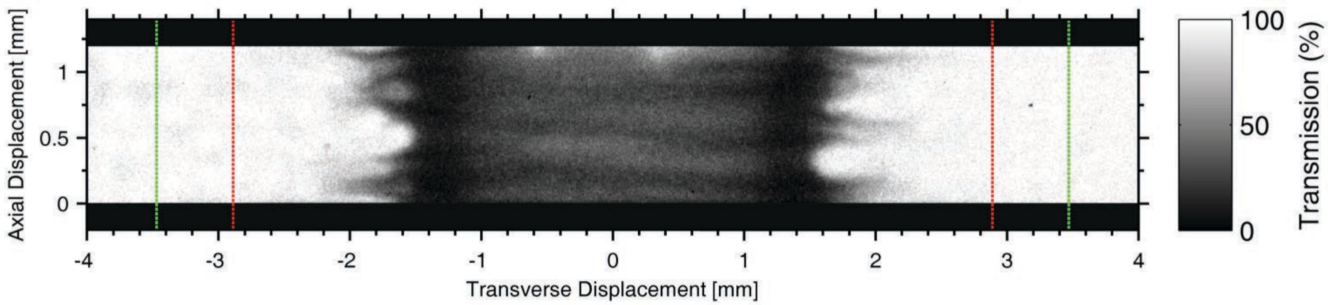

R. D. McBride *et al.*, Phys. Rev. Lett. **109**, 135004 (2012).

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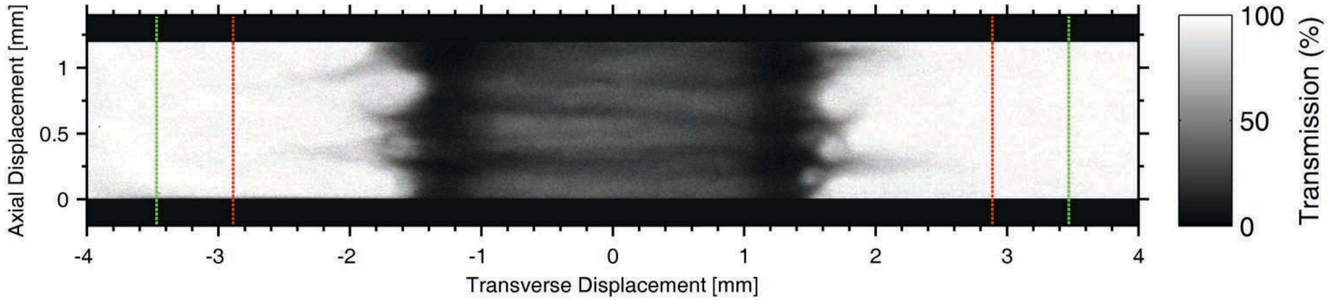

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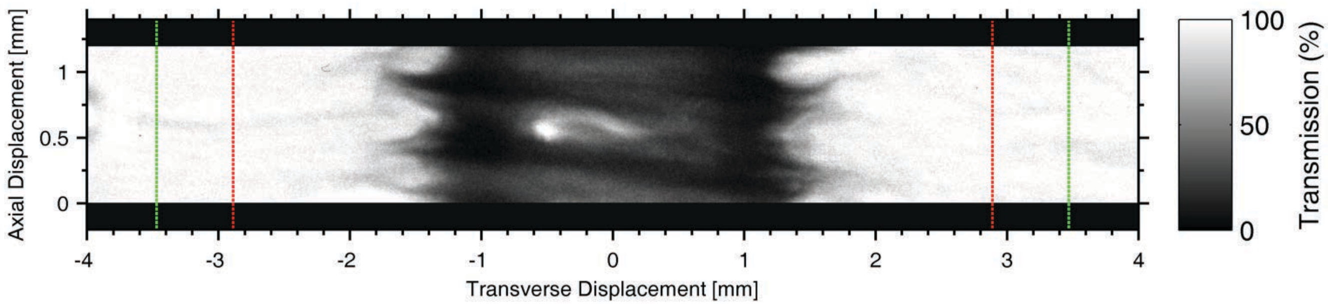

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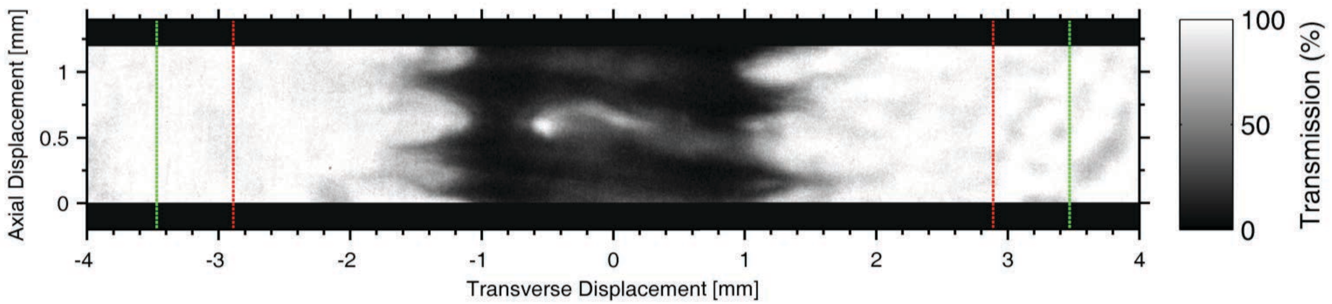

R. D. McBride *et al.*, Phys. Rev. Lett. **109**, 135004 (2012).

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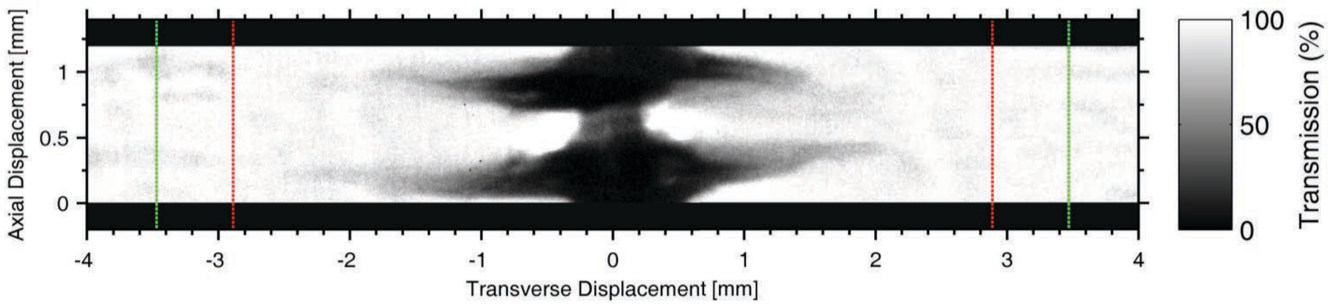

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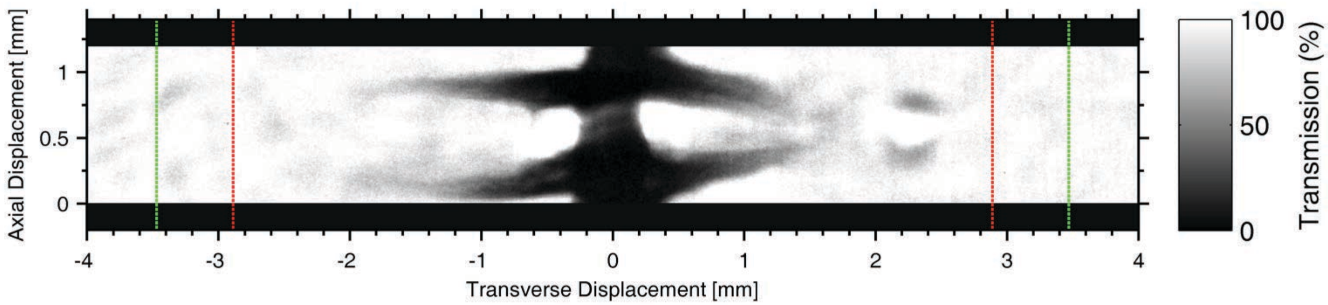

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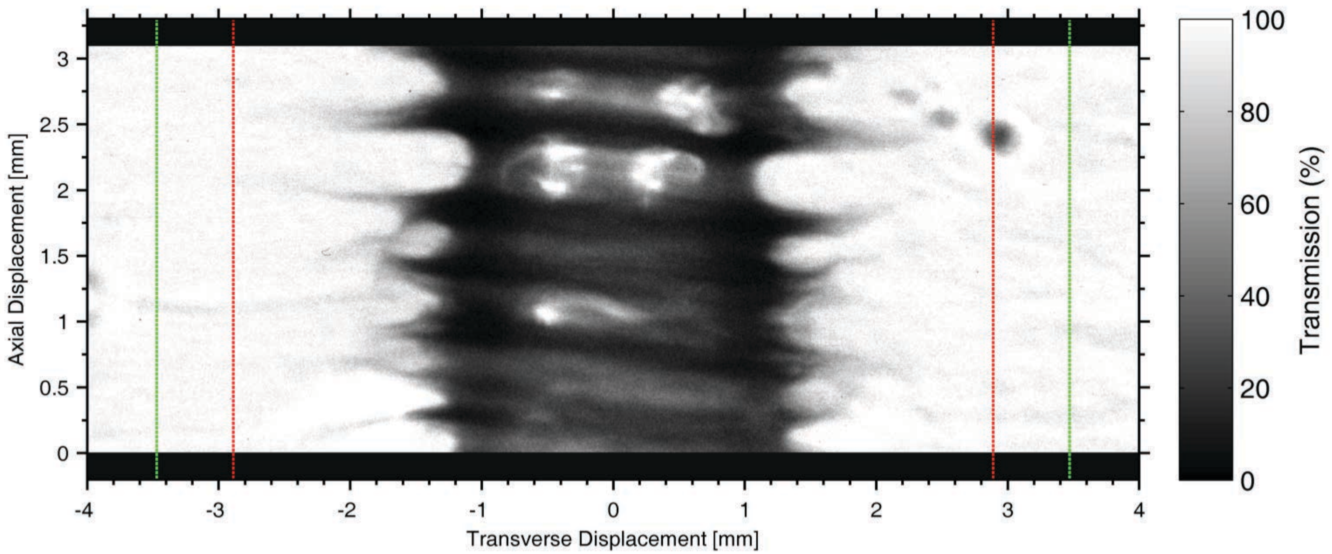

R. D. McBride *et al.*, Phys. Rev. Lett. **109**, 135004 (2012).

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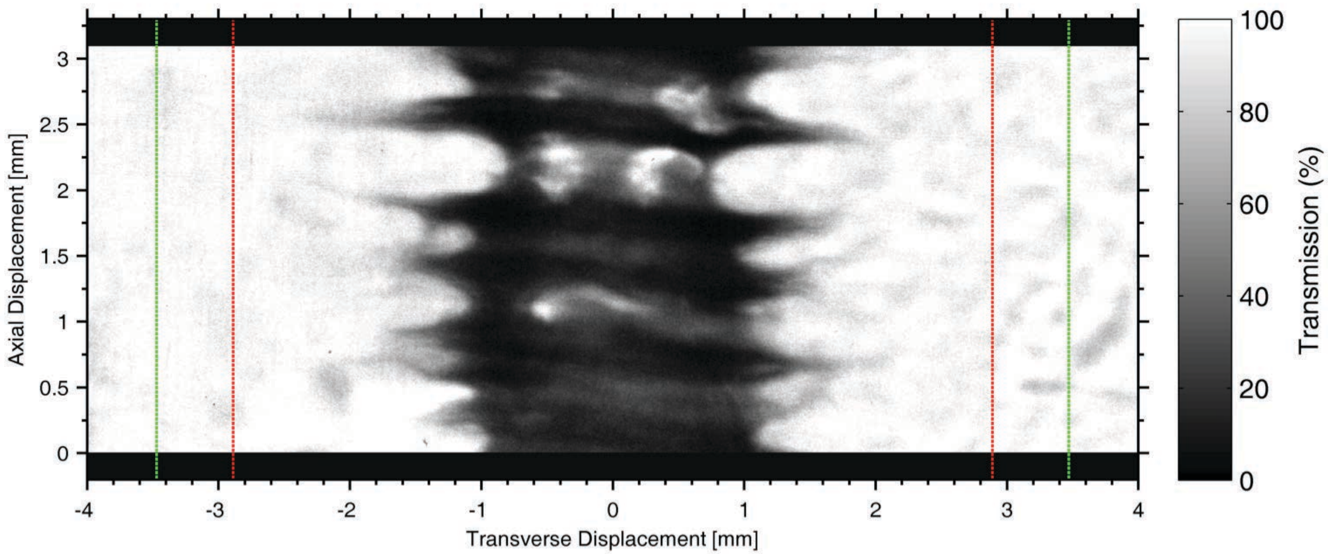

R. D. McBride *et al.*, Phys. Rev. Lett. **109**, 135004 (2012).

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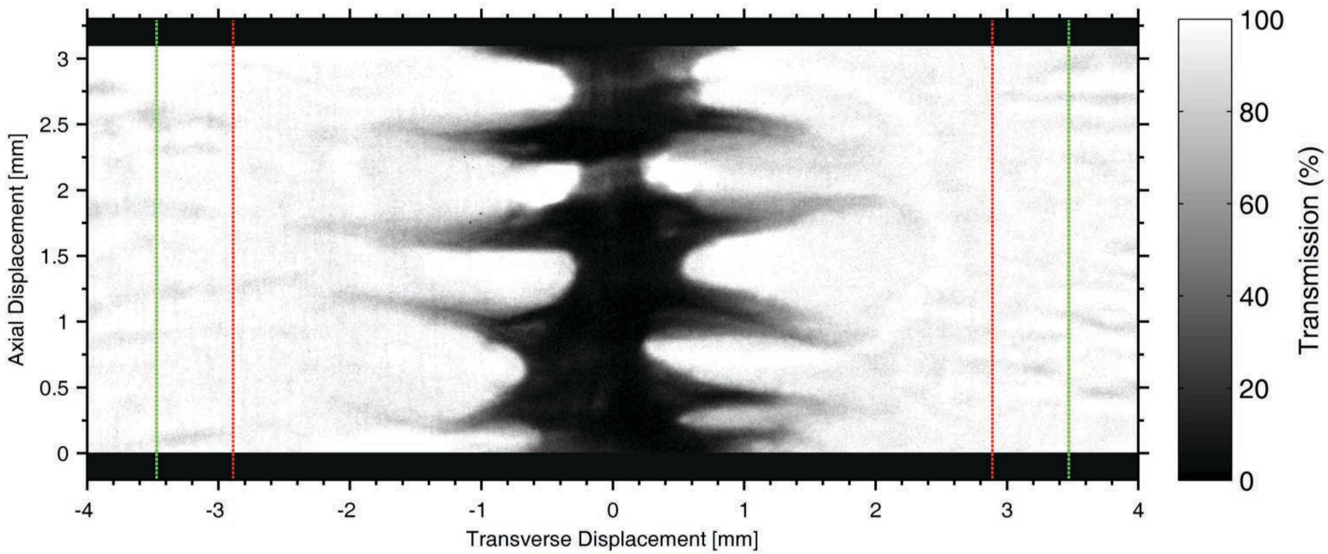

To study liner implosion instabilities, penetrating radiographs are taken to piece together implosion "movies":

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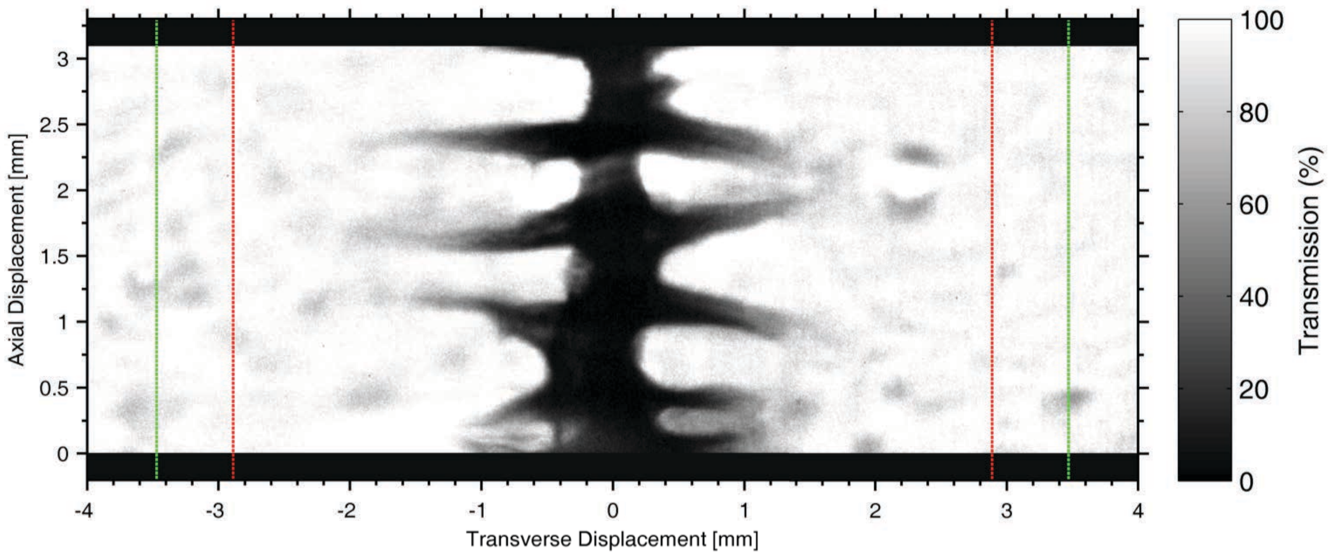
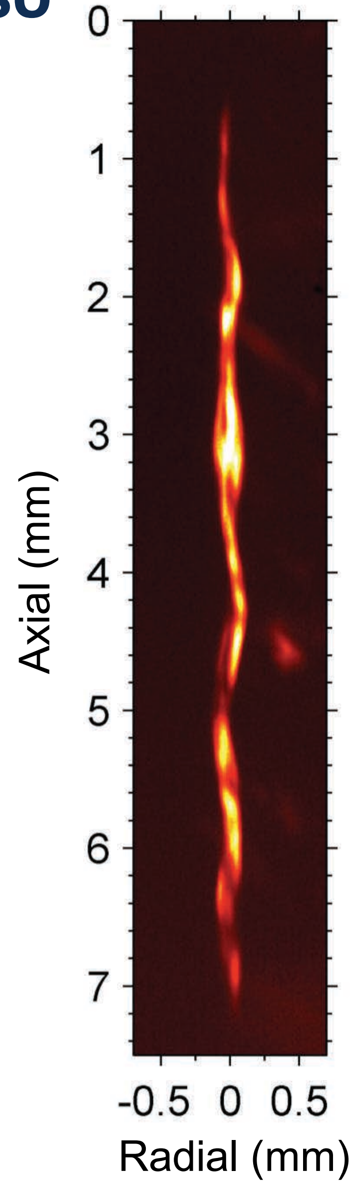


- **These experimental data are compared with detailed numerical simulations to understand the seeding and evolution of liner implosion instabilities**

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

Images of the hot and compressed fusing fuel (on axis inside of the imploding liner) are also collected



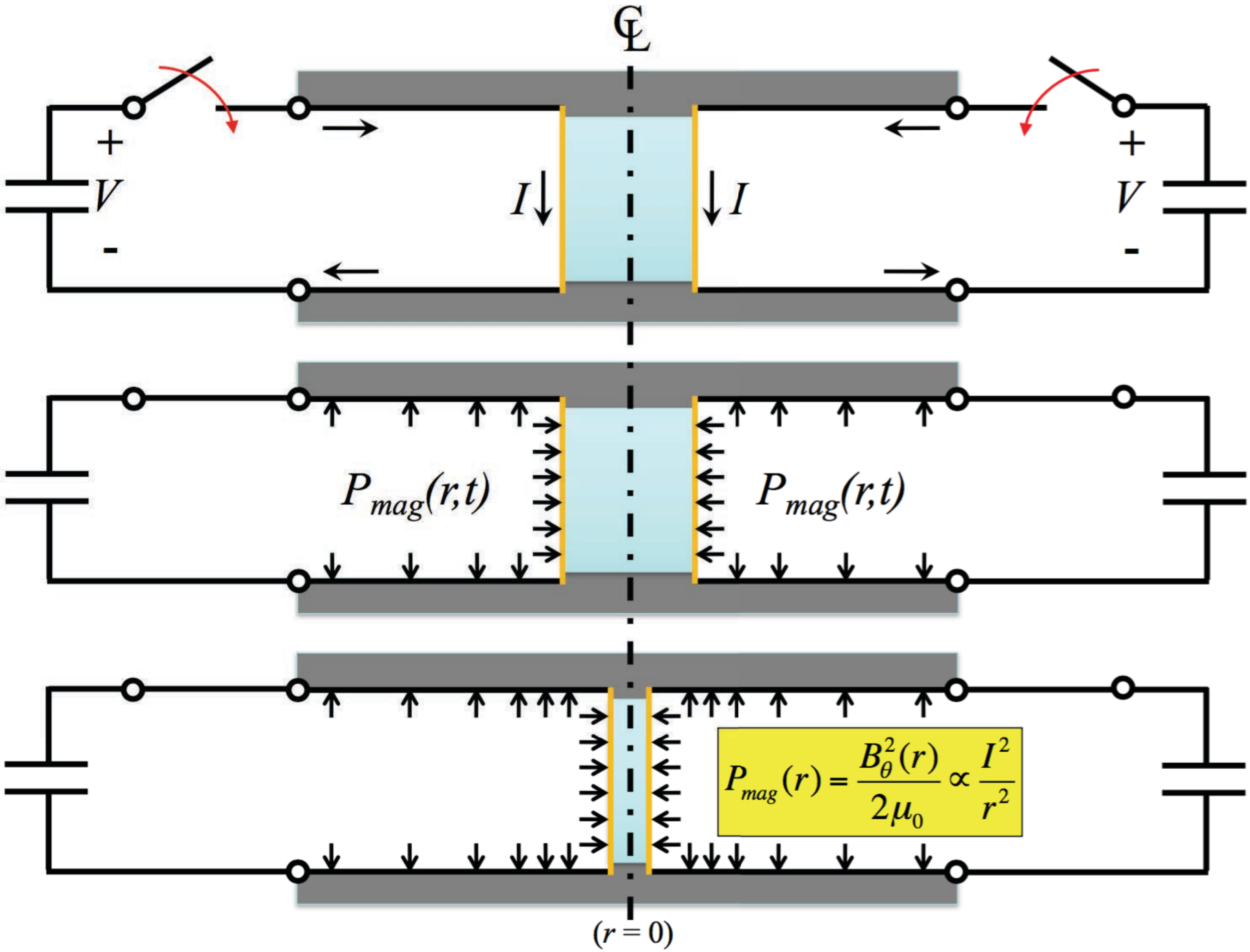
- **This high-resolution image was produced by an x-ray crystal optics system**
- **FWHM is 50-110 µm (this reacting plasma is less than the thickness of a human hair)**
- **Experimental data like these are compared with detailed numerical simulations to unfold plasma conditions**

M. R. Gomez et al., PRL **113**, 155003 (2014); E. C. Harding et al., RSI **86**, 043504 (2015).

MagLIF Status and Year 2020 Goals for the MagLIF Program at Sandia

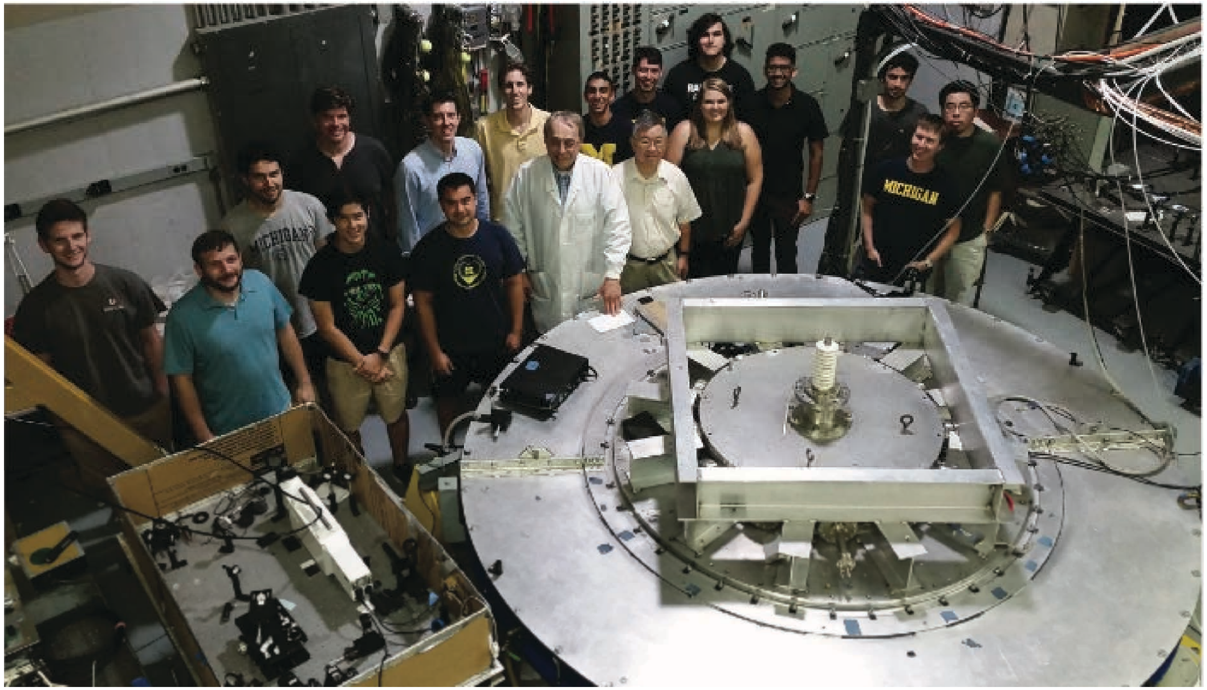
- In short, MagLIF is working
- Sandia now needs to demonstrate how MagLIF scales with driver power & energy to justify building a next-step/next-generation pulsed-power facility (i.e., Z-Next)
- Demonstrate scaling with modest upgrades to present Z facility:
  - DT fuel (presently use DD fuel)
  - 8 kJ preheat (presently a 4-kJ laser)
  - 30 T B_{z0} (presently 15–20 T)
  - 27 MA (we presently 18–20 MA)
  - 95-kV Marx Charge (typically use 80 kV)
  - 25 MJ stored (typically store 18 MJ)
  - 50-million-K plasma (have achieved 35 million degrees K, or 3 keV)
  - 0.1–1 MJ fusion yield (have achieved 500 J of DT-equivalent fusion yield)

Pulsed Power at U-M: MAIZE



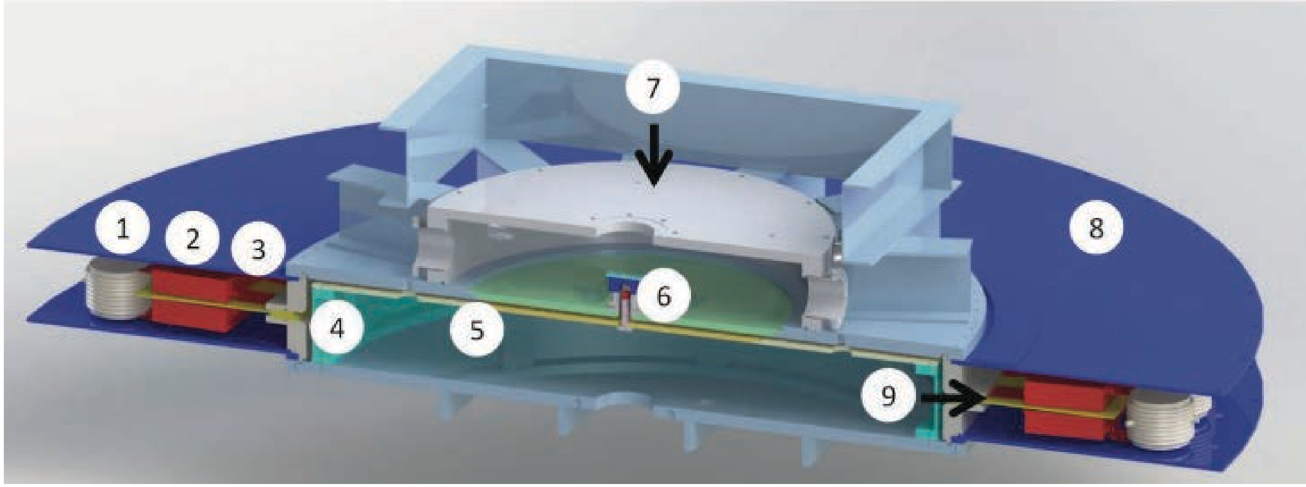
The Michigan Accelerator for Inductive Z-pinch Experiments (MAIZE)

In the NERS Plasma, Pulsed Power, and Microwave Laboratory



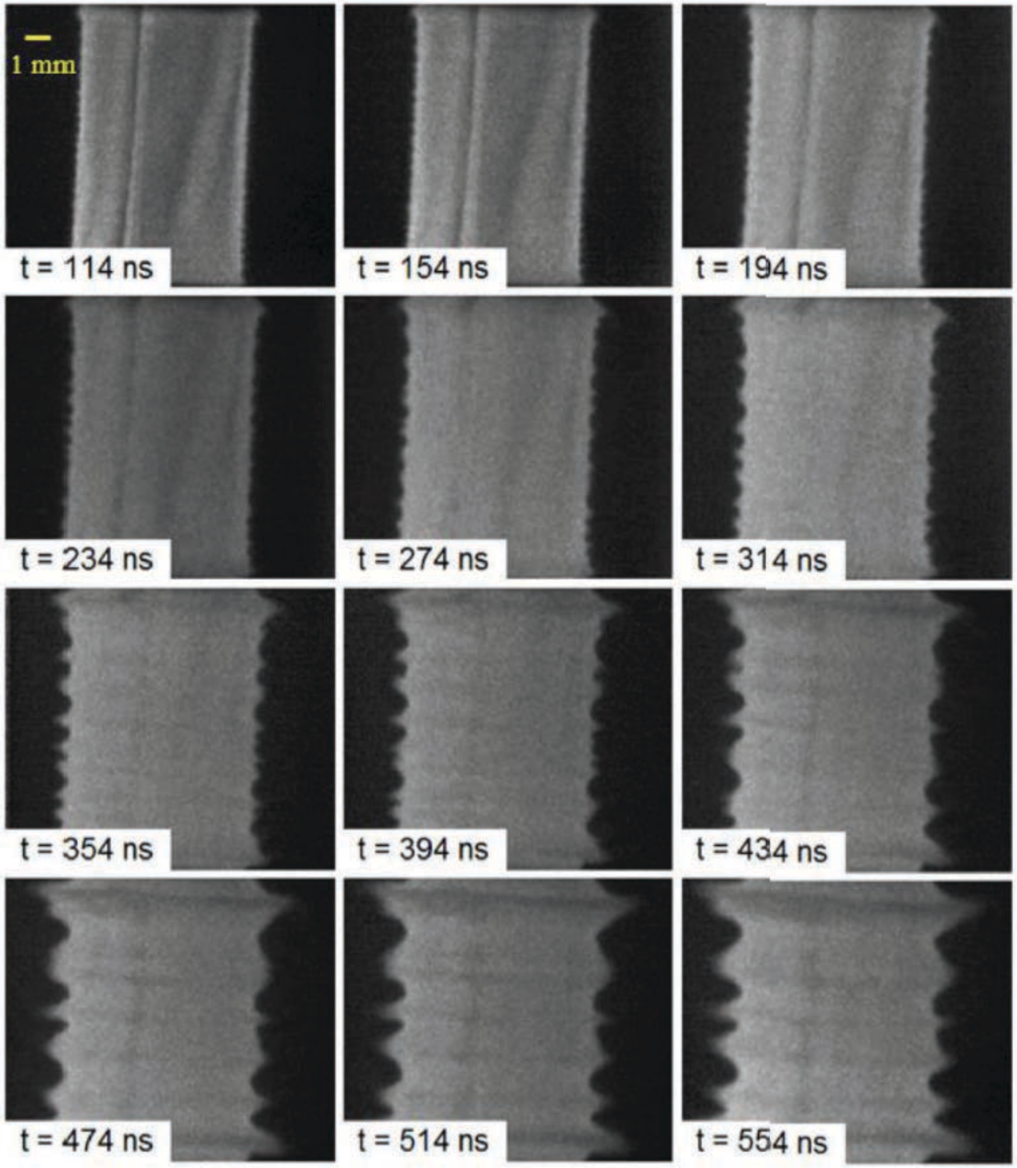
MAIZE is a Linear Transformer Driver (LTD):

~1 MA in 100 ns
~100 kV
~10 kJ, 0.1 TW
~3-m-diameter cavity



Use MAIZE to:

- Study implosion instabilities*
- Develop diagnostic instruments and techniques, which can then be transferred to Z and NIF
- Study power-flow issues
- Study the coupling of LTDs to HED matter
- Study magnetized plasma flows for laboratory astrophysics
- Create and study pulsed fusion/neutron sources as well as pulsed x-ray and gamma-ray sources



*A. M. Steiner, Ph.D. thesis, University of Michigan (2016).

MagLIF/Z Beyond 2020: Z300 & Z800

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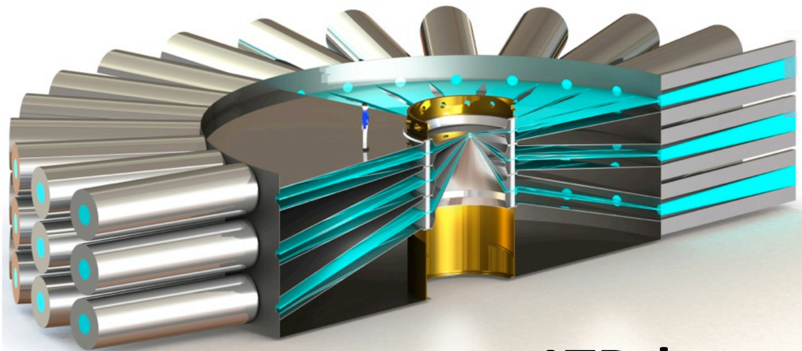


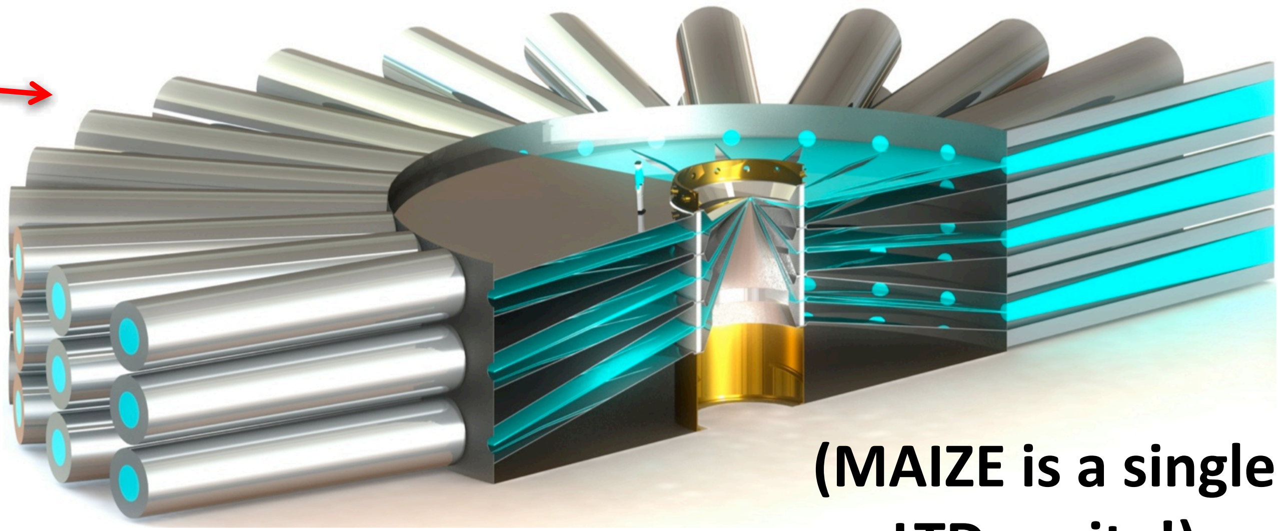
LTD-based architectures
(Linear Transformer Driver)

Z300:

- 48 MA, 320 TW delivered
- 48 MJ stored
- 30–80 MJ fusion yield
- 35 m in diameter (size of Z today)
- 2970 LTD cavities!

Z800:

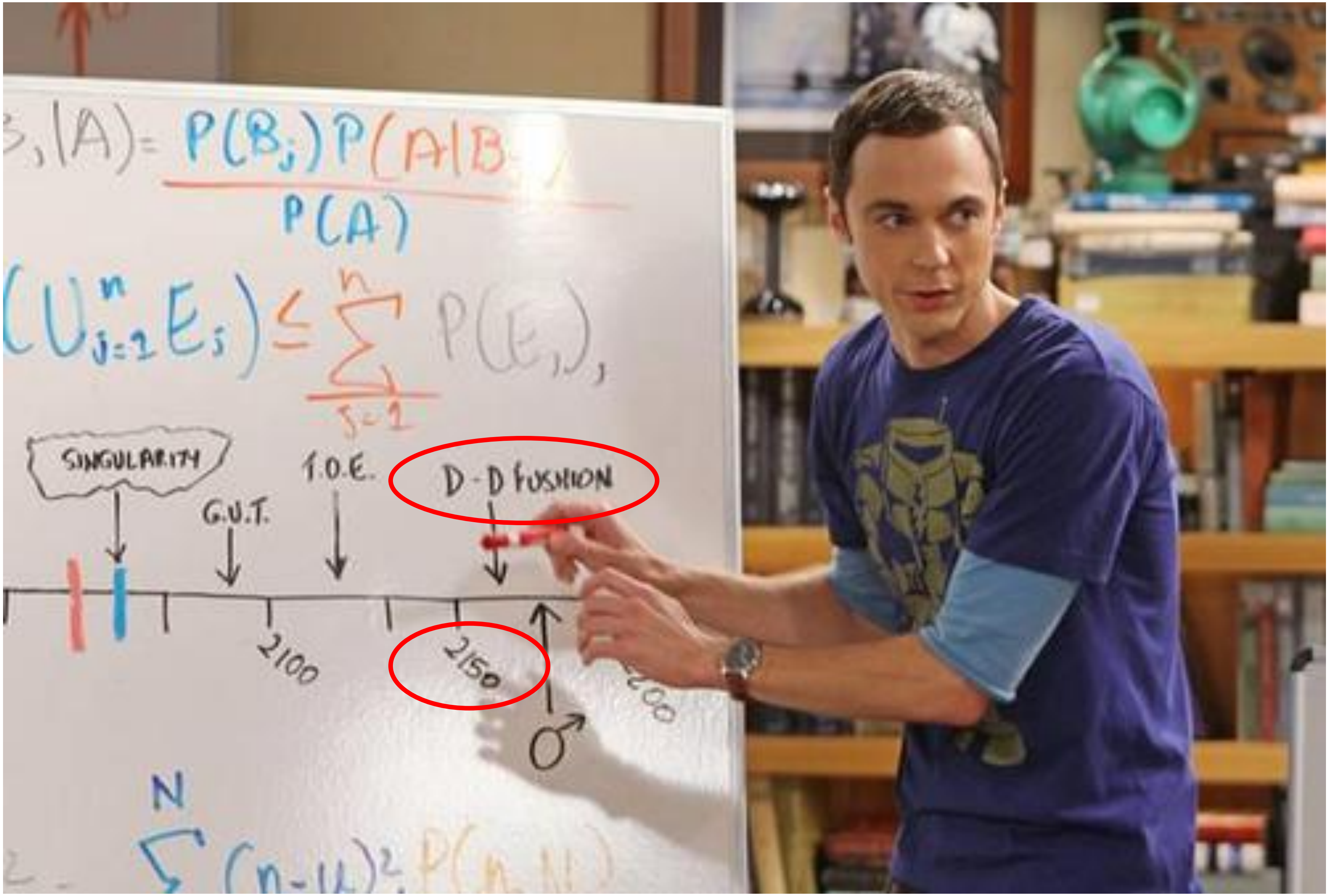
- 60 MA, 890 TW delivered
- 130 MJ stored
- 0.2–1 GJ fusion yield
- 52 m in diameter
- 5400 LTD cavities!



(MAIZE is a single LTD cavity!)

W. A. Stygar *et al*., Phys. Rev. ST Accel. Beams **18**, 110401 (2015).

So, is “fushion” ($h \to 0$) really 140 years away?



Concluding Remarks

- Pulsed power and magnetically driven implosions for fusion and HEDP are fun and exciting projects to be involved with
- Lots of U-M grads working on these projects at Sandia and elsewhere
- BBC Z Machine Clip: https://www.youtube.com/watch?v=eaopaLJk3-Y
- Thank you for your time!
- Questions?